WARNING SOUNDS FOR ELECTRIC VEHICLES

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ABSTRACT

Electric vehicles (or hybrid ones) are very silent at low speeds (below 30 km/h) and can be dangerous for pedestrian, especially vulnerable ones as visually impaired people. The European founded project eVADER aims at developing a prototype vehicle including an automatic pedestrian detection device and an array of speakers focusing a warning sound in the direction of the pedestrian. The warning sound should be optimized too, in order to be easily detectable while not too loud. Research is conducted in order to investigate the influence of some timbre parameters on the detectability and annoyance of warning sounds.
Different warning sounds were synthesized according to a fractional factorial design. Factors were related to three basic timbre parameters. Two laboratory experiments took place. The first one focused on detectability. The task of the listener was to detect an approaching car (20 km/h) as soon as possible. The second experiment was devoted to the unpleasantness of warning sounds. Stimuli were presented to listeners who had to evaluate their unpleasantness on a continuous scale.
The tests have shown that some warning sounds can make an electric vehicle as detectable as a diesel car, for a much lower sound level. However, most warning sounds also tend to increase the unpleasantness of the car sound. Nevertheless, some signals seem to provide a good compromise between the two objectives.

KEYWORDS – Electric and Hybrid Vehicles; Warning Sounds; Pedestrian Safety

INTRODUCTION

Electric and hybrid vehicles are very quiet at low speeds (typically below 30 km/h). The level of the noise emitted by such vehicles is 5 to 7 dB(A) lower than the one of conventional Diesel cars. This is very beneficial to people living in an urban area, because transportation noise is a major source of annoyance in cities. On the other hand, this represents a hazard for pedestrian, who may not hear an approaching car. Vulnerable people as visually-impaired ones have a very strong concern about such cars and manufacturers use additional warning sounds in order to prevent this risk. Though several studies have already been conducted in that field (e.g. (1), (2)), the easiest way to solve this safety issue is to use loud warning sounds, which cancels the noise reduction advantage of electric cars. Regulations, either already decided (NHTSA) or under preparation (in Europe), go this way. As an example, the regulation currently prepared in Europe states that "the (warning) sound level may not exceed the sound level of a similar internal combustion engine vehicle". It should be possible to use more efficient warning sounds.
The eVADER project brings together partners from universities, research centers, car manufacturers and a supplier. Last but not least, the European Blind Union (EBU) is a partner, so that end users are represented in the consortium. The goal of this project is to develop a prototype vehicle combining a high safety for pedestrian and a low noise annoyance for city residents. Several technical solutions are developed:

- An automatic pedestrian detection device;
- A set of loudspeakers focusing the sound in the direction of the detected pedestrian;
- A warning sound designed so that it can be detected in an urban environment at a low level.

This paper will describe studies focusing on this third objective. It will present two listening test experiments: one aimed at evaluating the influence of some timbre parameters on the detectability, and one aimed at assessing the annoyance of warning sounds. The two experiments were conducted by various partners of the project, which allowed to use large subjects samples.

DETECTABILITY

The first part of the study was related to the detectability of warning sounds. The main question was the following: “given the background traffic noise of an urban environment, is it possible to make a warning sound easily detectable in spite of a low level?” It was decided to limit the study to multi-tone sounds, in a middle frequency range (300 - 1500 Hz). The lowest frequency was chosen in view of the technical limitation of the loudspeakers to be used in the prototype; for a high radiation efficiency at low frequencies, very large speakers would have been necessary. The high frequency limit was set because people suffering from presbyacousis have high hearing thresholds at higher frequencies.

PROCEDURE

In this experiment, three timbre factors were investigated: the number of tones, the frequency variation and the temporal variation. Each factor could have three levels: as an example, the number of tones could be 3, 6 or 9. A fractional factorial design was used, so that 9 combinations were used (instead of 27 in a full factorial design). More details about the stimuli definition can be found in (3).
Therefore, 9 stimuli were synthesized; they all had the same A-weighted level. Then they were modified in order to represent a moving source, passing in front of a listener at the speed of 20 km/h. Finally, each modified stimulus was added to the recording of an electric vehicle recorded at 20 km/h by a dummy head located close to the road. This way, it was possible to simulate the situation of a pedestrian facing the road, waiting to cross this road and paying attention to any approaching car (figure 1).

