FEATURED ARTICLE

Electric Vehicles Get Alert Signals to be Heard by Pedestrians: Benefits and Drawbacks

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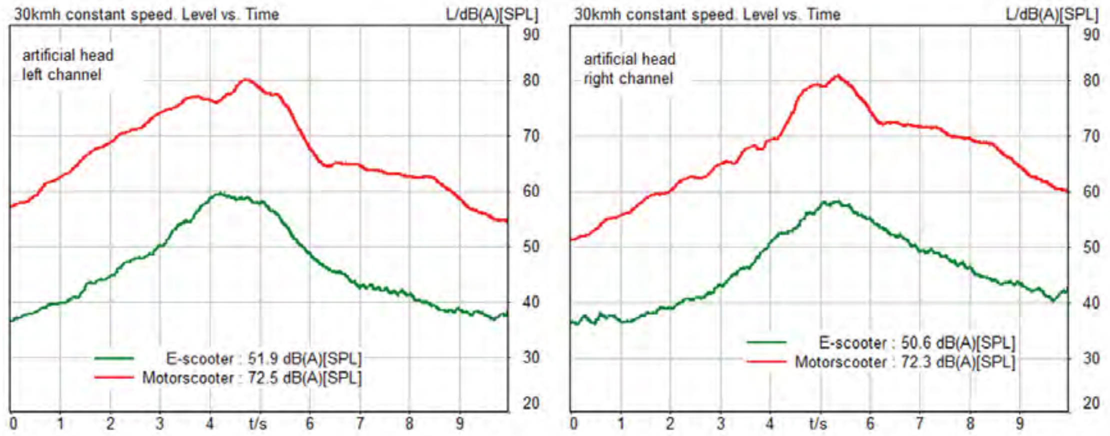
The Rise of Electric Vehicles and the Problem of Being Quieter

Hybrid electric vehicles (HEVs) and full electric vehicles (EVs), also known as battery electric vehicles (BEVs), are becoming more and more popular due to ecological motives, technological developments, rising fuel prices, and legal regulations and standards such as the European emission performance standards for reducing carbon dioxide emissions from new passenger cars. Public purchase incentives promote EV sales. All forecasts show a strong expectation that the annual sales of EVs (HEVs and BEVs are considered together and called EVs), and thus their numbers on roads, will significantly increase in the coming years. The nature of the EV market growth cannot precisely be predicted; it depends strongly on assumptions influenced by potential political actions and regulations. However, no predictions question the increasing market share of EVs.

Because EV technology leads to less noise emissions, it is hoped that that there will be a noticeable reduction in road traffic noise with the phasing out of the internal combustion engine (ICE). Road traffic noise is still the dominant source of environmental noise. For example, more than 100 million people in Europe live in areas where road traffic noise levels are considered harmful to human health (European Environment Agency [EAA], 2020). Moreover, it is estimated by the World Health Organization (WHO; 2018) that in western Europe alone, over a million healthy years of life are currently lost every year as a result of road traffic noise.

Figure 1. *Binaural measurement of the A-weighted sound pressure level (SPL;* x*-axis) over time (in s;* y*-axis) of scooter pass-by events (**left**, left channel; **right**, right channel). **Red**, scooter with combustion engine; **green**, electric scooter.*



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With the emergence of EVs, a reduction in road traffic noise by a few decibels is anticipated at least for low-speed situations, thus the potential for some reduction in adverse health outcomes (Campello-Vicente et al., 2017). There is an even greater potential for noise reduction in areas with a large number of powered two-wheel vehicles (e.g., motorcycles, motor scooters), such as in southern Europe. In these areas, replacement of powered two wheelers by electric ones could substantially reduce noise levels and noise annoyance as shown in **Figure 1** (Fiebig et al., 2012).

