Alternative alert signal concepts and their perceptual implications

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ABSTRACT
It is expected that electric motors will continuously replace combustion engines within the next decades due to political measures like tax incentives or the introduction of low emission zones. With an increasing spread of electric vehicles the concern goes along that a higher incidence rate of pedestrian and bicyclist crashes could occur. In order to avoid any potential drawback regarding pedestrian safety due to reduced exterior noise of electric vehicles, the introduction of alert signals is broadly discussed on different political levels. An alert signal as a continuous sound should, in short, inform pedestrians about an approaching vehicle and its type of operation. Although this target could be achieved by different signals, it seems that merely solutions based on tones and pitch-shifting respectively are discussed.

The paper will illustrate different alert signal concepts and will discuss their perceptual implications. It is evident that any alert signal design must be discussed in the context of legal restrictions as well. In general, the greatest challenge is to develop concepts enhancing pedestrian safety without neglecting ecological consequences, since in the future numerous electric vehicles might radiate their alert signals at the same time.

Keywords: Electric vehicle, sound design

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1. INTRODUCTION
Beyond doubt, the electrification of the powertrain of vehicles offers potential to reduce interior as well as exterior noise to a certain degree. This leads to the hope of road traffic noise affected persons for quieter cities, since in urban areas traffic noise could be potentially reduced. In particular, this noise reduction potential seems promising in approaching an overarching goal of the European noise policy, the creation and preservation of quiet zones in cities [1]. Thus, the European Commission demanded in its white book “Roadmap to a single European transport area” from 2011 to halve the use of ‘conventionally-fuelled’ cars in urban transport by 2030 and phase them out in cities by 2050 to substantially reduce harmful emissions [2].

At the same time, surveys have reported on an increased risk of accidents for pedestrians and cyclists with respect to collisions with electric vehicles [3]. Such investigations of accident statistics caused lively discussions [4] and end up in the general demand for additional acoustical warning signals for quiet vehicles in order to alert blind and visually-impaired persons sufficiently [5]. Although some studies questioned heavily the conclusions drawn from meta-analyses of accident statistics [6], the policy adopted the demand for additional alert signals to decrease the risk of pedestrians’ crashes with electric vehicles [7].

These developments led endeavors to identify and implement appropriate alert signals, which have to meet several requirements. For example, the UNECE working party on noise defined that any alert sound should be a continuous sound easily reminding the pedestrians of an approaching vehicle and therefore, the concluded, several types of sounds are not acceptable, like siren, chime, bell and melodious sounds, animal and insect sounds, natural sounds, or other sounds not commonly associated with a vehicle [8]. These statements led to the concept that at least one tone (and preferably more) should be included in an alert sound [9]. To further aid in the recognizability of vehicle the pitch should increase by at least 1% per 1 km/h increase [9].

Consequently, to address the mentioned issues to successfully avoid accidents and to minimize noise annoyance as much as possible, sustainable and elaborate concepts must be developed.

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2. ALERT SIGNAL CONCEPTS AND IMPLICATIONS ON TRAFFIC NOISE

2.1 Pitch shifting

The Pedestrian Safety Enhancement Act [7] defines as a general requirement that any pedestrian alert sound includes characteristics common to all sounds produced by vehicles driven by mechanical power that make those sounds recognizable as a motor vehicle based on the public’s experience and expectations of those sounds. For example, pitch shifting and increases in sound pressure level denote changes in speed and are common to all vehicles driven by mechanical power.

Accordingly, the NHTSA proposed in 2013 the standard No. 141 “Minimum Sound Requirements for Hybrid and Electric Vehicle” under chapter S5.1.6 Pitch shifting to signify acceleration and deceleration that “the fundamental frequency of the sound emitted by the vehicle must vary with speed by at least one percent per km/h between 0 and 30 km/h” [10]. Moreover, it was proposed that the sound emitted by the vehicle to meet the requirements must contain at least one tone, which means that the sound level of the tone is 6 dB greater than the noise level in the respective band.

Figure 1 illustrates the concept of pitch shifting in principle. Several tones in different third octave bands are changing in frequency (after 5 s) to indicate an increase of vehicle speed.

