Detectability and hearing impression of additional warning sounds for electric or hybrid vehicles

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ABSTRACT

Electric or hybrid electric vehicles (EVs/HEVs) have the advantages that they make lesser noise compared to conventional engine vehicles. This quietness is, however, a matter of concern for pedestrians because the sound of EVs/HEVs may be inaudible in urban backgrounds. Hence, the application of additional sound-emitting device has been studied. Gathering wide range of acoustic knowledge on feasible design of the additional sounds is crucial for developing regulations or designing the device itself. Through the authors' researches, it has been revealed that the type of warning sounds significantly affected the required sound level as well as background levels. A warning sound stimulus, which had lesser loudness level, had lesser detectability. In this present study, the authors confirmed that the warning sounds could have similar detectability if they have similar loudness level. The frequency characteristics of the stimuli were varied while having equivalent powers in each 1/3 octave band so that they shall have equivalent loudness level. Moreover, the hearing impression of the stimuli were examined. The results showed that the impression of warning sounds could be varied while having equal detectability.

Keywords: Detectability, Impression, Additional Warning Sounds, EV/HEV
I-INCE Classification of Subjects Number(s): 11.9.9, 13.2.1, 63.1

1. INTRODUCTION

Electric or hybrid electric vehicles (EVs/HEVs) are comparatively quieter than conventional internal combustion engine vehicles (ICEVs), especially when they are driven at low speeds. The number of EVs/HEVs is expected to increase considering social demands for the reduction of greenhouse gases and the establishment of a low-carbon society. In some major con tries 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. These 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 vehicle becomes inaudible against background noise. According to the report of the National Highway Traffic Safety Administration (NHTSA), United States(1), EVs/HEVs are nearly twice as likely as ICEVs to be involved in accidents involving pedestrians. 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(2).

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(3). The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has announced a guideline regarding the quietness problem(4). 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(5) that is basically similar to that of the Japanese MLIT. The QRTV is also developing a global technical regulation (GTR) regarding

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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.*, (6)).

To design the sound itself or to discuss its implications for the community, it is crucial to know the feasible sound design for the warning sounds(3). The sound shall have the property that makes pedestrians easy to detect them. On the opposite side, an easily detectable sound might be an unpleasant one also. It is expected to develop a feasible sound design that is easy to listen to in urban sound environment but also no too uncomfortable.

To make sure of pedestrians awareness of the warning sound under various environmental noise, the design using sensitive frequencies on human hearing system is expected to be a effective solution. In the frequency range between 2 and 5 kHz, human hearing system usually exhibits very sensitive. On the other hand, from the view-point of frequency masking, the frequency range that is often observed in assumed applicable situation shall be avoided. It would seem that road traffic noise, that usually have the prominent frequency on around 1 kHz, is one of the most considerable masker. Hence, there are some kind of design strategies which intend to enhance detectability using frequency between 2 and 5 kHz and avoiding road traffic noise frequencies. One instance can be seen in Nissan's concept(6) that has two peaks spectral characteristics respectively at 600 and 2500 Hz and one dip at 1 kHz due to consideration of ear frequency sensitivity, hearing loss due to ageing, and ambient noise. Similar design strategy can be seen in some regulations and recommendations (*e.g.* (7)), which is intended to to exceed the level of assumed maskers at 1/3-octave bands from around 2 to 5 kHz.

Even if the 1/3-octave band levels are used for an indication to determine the detectability, there are still amount of freedom to design frequency characteristics within each band. A pair of example is one pure tone component in a complex tone and one narrow band noise that have commensurate power level within a band, which both have equivalent loudness. These tow sounds have equivalent masking effect and also evokes quite different hearing impression. This example shows the possibility designing the warning sounds that have equivalent detectability in an assumed environmental noise but also have different hearing impression.

In this study, the authors experimentally examined the difference of hearing impression within equivalent detectable warning sounds for quiet vehicles. The preferred sound levels and the listening impressions of 17 variation of possible warning sounds were investigated. The levels of each 1/3 octave band were set to be equivalent between all stimuli so that they shall have equivalent loudness level.