However, associations of the blind and visually impaired have pointed out that EVs pose a growing threat to all pedestrians, particularly to those who depend on hearing (Pierce, 2007). For example, the European Blind Union (EBU; 2019) advocated for the addition of mandatory sounds in all silent cars. The media picked up this topic and reported on the growing hazard due to "near-silent electric vehicles" (Birch, 2009) and on EVs as "silent killers" (Okulski, 2012).

Early studies investigating the danger of EVs to the visually impaired, based on the analysis of accident statistics, suggested a higher risk of collisions (US National Highway Traffic Safety Administration [NHTSA], 2009). This led to political action and increased efforts to develop adequate regulations. In particular, associations of the blind emphasized that visually impaired pedestrians require *acoustic input* to be aware of traffic to safely cross a street; otherwise they face enormous safety issues (EBU, 2019).

Early studies on the effect of artificially generated sound emitted by EVs showed, as expected, that an EV with artificially added sound will be detected at a significantly greater distance than an EV without artificially added sound (Kim et al., 2012). It became clear from the earliest research that certain noise characteristics, such as those from emergency alarms, animal sounds, and melodious sounds, are inappropriate for EVs because they could confuse identification of the source and/or that they could produce adverse human responses (United Nations Economic Commission for Europe [UNECE], 2012).

Nevertheless, it took several years until the idea of using alert signals and defining their characteristics for improved detectability of EVs was put into action. It also took time before (new) EVs were required to comply with regulations specifying alert sound requirements. Yet, there is still a debate about how pedestrians can be alerted by appropriate sound signals and how road traffic noise can be reduced through electrification of the powertrain.

The Starting Point

In 2009, the NHTSA published a technical report comparing the incidence rates of pedestrian and bicyclist crashes involving EVs to the incidence rates with ICE vehicles under similar circumstances. The report found an increased risk of accidents for pedestrians and cyclists concerning collisions with EVs compared with ICEs (NHTSA, 2009). Around the same time, the UNECE World Forum Working Party 29 recognized that the positive environmental benefits achieved by EVs brought with it the conflict that the reduced audibility of vehicles presented a danger to pedestrians. Thus, the use of acoustic means was proposed by the working group "Quiet Road Transport Vehicles" (QRTV; 2010) to mitigate potential pedestrian hazards.

The NHTSA publication (2009) about accident statistics triggered a substantial debate. For example, Sandberg et al. (2010) strongly questioned the conclusions drawn from meta-analyses of accident statistics and indicated that some details in the NHTSA report (2009) are arguable or at the very least unclear (e.g., consumer bias, no consideration of vehicle kilometers driven). A study investigating the accident risk posed by EVs compared with equivalent ICE vehicles in Great Britain for the years 2005 to 2008 observed that EVs were equal or less likely to be involved in collisions with pedestrians than ICE vehicles, but the authors questioned the validity of this outcome (Morgan et al., 2011). In 2011, an update of the NHTSA study showed similar trends to those in the 2009 report and again found higher incidence rates for EV versus ICE vehicles while paying special attention to the statistical power with a three times larger EV sample size (Wu et al., 2011).

Although the debate about the benefits and drawbacks of warning signals for EVs continues, regulations on minimum noise requirements for electric cars have been implemented on national and international levels.

The Actions

In 2010, the US Pedestrian Safety Enhancement Act (PSEA) was introduced and it became law in 2011 (PSEA, 2011). This act asked for rulemaking by determining the minimum sound level emitted from a vehicle that is necessary to enable visually impaired pedestrians to reasonably recognize a nearby EV as a vehicle in operation while at the same time considering the overall community noise impact (PSEA, 2011).

In the 2013, the European Parliament and the Council of the European Union (EU) demanded that manufacturers include acoustic vehicle alerting systems (AVASs) in vehicles so that vulnerable pedestrians would be aware of the presence of an operating vehicle (European Parliament, 2013). In 2014, the EU agreed on mandating all manufacturers to install AVASs and set deadlines for their mandatory installation in all new EVs (EU, 2014). The content of this regulation was later reviewed to include more detailed requirements on AVAS performance (EU, 2017).

