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PAPER

Psychoacoustic examination of feasible level of additional warning sound for quiet vehicles

Katsuya Yamauchi[1,*], Daniel Menzel[2], Masayuki Takada[3], Koji Nagahata[4], Shin-ichro Iwamiya[3] and Hugo Fastl[2]

[1] *Faculty of Engineering, Nagasaki University, Bunkyo-machi 1–14, Nagasaki, 852–8521 Japan*
[2] *AG Technische Akustik, MMK, Technische Universität München, Arcisstrasse 21, D-80333 München, Germany*
[3] *Faculty of Design, Kyushu University, Shiobaru 4–9–1, Fukuoka, 815–8540 Japan*
[4] *Faculty of Symbiotic Systems Science, Fukushima University, Kanayagawa 1, Fukushima, 960–1296 Japan*

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Abstract: The reduced noise of electric and hybrid electric vehicles has been of particular concern because of the potential danger that these vehicles pose to pedestrians when their approach is inaudible against background noise. To address this issue, the use of additional warning sounds in such vehicles is being considered in various countries. The aim of this study was to examine the feasible level of the warning sounds in some urban environments. The levels of three candidate warning sounds (sound of car horn, engine sound, and band-pass noise) were adjusted by the study subjects against four types of urban background noise presented in a laboratory environment. The subjects were asked to adjust the level of the warning sounds so that they were reliably audible or just detectable. The results showed that the level of background noise and type of warning sound significantly affected the perception of the warning sounds, but there was no significant cross-cultural difference between the German and Japanese subject groups. The observations showed that a warning sound that was reliably audible in a particular environment might be inaudible in another environment approximately 10 to 20 dB noisier. The results were also compared with current recommended levels of warning sounds for quiet vehicles.

Keywords: Quiet vehicles, Warning sound, Cross-cultural comparison, Sound level, EV/HEV

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1. INTRODUCTION

Vehicles that are fully or partly propelled by electric motors, such as electric vehicles (EVs) and hybrid electric vehicles (HEVs), are becoming common in urban fleets. In addition to being more environmentally friendly, such vehicles produce less noise than internal combustion engine vehicles (ICEVs), especially when driven at low speeds. The number of these quiet vehicles is expected to increase considering social demands for the reduction of greenhouse gases and the establishment of a low-carbon society. In some major countries such as Japan, United States, and Germany, policies to promote the use of EVs/HEVs are being introduced.

The reduced noise is beneficial in environments with higher levels of road traffic noise. Quiet vehicles can be regarded as one of the goals of the noise reduction drive of modern society. However, quiet vehicles are potentially dangerous to pedestrians when the approach of such a vehicle becomes inaudible against background noise (e.g., [1–3]). This is of particular concern to the blind community. The National Federation of the Blind and the World Blind Union have expressed their concerns and requested the development of a regulation requiring automobiles to emit a minimum level of sound to alert blind and other pedestrians [4]. Additionally, according to the report of the National Highway Traffic Safety Administration (NHTSA), United States [5], EVs/HEVs are nearly twice as likely as ICEVs to be involved in accidents involving pedestrians.

*e-mail: yamauchi@cis.nagasaki-u.ac.jp

Toward solving these problems, regulations and recommendations mandating or recommending the installation of additional sound-emitting devices in quiet vehicles have been discussed by various governments. The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has announced a guideline regarding the quietness problem [6]. The guideline states that a warning sound should be automatically emitted when the vehicle is driven at a speed of less than 20 km/h, the sound should be continuous and evoke the running condition of a vehicle, and its sound level should not exceed that of an ICEV running at a speed of 20 km/h. The Quiet Road Transport Vehicles (QRTV) Work Group, which was established by UN/ECE/WP.29/GRB (Group of Experts on Vehicle Noise, World Forum for Harmonization of Vehicle Regulations, United Nations Working Party 29), has approved an international guideline [7] that is basically similar to that of the Japanese MLIT. The QRTV is also developing a global technical regulation (GTR) regarding the requirements for sound-emitting devices. In the United States, the Pedestrian Safety Enhancement Act of 2010 has been approved, which mandates the NHTSA to establish performance requirements for alert sounds that would enable blind and other pedestrians to be reasonably aware of nearby EVs/HEVs. The automobile industry has also been working on the development of sound-emitting devices and the design of the actual sound itself. Indeed, some automobile manufacturers have launched warning systems for their EVs/HEVs (e.g., [8]).

