Assessment of warning sound detectability for electric vehicles by outdoor tests

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PACS: 43.50; 43.66

ABSTRACT

Electric Vehicles (EV) are characterized by a high reduction of the acoustic emission. The absence of warning sounds entails a risk situation for pedestrians. The previous research is focused on detectability of warning sounds in different noise environments. These experiments are performed indoors, where a pedestrian's conditions are not similar to real road crossing. Drivers' behaviour study demonstrated that different environments and workload have influence on reaction time. Consequently, this paper proposes a methodology for the analysis of detectability of real warning sound using a dynamic subject. The sample was composed by 65 participants walking around a pedestrian area. Participants had to react when they detected a vehicle approaching. The subject's response was affected by background noise, therefore, this parameter was measured. The results establish that power levels have influence on the detectability. There is an optimum power level which improves efficiency of vehicle detection. Besides, warning sound features and learning effect, based on previous experience, have influence on subject response.

Keywords: Outdoors experiment, reaction time, warning sound, electric vehicle and background noise.

1. INTRODUCTION

The denominated quiet vehicles, Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) in electric mode, do not have relevant engine and other mechanical noise sources, when these are compared with Internal Combustion Engine vehicles (ICE) [1]. Consequently, EV are less audible at low speeds than ICE [2], [3]. At speeds above 35 km/h, tyre/road and aerodynamic noise predominates over engine noise [4], therefore EV are audible when this limit is exceeded.

Maximum noise level difference between EV and ICE, around 20 dB, is presented in stationary position [5]. Therefore, for slowly approaching, EV are detected at a significantly closer distance than ICE [6]. According to the National Highway Traffic Safety Administration (NHTSA), this level reduction of noise implicates an unsafe situation on the road [7]. For the purpose of reducing the crash risk, EV are going to be provided by warning sound devices.

The absence of warning sounds supposes that pedestrians only obtain the information through their visual field [8]. Consequently, this risk is higher for the unprotected group of people: visually impaired, children, elderly or cyclists. This group cannot perceive the quiet vehicles in the correct security conditions [7], [9], [10]. With these warning sounds, pedestrians would have more information about their surroundings and they could notice the vehicle presence and the driver behaviour, so they could better estimate the traffic risk.

Recently, the European Union has regulated the Acoustic Vehicle Alerting System (AVAS) installation [11]. The minimum overall level in the spectrum and in each octave band are established by this regulation. Particularly, the minimum overall noise level is set at 50 dB(A) to speeds of 10 km/h and 56 dB(A) to 20 km/h. Depending on the speed, this normative suggests a frequency shift. The speed of 20 km/h is established as maximum and the device could be disabled. The United States regulation on AVAS establishes that it will be required at speeds up to 30 km/h. The final American rule do not establish "pitch shifting" to detect the vehicle speed increase. In contrast, it replaces sound modification with noise pressure level increase [12]. The Japanese Ministry of Land, Infrastructure, Transport and Tourism has set the limit to warning sound emission at 20 km/h [13]. According to aforementioned references, EV are not allowed to exceed ICE noise level, for the same vehicle category and operating conditions.

Depending on features, there are two main typologies of previous studies and for both typologies the subject is static. 1) Research developed indoors under low background condition, as interactive evaluation of sound used by Dhammika [14]. 2) The studies emplaced at open space with real background noise. In this way, a pedestrian's acceptability to different sound on a public road was analysed [5]. This research evaluated acceptability by the subject seated when a vehicle was approaching at a speed of 15 km/h. The results demonstrated that sounds had higher acceptability than an engine noise.

The vehicle detectability was analysed at the Emerson's outdoors study, and it implied measurement of background noise [15]. 15 visually impaired people seated on either sides of the road were the study subjects. The experiment was based on the approach of different vehicles (ICE and HEV with warning sound and without it) to pedestrians at a speed of 20 km/h. The vehicle detection distance was determined during the test. The results indicated that warning sounds with a maximum energy at 500 Hz and an amplitude modulation can help to optimize the detectability.

Other studies are developed outdoors to record vehicle pass-by or background noise. Afterwards, the subject test takes place in a controlled room [16-18]. Parizet [16] studied the pedestrian's detection when a car arrives using nine sounds. The subject sampled was shaped by 100 sighted and 53 visually impaired people. The vehicle approached from a distance of 30 m at a speed of 20 km/h. It was for two road conditions, wet and dry. The results established timbre parameters which reduce reaction time. The authors concluded that efficient warning sounds have a low number of harmonics, absence frequency modulation and irregular amplitude modulation. Besides, warning sound audible range was analysed in different environments, as Yamauchi studied [17]. The experiment was characterised by 3 warning sounds, 4 background noises and 31 participants (German and Japanese subjects). The results indicated that environmental conditions and warning sounds have influence on minimum audible level. Poveda [18] examined background noise influence on warning sound detectability and established the risk for pedestrians. This research determined reaction time when a vehicle was approaching. The response of 131 participants was studied using 8 warning sounds and 3 environmental situations. At a speed of 28 km/h, the vehicle approaching was simulated under laboratory conditions. The authors showed the influence of surroundings on warning sound detectability. Reaction time can be affected by sound masking, therefore increasing background noise will decrease the detectability. Researchers concluded that warning sounds similar to ICE vehicle enhance the detectability.

