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Effect of additional warning sounds on pedestrians' detection of electric vehicles: An ecological approach

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ABSTRACT

Virtually silent electric vehicles (EVs) may pose a risk for pedestrians. This paper describes two studies that were conducted to assess the influence of different types of external sounds on EV detectability. In the first study, blindfolded participants had to detect an approaching EV with either no warning sounds at all or one of three types of sound we tested. In the second study, designed to replicate the results of the first one in an ecological setting, the EV was driven along a road and the experimenters counted the number of people who turned their heads in its direction. Results of the first study showed that adding external sounds improve EV detection, and modulating the frequency and increasing the pitch of these sounds makes them more effective. This improvement was confirmed in the ecological context. Consequently, pitch variation and frequency modulation should both be taken into account in future AVAS design.

1. Introduction

Motor vehicles are becoming ever quieter, particularly electric and hybrid ones. When they are driven along at low speed, electric vehicles (EVs) produce less noise than ones with an internal combustion engine (ICE) (e.g., Gary-Vega et al., 2011; Kim et al., 2012; Mendonça et al., 2013). Silence may be seen as an advantage by motorists, because quiet cars are considered to be more comfortable (Cocron et al., 2011; Cocron and Krems, 2013; Hjorthol, 2013). However, driving performances fall markedly when regular auditory clues are removed (e.g., Hellier et al., 2011; Horswill and Plooy, 2008; Merat and Jamson, 2011; Nelson and Nilsson, 1990; Yamauchi and Feng, 2014). This could be seen as an increase in speed variability, showing that auditory feedback helps drivers maintain a stable speed (Hellier et al., 2011). Furthermore, pedestrians who cannot hear an oncoming vehicle are more at risk (Hanna, 2009). Even with a quiet car, motorists receive information from the speedometer on their dashboard. Pedestrians do not have access to these devices, however, and therefore have to rely on visual and auditory clues to estimate the traffic situation. The aim of the present studies was to assess the influence of different types of external sounds on EV detectability by pedestrians.

The subjective importance of acoustic clues for estimating the parameters of a vehicle has been assessed in several studies. In a survey carried out in North Carolina, 86% of respondents stated that acoustic clues play a key role in estimating the location and direction of an oncoming vehicle, and that sound makes them more aware of the situation (Wogalter et al., 2013, 2001). It is the level of the sound, more than its direction, that allows pedestrians to determine the location of a vehicle (Lutfi and Wang, 1999). The engine's noise also allows them to determine whether the vehicle is turning or coming straight at them (Ashmead et al., 2012).

Numerous studies have highlighted the difficulty of estimating vehicle speed. When they have to rely on visual information, pedestrians tend to underestimate lower speeds and overestimate higher ones (Scialfa et al., 1991). As for drivers, they tend to underestimate their own speed (Recarte and Nunes, 1996), and overestimate that of other drivers (Aberg et al., 1997). When pedestrians have to estimate speed using only auditory stimuli, the pattern of results changes, as Sun et al. (2015) found that pedestrians tended to underestimate speeds above 45 km/h, and overestimate ones below 35 km/h, although they did not provide any information about the nature of the sound.

The problem is that people, especially very young children, are quite bad at using sound to estimate vehicle movement (Barton et al., 2013; Pfeffer and Barnecutt, 1996). Older people also have difficulty using auditory cues, owing to presbycusis (Mendonça et al., 2013; Yamauchi et al., 2013). Moreover, they tend to accumu-

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late difficulties linked to their age-related decrease in perceptual, physical and cognitive abilities (Tournier et al., 2016). Finally, individuals with visual impairments are particularly exposed to the danger of quiet cars because they can only use the auditory cues to evaluate the speed and distance of an approaching car. Mendonça et al. (2013) compared the detectability of a hybrid car with that of a small petrol-driven car and a diesel pickup truck, taking into account other variables such as speed, pavement type and ambient noise level. All these variables interacted and influenced detection. The diesel pickup was detected better than the small petrol car which, in turn, was detected better than the hybrid car. The danger from quiet cars is exacerbated by low-noise pavements, low speed, high ambient noise and age (younger and older) of pedestrians. The negative effect of low speeds on detection was confirmed by two studies (Barton et al., 2012; Stelling-Kończak et al., 2015). Stelling-Kończak et al. (2015) also confirmed the deleterious effects of old age and high ambient noise on detection. According to Garay-Vega et al. (2010), when a vehicle is travelling at 10 km/h, people detect it 2 s later if it is an EV rather than an ICE car. In the experiment conducted by Parizet et al. (2014a,b) the mean detection distance was less than 5 m for an EV, compared with about 20 m for an ICE car. This kind of result is strongly moderated by the type of ICE car being assessed (Glaeser et al., 2012). One way of improving the detectability of silent vehicles is to implement acoustic vehicle alerting systems (AVAS). These involve adding artificial sounds to vehicles to alert pedestrians to the presence of cars travelling at low speed.