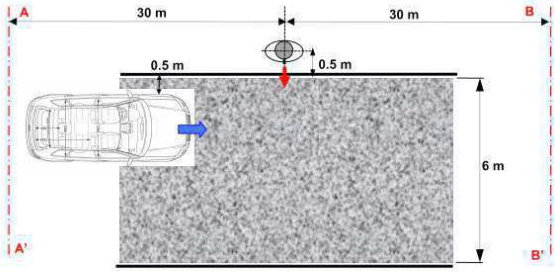

Figure 1. “Waiting to cross” scenario

The recording of the electric vehicle alone as well as the one of a similar diesel car were added to this set of stimuli. The level of warning sounds were adjusted so that they increase the level of the electric vehicle only slightly (less than 2 dB(A) , see figure 2). The level of the diesel car was more than 5 dB(A) higher.

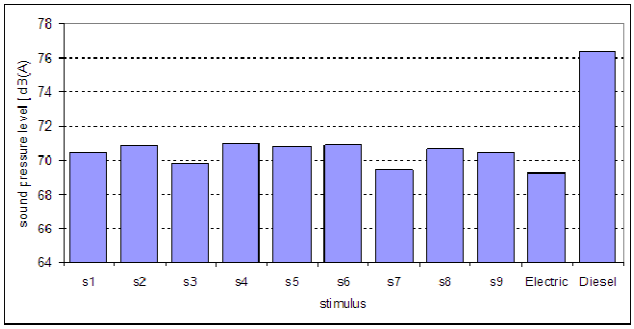

Figure 2. Peak level (A-weighted SPL) of each stimulus used in experiment 1

During the experiment, the listener was hearing a background traffic noise through headphones. Rain noise was added, as this represents a very difficult situation for blind pedestrian. The level of this noise was 69 dB(A). At randomly selected times, one of the car stimuli was added to the noise. This car could arrive from the left or from the right of the listener. The task of the listener was to detect the approaching car as soon as possible and its direction. He gave his answer by pressing a key of a computer keyboard. Two keys were used: the <Enter> key

in the case of a "right" answer, and the <Space> bar for the "left" answer. The response time (from the starting of the stimulus) was measured and stored by the computer.
Each sound was presented 8 times (4 times from each direction) so that a listener was presented 88 stimuli (in a random order) in total. 110 subjects participated to the experiment; among them, 33 were visually-impaired people.

RESULTS

The averaged response time was converted to distance from the listener at detection. These distances are shown in figure 3. The red area in figure 3 represents the “risk area”. If the pedestrian starts crossing the road while the car is closer than 5 meters away, he may be hit by the car, given the averaged reaction time needed by the driver to start breaking (e.g (4)). The electric vehicle is detected in this area, which confirms that EV can be dangerous for pedestrian (e.g. (5)).

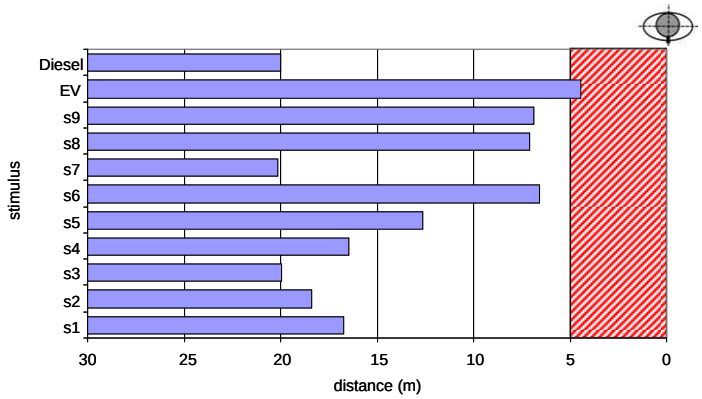

Figure 3. Averaged distance from the listener at detection. The red area represents the "risk area"