The test typology inside an insulated room is justified by the importance of controlling environmental conditions, it being possible to guarantee prefixed experiment parameters. The static position of the subject presents the incertitude about what would be the response produced by the same subject in a dynamic urban environment. For instance, some conditions of the pedestrian's surroundings are being depreciated during static tests and these could not be extrapolated to real environment. For this reason, it is necessary to study the pedestrian's response under these dynamic test conditions that largely differ from simulated conditions inside an insulated room. Makishita [19] demonstrated the fact that test conditions influence on drivers' reaction time. The research established significant differences between reaction time at a public road and in a simulated city street. According to the study, experiment conditions influence on psychoacoustic behaviour of listeners.

Therefore, the investigation focuses on the following characteristics. The experiment is carried out at a pedestrian area. The subject is walking and carrying the equipment. Background noise is measured during the experiment. The signals simulate a vehicle approaching at a speed of 30 km/h. During auditory test each sound is presented at 3 sound levels.

Prime objectives have been identified as: 1) determing background noise influence on detectability, 2) comparing efficiency of different warning sound to reduce pedestrian's risk [20-22] and 3) defining subject's behaviour with respect to warning sound noise level. The goal of the present study is to improve EV auditory detectability, but limit noise pollution generated by this source.

2. METHODOLOGY

The experiment evaluated the audibility of EV on street-crossing simulation. The subjects were tested outdoors and background noise was recorded. They perceived warning stimuli through headphones while they were walking. More details about the research method are provided in the subsequent sections.

2.1. Sound stimuli

Different warning sounds were extracted from bibliographic references [20-22]. Signal sounds used for the tests were selected as all of them allowed evaluation in similar test conditions. Consequently, the following conditions were established as criteria choice: frequency content of sounds should not present relevant changes over time, audio files should not include background noise and should be considered same motion condition, namely stationary vehicle.

To select warning sounds, those which had opposite results of annoyance and suitability were considered, according to Delta Senselab evaluation. Warning stimuli considered as slightly annoying were: “Q4noise”, “Jet4low” and “Low Friction”. Other two signals included in this study as moderately and highly annoying were: ”Motorgear” and “N-Clean”.

During warning sound design, the frequency was considered to improve efficiency. All these signals concentrated their energy at the optimal frequency range between 100 and 2000 Hz, as shown in Fig. 1.

The “Jet4low” concentrated the energy on the low frequency range, specifically between the interval of 100 to 1000 Hz. This sound presented a predominant contribution near the band of 250 Hz, with regard to remaining octave frequency bands.

“Low Friction” signal was characterized by having a reference frequency around 300 Hz, although lower frequencies included an important energy concentration until 100 Hz. This stimulus showed a larger energy distribution for the different spectrum frequencies, when it was compared with other acoustic signals.

Energy was concentrated at low frequencies in the signal “Motorgear” in the range of frequencies from 100 to 500 Hz. At the same time, different harmonics nearby the frequencies of 700, 1000, 1300 and 1600 Hz were contained on the spectrogram.

The energy in “N-Clean” signal was located predominantly at frequencies 125 Hz and 250 Hz, but it also showed the energy density distribution at the spectrum until 4000 Hz.

“Q4noise” sound was characterized by having higher energy density at low frequencies, in the interval between 250 Hz and 500 Hz. Furthermore, this stimulus presented alternative peaks around 200 and 300 Hz.

At the European regulation [23] the limitation for the sound level generated by the AVAS was determined. In this way, EV could not overtake the ICE sound levels included in the same category (M1) operating under the same conditions. That limitation was considered during the tests.

For this reason, the sound power level of a light vehicle with an ICE was quantified using the “Mèthode de Prévision du Bruit des ROUTES - NMPB” [24]. This French model was established to consider the noise produced by traffic flow. Sound power level produced by a model vehicle was established at 92 dB(A). This value was extracted by extrapolating Pass-by model for traffic flow to individual motion vehicle and setting estimated operating conditions. Vehicle motion was