In 2017, the UNECE published uniform provisions concerning approval of quiet vehicles with regard to their reduced audibility. It defined that any alert signal should be a continuous sound that easily notifies pedestrians of an approaching vehicle (UNECE, 2017). In detail, AVAS mean a component or set of components installed in vehicles with the primary purpose of fulfilling the alert sound regulation requirements (UNECE, 2017).

Table 1. *Center frequencies and sound pressure levels for four-band alert signals*

One-Third Octave-Band Center Frequency (Hz)	Minimum A-Weighted SPLs (dB)	Example of Measured Alert Signal
315	52	48
400	51	52*
500	52	49
630	53	55*
800	53	51
1,000	54	52
1,250	54	55*
1,600	51	49
2,000	51	48
2,500	50	51*
3,150	47	44
4,000	45	43
5,000	43	41

One-third octave-band center frequencies and minimum A-weighted sound pressure levels (SPLs) for four-band alert signals are shown for the condition "constant vehicle pass-by speeds equal or greater than 20 km/h but less than 30 km/h" as defined in Federal Motor Vehicle Safety Standards (FMVSS) No. 141. *Example of a measured alert signal meeting the minimum level requirements of FMVSS No. 141 due to the one-third octave bands.

It is worth mentioning that the first NHTSA notice of proposed rulemaking (NPRM) regarding minimum sound requirements for HEVs and EVs in 2013 was "overengineered." As a consequence, the initial NPRM proposal of minimum level thresholds in eight one-third octave bands (NHTSA, 2013) was reduced in the final rule to either four or two bands (Federal Motor Vehicle Safety Standards [FMVSS]; 2016). Similarly, the option of including a pause switch so drivers could disengage the AVAS was permitted in the European Regulation No. 540 (EU, 2014) but banned in the UNECE regulation (UNECE, 2017). These examples illustrate the ongoing need for modifications of alert-sound specifications in standards and regulations.

Regulations for Alert Signals

Today, several regulations exist to manage requirements regarding the audibility of EVs. In the United States, FMVSS No. 141 (2016) defines the minimum sound requirements for HEVs and EVs. For the European Union, United Nations Regulation No. 138.01 covering uniform provisions for approval of quiet road transport vehicles with regard to their reduced audibility regulates the alert-sound requirement. There are similar national regulations in many other countries, including Japan and China, based on UNECE R138.01 (2017). As a consequence, as of July 2021, manufacturers must install an AVAS in all new EVs in the EU (2014). Moreover, all newly manufactured EVs, to which FMVSS No. 141 applies in the United States, have had to comply with this minimum sound safety standard as of September 2020 (FMVSS, 2019).

The US standard establishes performance requirements for pedestrian alert sounds that are designed to reduce the number of injuries resulting from EV crashes with pedestrians by providing a sound level and characteristics that are detectable and recognized by pedestrians. An alert sound is understood as a vehicle-emitted sound that enables pedestrians to discern vehicle presence, direction, location, and operation (FMVSS, 2016).

Table 2. *Center frequencies and sound pressure levels for two-band alert signals*

One-Third Octave-Band Center Frequency (Hz)	Minimum A-Weighted SPL (dB)	A-Weighted Band Sum (dB)	Example of Measured Alert Signal
315	47		47
400	47		47
500	47		55*
630	47		46
800†	47†		46†
1,000	47	57	46
1,250	47		55*
1,600	47		46
2,000	47		45
2,500	47		45
3,150	47		44

One-third octave-band center frequencies and minimum A-weighted SPLs for two-band alert signals are shown for the condition "constant vehicle pass-by speeds equal or greater than 20 km/h but less than 30 km/h" as defined in FMVSS No. 141. †One of the two bands meeting the minimum requirements must be one of the 315- to 800-Hz bands and the second needs to be one of the 1,000- to 3,150-Hz bands. *Example of a measured alert signal meeting the minimum level requirements and the band sum criterion of FMVSS No. 141 due to the one-third octave bands.