![Figure 1 – Example of pitch shifting in dependence of speed](image)

It is known that the proposed rules by NHTSA were heavily commented by other parties and they requested to define a noise level that effectively alerts pedestrians without being excessively loud. The first approach in [10] was that the vehicle sound should reach minimum A-weighted sound pressure levels in each of the one-third octave bands. This requirement results in relative high overall sound levels. Although the final ruling including the respective specifications is not available yet, it appears very likely that the alert signal concept of tones and pitch shifting will be kept.

In order to demonstrate potential alert signals, the NHTSA proposed some sound files as examples on the NHTSA website meeting and violating the proposed specifications [11]. In order to provide context, the different alert sounds are combined with an ambient sound consisting of pink noise filtered such that the spectral shape conforms to the average of several typical ambient conditions.

Figure 2 (left) displays one example provided by the NHTSA, which meets the proposed specifications and shows that by means of tonal components the pass-by of a car should be recognized. The requirements for recognition – the sound must contain at least one tone, one tone has to be no higher than 400 Hz, and the sound must have broad-band content in each one-third octave band from 160 Hz to 5000 Hz – was intentionally just met.

Another sound example is shown in figure 2 (right), which represents a noise of a constant speed situation. This sound was developed within the European research project Electric Vehicle Alert for Detection and Emergency Response (eVADER) [12]. Few harmonic components are used, which are partly subject to modulation.
Figure 2 – Left: Example sound 3 based on low levels of broadband noise and strong tonal components that have been slightly modulated in pitch and amplitude to produce a rich tonal sound meeting just the proposed detection requirements in all specified one-third octave bands [10], Right: Acoustic warning signal proposed within the eVADER project [11]

2.2 Implications of introducing alert signals proposed by NHTSA on traffic noise

Besides the requirement to provide vehicle operation information to pedestrians and vulnerable road users to reduce the risk of crashes with pedestrians, it is also essential to consider the impact of introduced warning signals on resulting road traffic noise, since one million healthy life years are lost every year from traffic related noise in the western part of Europe and approximately 1.8 % of all myocardial infarctions are attributable to road traffic noise, which was estimated by WHO in 2011 [13]. Consequently, the European Parliament demanded that any development of an acoustic vehicle alerting system shall give consideration to the overall community noise impact. This aspect is usually not fully addressed in the process of developing warning signals for electric vehicles, since detection, localization and annoyance aspects are frequently only discussed with respect to single cars instead in the context of multiple vehicle scenarios.

The rules proposed by the NHTSA in 2013 [10] suggest that an electric vehicle must emit a sound having at least the A-weighted sound pressure level in each of the defined one-third octave bands specified in different tables according to the respective speed and that pitch shifting must be implemented to signify acceleration and deceleration. For it, the fundamental frequency of the sound emitted by the vehicle must vary with speed by at least one percent per km/h between 0 and 30 km/h. Moreover, at least one tone must be included in the sound emitted by the vehicle, and at least one tone must be lower than 400 Hz. To study potential psychoacoustic effects caused by the presence of several electric vehicles equipped with alert signals, some simplified prototype signals were generated (without considering broad-band noise contributions for the sake of simplicity). Different sounds were generated having tones in the respective one-third octave bands, which slightly vary in pitch representing slightly different vehicle speeds. A hypothetic difference in vehicle speed of 1 km/h results in a difference of 1% of the respective tone frequencies.

Figure 3 illustrates some psychoacoustic effects caused by the superposition of alert signals based tones. Due to the assumed slightly different speeds of vehicles present in the virtual road traffic scenarios, the alert signals show consequently slightly shifted tones in frequency. Exemplarily, the noises of one electric vehicle, of two electric vehicles with a speed of 10 km/h and 11 km/h and the resulting noise of 5 vehicles with different speeds are analyzed. It can be seen that due to the superposition of shifted tones diverse modulations are evoked (see fig. 3), which lead for example to a considerable increase of fluctuation strength. Moreover, if temporal and spectral noise patterns are analyzed, based on the Relative Approach analysis [14], as expected the amount of perceivable noise patterns increases leading to an increase of attracted attention. It is obvious that due to the slightly shifted tones disharmonic can be provoked. It is known that disharmonic sounds are perceived as
unpleasant relative independent of their absolute loudness. Moreover, it is expected that the superposition of tonal components due to the presence of several vehicles impacts strongly localization and detection performances as well.

