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Design of acoustic vehicle alerting system sound assuming listening situation of pedestrians

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ABSTRACT

The role of acoustic vehicle alerting system (AVAS) sound is to tell pedestrians the approaching of quiet vehicles such as electric vehicles (EV) or hybrid-electric vehicles (HEV). We propose the AVAS sound that satisfies both of comfort and perception. The comfort of AVAS sound in this study means pedestrians do not feel noisy. The perception of AVAS sound means pedestrians to notice of the approaching quiet vehicles at safely avoidable distance. The AVAS sound model produced in this study has two peak frequencies. These models are two kinds of the steady sound with constant sound level and the fluctuating sound formed by modulating amplitude of steady sound. We measured impression of AVAS sound and perceptual distance. The impression of AVAS sound was measured by the psychological questionnaire using SD method. The perceptual distance: the distance between subject and HEV when the subject notices the approaching of HEV emitting the AVAS sound was measured in a test road. We also measured the perceptual distance of different listening situation such as standing or smartphone operation during walking. We show the sound characteristic to improve the comfort and the perception of AVAS sound, and the effect of the listening situation on the perceptual distance.

Keywords: Acoustic vehicle alerting system sound, Listening situation, Perceptual distance

1. INTRODUCTION

Acoustic vehicle alerting system (AVAS) sound is a sound to tell pedestrians the approaching of the EV/HEV. Ministry of Land, Infrastructure, Transport and Tourism (MLIT) published the guideline for the measure against the quietness problem of HEV/EV in 2010 (1). The UN Regulation No.138 on Quiet Road Transport Vehicles was published in 2016 (2, 3). And then, MLIT announced that the mandatory of installing AVAS in HEV/EV will be enforced from March 2018. Pedestrian's perception for the approaching HEV/EV is improved by increasing the sound volume of AVAS but it feels discomfort when the sound volume is large. On the other hand, pedestrians become difficult to hear because AVAS is masked by the road environment sound when the sound volume of AVAS is small.

The purpose of this study is to clarify the AVAS sound model that has clarity and comfort, and makes it possible for pedestrians to recognize the approach of vehicles when the listening situations are different. The AVAS model prototyped in this study is noise with two peak frequencies. These AVAS models are two kinds of the steady sound with constant sound pressure level and the fluctuating sound formed by modulating amplitude of steady sound.

We focused on the road environment sound and the discomfort of sound, and performed an impression evaluation experiment and a perceptual distance experiment. In the impression evaluation experiment, a subjects sat on a chair in the soundproof room were exposed to the AVAS, the impression of AVAS was evaluated by the psychological questionnaire by SD method, and the common factor was estimated by factor analysis. In the perceptual distance experiment, HEV mounted with AVAS model was approached from the back of subject, and the distance between the subject and HEV when the subject perceived HEV was measured. In this study, the minimum avoidance time was estimated from whole-body reaction time

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and average walking speed of an elderly person. Then, we proposed the criteria of the minimum distance necessary to safely avoid the HEV where the pedestrian approaches by multiplying the minimum avoidance time by the vehicle speed. From the experimental results, we found that effects of the AVAS sound model on perceptual distance and comfort sensation and effects of the difference of the listening situation on the perceptual distance.

2. EXPERIMENTAL METHODS

2.1 AVAS sound model and sound conditions

Figure 1 shows that the example frequency spectrums of AVAS sound model prototyped in this study. The AVAS sound model is made from white noise and has two peak frequencies. Table 1 shows the sound stimuli conditions of AVAS sound model in this study. The peak frequency I selected 630 Hz from range below 1000 Hz small in hearing ability difference. The peak frequency II was selected from the frequency band 2500 Hz to 4000 Hz of high auditory sensitivity (4). The sound pressure level distance was added to the sound conditions for the purpose of reducing the discomfort sensation with listening of AVAS sound assuming the AVAS sound feels noisy if the sound pressure level of the peak frequency II is large. These AVAS sound models are two kinds of the steady sound with constant sound pressure level and the fluctuating sound formed by modulating amplitude of steady sound. We added the fluctuating sound to the sound stimuli conditions of AVAS sound model because the fluctuating sound because the fluctuating sound can be noticed by small sound level to the approaching of HEV. The modulation cycle and the amplitude modulation factor were added to the sound conditions of fluctuating sound of AVAS sound model. We created a total of 66 AVAS sound models combining the sound stimuli conditions of Table 1.

