Applied Acoustics 86 (2014) 50–58

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Auditory warnings for electric vehicles: Detectability in normal-vision and visually-impaired listeners

Etienne Parizet [a,*], Wolfgang Ellermeier [b], Ryan Robart [a]

[a] Laboratoire Vibrations Acoustique, INSA-Lyon, Université de Lyon, F-69621 Villeurbanne, France
[b] Institut für Psychologie, Technische Universität Darmstadt, Alexanderstr. 10, 64283 Darmstadt, Germany

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 6 March 2014
Accepted 16 May 2014
Available online 12 June 2014

Keywords:
Electric vehicle
Auditory warning
Alert sound
Visually impaired
Blind
Pedestrian safety
Reaction time

ABSTRACT

Electrical vehicles operating at low speed are often too quiet to be detected by pedestrians in time. In order to study the efficiency of additional auditory warning signals they might be equipped with, a sample of 100 sighted and 53 blind listeners was exposed to a virtual road-crossing scenario in which they had to detect whether an approaching vehicle came from the right or left. Nine warning signals, designed to differ in particular sound features such as FM, AM or the number of harmonics were studied and compared with the recording of an unfitted electrical vehicle (EV) and a conventional diesel car.

The responses measured in the scenario in which cars approached at irregular intervals over two 20-min periods showed no reaction-time differences between blind and sighted participants, and a significant advantage when listening under dry weather conditions as opposed to recordings mixed with the sound of rain. Most importantly, however, regardless of listening conditions and the population studied (sighted or blind), the additional warning signals differed greatly in efficiency. Some signals facilitated detection of the EV as much as making it as noticeable as a control diesel car of significantly higher sound pressure level. Other signals were largely ineffective compared with the unfitted EV. Analysis of the signal characteristics suggested a relatively low number of harmonics, absence of frequency modulation, and irregular amplitude modulation to be the most salient features facilitating timely detection.

1. Introduction

At low speed, electric vehicles produce very little noise, as compared to gasoline or diesel engine cars. The noise level difference between an electric vehicle and one with an internal combustion engine (ICE) can be as large as 6 dB(A) at 10 km/h [1]. This difference becomes smaller at higher speeds. Above approximately 40 km/h, both types of cars are equally loud, because tire noise becomes the most important noise source.

In a city, due to ambient traffic noise, this lower sound level makes it more difficult for pedestrians – and much more dramatically for visually impaired ones – to detect an approaching electric vehicle. This was demonstrated by Garay-Vega et al. in a laboratory experiment [2]. Fourty-eight visually-impaired participants were presented with binaural recordings of conventional or electric vehicles approaching at low speeds (6 mph), in two kinds of background noise, differing in level (31 or 50 dB(A)). They had to detect the approaching car and made their response by pressing a computer key. Results indicated a higher number of missed detections for the electrically driven cars. Also, subjects detected ICE vehicles sooner than the EVs: the difference amounting to as much as 1.5 s. These results were confirmed by other laboratory studies (e.g., [3,4]) and by an in situ experiment [5]: In this experiment, twelve visually impaired subjects had to detect a car approaching on a very smooth road surface at a maximum speed of 30 km/h. At 10 km/h, ICE vehicles were detected at a safe distance (more than 10 m away). In contrast, the electric vehicle was detected only a few meters from the pedestrian. This might be dangerous for a pedestrian intending to cross a road. Indeed, a statistical survey [6] reports a significantly higher incidence of pedestrian or bicyclist crashes due to electric vehicles, though the low number of electric vehicles sold at the time this study was conducted makes the comparison a little difficult. In order to prevent this increased risk, manufacturers use, or plan to use, additional warning sounds, emitted by a loudspeaker attached to the front bumper or the wheel arch. Some specifications for these warning sounds already exist. As an example, the National Highway Traffic Safety Administration recommends values for the frequency bandwidth and sound level of such signals [7] and a similar regulation is currently being prepared by the European

* Corresponding author. Tel.: +33 (0)4 72 43 81 21.
E-mail addresses: etienne.parizet@insa-lyon.fr (E. Parizet), ellermeier@psychologie.tu-darmstadt.de (W. Ellermeier).

http://dx.doi.org/10.1016/j.apacoust.2014.05.006

authorities. This last project defines acceptable warning sounds in a surprisingly vague manner: they should sound "*similar to the sound of a vehicle of the same category equipped with an internal combustion engine* and *the sound level may not exceed the sound level of a similar internal combustion engine vehicle*" ([8], Annex IX, part A, points 4.a to 4.c). Such a regulation would, of course, run counter to efforts to reduce traffic noise annoyance via the introduction of electric vehicles. Thus, there is a need for studies investigating the specification of efficient but low-level warning sounds.

