

Psychoacoustic Requirements for Warning Sounds of Quiet Cars

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ABSTRACT

According to upcoming legislative regulations in certain countries, electric and hybrid-electric vehicles (EVs and HEVs) will have to be equipped with devices to compensate for the lack of engine noise needed to warn pedestrians against the vehicles. This leads to the question of appropriate sound design which has to meet specific psychoacoustic requirements. The present paper focuses on auditory features of warning sounds to enhance pedestrians' safety with a major focus on the detectability of the exterior noise of the vehicle in an ambient noise. For the evaluation of detectability, the psychoacoustic model developed by Kerber and Fastl will be introduced allowing for the prediction of masked thresholds of the approaching vehicle. The instrumental assessment yields estimates of the distance of an approaching vehicle at the point it becomes audible to the pedestrians. This way the risk of collision can be assessed assuming that only auditory cues are used by pedestrians to identify vehicles before crossing a street. The corresponding algorithm was applied in a field study to assess the detectability of selected EVs and HEVs as opposed to conventional vehicles. A second focus of this paper will be on the issue of recognisability. It is suggested to design sounds which both are perceptually indicative of the vehicle behaviour and inform about the specific type of propulsion and vehicle make. As a result, the concept of a sound signature specific for vehicles with electric propulsion is proposed which may enhance detectability considerably while recognisability is retained to a large extent.

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INTRODUCTION

Due to their lower noise emissions, the introduction of electric and hybrid electric vehicles (EVs, HEVs) has raised the issue of pedestrians' safety, and thus forced car manufacturers to develop counter-measures in terms of a sound device. It is argued that quiet cars such as EVs and HEVs do not produce sufficient noise to make them detectable in a background noise early enough to avoid collision if only auditory cues are used for detection [1]. Figure 1 indicates that the argument particularly applies at low speeds. It is shown that the engine noise of a vehicle with an internal combustion engine (ICE) dominates the overall noise level for speeds below approximately 30 km/h, while tyre-road noise determines the overall noise level above.

Therefore, quiet cars are considered a threat to pedestrians in general whereas vulnerable road users such as the blind and visually impaired [2] are particularly affected. The argument was supported by research into the statistics of traffic accidents in the United States showing a significantly higher incidence rate for hybrid vehicles at low speeds [3]. Consequently, governmental agencies are about to introduce

regulations which require car manufacturers to equip all vehicles that can run on electric motors only, with a sound device to compensate for lacking engine noise components. Currently, Japan and the United States have a leading role in the endeavour to define standards for this requirement. Although no final rule for the required sound device has been published yet, there is wide agreement about a number of necessary features which have already been implemented predominantly in Japanese cars (see [4]). Accordingly, the warning sound should

- be produced in a speed range up to 20-30 km/h
- be generated for forward and reverse driving alike
- convey information about the behaviour of the vehicle and vary at least with speed.

In regard to level and character of the sound, no published specifications are known to the authors. The sound level is expected to be defined in terms of a minimum requirement by reference to ICE vehicles at the lower end of the noise emissions scale (see [5]). As far as the sound character is concerned, various alternatives have been discussed ranging

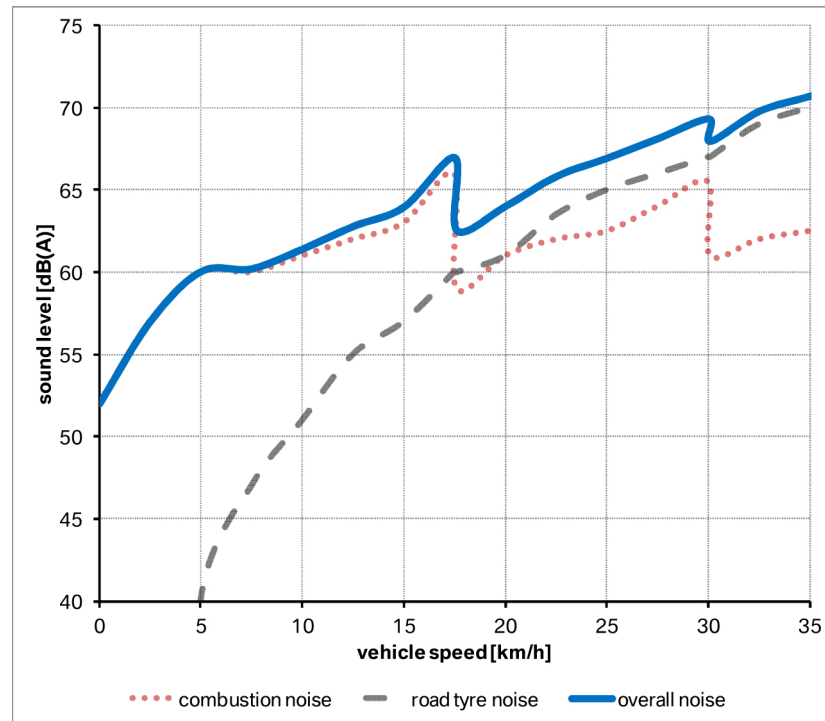


Figure 1. Sound levels of exterior vehicle noise components as a function of vehicle speed exemplified for a hatchback with 4-cylinders gasoline engine. Peaks indicate gear shifts of the vehicle.

Table 1. Psychoacoustic assessment and corresponding evaluation (positive/negative) of the sound alternatives proposed by NHTSA [6].