Pedestrian Alert Sounds

There are two options for designing pedestrian alert sounds in compliance with FMVSS No. 141. In one option, four nonadjacent one-third octave bands spanning no fewer than 9 of the 13 bands from 315 to 5,000 Hz must exceed specified required minimum one-third octave-band levels. **Table 1** shows the performance requirements for four-band alert sounds designed for vehicle constant pass-by speeds from 20 km/h to just under 30 km/h.

The second option is for an alert sound in two nonadjacent one-third octave bands from 315 to 3,150 Hz if it meets a minimum A-weighted sound pressure level in each band and a band sum requirement. In addition, one of the two one-third octave bands meeting the minimum level requirements must be in bands ranging from 315 to 800 Hz and the other must be between the midband frequencies of 1,000 to 3,150 Hz. **Table 2** shows the performance requirements for two-band alert signals for the same vehicle constant pass-by speeds as shown in **Table 1**.

Originally in the notice of proposed rulemaking (NHTSA, 2013), a change in frequency as a function of vehicle speed was proposed to allow pedestrians to detect vehicle acceleration and deceleration. But after further consideration, this pitch-shifting requirement was replaced in the final rule with an increase in sound pressure level by a specified amount because expected repeatability issues in compliance evaluations. Instead of pitch shifting, a relative change in level of 3 dB is required to signify acceleration and deceleration when moving from 1 relevant operating condition to the next (e.g., changing from 10 to 20 km/h constant-speed condition).

UNECE Regulation No. 138.01 requires that EVs must use an AVAS if the vehicle exterior noise without an additional alert sound does not meet specified overall levels with a margin of +3 dB(A). If the vehicle does not meet these requirements, it must use an AVAS at any speed up 20 km/h. Apart from minimum overall sound levels for certain speeds, minimum levels of at least two one-third octave-band levels must be exceeded, as in the US standard. Moreover, the regulation requires that at least one band from the vehicle exceed the defined minimum levels, below or within the 1,600 Hz (midband frequency) one-third octave band.

In addition, and unlike the US NHTSA regulation, a "frequency shift" must be implemented to signify acceleration and deceleration so that the frequency content of the AVAS sound is a function of the vehicle speed. To do this, at least one tone within the specified frequency range must vary proportionally with speed by an average of at least 0.8% per 1 km/h in the speed range from 5 to 20 km/h inclusive when driving in the forward direction. A detailed specification of what can be considered as a tone within the AVAS signal is not given. However, it is specified that a sound-analysis system that is capable of spectral analysis at a sampling rate and with a frequency resolution sufficient to differentiate between the frequencies of the various test conditions must be used (UNECE, 2017). The major issues of the requirements stated in FMVSS No. 141 and UNECE R138.01 are presented in **Table 3**.

The UNECE regulation defines a maximum overall sound level of 75 dB(A) at a 2-m distance for vehicles equipped with an AVAS. FMVSS No. 141 does not directly specify a maximum sound pressure level to avoid "unnecessary" loud alert sounds. Overall, the resulting minimum overall level requirements comparing the US and UNECE regulations are quite similar, although the US standard is slightly more conservative (see **Table 4**).

Car manufacturers are allowed to design their own AVAS as long as they meet the legal requirements. Thus, the broad frequency range and flexible choice of possible one-third octave bands in the regulations are intended to provide manufacturers with the flexibility to design alert sounds that are acceptable to their customers (FMVSS, 2016). FMVSS No. 141 was recently proposed to be amended to allow manufacturers to install a number of driver-selectable pedestrian alert sounds in each EV (FMVSS, 2019), and this is also permitted in UNECE R138.01.