While many papers about alarm sounds in work environments have been published (airplane cockpits, intensive care units or machinery rooms; see [9] for a review), only few studies have focused on warning sounds for low-noise vehicles. Yamauchi et al. used three warning sounds (engine noise, car horn and band-pass noise) in a laboratory study involving German and Japanese listeners [10]. The audibility of each sound was measured in different background noises. Results indicated a strong influence of the kind of warning sound, depending on the background noise. The difference reached up to 10 dB between the band-pass noise (which was the most easily detected sound) and the car horn. No cross-cultural difference in detectability emerged. Wall Emerson et al. [11] conducted an in situ experiment for which five artificial sounds were synthesized and played back by a loudspeaker mounted to an electric vehicle. Fifteen blind participants were seated at the side of the roadway and were asked to indicate when they detected the arriving car (at a speed below 20 km/h). Several trajectories were investigated (the car was moving on a straight line, or was making a right turn, etc.). Differences in the effectiveness of the five warning sounds in communicating these maneuvers were observed; unfortunately, the report fails to provide information about the levels of the warning sounds or other replicable acoustical specifications. The authors advocate that efficient warning signals should (a) have maximum energy around 500 Hz and (b) be amplitude modulated. Misdariis et al. used 10 sounds, which could be represented in a two-dimensional timbre space [12]. The first dimension was related to temporal modulation and the second one to spectral flatness (distinguishing a random noise from a tonal sound). The amplitude of the signals was modified so as to simulate an approaching source at 20 km/h. Six participants had to detect each sound in a background noise. Again, there were strong differences in the detectability of the sounds: the shortest reaction time (RT) was obtained for a siren sound (4 s) and the longest RT (11 s) for a modulated electric hum. Furthermore, there was evidence for differential learning effects.

Clearly, additional research on efficient warning sounds for electric vehicles is needed, particularly since the few studies on the topic have (a) only employed a limited number of warning sounds, (b) often did not vary them systematically, and (c) had very small samples of listeners, especially of visually impaired ones to validate the efficiency of the signals. The present study aspired to fill these gaps by (1) designing warning signals by varying timbre parameters that have proved to be promising in previous research, (2) presenting these alerting signals in realistic roadside scenarios in which cars may approach from either side and in different weather conditions, (3) rendering these dynamic auditory scenarios with some degree of spatial auralization, and (4) evaluating the detectability of the vehicle-plus-warning sounds using both normal-vision participants and a relatively large sample of visually impaired listeners recruited by collaborating laboratories in several European countries.

As to the first goal of optimizing the sound characteristics for better detectability, the present study focuses on two sound features: (1) the frequency bandwidth of the warning sounds and (2) temporal modulation. While the NHTSA requirements [7] recommend minimum sound levels in eight third-octave frequency bands between 315 and 5000 Hz, one might consider it more efficient to concentrate the energy in a much smaller frequency region. This way, given a limited overall level, the warning sound is more likely to be heard in the presence of background noise. Furthermore, it is generally assumed that temporal modulation can help the listener to segregate the warning sound from the ambient noise. More specifically, research on auditory alarms [13,14] has shown that increasing the rate at which components of a warning sound are presented also raises its perceived urgency. The effect of these timbre parameters will be investigated in the laboratory by measuring their effect on the detection performance of both normal-vision and visually impaired listeners.

2. Method

The main part of the experiment consisted of presenting an auditory road-crossing scenario to participants and to ask them to determine the direction from which a car approached in a background of traffic noise. In the following, the auralized situation and the warning stimuli used will be described in detail.

2.1. Stimuli and design

The simulated situation (depicted in Fig. 1) was one of a pedestrian standing on the sidewalk, close to the carriageway and facing it, about to cross the road. A car is passing perpendicularly in front of him or her, at 20 km/h, the shortest distance between the car and the pedestrian being 1 m (see Fig. 1).

Two cars were recorded in this situation, using a dummy-head (Head Acoustics HMS II) at the location of the pedestrian. One of these cars was an electric vehicle (Renault Fluence) and the other one a similar car equipped with a diesel engine. Recordings were made from a distance of 30 m ahead of the dummy-head to the same distance past it, so that the duration of the signals was 10.8 s. The recording device (Brüel & Kjaer Pulse front end) converted the signals with a sampling frequency of 44.1 kHz and 16 bits resolution.

The warning signals to be added to the electrical vehicle sound were combinations of pure tones. Specifically, the influence of two timbre parameters was investigated: the number of sinusoidal components used and the presence of temporal modulation.

The bandwidth of the sounds was limited between 300 and 1500 Hz. The lowest frequency was selected because of technical limitations of the loudspeakers to be used on the future prototype. The small size of these loudspeakers limits their radiation efficiency to frequencies above 300 Hz. The upper limit was selected for two reasons. First of all, the hearing threshold below 1500 Hz is not greatly affected by age [15]. Secondly, one goal of the project is to combine good detectability with a low overall level of warning sounds. Focusing the energy in a limited frequency band should allow the signal to be above the detection threshold in that band.

The warning sounds were synthesized according to a three-factor design varying (a) the number of sinusoidal components, (b) the amount of frequency modulation, and (c) the amount of amplitude modulation. All factors had three levels, which are detailed below.

– Number of components (factor 2 in the following). All stimuli were made of a set of harmonic frequencies, with the lowest component fixed at 300 Hz. At level 1, three frequencies separated by 300 Hz (300, 600 and 900 Hz) were used. At level 2, six harmonics separated by 150 Hz, and at level 3, nine harmonics each 150 Hz apart were generated, so that the frequency range was 300–1500 Hz. All harmonics had the same initial level.