The accumulation of a broad range of acoustic knowledge for the feasible design of warning sounds for quiet vehicles is crucial to developing relevant regulations and designing the sound itself. Nevertheless, the acoustical properties of the ideal design, including basic issues such as the adequate sound level, have still not been sufficiently established. Although some studies have been conducted to qualitatively examine the effect of adding sounds to quiet vehicles, some of them were conducted using real vehicles that were only equipped with sound-emitting devices onsite [9,10]. Although the effectiveness of the system on awareness could be clarified, it was difficult to assess the feasibility level with regard to repeatability of experimental condition. Sekine *et al.* [11] demonstrated the effectiveness of adding sound to quiet vehicles for awareness by pedestrians. Their experiments were conducted in quiet environments ($L_{\mathrm{Aeq}} = 44$, 50, and 56 dB). It is, however, still unclear whether the sound level suggested by existing guidelines, the warning sounds of such a sound level, and the sound level of an ICEV running at a speed of 20 km/h would be effective in real urban environments, which are occasionally louder.

Hence, the aim of our study was to examine the feasible level of possible warning sounds in some urban environments. A pilot study on this subject was performed in Japan [12], and the input device and test procedure were improved for the present study. The required levels of three possible warning sounds were adjusted by the subjects against four different urban background noises presented in the laboratory environment. Moreover, considering that EVs/HEVs are used globally, it was of vital interest to determine any cross-cultural effects on the adjusted sound levels. For this reason, the experiments were conducted in both Germany and Japan. The results were further compared with current warning signal recommendations for quiet vehicles.

Table 1 Noise level and road environmental conditions of each background noise.

	$L_{\mathrm{Aeq,5min}}$ [dB]	Environmental condition
Env.1	65.9	Two-lane busy street in downtown, including sound of crowd, female announcement, and ambient music from shops
Env.2	67.8	Two-lane street in a residential area
Env.3	73.2	Six-lane heavy-traffic road
Env.4	60.4	Narrow street in a shopping area

2. METHOD

2.1. Stimuli

Four background noises were recorded in Fukuoka, Japan, namely on a two-lane busy street in the downtown area, a two-lane road in a residential area, a six-lane heavy-traffic road, and a narrow road in a shopping area. The recordings were done binaurally using a head and torso simulator (HATS/Brüel & Kjær type 4100) positioned on the sidewalk. The A-weighted equivalent noise levels throughout the recording time ($L_{\mathrm{Aeq,5min}}$) were also measured by a sound level meter (Brüel & Kjær type 2238) simultaneously. The measured sound levels and road environmental conditions are shown in Table 1.

Three candidate warning sounds were used in the study, namely, the sound of a car horn, the sound of an idling gasoline engine, and bursts of band-filtered white noise. The car horn sound was obtained from a commercially available CD compilation of sound effects, and its duration was approximately 300 ms. The idling gasoline engine sound was recorded from an ICEV (with a four-cylinder 1,500 cc gasoline engine) on a flat ground in open air without surrounding buildings. The microphone was set up 2 m behind the vehicle and 1.2 m above the ground. The duration of the sound was 20 s with 250 ms linear rise and decay. The bursts of band-filtered noise were generated by filtering a white noise through a high-pass filter (with a cutoff frequency of 1 kHz and slope of 12 dB/octave) and a

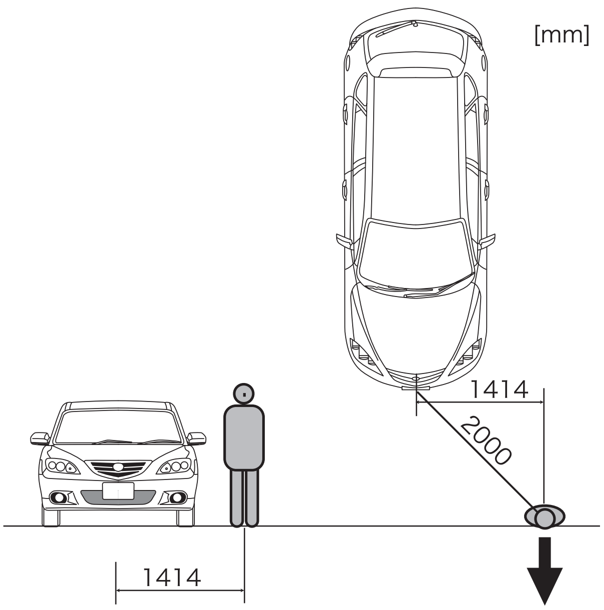

Fig. 1 Assumed relative position between the pedestrian and the vehicle providing warning sounds.