The Conflict of Goals

Environmental noise protection hoped for reduced road traffic noise in urban areas due to an increasing percentage of EVs. Without a doubt, the electrification of vehicle powertrains brings a potential to reduce exterior noise in the low-speed range, a condition particularly relevant for cities. This hope was reflected in the white paper from the European Commission (2011) demanding cutting in half the use of "conventionally fueled" cars in urban transport by 2030 and phasing them out in cities by 2050. This is based on

Table 3. *Comparison of European and United States regulations on minimum sound requirements hybrid electric vehicles*

	Europe	**United States**	
Speed range (forward motion)	Up to 20 km/h (±1 km/h)	Up to 30 km/h (+2km/h)	
Reverse	6 km/h (±2 km/h)	0 km/h (stationary)	
Minimum third-octave levels for nonadjacent bands	Mandatory	Mandatory	
Frequency range	160 Hz to 5,000 Hz	4 Nonadjacent one-third octave bands spanning no fewer than 9 bands from 315 Hz to 5,000 Hz	2 Nonadjacent one-third octave bands from 315 Hz to 3,150 Hz
Sound while vehicle is stationary	Not mandatory	Mandatory	
Pitch shifting	Mandatory	Not mandatory	

European regulations are in United Nations Economic Commission for Europe (UNECE) 138.01. United States Regulation are in FMVSS No. 141.

Table 4. *Comparison of European and US minimum overall sound pressure level requirements for hybrid electric vehicles*

	Europe	**United States**
Constant speed of 10 km/h	50 dB(A)	51 dB(A)
Constant speed of 20 km/h	56 dB(A)	57 dB(A)
Constant speed of 30 km/h	—	62 dB(A)
Reverse	47 dB(A)	48 dB(A)

European regulations are in United Nations Economic Commission for Europe (UNECE) 138.01. United States regulation are in FMVSS No. 141. United States requirements are the band sum of two bands with respect to the two-band alert option.

the belief that a high percentage of EVs helps to significantly reduce adverse environmental effects (EAA, 2016).

Large-scale introduction of alert signals for increased pedestrian safety might counteract the goal of environmental noise reduction. However, after the final environmental assessment, the NHTSA concluded that little or no negligible impacts on the human environment are anticipated. It also estimated that the increase of environmental noise due to the safety standard for EVs is negligible (FMVSS, 2016). The NHTSA argued that even if EVs were to reach 50% deployment, a maximum level increase of less than 1.0 dB in urban environments is expected. According to NHTSA, because differences of less than 3 dB are generally considered unnoticeable by humans, the environmental impact is likely to be negligible. Indeed, recent pass-by noise measurements of EVs with or without AVAS support the assumption of only a minor sound pressure level increase due to alert sounds, at least for speeds higher than 10 km/h (Laib and Schmidt, 2019).

However, this assumption probably underestimates the potential noise annoyance effects due to the introduction of warning signals for EVs. Because various regulations require that alert sounds be designed to improve the audibility and detectability of electrified cars, increased noise annoyance might be easy to predict on the basis of the minor sound pressure level increases (Genuit, 2016). Accordingly, Laib and Schmidt (2019) argued that AVAS sounds from multiple vehicles at the same time can lead to a cacophony that could be more annoying than one might predict based on sound pressure level alone.

On the other hand, associations of the blind still think that there are areas for improvement in the EU legislation. They demand an extension of the speed range, an increase of minimum sound levels, and a mandatory sound when the vehicle is not moving (EBU, 2019).

The Psychoacoustic Aspect

As pointed out in Regulations for Alert Signals, car manufacturers can individually design their alert signals in compliance with the regulations. The goal of alert signals is to attract sufficient attention to inform pedestrians of the presence of an EV. Accordingly, it was observed that designing sounds based on psychoacoustic principles can double the detection distances relative to a reference vehicle and that artificial sounds based on combustion noise seem to be relatively ineffective (FMVSS, 2016). Studies have also shown that well-designed alert sounds with prominent noise patterns (e.g., roughness) lead to earlier detection of approaching vehicles (Steinbach and Altinsoy, 2020). In particular, dynamic alert signals using level variations or frequency shifts lead to earlier detection by pedestrians compared with alert sounds with a barely noticeable sound change from standstill to low speeds (Steinbach and Altinsoy, 2020).