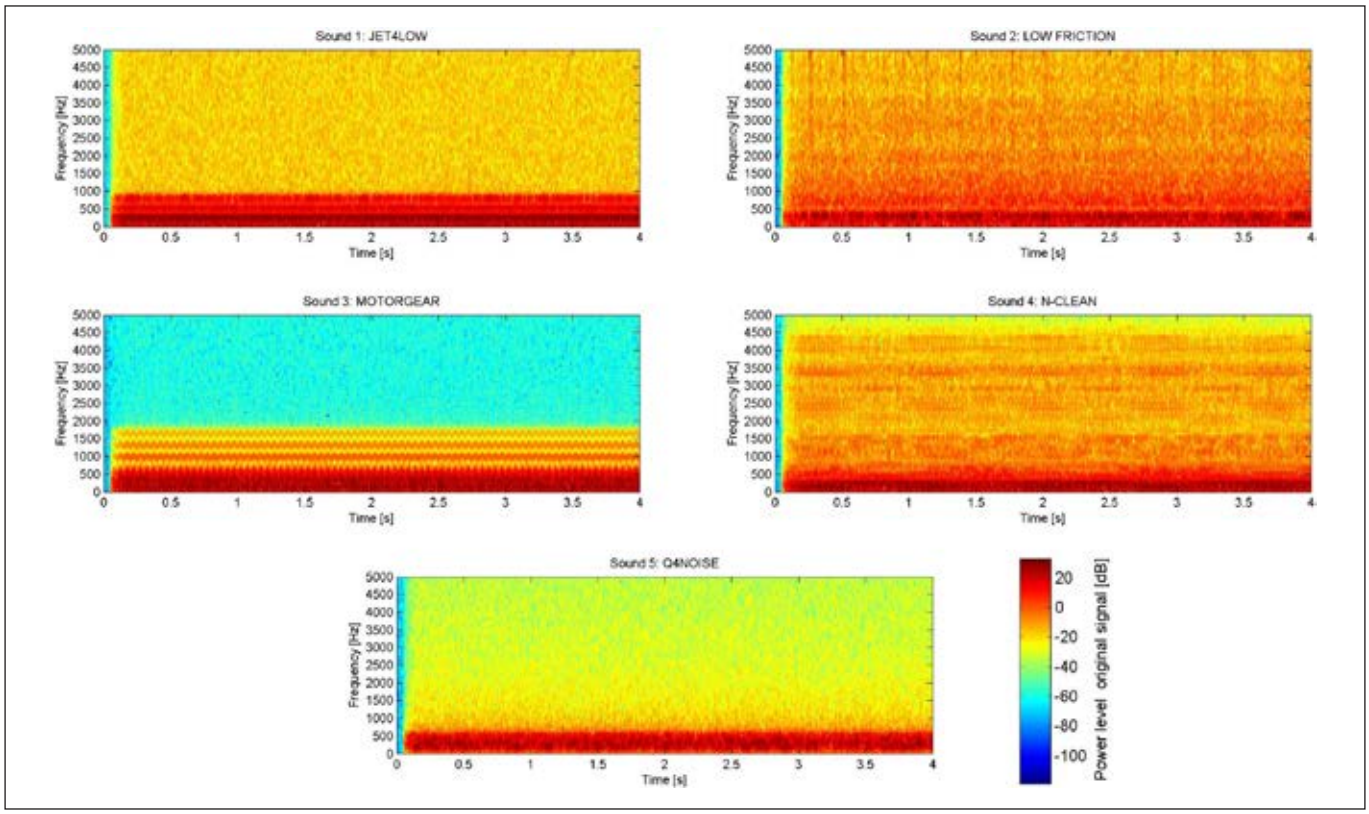

Figure 1. *Spectrogram of the different warning sound signals used during the tests.*

simulated at a constant speed of 30 km/h on an intermediate asphalt R2 [24]. In the R2 asphalts category BBTM 0/10 type 1, BBSG 0/10, ECF, BBUM 0/10 surfaces were included.

A pedestrian was positioned 2 m from the centre of the vehicle (minimum distance between subject and car) and EV was located at a 30 metre distance from ahead of the subject, according to Fig. 2. Under these speed and distance conditions was established the recording length.

The possibility of reducing road traffic noise level was analysed through source noise reduction. Consequently, a pair of sound power levels were established at 85 and 75 dB(A). These were considered below 92 dB(A) limit, justified by the fact that these warning sounds were designed to be more efficient than ICE sound. This estimation was considered to analyze the relevance of the sound power level into detectability of each signal. At the same time that the signals could reduce reaction time with a lower sound power level, these could reduce pollution and increase pedestrian safety in cities. Hence, five warning sounds were used in the study, each of them for three power levels.

Audio recording of warning sound was processed to simulated the Pass-by of a vehicle provided with an AVAS, it was considered circulating at a steady speed. Also, the pressure level attenuation by distance and Interaural Time Difference (ITD) was considered. The peak pressure levels issued by the vehicle were set at 78, 71 and 61 dB(A) depending on the power level considered, as it is represented in Fig. 3.

Between output signal and the real stimulus there were not a linearly related, due to the fact that input impulse in the frequency spectrum was modified by the response emitted. This effect produced by the headphones was corrected by impulse response inverse filter.

2.2. *Instruments setup*

The subjects carried different elements to allow execution, control and registration, while they were walking around the area. This situation implied that experimental setup should be lightweight and easily transported. These devices were a laptop inside of a shoulder bag, a microphone, headphones and a push-button.

The real background noise was acquired in auditory test by means of a microphone. On the one hand, environmental noise recorded in the area showed if there were anomalous tests. As well, the background noise level during the experiment was measured.