2. EXPERIMENT STIMULI

In the series of experiments conducted in this study, we designed and generated some stimuli to be used. The stimuli were intended to have equivalent levels in five 1/3-octave bands between 2 and 5 kHz but have different frequency characteristic in each band; pure-tone component or narrow band noise.

The base stimulus consisted of five pure-tone component in each 2, 2.5, 3.15, 4, and 5 kHz band. One, two, or five of the components were replaced by narrow band noises. Seventeen kind of stimuli were created in total (H_1 – H_17). The center frequency of the pure-tones and narrow band noises were set to be 2093, 2637, 3136, 4186, and 5274 Hz in consideration of the consonance theory.

There are some instances that the warning sounds for quiet vehicles have lower frequency components than dominant road traffic noise frequency so that they are able to be heard by the people who has hearing loss due to aging. The stimuli used in this study also added some lower-frequency components. Three pure tone components within 125, 160, and 200 Hz band were added, which were at 2^{-4} times frequency of 2k, 2.5k, and 3.15 kHz band component, namely 131, 165, and 196 Hz. These lower-frequency components were common among seventeen stimuli.

3. EXPERIMENT 1: DETECTABILITY EXAMINATION

3.1 Method

To examine the detectability of the stimuli, *i.e.* possible warning sounds for quiet vehicles, a level adjusting experiment using binaural recording background stimulus and warning sound stimuli was conducted. The outline of the procedure was similar to the authors' previous studies(8, 9, 10).

3.1.1 procedure

The experimental setup is illustrated in Figure 1. The signals were presented over Sennheiser HD-650 headphones. The input voltage to the headphones was measured, so that, taking into account the headphones' sensitivity, the playback level could be calibrated. The experiment was conducted in a sound-proof room in Nagasaki University.

Subjects could adjust the level of the warning sounds using a slider. The sound presentation was repeated until a button was pressed by the subjects indicating a satisfactory level adjustment. One of the background stimuli was presented, and then 10 s later one of the warning sounds was overlapped. The subjects were asked to imagine that they were on a road and that the vehicle providing the warning sound positioned 2.0 m behind

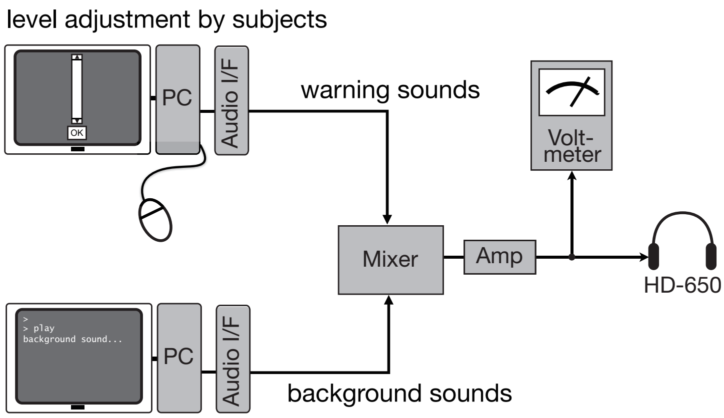

Figure 1 – Equipments setup for experiment 1.

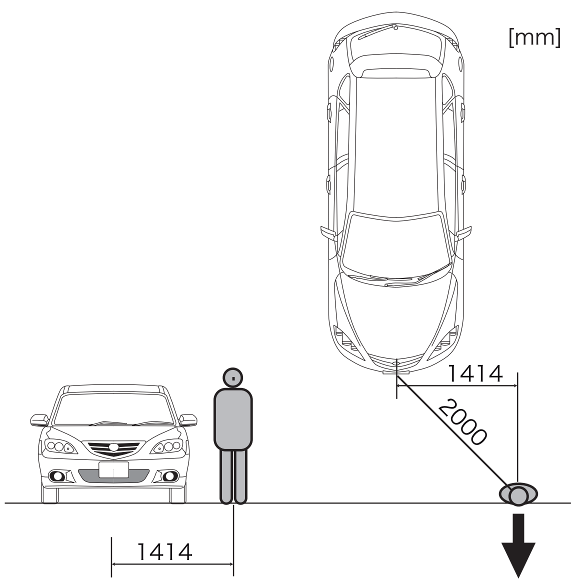

Figure 2 – Assumed relative position between the pedestrian and the vehicle providing warning sounds.