Figure 3 – Simulations of a single alert signal (left) and of micro-traffic scenarios with two vehicles with different speeds (10 km/h and 11 km/h) (middle) and with five vehicles all with different speeds (right). From top to bottom: FFT vs. time, Relative Approach analysis quantifying the amount of perceivable temporal and spectral patterns [14], Fluctuation strength, and Modulation spectrum vs. band (degree of modulation)
Moreover, a proposed sound (sound 3) on the NHTSA website [11] meeting the suggested specifications in [10] was resynthesized based on noise spectra and tones using a simulation tool, which was developed in the European research project “Cityhush” [15]. First, based on the proposed sound a binaural signal including Doppler Effect was generated to indicate a pass-by event (fig. 4 top) and the assumed speed of the vehicle was exemplarily modified using the proposed pitch shifting rule to generate different pass-by events and superpose them (fig. 4 bottom).

![Figure 4 – Simulation of sound 3 proposed by NHTSA [11] as a pass-by event (top) and simulation of a micro-traffic scenario consisting of four pass-by events of vehicles with different speeds and moving directions based on sound 3 characteristics (bottom). FFT vs. time](image)

As expected, the superposition of several pass-by events leads to audible fluctuations. Exemplarily, figure 5 shows that the amount of noise patterns increases up to 15%, which means that the resulting road traffic noise is much more attracting attention. Moreover, it appears difficult to separate and localize the driving directions of the single cars in the created scenario. The modulation effects complicate the identification of position and moving direction of the respective vehicles.

![Figure 5 – Simulation of sound 3 proposed by NHTSA [11] as a pass-by event proposed (top) and simulation of a micro-traffic scenario consisting of four pass-by events with different speeds and moving directions based on sound 3 characteristics (bottom). Relative Approach analysis vs. time](image)
In simulated high-traffic conditions, the NHTSA found a difference in sound level of no greater than 0.3 dB(A) at all speeds and under all conditions compared to the no action scenario [11]. They estimated that even if EVs/HVs were to reach 50% deployment, the proposal causes a maximum difference of 0.7 dB above the sound level in urban environments and they concluded because differences of less than 3 dB are generally not noticeable by humans, the environmental impacts are expected to be negligible [10]. This statement let suspect an underestimation of later annoyance effects due to the introduction of warning signals for hybrid and electric vehicles. Since alert sounds are designed to be detectable, recognizable and to attract sufficient attention, noise annoyance cannot be predicted sufficiently on the basis of the minor increase of overall sound pressure level only.

2.3 Modulation concept

An alternative concept is conceivable in contrast to tonal components shifted in pitch. By means of amplitude modulation the carrier signals are changed to indicate for example the movement of an electric vehicle. Figure 6 illustrates the principle of amplitude modulation. An envelope containing the basic information is multiplied with a carrier signal leading to a characteristic modulated signal. The frequency of the modulation and the modulation depth are characteristic parameters of the modulation signal. The carrier signal can be any kind of signal, a tone, narrow-band noise or even broad-band noise.

![Figure 6 – Example of amplitude modulation as a result of the multiplication of a sinusoid envelope with a sinusoid carrier signal](image)

A possibility to indicate the operation of an electric vehicle could be to define a carrier signal and to modulate it in dependence of the speed of the vehicle, which would allow recognizing and localizing the vehicle. Based on such concepts, random broad-band noise impulses can be generated, where the repetition rate is related to vehicle operating parameters like speed. Figure 7 displays different ways to use modulation to alert pedestrians and to convey the information of an accelerating electric vehicle by modulation. In contrast to the pitch shifting concept, the speed of the vehicle is indicated by changing the modulation frequency (fig. 7 top left). With increasing speed, the modulation frequency increases. In addition to it, the changing modulation frequency can be also combined with a change of loudness (fig. 7 top right). Of course, the carrier signal is not limited to tones, but can also be random narrow or broad-band noise. Moreover, amplitude modulation and pitch shifting could be combined (fig. 7 bottom), which means that the carrier signal changes its frequency in dependence of the speed and at the same time the signal is modulated with a constant (fig. 7 bottom left) or varied modulation frequency (fig. 7 bottom right).
Figure 7 – Examples of different modulation concepts to help pedestrians to recognize electric vehicles

Moreover, since the character of amplitude modulated sounds depends largely on the realized modulation index, this signal parameter can also be applied to optimize alert signals for electric vehicles. The impact of the chosen modulation index on the time signal is exemplarily shown in figure 8. With an increasing modulation index, the resulting signal is more attention attracting. This signal parameter could be related to the vehicle’s load.