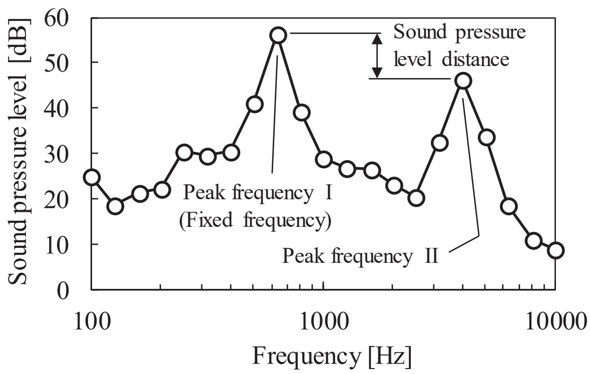


Figure 1 – Example frequency spectrum of AVAS sound model

Table 1 – Sound stimuli conditions of AVAS sound model

Peak frequency I, Hz	Peak frequency II, Hz	Sound pressure level distance, dB	Modulation cycle, s	Amplitude modulation factor
630	2500 3150 4000	0 10	0 (Steady sound) 0.25 0.5 1 1.5 2	0.45 0.9

2.2 Impression evaluation experiment

We conducted the impression evaluation experiment in the soundproof room (floor area 2.7 m^2, floor height 2.3 m, background noise level $L_A = 30 \pm 2$ dB) shown in Figure 2. The subject sat the chair that set in the center of soundproof room, and the subjects was exposed the AVAS sound from the back. The environmental sound recorded in a quiet residential area was emitted from the sub-speaker, and after 20 seconds, the AVAS sound model was emitted for 20 seconds from the main speaker. After that, the subject filled out the psychology questionnaire, and after one minute of resting time, one experimental condition finished. To measure the impressions of the AVAS sound model, we used the SD method composed of 13 adjective pairs, such as "discomfort - comfort". The rating scale for the SD method consisted of seven grades. The volume of the AVAS sound model was set to 55 dB equivalent sound level ($L_{\mathrm{Aeq,20s}}$). The volume of the environmental sound was set to 45 dB equivalent sound level ($L_{\mathrm{Aeq,40s}}$). Thirteen healthy university students with an average age of 22.3 years took part in this experiment.

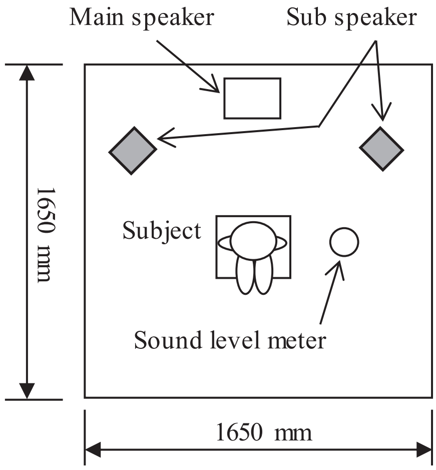


Figure 2 – Experimental environment of impression evaluation experiment

2.3 Perceptual distance experiment

We performed the perceptual distance experiment in the multipurpose test track for automotive vehicles of College of science and technology, Nihon University. The multipurpose test track is a straight road with a total length of 618 m and a width of 30 m, and an asphalt concrete pavement. A-weighted sound pressure level (L_{A}) of the environmental sound measured during this experiment was 45.6 ± 2.2 dB (mean ± standard deviation). In the perceptual distance experiment, HEV mounted with AVAS model approached from the back of subject at the veichle speed of 10 km/h, and the distance between the subject and HEV when the subject perceived HEV was measured. We examined the influence of differences in pedestrian listening situation on perceptual distance. The listening situation was set four kinds of combination of standing/walking state and with/without smartphone operation. Subjects were instructed to browse news sites (Google News or Yahoo! News) with one hand when operating smartphone. Figure 3(a), (b) show the measuring method of perceptual distance. The measurement method of the perceptual distance is different in standing state and walking state. The experimental course set up in the multipurpose test track assumes a residential road where the pedestrian walkway and roadway are not separated. The perceptual distance P_{S} in the standing state shown in Figure 3(a) is obtained from Equation (1).

$$P_{\mathrm{S}} = 100 - Vt \tag{1}$$

Where, V is the vehicle speed, t is time from vehicle start to subject's vehicle perception. The perceptual distance P_{W} in the walking state shown in Figure 3(b) is obtained from Eauation (2).