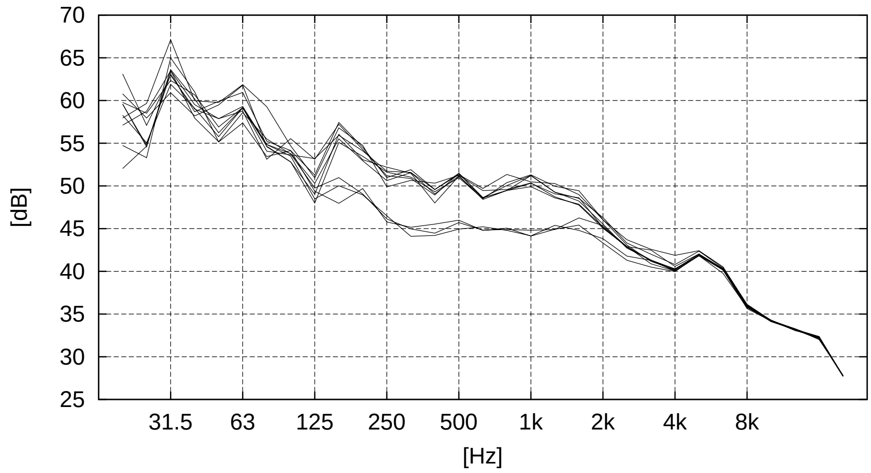

Figure 3 – 1/3-octave band levels of the background stimulus (2–20 s).

them diagonally backward right, as shown in Figure 2.

There were two tasks in each experimental session: one task was to adjust the level of warning sounds so that they were clearly audible and could be reliably detected in the background noise (hereafter referred to as "reliable level"). The other task was to adjust the warning sounds so that they were just audible in the background (hereafter referred to as "minimum level"). All stimulus combinations were presented in pseudo-random order in experiment session taking one of the tasks. The subjects took part twice for each session. The order of the tasks was switched for each new subject.

3.1.2 stimuli

The background stimulus were recorded binaurally using a head and torso simulator (HATS; Brüel & Kjær type 4100) located on the sidewalk. The recording was performed in a parking lot close to a two-lane road. The length of the background stimulus was 60 s. Figure 3 shows the 1/3-octave band levels for each 20 s duration of the stimulus every 2 s from the beginning to 20 s. The noise level of the stimulus was deemed stable.

The experimental stimuli, *i.e.* potential warning sounds, were played-back over a loudspeaker in an anechoic room and recorded via the HATS. The loudspeaker was positioned diagonally 2.0 m behind the HATS so that it can be simulated a assumed position of the subject (Figure 2).

3.1.3 subjects

Ten Japanese subjects, 3 females and 7 males, aged between 21 and 26 (median 23.5) participated in the experiment. None of the subjects reported any auditory abnormality.

3.2 result

The average and standard deviation of two adjusted levels for each stimulus were 0.6 ± 2.3 dB for the reliable level adjustment, and those were -0.6 ± 5.2 dB for the minimum level adjustment. It seemed that the adjustments by the subjects were stable, then the analysis was performed using the averaged values of two adjustments by each subject.

Figure 4 shows the inter-individual medians and interquartile ranges of the averaged adjusted levels for each stimulus. The white symbols represent the reliable levels, and the black symbols represent the minimum levels. The A-weighted equivalent noise level (L_{Aeq}) of the background stimulus is indicated by horizontal line.

No significant differences between stimuli were found. All experimental stimuli were evaluated that they all were equivalently detectable in the urban background. All stimuli had equivalent levels in 1/3-octave bands. The result suggested that levels of 1/3-octave bands could be an indicator for the detectability of the warning sounds, which confirmed the findings in previous studies(10).

The reliable levels were approximately 2–3 dB higher than the equivalent noise level of the background, while the minimum levels were approximately 5–8 dB lower than that of the background. This tendency was similar to the previous studies(8, 9, 10).