Figure 8 – Signals with a different modulation index
Figure 9 shows the time signal and the FFT vs. time analysis of a potential alert sound, where a non-sinusoid envelope is multiplied with a broad-band pink noise. Due to the broad-band carrier signal, which is modulated, the moving object, the electric vehicle, should be well localizable.

Figure 9 – Alert signal indicating the acceleration of an electric vehicle based on a constant broad-band carrier signal and a speed dependent modulation frequency

### 2.4 Implications of introducing alert signals based on modulation concepts

The main advantage of using broad-band noises as carrier signals is the avoidance of dissonance phenomena, which can occur heavily with shifted tones. Moreover, such broad-band signals facilitate the localization of spatially distributed and moving sources. Due to the concept of modulated random noises, the superposition of sources emitting alert signals did not result in specific psychoacoustic effects. As exemplarily indicated in figure 10 the superposition of alert signals emitted by vehicles in different operating conditions decreases the “clarity” of the single envelope, which leads to the effect that the resulting sum signal has a stronger irregular time pattern. Thus, the impulsiveness, roughness or fluctuation strength of the overall noise caused by different superposed alert signals will in most cases decrease, since the modulation of the single alert signal is “disturbed” by other alert signals. This effect is demonstrated in figure 11. This means that, although the sound pressure level of the resulting traffic noise caused by several vehicles naturally increases, the noticeable and distinct features from the psychoacoustics perspective will be less pronounced. This has a positive impact on resulting road traffic noise annoyance. Of course, the impact of several electric vehicles emitting alert signals on detection and localization performance must be further investigated.

Figure 10 – Single alert signals based on varying non-sinusoidal envelopes varying in dependence of vehicle speed (left, middle) and their superposition (right). FFT vs. time
3. CONCLUSIONS

The introduction of alert signals for a better protection of visually-impaired persons must consider resulting noise annoyance effects as well, since one million healthy life years are lost every year from traffic related noise in the western part of Europe as estimated by the WHO [13]. It is expected that annoyance caused by road traffic noise with alert signals included will be an important issue, since alert signals are particularly designed to attract sufficient attention in urban noise contexts. In [17] it was exemplarily shown by means of road traffic noise simulations that the strength of perceivable patterns due to obtrusive warning signals can even be higher than the mount of distinctive noise features occurring in comparable ICE vehicle scenarios.

An alternative signal concept to the usually proposed concept of pitch shifted tones could be the elaborate use of amplitude modulation, where several parameters can be used to create adequate alert signals. The frequency (range) of the carrier signal, the form of the envelope, its frequency and the modulation index are potential signal properties to be used for the design of alert signals. Such signals might allow for improving localization abilities and decreasing impacts on environmental noise at the same time. Accordingly, Robart et al. showed the positive effect of amplitude modulation on the detectability of electric vehicles [18].

Although in [19] it is defined that an alert sound should be easily indicative of vehicle behaviour and should sound similar to the sound of a vehicle of the same category equipped with an internal combustion engine, the proposed modulated signals, even when they do not resemble very much combustions engines, are associated with moving objects and thus are appropriate to signal a moving, maybe dangerous object. It appears necessary to consider still alternative alert signals to achieve the ambitious goals with respect to the conflicting objectives of warning pedestrians and of minimizing the acoustical impact on the environment.

Finally, it is of vital importance that further research efforts are made with respect to the development and implementation of comprehensive approaches to warn efficiently vehicle drivers as well as pedestrians about the danger of collision far beyond concepts of simply continuously emitting warning signals and hoping that all vulnerable pedestrians are able to hear early enough the approaching vehicle to avoid any crash. The accident-free car must be the long-time objective.
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