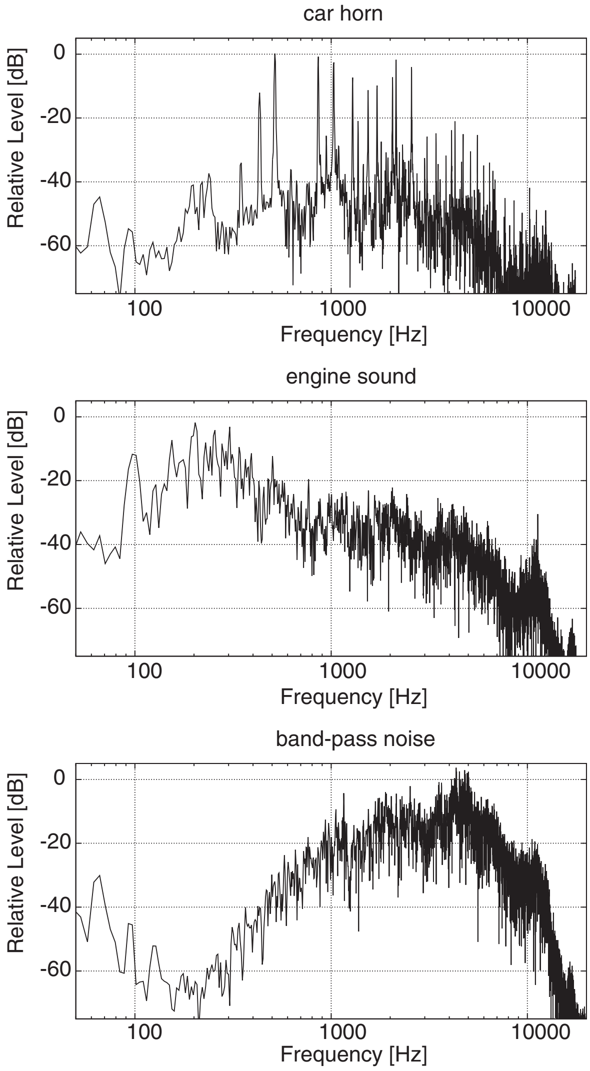

Fig. 2 Frequency characteristics of three warning sound stimuli (right-ear channel, stable section).

low-pass filter (with a cut-off frequency of 10 kHz and slope of 12 dB/octave). The source was then given a temporal pattern consisting of four bursts and a 1,400 ms pause. Each burst had a 350 ms onset and a 350 ms pause duration with a 25 ms rise and decay. Each candidate warning sound was played back over a loudspeaker in an anechoic room and recorded by a HATS. Figure 2 shows FFT spectrum of each warning sound. The loudspeaker was positioned diagonally 2.0 m behind the HATS to simulate the assumed position of the subject (Fig. 1).

2.2. Set-up and Procedure

The experiments were performed in a darkened soundproofed booth in Technische Universtät München in Germany and in a darkened soundproofed room in Nagasaki University in Japan.

The experimental setup is shown in Fig. 3. The signals were presented over Sennheiser HD-650 headphones. The input voltage to the headphones was measured so that the playback level could be calibrated taking into account the sensitivity of the headphones.

The subjects could adjust the level of the warning sounds through a slider visible on a computer screen. The sound presentation was repeated until a button was pressed by the subjects indicating a satisfactory level. One of the background noises was first presented, and then, one of the warning sounds was overlapped with it about 10 s later. The subjects were told to imagine that they were on a road and that the vehicle producing the warning sound was positioned 2.0 m diagonally behind them to the right, as shown in Fig. 1.

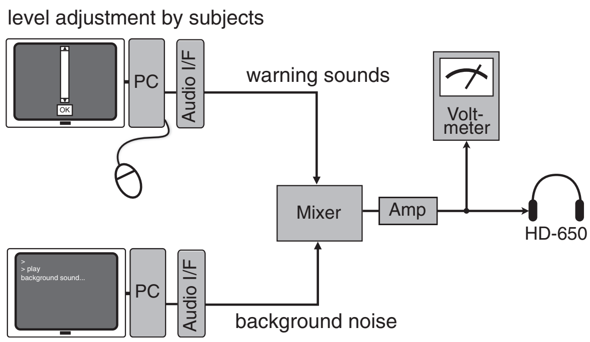

Fig. 3 Experimental setup.