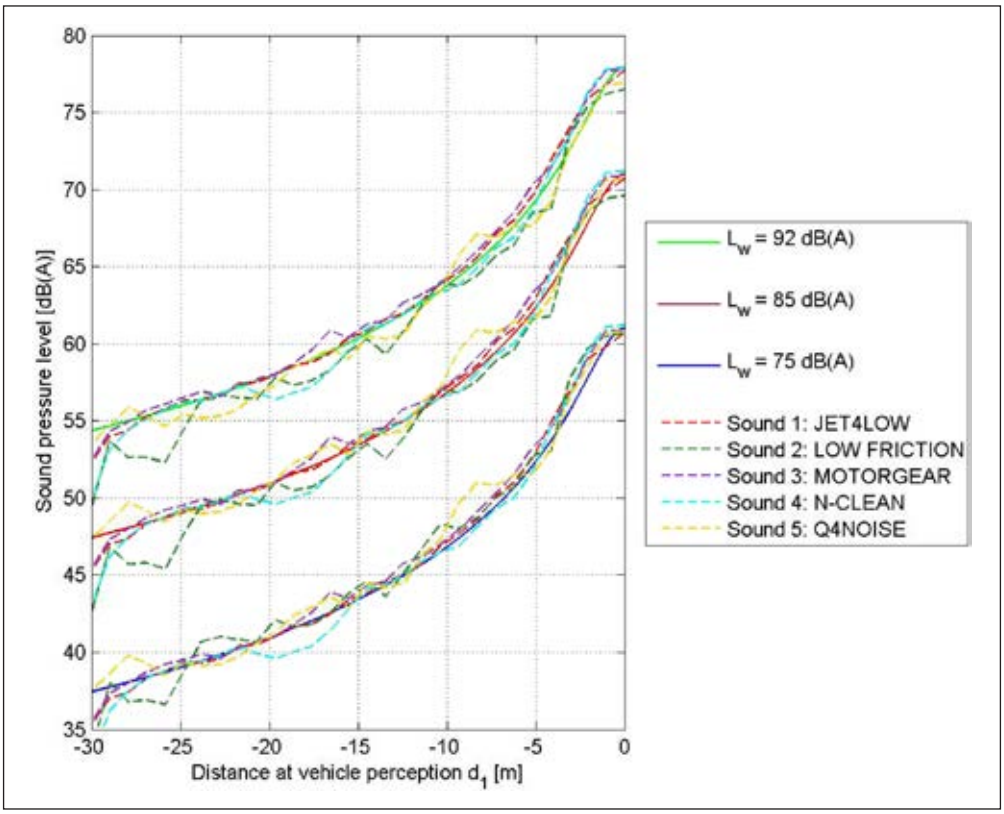

Figure 2. *Schematic representation of the investigated Pass-by condition.*

The laptop was used as a government element, allowing the process control and recording the parameters. The subject transmitted his or her response to stimulus through the push-button and then these data were sent to recording device. Headphones were used to simulate the sound of approaching vehicle, according to Fig 4.

2.3. Procedure

All tests were developed in the same pedestrian zone, in order to ensure the same conditions for each listening test and minimize environmental influences. The area was composed by concrete sidewalk and some ground plots with ornamental trees, flowers and grass, as shown in Fig. 5. The background noise was low with few human disturbances, allowing to diminish the presence of invalid subjective test (anomalous measures).

During the test, subjects were walking around the area. Acoustic stimuli were presented in random order and sequence was different for each subject. Time interval between warning sound was variable. Test simulated a vehicle provided with a warning sound when it was approaching to a subject, as it is shown in Fig. 2.

