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Study of the effectiveness of electric vehicle warning sounds depending on the urban environment

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ABSTRACT

Electric and Hybrid Electric vehicles (EV and HEV) seem to be the future of transport in smart cities and the key for the total reduction of noise disturbance and pollution in urban areas. However, several problems have to be solved to guarantee the safety of these types of vehicle. Up to now, the use of HEV has shown the dangers of a "quiet" transport system in urban environments; in fact, it has been estimated that an HEV is twice as likely to be involved in a pedestrian crash as would be an internal combustion engine (ICE) vehicle in the same situation. With the aim of improving their safety, different kinds of warning sounds are being designed to increase the detectability of EV and HEV without themselves becoming new annoying sound sources. The sound directivity, frequency of emission and intensity of warning sound systems will guarantee their efficiency and limited noise impact.

Several research works bring to the fore a significant variation of the pedestrian response time to different acoustic stimuli. However, it is necessary to examine the suitability of these warning sounds according to the urban environments in which they are going to be emitted. Distinct areas inside the city have different soundscapes whose spectral content can vary significantly, masking some of the sounds suggested as an alert.

This paper analyses in detail the main characteristics of several warning sounds proposed by the industry, conducting a comparative study of the different design trends. A total of 131 sighted listeners were exposed to a virtual road-crossing test. The behaviour and appropriateness of warning sounds are analysed depending on the urban environment. For this purpose, three clearly different soundscapes have been selected: stopped vehicles at a traffic light, a pedestrian shopping area and the vicinity of a playground. The results highlight the wide variability in pedestrian reaction time for the different warning sounds used. Some signals considerably improve the detectability of the vehicle, providing results even above the ICE vehicle ones. However, other warning sounds do not decrease the reaction time with respect to the EV. In addition, a clear dependence is observed between the detectability and the soundscape involved, changing the results for the same warning sound depending on the acoustic environment.

1. Introduction

Air quality in urban areas, as well as the reduction of non-renewable energy source dependency are two of the most important challenges that today's society has to deal with. EVs and HEVs could be an important step in the reduction of gas emissions and thus, a vital part of the solution for urban environment pollution. Moreover, the use of electric engines as propulsion systems considerably reduces the noise emitted compared to internal combustion ones. This behaviour may help to reduce the environmental noise in urban areas. It is important to emphasise that traffic noise, according to The World Health Organisation, is responsible for over 20,000 deaths each year from resultant cardiovascular problems, sleep disturbance, cognitive impairment and other diseases resulting from noise.

Despite the many advantages presented by EVs and HEVs, some outstanding issues are still to be addressed. Under some situations, the noise generated by tyre/road contact may be high enough to alert the pedestrian of an approaching vehicle. However, the level of noise can be reduced under other circumstances, particularly when the speed decreases. This behaviour is illustrated by Lelong

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et al. [1]. This study analyses the sound pressure level generated by several vehicles at different speeds. The results reveal a significant difference between internal combustion engines and hybrid/electric engines, especially at speeds below 50 km/h. Other studies [2,3] show similar results on the comparison of sound generated by different propulsion systems.

Low levels of noise emitted by EVs and HEVs may represent a significant danger to pedestrians and cyclists, and especially for visually impaired people. Garay-Vega et al. [4] describe some critical safety scenarios in order to analyse the influence of electric vehicles on the auditory detectability by visually impaired people. The experiment consists of a laboratory listening test and uses binaural recordings from different vehicles. The study shows an increase in the pedestrian reaction time when an EV is present. Similar results are obtained in [5] by two types of assessment: threshold level tests and reaction time experiments. Different vehicle sounds are presented to the listener together with a background noise. The approach of an electrical vehicle at low speed turn out to be less audible than an ICE vehicle. Similar results are obtained in [6] by a reaction time experiment, over 37 subjects, using 14 ICE vehicles, 4 HEV and 6 EV.