Listening experiments suggest that the underlying affective structure of AVAS sounds can be described by factors such as ”clarity,” “quality,” and ”power” and that alert sounds can be specifically designed both to increase detection time and to improve the alert sound quality (Matsuda et al., 2019). Obviously, the sound pressure level of the exterior noise of a vehicle is not the sole determiner of its detectability.

This indicates that the assessment of human responses to alert sounds cannot be simply predicted on the basis of overall sound level. In particular, the prediction will be inaccurate if the estimates of noise annoyance do not consider superposition effects of multiple vehicles emitting alert sounds. In the case of superposed alert sounds, “interesting” psychoacoustic phenomena can occur. For example, it is expected that dissonant sounds will result from the superposition of warning signals differing in pitch, pitch-shifting factor, and noise character and that this might lead to a less harmonious urban soundscape (Laib and Schmidt, 2019). Because car manufacturers can individually design their alert signals, superposition of alert sounds from different brands of EVs might create unexpected and prominent alert signal compositions.

Figure 2 illustrates the psychoacoustic effects caused by the superposition of alert signals based on a few tones in a virtual road traffic scenario according to Genuit (2016). If the vehicles have slightly different speeds (indicated in **Figure 2**, *right*), the alert signals based on a few tones slightly shifted in frequency produce an overall disharmonic sound composed of multiple modulations (see **Figure 2**, *bottom right*). To avoid those disharmonic modulations and to achieve a reasonable detectability, the use of amplitude modulations is frequently proposed (cf Robart et al., 2013).

Audible amplitude modulations seem to be beneficial for increased detectability and localizability. Regulations specifying minimum sound requirements do not require any form of modulation, although it is not excluded.

If traffic noise resulting from introduction of alert signals increases by 0.5 dB, there is no reason to expect a significant increase in (highly) annoyed people. However, it is well-known that certain noise properties, such as prominent tones, can lead to an increase in noise annoyance (Schäffer et al., 2016). To account for such annoyance-relevant properties beyond the sound pressure level, penalties in decibels are frequently added to a measured overall sound pressure level to reflect increased noise annoyance. For example, the German standard DIN 45681 (2005) proposes that tones penalties of 3 dB (or even 6 dB) be added to the measured overall sound pressure level. Also, dissonant noise patterns caused by several "untuned" superposed alert signals can increase noise annoyance in addition to the absolute level. Thus, we need to apply a penalty of a few decibels to the new road traffic noise to quantify its "perceived" level increase due to annoyance. If we follow this logic, the impact on the human environment might be more than only "negligible." Consequently, a study of the acceptance of AVAS showed a significant increase in the emotional arousal level, measured with the self-assessment manikin method (SAM), as a result of an AVAS sound based on prominent tonal components (Fagerlönn et al., 2018).