Warning sounds had quite different efficiencies, depending on their timbre. Some warning sounds are nearly inefficient (s6, s8 and s9). Some other ones make the EV as easy to detect as the diesel car (s3 and s7). And figure 2 clearly shows that such differences are not related to the level of these sounds - timbre features are the only reason for such differences. Further analysis showed that some controlled features were favorable to detection:

- A low number of tones: the overall sound level was kept constant, so that the difference between each tone level and its detection threshold was greater when the number of tones was low.
- Amplitude modulation: fluctuations in amplitude help the listener to detect the signal in the background of traffic noise.

UNPLEASANTNESS

The second part of the study was related to the unpleasantness of the warning sounds. The listener was asked to evaluate their unpleasantness, imagining to stand in the street, facing the road, listening to the cars passing by at 20 km/h.

PROCEDURE

The experiment was devoted to the evaluation of the unpleasantness of 20 warning sounds: 11 stimuli were the same as in experiment 1, and 9 stimuli were added representing an EV at 20 km/h with a warning sound characterized by different levels of the three components of the sound determined as favorable characteristics for detection in the previous experiment. The experiment was conducted in two conditions: some listeners were presented the stimuli without any background noise and for some other ones, a low-level traffic noise (57 dBA) was added to each stimulus. In both cases, the task of the listener was to evaluate the unpleasantness of the sound. He gave his answer by moving a cursor on a continuous scale, labeled from "not at all unpleasant" to "extremely unpleasant". The position of the cursor was stored as a number between 0 (for "not at all unpleasant") to 1000 ("extremely unpleasant"). Each sound was presented twice, the order of presentation being randomly selected. 145 subjects participated to this last experiment, which was conducted in four laboratories.

RESULTS

The repeatability of each listener was evaluated by computing a mean squared difference between the two values he gave for each sound, namely:

$$C = \sqrt{\frac{1}{20}\sum_{n=1}^{20}\left(x_{n1} - x_{n2}\right)^2}$$

where x_{n1} and x_{n2} represent the two evaluations of sound n. Individual coefficients range between 50 and 450 (mean value: 179, standard deviation: 65). For 23 subjects, this coefficient is higher than 250, which represents a full category of the scale: such subjects can be considered as inconsistent. Such a high number of inconsistent subjects means that the task was difficult. So it was decided to select most reliable subjects for further analysis. The maximum value for C was fixed to 150, which allowed selecting 56 people. 26 of them did the experiment with the background traffic noise and 30 without this noise.

An analysis of variance was done (repeated measures, background noise condition as an inter-individual factor and stimuli as intra-individual ones). The stimuli was the only influential factor [$F(19, 988) = 48.5$, $p<0.0001$]. The unpleasantness of each sound was averaged over this subpanel; results are shown in figure 4. Homogeneous groups of sounds are represented by thick horizontal lines (these groups have been determined using Scheffe's technique).

As it can be seen on figure 4, most warning signals strongly increase the unpleasantness of the sound. This can be due to the fact that people felt very unfamiliar with such warning sounds. Three of them can be considered as equally unpleasant as the diesel car. The particularity of these sounds is that no temporal fluctuation was applied to their amplitude. Amplitude fluctuation increased unpleasantness; the first experiment had shown that it also increased the detectability of sounds.

In summary, figure 5 gives an overview of the results combining the detectability and annoyance experiments. Only the same 11 sounds used in both experiments are presented. This figure shows that, for warning signals, unpleasantness increases with the efficiency of the sound. This is in line with some previously published results about warning sounds. The relation between efficiency and unpleasantness has already been proved for other kinds of warning sounds (e.g. (6), (7) and (8)).