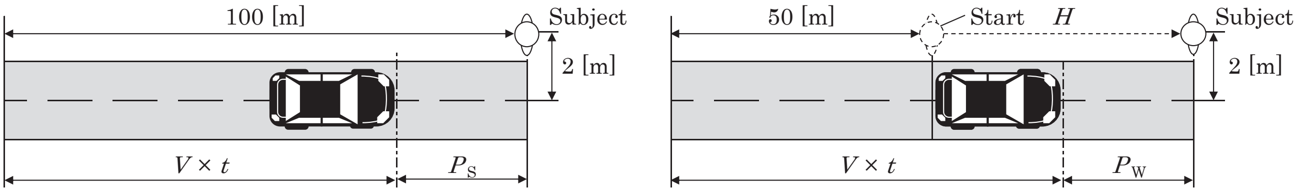
$$P_{\mathrm{W}} = (50 + H) - Vt \tag{2}$$

Where, H is the walking distance, V is the vehicle speed, t is walking time. Twenty four healthy university students with an average age of 22.3 years took part in this experiment.

3. RESULTS AND DISCUSSION

3.1 Results of factor analysis and impression evaluation of AVAS

Table 2 lists the factor loading obtained from a factor analysis based on the SD method concerning the impression evaluation experiment of AVAS sound model. The first factor was



(a) Standing state (b) Walking state

Figure 3 – Outline of perceptual distance experiment

interpreted as a clarity factor indicating the clarity of sounds such as "sharp" and "clarity". The second factor was interpreted as a comfort factor indicating the comfort sounds such as "like" and "comfort". Figure 4 shows the relationship between the average factor loadings of first factor and second factor. These AVAS sound models satisfy clarity and comfort if the average score of each of the first factor (clarity factor) and the second factor (comfort factor) are both positive. Table 3 lists AVAS sound models that satisfy both the clarity and the comfort shown in Figure 4.

Table 2 – Factor loadings of impression evaluation experiment

Adjectives	Factor 1	Factor 2	Factor 3
Sharp - Blunt	**0.820**	0.006	0.000
Clear – Blurry	**0.761**	0.078	0.155
Light – Heavy	**0.701**	0.058	-0.308
New – Old	**0.622**	0.061	0.029
Flashy – Plain	**0.554**	-0.073	0.311
Early – Slow	**0.412**	-0.219	0.054
Like – Dislike	-0.049	**0.903**	0.114
Comfort - Discomfort	-0.112	**0.875**	0.107
Clean – Dirty	0.476	**0.515**	-0.044
Smooth－Rough	0.148	**0.492**	-0.071
Quiet – Noisy	-0.157	**0.438**	-0.452
Large – Small	-0.152	0.120	**0.679**
Powerful－Unsatisfactory	0.238	0.013	**0.577**
Contribution ratio	27.26%	18.47%	5.91%
Cumulative contribution ratio	27.26%	45.74%	51.65%