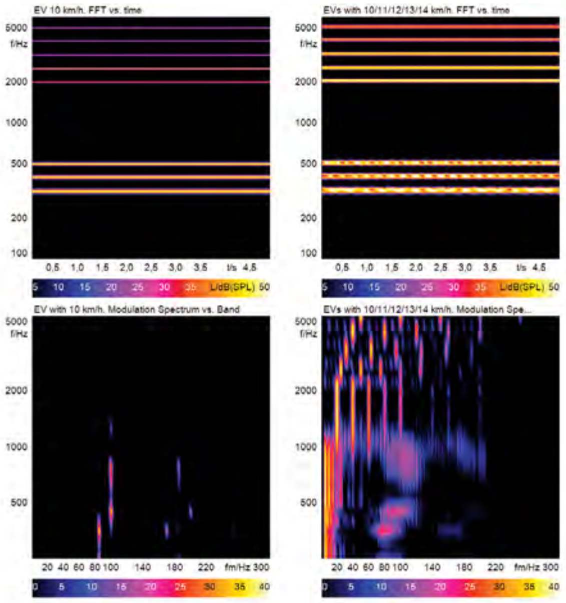

Figure 2. *Simulations of a single alert signal based on a few tones emitted by one car (**left**) and of a microtraffic scenario with five vehicles all with slightly different speeds (10, 11, 12, 13, and 14 km/h) applying pitch shift (**right**).**Top**, spectra over time (fast Fourier transform vs. time) displayed for both scenarios; color, sound pressure level for each frequency. **Bottom**, modulations occurring in both scenarios (modulation spectrum vs. band [degree of modulation] for the different simulations above), with information about the modulation rates (x-axis) and the carrier frequencies (y-axis); **color**, strength of modulation in terms of the degree (percentage) of modulation. From Genuit, 2016.*

The Future

Although much has already been learned, it is clear that more study is needed to determine the actual impact of alert signals on pedestrians and bicyclists with respect to both accident rates and noise annoyance. This can become critical as the number of EVs in road traffic increases and all new EVs are required to emit alert sounds in compliance with the regulations of their nation. The study of benefits and drawbacks of the nationwide alert sounds must focus on road traffic noise effects on the public as well as on the accident rates associated with them. Of course, it is also necessary to consider the well-being of visually impaired persons because these sounds are particularly important for that group. Any adjustment in the regulations and specifications, up to a waiver of alert sound requirements, must be well grounded in the observation of the real impact of the alert signals.

It goes without saying that diverse alternative technological solutions are conceivable for supporting, or even replacing, the recent pedestrian alert sound safety standards. Technical solutions, such as a vibration transponder for persons at risk, are not considered adequate because a highly trained sense (hearing) would be replaced by a less trained sense (touch). Moreover, silent cars will be a potential danger to all traffic participants including those not using a vibration transponder; other vulnerable road users without transponders including children, cyclists, elderly persons; and distracted pedestrians (EBU, 2019). In addition, pedestrian-centered approaches based on smart devices shift responsibility from the driver to the pedestrian, requiring that the pedestrian has to pay (extra) attention and that the respective device is functioning properly.

Car manufacturers are working to achieve a vision of accident-free driving by implementing more and more assistance systems such as automatic emergency braking or automatic pedestrian detection. Thus, the use of alert signals might ultimately become obsolete due to technological progress that would result in accident-free driving; this of course depends on the phase out of existing vehicles due to service life or to legislation. Car-to-car communication can be used to avoid unreasonable emission of alert sounds; for example, when 10 cars at an intersection already emit an alert signal, it might not be necessary for additional cars to do so.

Future technological systems can also be used to help visually impaired persons safely navigate through unsafe conditions such as crossing roads. Indeed, in areas with loud background noise, it would be unsafe to rely only on the audibility of the alert system of a car. Yamauchi et al. (2015) observed that quiet vehicle warning sounds in environments with loud background noise are not audible and thus of limited benefit in addressing the danger that such vehicles pose to pedestrians. Here, ideas to adapt alert sounds to the respective sonic environments are currently being discussed to optimize the balance of noise pollution and sufficient audibility (Kournoutos and Cheer, 2019).

The ultimate goals must be to avoid fatal accidents, to support visually impaired persons (and other groups needing additional support), and to minimize any impact on environmental noise leading to noise annoyance. The search for the perfect solution must guide further discussion of alert signals beyond nonscientific debates.

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André Fiebig earned his PhD in psychoacoustics at the Technische Universität (TU) Berlin, Germany. For the past 13 years, he has worked at HEAD acoustics GmbH, where he developed test procedures for sound quality applications. Since 2019, he has been a visiting professor at the TU Berlin, teaching psychoacoustics, noise effects, and soundscapes. He chairs the technical committee on noise in the German Acoustical Society. His research focus is cognitive stimulus integration of streams of auditory sensations in the context of psychoacoustics. He is also interested in the application of the soundscape approach for environmental noise assessment.

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