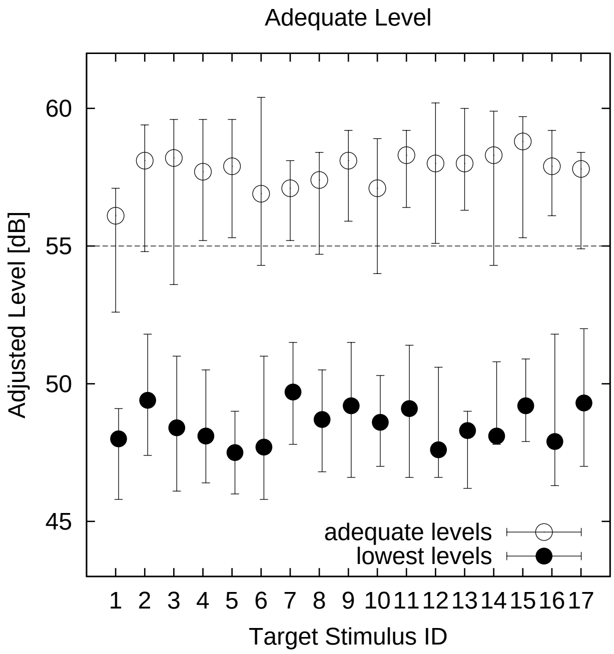

Figure 4 – Inter-individual medians and interquartile ranges of the averaged adjusted levels. (White symbols: reliable level. Black symbols: minimum level. Horizontal line: background noise level (L_{Aeq}).)

4. EXPERIMENT 2: EXAMINATION OF HEARING IMPRESSION

4.1 Method

To examine the difference of hearing impression of each stimulus, a subjective evaluation experiment using the semantic differential (SD) method was conducted.

4.1.1 procedure

Each stimulus were independently presented over Sennheiser HD-650 headphones. No background sound was presented in this experiment. The playback level of the stimuli was 55 dB. The experiment was conducted in a sound-proof booth in Nagasaki University.

The subjects were asked to rate the impression of each stimulus on 5-point SD scales of 14 adjectives (as shown in Table 1). The adjective scales were individually appeared in pseudo-random order on the display in front of the subjects. All stimulus were presented in pseudo-random order in an experiment session. The subjects took part twice for the session.

4.1.2 subjects

Nine Japanese male subjects aged between 21 and 24 (median 23) participated in the experiment. None of the subjects reported any auditory abnormality.

4.2 Result

Before the analysis of the rated values, the reliability of subjects' rating was confirmed. The rating scores that the difference between two rating for each stimulus and each scale was more than 3 were regarded as invalid, then 6.9% of rating scores were excluded from the analysis.

The averaged rating scores for each subject were applied to the factor analysis using the principal axis factoring. The two-factors solution was chosen on the basis of Keiser's criterion. The factor loadings after the varimax method rotation is presented in Table 1. The first factor was interpreted as "evaluation factor" because the adjective scales such as "muddy—clear," "clean—dirty," and "bright—dark" had high loadings on this factor, which was corresponding to both sharpness and aesthetic impression. The second factor was interpreted as "powerful factor" because the adjective scales such as "powerful—unsatisfactory," "strong—weak," and "quiet—noisy" had high loadings on this factor. The result showed that these two impression factors were independent on the relative difference of hearing impression of the experimental stimuli. This suggested that the powerfulness of warning sounds could vary among similar aesthetic impression.

Table 1 – Factor loadings

	Factor 1	Factor 2	Commonalities
muddy — clear	0.997	-0.075	0.999
clean — dirty	-0.963	-0.065	0.931
bright — dark	-0.960	-0.052	0.923
gruff — mild	0.959	0.047	0.921
sharp — dull	-0.959	0.072	0.924
deep — thin	0.882	0.194	0.815
heavy — light	0.808	0.318	0.755
agreeable — disagreeable	-0.666	-0.076	0.449
soft — hard	0.576	-0.496	0.577
unpleasant — pleasant	0.532	0.176	0.314
powerful — unsatisfactory	0.014	0.876	0.768
strong — weak	-0.081	0.821	0.680
quiet — noisy	-0.149	-0.551	0.326
annoying — unannoying	0.061	0.159	0.029
Proportion of var. [%]	51.4	15.8	67.2

The factor scores of each stimulus were illustrated in Figure 5. The positive direction of horizontal axis indicates "clear" and "bright" impression, while the negative indicates "muddy" and "dark" impression. Concerning the vertical axis, the positive indicates "weak" and "unsatisfactory" impression, while the negative indicates "powerful" and "strong" impression.