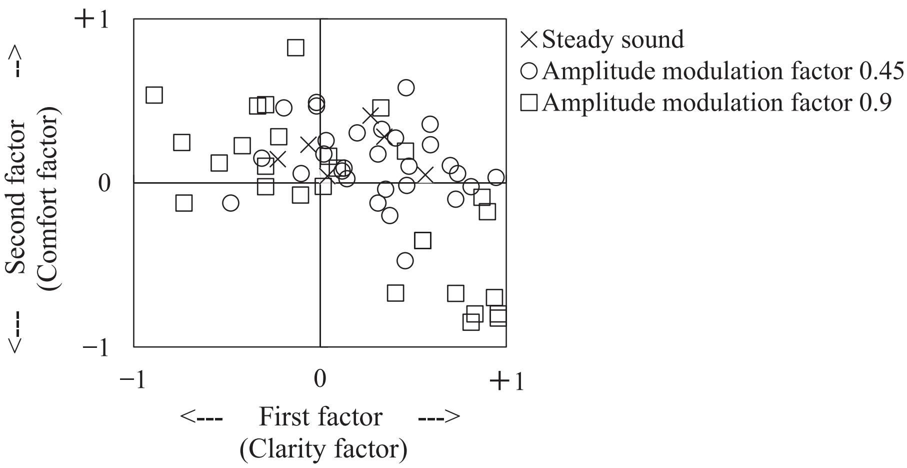


Figure 4 – Relationship between first factor and second factor

Table 3 – AVAS sound models that satisfy both the clarity and the comfort

<table>
<tr><th>Peak frequency II, Hz</th><th>Sound pressure level distance, dB</th><th>Amplitude modulation factor</th><th>Modulation cycle, s</th></tr>
<tr><td rowspan="4">2500</td><td rowspan="4">0</td><td colspan="2">0</td></tr>
<tr><td rowspan="2">0.45</td><td>1</td></tr>
<tr><td>1.5</td></tr>
<tr><td>0.9</td><td>1</td></tr>
<tr><td rowspan="9">3150</td><td rowspan="6">0</td><td colspan="2">0</td></tr>
<tr><td rowspan="4">0.45</td><td>0.5</td></tr>
<tr><td>1</td></tr>
<tr><td>1.5</td></tr>
<tr><td>2</td></tr>
<tr><td>0.9</td><td>1</td></tr>
<tr><td rowspan="3">10</td><td rowspan="3">0.45</td><td>0.25</td></tr>
<tr><td>1</td></tr>
<tr><td>2</td></tr>
<tr><td rowspan="11">4000</td><td rowspan="5">0</td><td colspan="2">0</td></tr>
<tr><td rowspan="3">0.45</td><td>0.25</td></tr>
<tr><td>0.5</td></tr>
<tr><td>1</td></tr>
<tr><td>0.9</td><td>1</td></tr>
<tr><td rowspan="6">10</td><td colspan="2">0</td></tr>
<tr><td rowspan="4">0.45</td><td>0.5</td></tr>
<tr><td>1</td></tr>
<tr><td>1.5</td></tr>
<tr><td>2</td></tr>
<tr><td>0.9</td><td>1</td></tr>
</table>

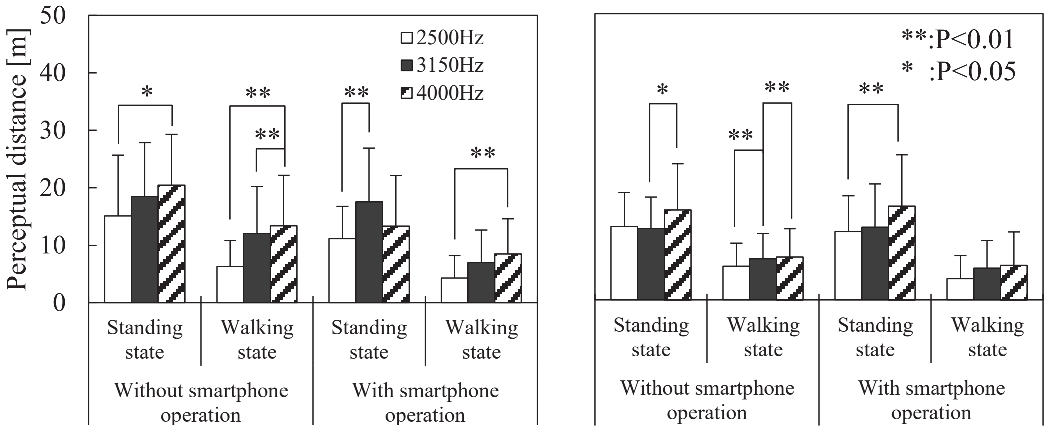
3.2 Results of perceptual distance measurement

Figure 5 shows the average values of perceptual distance of the standing and walking state obtained from the perceptual distance measurement experiment. According to Figure 5, the perceptual distance tends to be longer as the peak frequency II is higher in many conditions. Statistical significance was examined by one-way analysis of variance and Tukey-Kramer's multiple comparison test to clarify differences in peak frequency II at the same sound pressure level distance. As a result, significant differences (*:$P<0.05$, **:$P<0.01$) were found among the peak frequencies II except for walking state with smartphone operation with a sound pressure level distance of 10 dB. Moreover, when the same test as described above was performed on the condition of the modulation cycle at the same amplitude modulation factor, no significant difference was found due to the difference in the listening situation.

4. DESIGN INDEX OF AVAS SOUND

4.1 Suggestion of minimum avoidance time for AVAS design

In this study, as a criterion to evaluate the measured perceptual distance, we set the minimum distance that is reference distance necessary for the pedestrian to recognize the approaching vehicle and safely taking evasive action. The minimum avoidance time was referred to the whole body reaction time and the average walking time database. The minimum avoidance time T proposed in this research is calculated from Equation (3).