Each experimental session comprised two tasks. One was the adjustment of the level of the warning sounds so that they were clearly audible and could be reliably detected against the background noise (hereafter referred to as "reliable level"). The other task, which was performed for two of the four background noises, was the adjustment

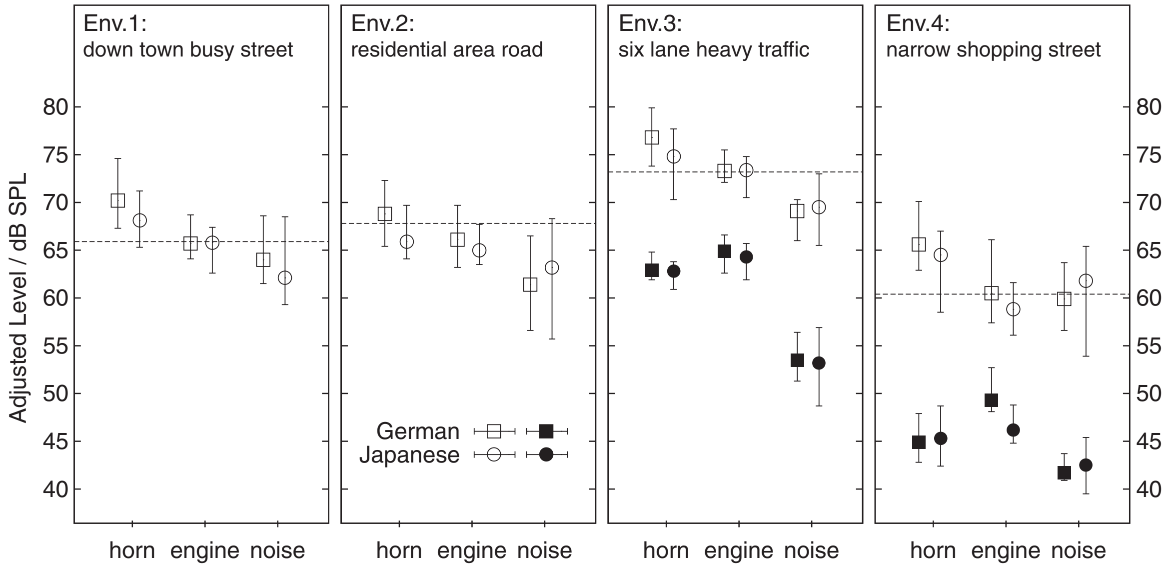

Fig. 4 Inter-individual medians and interquartile ranges of the averaged adjusted levels. (White symbols: reliable level. Black symbols: minimum level. Horizontal lines: background noise level (L_{Aeq}).)

of the warning sounds so that they were just audible against the background noise (hereafter referred to as "minimum level"). The order of these tasks was switched for each new subject. Each of the stimuli combinations was presented once and the order of the presentations was pseudorandom. All the subjects underwent a second trial some days later to enable examination of intra-individual differences.

2.3. Subjects

Fifteen German subjects comprising 4 females and 11 males aged between 26 and 49 years (mean and median ages of 31.3 and 30 years, respectively) participated in the experiments performed in Germany. Sixteen Japanese subjects comprising 5 females and 11 males aged between 23 and 55 years (mean and median ages of 30.2 and 30 years, respectively) participated in the experiments performed in Japan. None of the subjects reported any auditory abnormality.

3. RESULTS

Figure 4 shows the inter-individual medians and interquartile ranges of the averaged adjusted levels for all the stimuli conditions. The square and circular symbols respectively represent the adjusted levels for the German and Japanese subjects. The white symbols represent the reliable levels, and the black symbols the minimum levels. The equivalent noise levels of the background noises are indicated by horizontal lines.

As expected, the adjusted levels were significantly affected by the level of the background noise. An analysis of variance (ANOVA) was performed to investigate the effects of the background noise on the adjusted reliable levels and minimum levels. The result of the ANOVA showed that the main effects of the background noise on both the reliable and minimum levels were statistically significant ($p < 0.001$). It can be seen that the differences between the adjusted and the background levels were varied among the type of warning sounds, while those were not affected by background level. Each warning sound showed similar difference. The differences between the adjusted levels for the different background noises corresponded to the respective differences between the levels of the background noises.