1.1. European legislation

The present research aims to assess the features that AVAS must have to be the more effective. There are some legal constraints about these features. The rules governing the implementation of an AVAS are set out in a European Regulation (2014). These systems are not yet mandatory, but if a vehicle is equipped with one, it must comply with the following recommendations: 1) automatic generation of a sound from start up to approximately 20 km/h (forward and reverse); 2) presence of a switch to halt its operation (*pause switch*); 3) attenuation of the AVAS sound level during certain periods of operation; and 4) generation of a continuous sound that provides information to pedestrians and vulnerable road users about a vehicle in operation. In addition, the regulation lists those sounds that are either prohibited (sirens, horns, bells, alarms, intermittent sounds, etc.) or should be avoided (melodies, animal or insect sounds, and confusing sounds making it difficult to identify the vehicle and/or its operation). To meet the regulation's requirements, the AVAS sound should reflect the behavior of the vehicle (e.g., changes in the noise level or other characteristics according to vehicle speed), the level of sound generated by the AVAS should not exceed that of a similar ICE vehicle, and, the system should consider the impact of noise on the population.

The European Union regulation may well be amended as part of the global settlement agreement, as the date of its entry into force draws nearer. At this time, the available information about the forthcoming global settlement was that 1) the AVAS will have to automatically generate a sound across a minimum vehicle speed range of start up to approximately 20 km/h, as well as while reversing, 2) an evaluation will have to be performed at 10 and 20 km/h, 3) the sound frequency will have to include at least two one-third octave bands, which must exceed minimum levels set out in a table, 4) at least one of the one-third octave bands must be below 1.6 kHz, 5) there must be one specific overall level in reverse gear, and a mean frequency shift every 5–20 km/h of at least 0.8% km/h (one frequency is sufficient), but the emission of a stationary alerting signal when the vehicle is temporarily at a standstill (vehicle speed 0 km/h and *ready for movement* status) is not mandatory, and 6) an AVAS is not needed if the vehicle's noise level is 3 dB above the required levels.

1.2. Effects of added warning sounds on vehicle detection

To deal with the problems generated by quiet vehicles, manufacturers have been equipping their EVs with AVAS, and studies have been set up to assess the efficacy of the different warning sounds these systems emit. In the study conducted by Goodes et al. (2009), 27 blind participants were asked to raise their hand whenever they detected an approaching vehicle. The test car travelled at 15 km/h, and the ambient noise level was 49 dB. Results indicated that adding warning sounds to an EV increases its detectability. The authors also assessed the combination of an artificial engine noise and a bell that rang every 2 s. Adding this sound increased EV detectability, compared with the version without a bell. In the research conducted by Chamard and Roussarie (2012), adding an AVAS improved EV detectability to approximately the same level as that of an ICE car, although the perceived danger of an EV with warning sounds remained greater than for an ICE car. The ability of warning sounds to improve EV detectability was confirmed by Kim et al. (2012) in a study with blind participants who were asked to detect a car travelling at 10–15 km/h. In this study, an ICE car was added for comparison's sake. Finally, a hybrid vehicle without AVAS was detected at a shorter distance (27.5 m) than the same vehicle with AVAS (38.3 m), while the latter was just as or more detectable than an ICE car (34.5 m). The experiment was conducted in two different ambient noise contexts: a road (55.1 dB) and a car park (47.8 dB). Despite the difference between the two contexts, no significant effect of ambient noise level on vehicle detectability was found.

Nonetheless, other studies have found an effect of ambient noise on vehicle detection distance (e.g., Stelling-Kończak et al., 2015; Altinsoy and Landgraf, 2014; Emerson et al., 2011; Gary-Vega et al., 2011). Altinsoy and Landgraf (2014) clearly demonstrated this effect on the detection of a vehicle with participants wearing headphones. These authors found that detection distance depended on the ambient noise level. With a level of about 54 dB, an EV was detected at a mean distance of 14 m, whereas an ICE vehicle was detected at 36 m. Moreover, in the study by Ulrich et al. (2014), auditory vehicle detection performance was significantly better in a non-competing noise condition than in a competing noise one. According to Yamauchi et al. (2014), the sounds emitted by an AVAS need to be approximately 2–3 dB above the ambient noise level.

The study conducted by Emerson et al. (2011) with 28 blind participants and 12 sighted ones demonstrated that ambient noise level is not the only factor that determines vehicle detectability. The impact of ambient noise also depends on its similarity with the sound of the car. The more similar their frequencies, the more the ambient noise will interferes with the detection of the vehicle. In other words, when the noise level is the same, the car sound is detected better when it differs from the ambient noise. Low-frequency sounds (20–100 Hz) should therefore be avoided, as these are the most common frequencies in urban areas. ICE cars emit a sound at a frequency of about 100 Hz. The study by Emerson showed that blind people can detect a hybrid vehicle emitting sound at 100 Hz more easily than a hybrid car emitting at lower frequencies. Using high (1000 Hz) or very high (nearly 3000 Hz) frequencies, could increase detectability (Misdariis et al., 2012), even at low noise levels.

Detectability also depends on the sound occurs gradually or suddenly (a starting car is detected better than a moving one), and whether the fluctuations of the sound are linked to speed variations (Emerson et al., 2011). However, when all features are equal, the relation between sound pressure and detection distance is linear (Sakamoto et al., 2014). Conversely, sounds of the same