(a) Sound pressure level distance 0 dB (b) Sound pressure level distance 10 dB
Figure 5 – Measurement results of perceptual distance

$$T = T_1 + T_2 + T_3 \tag{3}$$

Where, T_1 is the whole-body reaction time, T_2 is the avoidance action time (the time required to move 1 m estimated from the average walking time), and T_3 is the face around time. In this study, T_1 = 0.7 s, T_2 = 1.2 s, T_3 = 1.0 s, and in consideration of the maximum value of the above database, T = 3.0 s was set as the minimum avoidance time. The reference distance P_{STD} is calculated from Equation (4) by multiplying the minimum avoidance time T obtained from Equation (3) by the vehicle speed V. The reference distance is 8.4 m because the vehicle speed V in this experiment is 10 km/h (2.8 m/s). If the measured perceptual distance exceeds the reference distance, it means that the pedestrian notices the approach of the vehicle and can safely avoid.

$$P_{\mathrm{STD}} = T \times V \tag{4}$$

4.2 Proposal of AVAS sound in consideration of listening situation

In this study, we considered that the AVAS model is not easily affected by the listening situation when the perceptual distance does not change even if the listening situation changes. Figure 6 shows the difference in perceptual distance between the condition of standing state without smartphone operation with the longest average perceptual distance and the condition of the walking state with smartphone operation of the shortest average perceptual distance. The sound conditions indicated by mark † in Figure 6 are the top two of the AVAS sound models in which the difference in perceptual distance is small and which is not easily influenced by the difference of listening situation. The AVAS sound proposed in this research needs to have clarity and comfort in addition to the perception exceeding the reference distance. Therefore, the

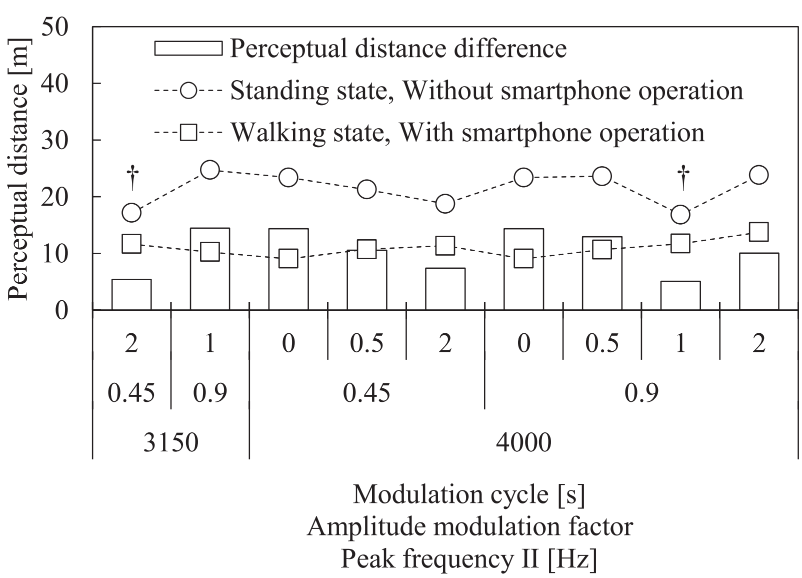


Figure 6 – Perceptual distance difference at sound pressure level distance 0 dB

AVAS sound model satisfying both the sound conditions distributed in the first quadrant of Figure 4 and the sound conditions of the mark † shown in Figure 6 was examined. As a result, it was found that the AVAS sound model of the sound conditions of the mark † had clarity and comfort.

5. CONCLUSIONS

In this research, we examined the AVAS sound model that has clarity and comfort, and makes it possible for pedestrians to recognize the approach of vehicles when the listening situations are different. The conclusions obtained are shown below.

(1) The factor structure of the AVAS sound model is divided into clarity factor and comfort factor, and these factors can explain about 45% of whole. The extracted two factors are the same in all the AVAS sound models.

(2) The clarity and the comfort of AVAS sound are improved when the amplitude modulation factor of the notification sound is set to 0.45.

(3) The perceptual distance tended to increase as the peak frequency II increased when comparing the same condition of sound pressure level distance. This tendency is the same in different listening situation.

(4) We estimated the minimum avoidance time that pedestrians notice the approach of the vehicle and are able to safely avoid based on the human whole-body reaction time and average walking time. The minimum avoidance time was multiplied by the vehicle speed to calculate the reference distance, which is the minimum required distance for safe avoidance.

(5) The sound condition of the AVAS sound model that satisfies perception, clarity and comfort when the peak frequency I is fixed at 630 Hz is the peak frequency II 4000 Hz-sound pressure level distance 0 dB-modulation cycle 1 s-amplitude modulation factor 0.9, the peak frequency II 3150 Hz-sound pressure level distance 0 dB-modulation cycle 2 s-amplitude modulation factor 0.45.

ACKNOWLEDGEMENTS

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