But, if results are considered more precisely, some differences between sounds can be noted. For example, s1 and s15 are equally unpleasant, but s1 is easier to detect. On the other hand, s1 and s7 have similar performances as regard to detection, but s1 is much less unpleasant than s7.

As a result of this set of experiments, s1 (3 number of tones, no temporal and no frequency fluctuation) seems to be a good candidate as warning sound.

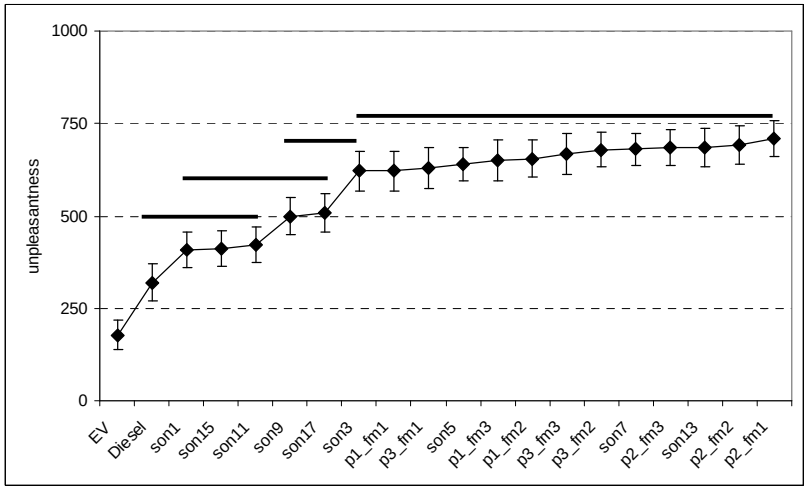

Figure 4. Unpleasantness of each sound

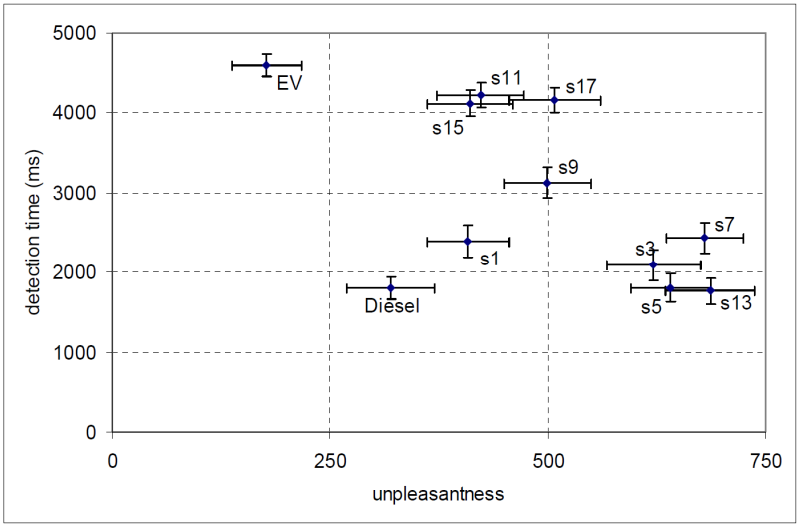

Figure 5. Comparison of results from detection and unpleasantness experiments

CONCLUSIONS

This paper presented two experiments aiming at evaluating the influence of basic timbre parameters of a warning signal on its detectability and annoyance. It has been shown that some warning sounds can make an electric vehicle as detectable as a diesel car, for a much lower sound level. Nevertheless, people reported these signals to increase the unpleasantness of the car sound. It is hypothesized that this was due to the unnaturalness of such signals and to their novelty. Further studies during which subjects could get used to such sounds would be useful. Nevertheless, some signals seem to provide a good compromise between the two objectives.
Finally, it should be recalled that the goal of these studies was not to define a warning signal for a typical application, but to investigate the influence of timbre parameters. This way, it is expected that car manufacturers will have some guidelines when defining their own signal, which should also fulfill some brand image requirements.

AKNOWLEDGEMENT

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