It can also be seen that the type of warning sound had a significant effect. The main effects of the warning sounds on both the reliable and minimum levels were statistically significant ($p < 0.001$). In each case, the sound of the car horn required a higher level than those of the other sounds to be clearly discernible, whereas the band-limited noise was easily detectable. The levels of the clearly audible warning signals were approximately between 10 and 20 dB higher than their respective audibility thresholds.

The adjusted levels of the German and Japanese subjects were not significantly different for any of the stimulus conditions. The results of the ANOVA showed that the main effects of the subject groups (German/Japanese) were not statistically significant. Additionally, Tukey's multiple comparison procedure revealed no significant difference between the subject groups for any of the background noise and warning sound combinations.

The intra-individual differences between two trials of each subjects, which are absolute level differences between two trials, are shown in Fig. 5. The differences range approximately 2 to 6 dB. The result of ANOVA showed

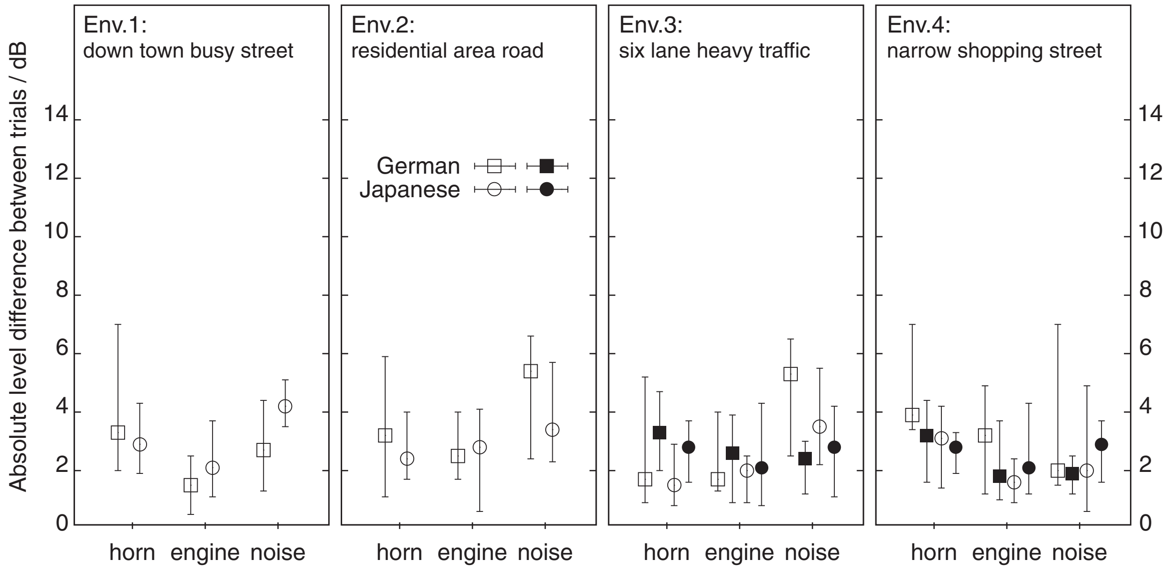

Fig. 5 Inter-individual medians and interquartile ranges of intra-individual differences between trials. (White symbols: reliable level. Black symbols: minimum level.)

that the main effect of the background, type of warning sounds, and the subject groups were not statistically significant. Because the differences between two trials were not significant, the validity of averaging two trials was determined.

Inter-individual interquartile ranges were as high as 10 dB. This rather large variability was likely caused by strong fluctuations in the background noises (e.g. varying numbers of cars passing by on the road). These fluctuations were probably also the reason for the intra-individual differences between the two trials (Fig. 5).

4. DISCUSSION

The results shown in Fig. 4 indicate that there was no significant difference between the adjusted sound levels of the two subject groups. This means that there was no cross-cultural difference between the sound level perceptions of the subjects. It should be noted, however, that these experiments only focused on the audibility against urban environmental noise. Differences between sound qualities with regard to individual preferences, for example, still require investigation.

The results indicate significant effects of the type of warning sound and the background noise on both the reliable and minimum levels. The reliable levels for the noise, which had wider frequency range, tended to be the lowest among three kinds of warning sounds. Although the noise was regarded as the most detectable within the present result, the further investigations were still required to determine the suitability for the the additional warning sounds. The results also show that the differences between the reliable and minimum levels were approximately 10 to 20 dB. These findings suggest that a sound of a given level that is clearly audible in one environment may not be audible in another louder environment; e.g., the reliable level of the horn and engine sounds in Environment 4 were at the detectability threshold or lower than the minimum level in Environment 3.