Sound Alternative	Detectability	Recognisability	Annoyance
Recordings of Actual Internal Combustion Engine Sounds	Low (-)	very high (++)	High (-)
Synthesized ICE-Equivalent Sounds	Low (-)	very high (++)	High (-)
Combination of Synthesized Non-ICE Sounds and ICE Components to Aid Recognition	high (+)	High (+)	Low (+)
Synthesized Non-ICE Sounds Developed to Enhance Detectability	very high (++)	very low (-)	very high (-)

from recordings of ICE noises to synthesized sounds which are optimized for detectability but can hardly be associated with vehicle noise (see [Table 1](#)). In the following, major requirements of the sound character will be discussed from a psychoacoustic perspective and a concept of the sound design for the powertrain noise of vehicles with electric propulsion will be proposed.

PSYCHOACOUSTIC REQUIREMENTS

Clearly, the requirements for warning sounds of quiet cars should go far beyond the mere specification of a minimum noise level and should consider the needs of pedestrians in terms of the auditory cues needed to warn them against the vehicles. The pedestrians safety enhancement act (PSEA) imposed by the U.S. Congress, explicitly states a number of those needs (see [Table 2](#), [6]) and directed the Department of Transportation into rulemaking. These required sound

Table 2. Auditory cues needed by pedestrians according to the U.S. PSEA.

Information about the vehicle's ...	implies that the sound has to ...	Major Psychoacoustic Concepts
... presence	... indicate that the vehicle is audible in the ambient noise	Detectability, spectral masking
... location	... convey the position of the vehicle in the surroundings	Localization, binaural hearing
... direction	... tell if the vehicle is approaching or departing	Level/loudness change, Doppler-effect
... operation	... indicate the dynamics of acceleration and deceleration	Recognisability

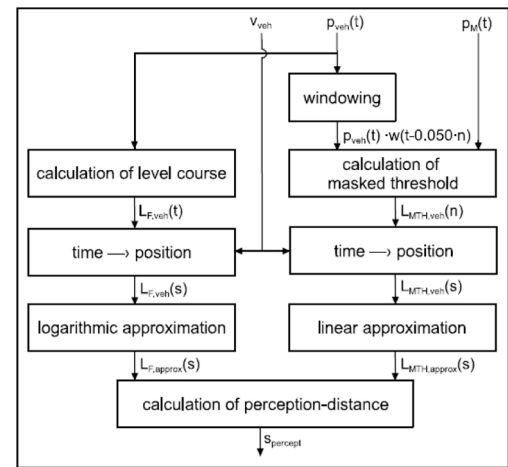
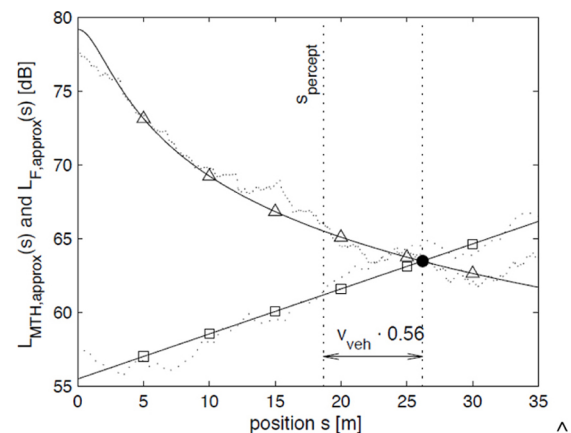
features are not independent from each other and may even be conflicting in the extremes. Broad-band noise, for instance, could be localized well in quiet surroundings but would get a low detectability score due to adverse masking effects in many ambient noise situations. This conflict could be solved, however, if the sound contained both a component with a broader spectrum to foster localization and elements such as tonal components or modulations which may be suitable to enhance detectability. In the following, the psychoacoustic phenomenon of spectral masking will be analysed in larger detail and a predictive model for the detectability of approaching vehicles will be introduced.

DETECTABILITY

Psychoacoustic Modelling of Masked Thresholds of Approaching Vehicles

The detectability of a sound in a background noise largely depends on the extent to which the signal is spectrally masked [7, 8]. In his attempt to employ this concept for approaching vehicles, Kerber [8] has developed a psychoacoustic model to predict masking thresholds as a function of the distance to the listener (perceptual distances). Figure 2 depicts the components of the algorithm which shall be briefly introduced. The procedure shown in the left branch of the diagram involves the calculation of the sound level of the vehicle at the listener's position based on vehicle speed v_{veh} and the time varying sound-pressure of the approaching vehicle p_{veh} . The right branch first involves the calculation of the time-dependent masking threshold of the approaching vehicle in a stationary masker p_M . This is achieved by segmenting the course of the approaching vehicle into quasi-stationary pieces for which the masking thresholds are calculated according to the model by Fastl and Zwicker [7]. Further, using vehicle speed, masked thresholds depending on the vehicle position are calculated. According to the definition of masked thresholds, a vehicle becomes audible at that position where the sound level of the vehicle exceeds its masked threshold, i.e., where $L_{F, approx}(s)$ is greater than $L_{MTH, approx}(s)$ (see Figure 3). A pedestrian would be able to detect the vehicle at this point but could only act after a certain amount of reaction time has passed (see [9]). This

time is assumed to be 0.56 seconds and, in Figure 3, separates the position where the vehicle becomes audible with the position $s_{percept}$ where a pedestrian would finally react.

**Figure 2. Flow Chart of the algorithm for the calculation of perceptual distances of approaching vehicles.****Figure 3. Principle of the calculation of perceptual distances out of the approximation for level course (triangles) and masked thresholds (rectangles) for a selected car. The dotted lines indicate the measured courses of the signal.**