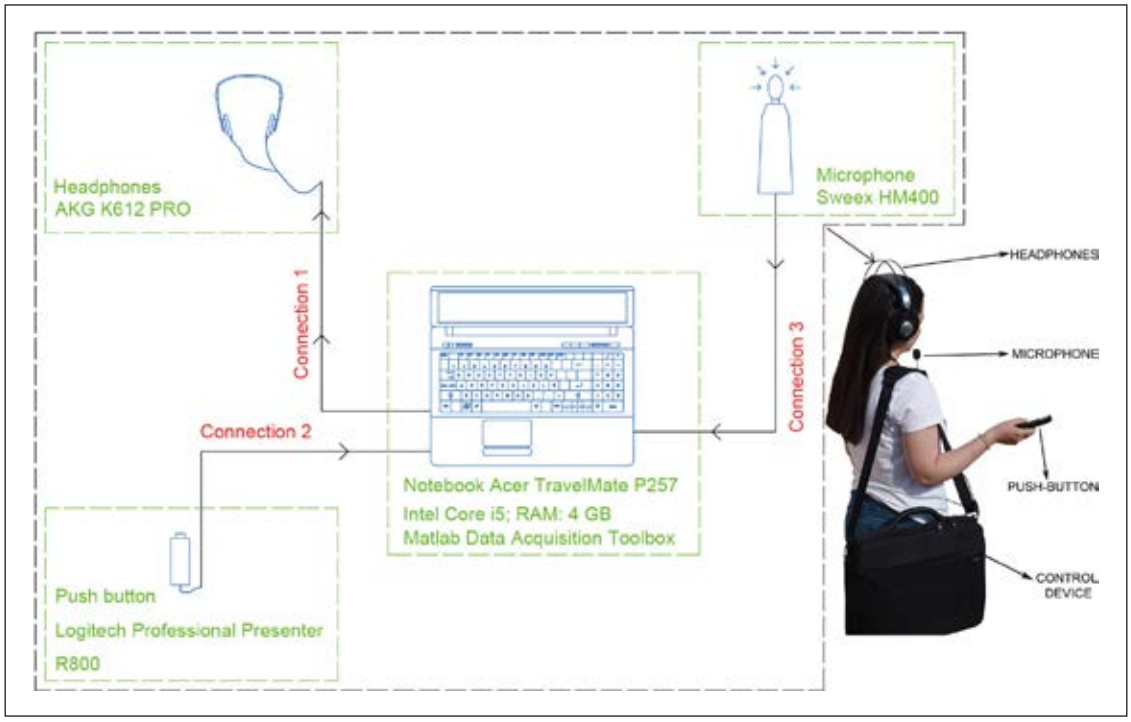

Figure 3. *Pressure level as function of the approaching to pedestrian.*

Figure 4. *Essay setup.*

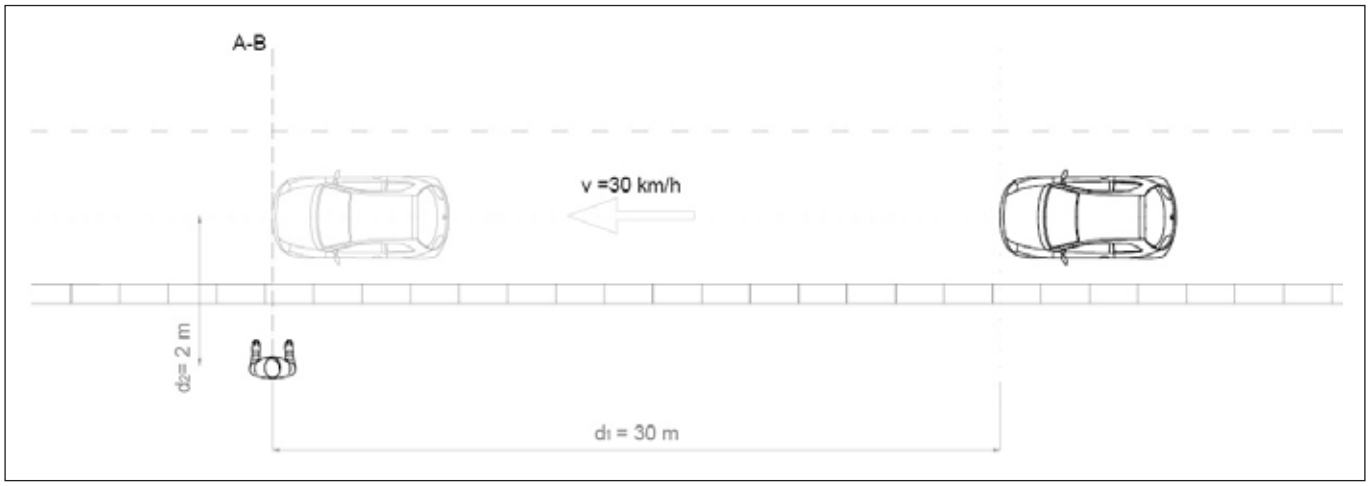

Figure 5. *General views of the test location.*

Some disturbing sounds were added to the signal, such as those made by a tweeting bird or a barking dog. Since the study also took into account the association between sound stimulus and the presence of vehicle, the disturbing sounds eliminated the possibility that the subject impulsively reacted to any environmental sound, therefore sound was always related to noise source.

Road-crossing was explained to the participants, they had to detect a vehicle arriving to them. When warning sound stimulus was associated with a vehicle, subjects had to record their response in the shortest possible time. If the stimulus was associated with environmental source, subject should not react. Response time depends on the perception time and the association time.

2.4. Background noises

The experiment was developed outdoors and different sounds were presented to subjects using the open headphones AKG K612 PRO. For this reason, each test was conditioned by different background noise produced at the environment.

During the auditory test, the subject received two background noise, first of them was a pink noise and the second one was a real environmental noise. The standardized background noise was applied for two purposes, to guarantee a minimum background noise level and to avoid the annoyance caused by eardrum vibration when the ears were covered by headphones.

The pink noise was added by the headphones to real background noise. This normalized noise was implemented with an equivalent sound pressure level of 37 dB(A). That result was extracted considering vehicle simulation conditions. The minimum sound pressure level produced by a EV equipped with AVAS was established at 75 dB(A) for a 30 m distance to pedestrian, it is presented at Fig. 3.

2.5. Subjects

In the study participated 65 subjects, comprising 50 males and 15 females aged between 16 to 58 years old. None of them reported any hearing impairment.

Through post-test analysis were excluded non-valid subjects due to presence of impulsive reaction to environmental noise or anomalous background noise measurements. 10 subjects were discarded. Finally, 55 listeners took part in the study, comprising 41 males and 14 females.

3. RESULTS

3.1. Effect of background noise on reaction time

The background noise is used to consider the circumstances surrounding the subject during auditory test. The acoustical environment was considered as the equivalent continuous background noise level (L_{Aeq}). This parameter was measured using fast time weighting. Testing period was established between the beginning of the pass-by simulation and the moment when subject responded.

Fig. 6 shows the reaction time recorded by subjects as response to the stimuli during the experiment. The subjects who did not react within the established time

interval for the approaching vehicle are not represented, this part of the sample is considered in Fig. 7 and 8.