These results are consistent with [7], which establish that an HEV is two times more likely to be involved in a pedestrian crash than would be an ICE vehicle in the same situation. To overcome this problem, it is proposed to provide the vehicles with an Acoustic Vehicle Alerting System (AVAS). Nevertheless, some issues should be resolved. On the one hand, the level of noise generated by the warning sound system must not increase the environmental noise pollution. On the other hand, the features of this sound should be selected appropriately to increase the auditory detectability. These questions have already been discussed in the literature. Wall Emerson et al. [8] examine the auditory detectability of different vehicles (ICE, HEV and EV with and without warning sounds) at 20 km/h by an in-situ experiment. The study was performed on a small group of blind people under low background noise level. Five alerting sounds were synthesised and emitted by a loudspeaker installed on an electric vehicle. Listeners had to indicate the detection of an approaching vehicle in order to establish the reaction time. Some warning sounds used on the experiment improve the detection of the vehicle. The authors conclude that sounds with amplitude modulation and a maximum of energy of 500 Hz, are more suitable for auditory detection. Another laboratory study [9] confirms a variation on the reaction time depending on the warning sound features. In this case, 10 different alerting sounds were used in a laboratory test. The warning sounds were classified into two groups depending on some basic features: modulated rate and spectral flatness. Sounds were processed and mixed with an EV recorded noise to simulate an approaching vehicle at 20 km/h. The authors conclude that continuous signals are less suitable for increasing the detectability of quiet vehicles. Yamauchi [10] examines the level of different warning sounds to be detected in a number of urban background noises. For this purpose, a group of people was polled by means of an auditory test in order to adjust the level of each sound using different soundscapes. The type of alerting sound as well as the level of the background noise significantly affected the results. On the other hand, Parizet et al. [11] study the reaction time against several alerting sounds in a pass-by auditory test simulation at 20 km/h. For this purpose, nine warning sounds were designed taking into account three main characteristics: number of components, frequency modulation and amplitude modulation. The study was conducted on a large group of people, with normal vision and visually-impaired. The results reveal the improvement of some warning sounds on the detectability of EVs. Similarly, a significant influence of the design characteristics on the reaction time was found. Warning sounds with a small number of harmonics, prominent AM and unmodulated frequency resulted more suitable for detectability issues.

The studies mentioned up to now underscore how useful warning sounds can be. For that reason, different Government Administrations are drafting a specific regulation for the use of AVAS. First drafts [12] suggest the use of warning sounds similar to the current ICE noise, with a certain level in the 300–5000 Hz bandwidth. The sound should be modified according to the speed of the vehicle and it will be active for velocities below 30 km/h. On the other hand, the Japanese Government [13] established that AVAS should automatically be activated at least during the speed range below 20 km/h. In the same way, it proposes the use of sounds similar to ICE vehicles noise, prohibiting the use of alerting signals with clearly pointed tonal components such as bells, sirens or horns. The sound must not exceed the level of sound generated by the traditional ICE vehicles. Similarly, the European Union [14] has set the operating rate of warning sounds system in the range of speeds from start up to approximately 20 km/h and during reversing. The alerting sounds should be similar to the sound emitted by an internal combustion engine.

Any expected regulation refers to the urban environment, a key factor in auditory detection. Requirements, both level and spectral content, will be different depending on the soundscape surrounding the vehicle [e.g. industrial area against residential area]. On the other hand, most of the drafts coincide on the use of AVAS for speed ranges below 20 km/h. This recommendation is below the maximum speed limit (30 km/h) allowed in residential areas by a large majority of countries. According to [1], the level emitted by an ICE vehicle and an EV at low speeds is clearly different. As speed increases, the difference is reduced, being negligible at 50 km/h. At 30 km/h, the difference in emission levels is still significant and therefore, the limit of 20 km/h recommended by the regulation could be set below the real needs, which leaves an insecurity range.

Due to the foregoing, additional research should be performed on the use of warning sounds. The detectability of vehicles with speeds above 20 km/h, as well as the influence of the soundscape surrounding the vehicle must be studied in detail. The present study is a contribution to the detectability of electric vehicles. The main objectives are: (1) to determine the risk for pedestrians of an approaching vehicle at 28 km/h; (2) to test the influence of background noise on the pedestrian reaction time; (3) to perform a comparative study of different warning sound design trends: (a) similar sounds to current internal combustion engines [12–14]; (b) sounds with a small number of tonal components and modulation [8,9,11,15]. The study has been developed in a laboratory environment through auditory tests.

2. Methodology

The present study consists of an auditory test that simulates a road-crossing situation. The experiment was performed in a laboratory room by means of headphones. Different warning sounds were presented to the listeners under various background noises. The following subsections describe in detail the procedure and the stimuli used during the test.

2.1. Procedure

An auditory test was performed to determine the listener's reaction time to different warning sounds. The essay recreated a road-crossing situation: a pedestrian standing on the sidewalk, at a distance of 3 m from the centre of the traffic lane, prepared to cross the road (see Fig. 1). Vehicles approached the listener individually at a speed of 28 km/h; covering a distance of ±30 m from the pedestrian.