The stimulus that consisted of five pure-tone components between 2 and 5 kHz bands (indicated as filled square in the figure; H_1) had the highest score on the first factor. Many of the stimuli that consisted of two pure-tone components (indicated as filled circles in the figure) were positioned at positive side on the first factor. The stimuli including 5 kHz pure-tone component, namely H_5, H_9, H_12, and H_14, had higher

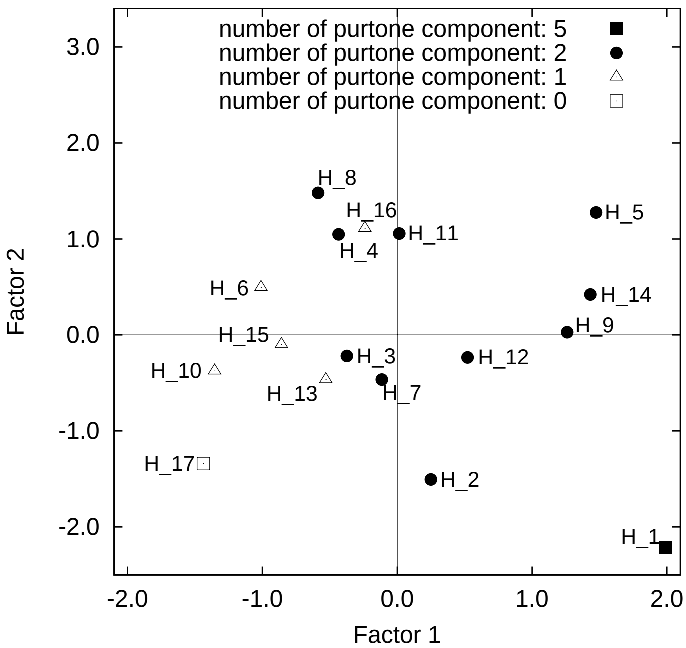

Figure 5 – Factor scores of each stimulus

scores. It was considered that the higher frequency pure-tone component evoked a clear and clean impression. On the other hand, for the stimuli that included one or less pure-tone components, the first factor score were negative (indicated as open triangles and open square). These stimuli were rated as muddy and dirty due to the dominant narrow band components.

The fundamental frequency of the experimental stimuli was 131 Hz. When the 131 Hz component was regarded as the root of a harmonic triad, the pure-tone components in 2.5 kHz and 5 kHz band were regarded as the major third of the triad. The stimuli including the third component (*e.g.* H_1, H_2, H_7, and H_10) were positioned at negative side on the second factor. On the other hand, the stimuli without third component, *i.e.* only including the root and fifth component of harmonic triad (*e.g.* H_4, H_11) showed the tendency to be positive on the second factor. It is difficult to conclude only from these insufficient instances but, it may suggest that the harmonic structure potentially affect on the hearing impression.

5. CONCLUSION

To obtain a knowledge designing easily detectable and not-annoying warning sound for quiet vehicles, a series of psychoacoustical experiments were performed. The target frequency range was determined between 2 and 5 kHz due to the human hearing sensitivity and road traffic noise masking. Seventeen stimuli were created to have equivalent levels in five 1/3-octave bands but to have different frequency components.

The detectability of the stimuli was examined through a level adjusting experiment using binaural recording background stimulus and warning sound stimuli. The result confirmed that all experimental stimuli had equivalent detectability in an urban background noise if the stimuli had equivalent levels in 1/3-octave bands. Moreover, relative difference of hearing impression of the experimental stimuli was revealed through the subjective evaluation experiment using adjective scales. The results showed that the impression of warning sounds could be varied while having equal detectability.

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