The five warning stimuli are presented at different sound levels, these are shown using points markers: green, blue and red. Different power levels of warning sound were independently analyzed, however results showed that sample behaviour tended to be similar. As it is observed in Fig. 6, the reaction time of the sample tends to increase when background noise is louder, this means that the listeners need a higher time interval for their reaction. Moreover, comparing power levels is possible to establish that the subject takes longer to produce his or her response when this parameter is lower.

Background noise levels were analysed for different reference levels, as is presented in Table 1. Noise recorded during auditory test were characterized using statistical descriptors. Independent measures were established using three separate samples that gave the same results, the mean valour was around 50 dB(A) and standard deviation was approximately 5 dB(A). The results showed that these parameters did not present considerable differences for the different power levels.

Reaction time statistics are shown separately for each power level of warning stimuli in Table 2. Reaction time difference between intermediate reference level and the low one was 0.82 s. On the other hand, reaction time between higher and intermediate levels tended to be reduced, being the difference of 0.18 s in absolute terms. No significant differences in response between higher and intermediate level were detected. However,

Table 1. *Statistical parameters for background noise recorded in auditory test.*

Reference level [dB(A)]	92	85	75
Mean [dB(A)]	50.36	50.03	50.26
Standard Deviation [dB(A)]	5.01	4.96	4.90

Table 2. *Statistical parameters for reaction time by power level.*

Reference level [dB(A)]	92	85	75
Mean [s]	1.61	1.79	2.61
Standard Deviation [s]	0.93	0.94	0.96

low level made that subjects' response to warning sound were slower. Standard deviation of reference levels was around 1 second.

This comparative shows that all different power levels were evaluated under the same environmental conditions. Nevertheless, the reaction times suggested that subjects required less time to response when warning sound increased. Being possible to establish that there is a relationship between reaction time and power level of the warning sounds.

3.2. Comparison of auditory reaction time and levels

As explained in the previous subsection 3.1, all warning sounds were presented to the subjects under similar background noise. Auditory tests of all subjects were carried out in pedestrian zone and mean of background levels were presented on the same order independently

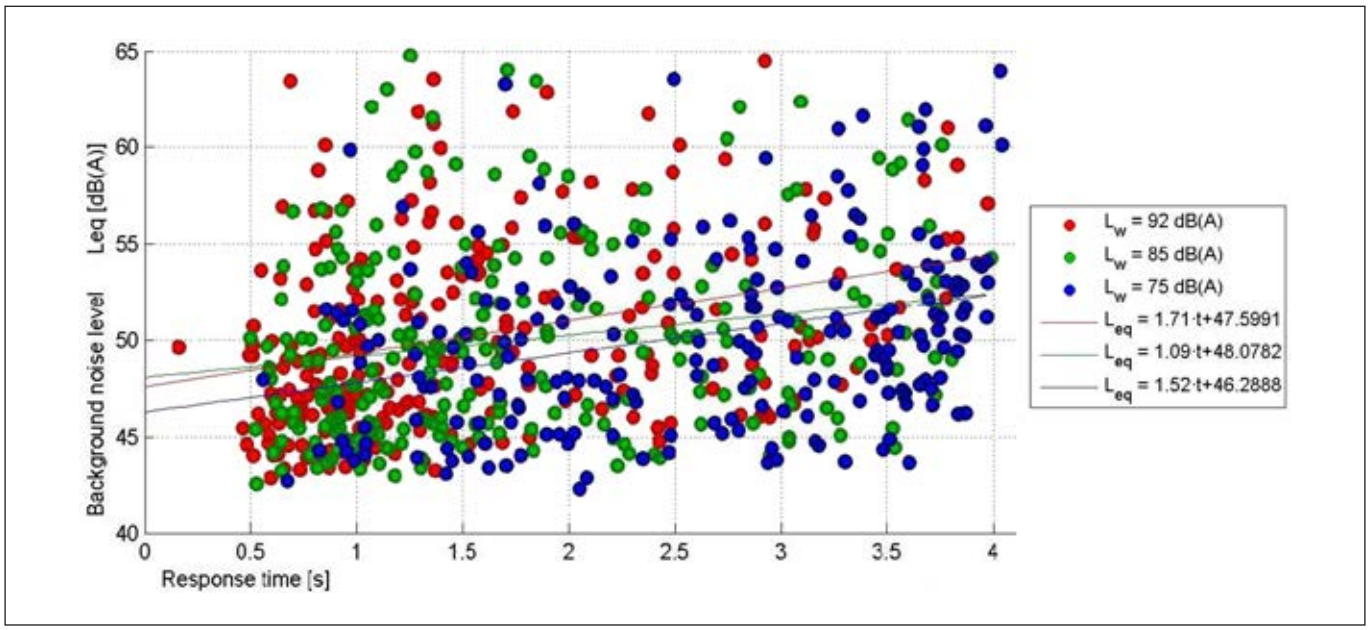

Figure 6. *Reaction time to vehicle as function of background amb ient noise level and sound power level.*

for each sample (see Table 1). Therefore, this subsection analyzes participants' responses, without taking into account background noise. Fig. 7 shows the distribution of sample percentile response time depending on three reference levels. To obtain these reaction time distributions for each power level, the 5 warning stimuli were considered.