It can thus be seen that the recommendation of a fixed warning sound level in current guidelines is potentially problematic. The Japanese MLIT and WP.29 guidelines recommend that the level of the warning sound should not exceed that of the sound of an ICEV running at a speed of 20 km/h [7]; for instance, it should not exceed 60 dB at a distance of 2.0 m from the center of the vehicle [6]. Such a sound may be adequate in a particular environment with a noise level of up to approximately 60 dB, but inaudible and therefore ineffective in a noisier environment.

An adaptive strategy for adjusting the level of the warning sound to the current background noise would be more effective. It would, however, be inadequate if the vehicle emitted a louder sound in a louder environment without limitation. A part of the quiet vehicle problem is environmental. It has been remarked by the Japanese visually impaired persons, even before HVs had appeared in the market, that the sound of vehicle is occasionally masked by other environmental sounds including sounds of louder vehicles [13]. It is also very important to reduce the amount of noisy vehicles that mask the sound of quieter vehicles.

5. CONCLUSION

The authors examined the feasible levels of warning sounds for quiet vehicles in some urban environments. The levels required for three candidate warning sounds were investigated against four types of urban background noises. The experiments were performed in Germany and Japan to examine cross-cultural differences.

The results showed that the background noise and type of warning sound significantly affected the required level of the latter. However, no significant cross-cultural difference was observed. The findings showed that a warning sound of a reliable level in a particular environment might not be audible in another that is approximately 10 to 20 dB noisier. It could thus be said that the use of additional warning sounds in quiet vehicles is of limited benefit in addressing the danger that such vehicles pose to pedestrians.

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REFERENCES

[1] S. Kerber, "The importance of vehicle exterior noise levels in urban traffic for pedestrian —Vehicle interaction," *ATZ Worldwide*, **108**(07–08), pp. 19–21 (2006).
[2] S. Kerber and H. Fastl, "Perceptibility of approaching vehicles in urban background noise," *Proc. Inter-noise 2007*, pp. 981–988 (2007).
[3] S. Kerber and H. Fastl, "Prediction of perceptibility of vehicle exterior noise in background noise," in *Tagungsband Fortschritte der Akustik — DAGA 2008, Dresden*, U. Jekosch and R. Hoffmann, Eds. (DEGA, 2008), pp. 623–624.
[4] National Federation of the Blind, "Key stakeholders agree on measures to protect blind pedestrians from silent cars —Urge passage as part of motor vehicle safety act," https://nfb.org/node/1056 (referred 2014-05-20).
[5] National Highway Traffic Safety Administration, "Incidence of pedestrian and bycyclist crashes by hybrid electric passenger vehicles," DOT-HS-811-204 (2009).
[6] I. Sakamoto, T. Tanaka, M. Sekine, K. Morita, S. Masayuki, K. Takeshi and A. Yoshiike, "Reviews on countermeasure to safety risk associated with quietness of hybrid or electric vehicles in Japan," *Proc. Inter-noise 2010*, 8 pages (2010).
[7] "Proposal for guidelines on measures ensuring the audibility of hybrid and electric vehicles," in *Consolidated Resolution on the Construction of Vehicles* (*R.E.3*)*, Annex 2* (2011).
[8] H. Konet, M. Sato, T. Schiller, A. Christensen, T. Tabata and T. Kanuma, "Development of approaching vehicle sound for pedestrians (VSP) for quiet vehicles," *SAE Int. J. Engines*, **4**, 1217–1224 (2011).
[9] P. Goodes, Y. B. Bai and E. Meyer, "Investigation into the detection of a quiet vehicle by the blind community," *Proc. Sound Quality Symp. 2008*, 8 pages (2008).
[10] P. Nyeste and M. S. Wogalter, "On adding sound to quiet vehicles," *Proc. Human Factors and Ergonomics Society 52nd Annu. Meet.*, pp. 1747–1750 (2008).
[11] M. Sekine, T. Tanaka, I. Sakamoto and K. Morita, "Research on the acceptability evaluation of sounds to warn the approach of an electric vehicle," *Proc. Inter-noise 2009*, 9 pages (2009).
[12] K. Yamauchi, M. Takada, K. Nagahata and S. Iwamiya, "An examination on required sound levels for the external acoustic sign for quiet vehicles," *Proc. Inter-noise 2011*, 6 pages (2010).
[13] K. Nagahata, "A critique on the quiet vehicle problem from the view point of soundscape study," *Proc. Inter-noise 2011*, 4 pages (2011).