As can be seen in Fig. 7, the 50th percentile reaction time of the intermediate power level was 1.6 s. However, reaction time was 3.12 s when warning stimuli was presented at low power level. The difference in the reaction time percentile between these reference levels was 1.52 s. The response percentile indicates that interval time increase notably by the low power level signal.

Response difference was presented in all percentile ranges. This reaction time gaps between the low and the intermediate levels were 0.93 and 1.11 s, for 25th and 75th percentiles respectively. Hence, time interval is reduced around 1 s, but it continues being relevant. As can be determined through the intermediate and the low power level, reaction time tends to reduce when source level increases.

Related to the previous paragraph, the 80% of the subject sample reacted to the warning stimuli before 4 s for the low power level. In contrast, the 95% of the subjects detected the vehicle before 4 s at the intermediate. This sample behaviour revealed that this power level of 85 dB(A) improved the detectability more than 75 dB(A) in the same environment.

On the other hand, similar response distributions were observed between the higher and the intermediate power levels. This comparative showed that the subjects' response converged to similar reaction times. Owing to the maximum difference reaction time was 0.24 s (75th percentile) and minimum difference was 0.13 s (25th percentile). However, the source noise level increase of 7dB(A) is relevant considering the vehicle accumulation in cities. This situation implicates a noise rise that is not justified by the short detectability difference between both levels. Summarising, the results show that the optimum warning sound level is 85 dB(A).

3.3. Evaluation of warning-sound at optimum level

The optimum power level is established at 85 dB(A) derived from the analysis developed at the subsection 3.2. Consequently, it is possible to achieve good levels of detectability without compromising the acoustical environment. For the power level of 85 dB (A), the responses to the different warning signals are analysed, as can be seen in Fig. 8.

During the test, eight subjects did not react in response to "Q4noise" signal, these non-response participants

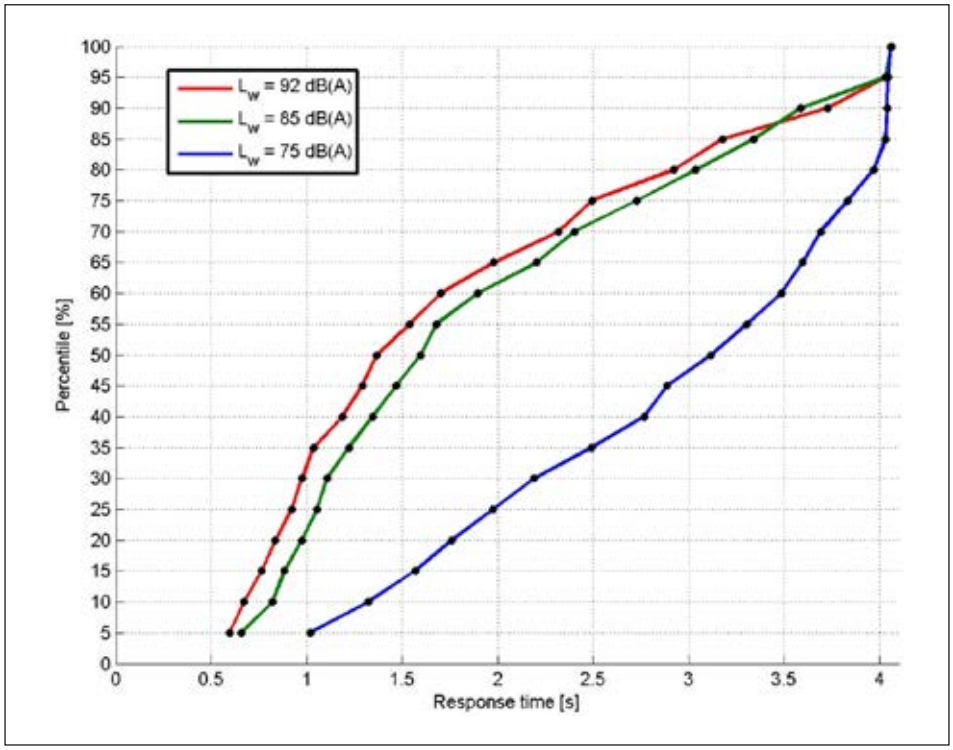

Figure 7. *Distribution of response time with different sound power levels.*

represented a relevant percentile around 10%. Comparing the subjects' responses, it is possible to know that "Q4noise" presented more adverse responses than others used signals. This fact indicated that this warning signal presents a low association with a road vehicle.

"Low Friction" was the second stimulus with slow participant response times. Similar behaviour than "N-Clean" and "Jet4Low" signals. Despite this, the trend showed that "N-Clean" was more detectable than "Jet4Low", as is presented in Fig. 8.

Finally, the most efficient warning sound was "Motogear", it was probably justified because this sound simulated ICE sound. The reaction time is influenced by the time period between the beginning of the approach vehicle simulation and the sound identification. Due to this fact, "Motorgear" sound presented a reduction on the time interval required by pedestrians.

Significant differences were presented between reaction time of "Motorgear" and "Q4noise", the most efficient and inefficient, respectively. For the 50th percentile, time gap between both warning sounds was 0.52 s. However, 2.04 s was the response time needed by subjects to react to "LowFriction" at 50th percentile while "Motorgear" presented a time of 1.30 s. Consequently, the difference between them was 0.74 s.

The analysis determines that pedestrians' behaviour is influenced by warning sounds features. By means of outdoors experiment, it is possible to determine that the warning stimuli that is closely associated with a road vehicle shows an earlier response.

4. CONCLUSION

The present paper proposes an alternative dynamic pedestrian test carried out outdoors, instead of the current indoor test. The laboratory test improves the control of variables, however the subject's surrounding are less similar to urban environments. The pedestrian's behaviour was evaluated in similar real conditions thanks to the proposed test using more parameters than the laboratory test.

The experiment was developed in a quiet area and a wide sample of 55 subjects was taken into account in order to control disturbance on parameters. Background noise was recorded to analyse the influence on response for each subject. During the test, it simulated an approaching vehicle at a speed of 30 km/h from 30 m while the pedestrians were walking.

Study results show that it is possible to establish a relationship between power sound level and reaction time, when warning sound increases the pedestrian's response time decreases. This trend is presented for warning sound power under the level established as

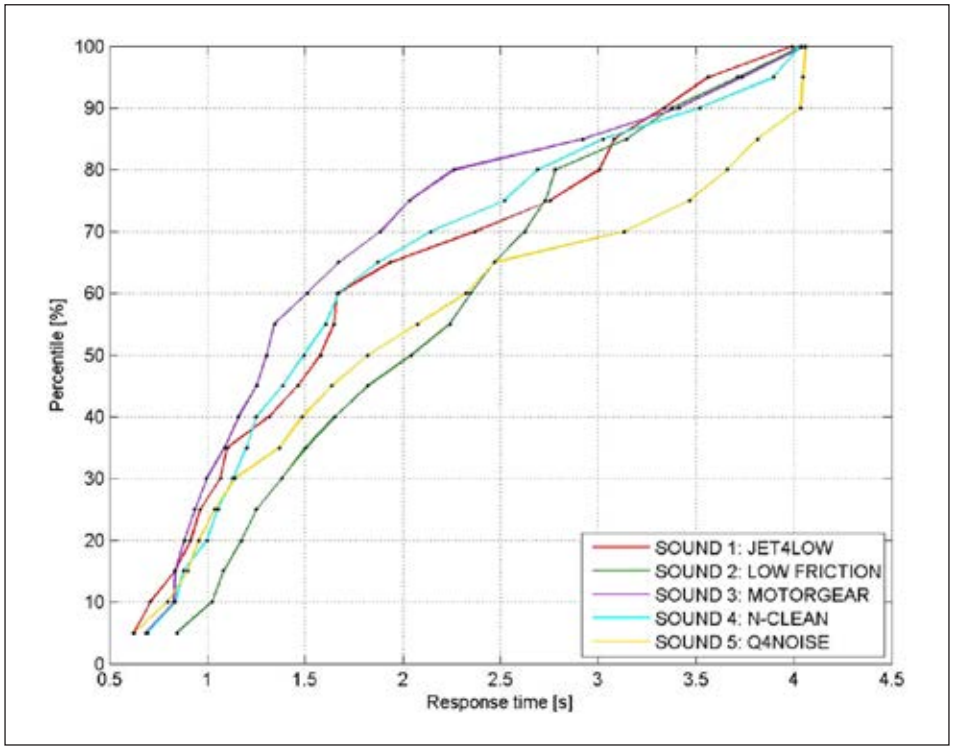

Figure 8. *Distribution of response times with different warning sounds at same power level of 85 dB(A).*

optimum, from this value the detectability is the same order and shows independent behaviour of the power signal.

The optimum power level is 85 dB(A) under experiment conditions. The optimum is justified because a higher level does not improve pedestrian safety, since auditory detectability is similar as shown in Fig. 7. However, this increase produces a significant growth in noise pollution in urban areas where the number of vehicles are high.

The results prove the influence of background noise on detectability, and it has been shown that when raising the background noise the reaction time increases. Hence, the safety conditions are reduced at the same power level. This relation is consistent with previous research developed indoors [17], when the subject does not walk and does not interact with the surroundings.

Statistical distribution shows the contribution of each sound to improve the detectability. The warning sounds are ranked based on their efficiency in the following order: “Motorgear”, “N-Clean”, “Jet4Low”, “Low Friction” and “Q4noise”, grouped from the more easily detected signal to less efficient sound. “Motorgear” is more efficient sound than the other analysed signals, this fact is probably justified by the influence of previous experience. “Motogear” sound simulates ICE, which is associated with a vehicle coming more quickly. Consequently, reaction time is significantly lower for this warning signal. Similar conclusion is presented in other studies [18], [25] using different stimuli and indoor exposure.

The study presents limitations with respect to the control experiment, increasing the incertitude of measurement. In contrast, the control of parameters is guaranteed during indoor experiment. Consequently, the present methodology is proposed as a complementary study that would validate results in a controlled environment through conditions similar to reality. These experiments would allow a comparative analysis between qualitative test (real pedestrian behaviour) and quantitative test (quality control of measurement).

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