Subjective evaluation of additive sound designed to reinforce acoustic feedback of electric vehicle

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ABSTRACT

Because booming sound of internal combustion engine is eliminated in electric vehicle (EV), it has been complained that EV is not fun-to-drive and drivers cannot get information of driving speed by its sound. In order to overcome this problem, signal processing method of additive engine sound has been suggested. However, because it strongly affects interior sound quality and so does brand image, this strategy must be carefully evaluated before applied. In this study, two types of signal processing methods were adapted to recorded EV sound and subjective evaluation was conducted. Total 10 stimuli were judged by 30 drivers in terms of sensation of acceleration, sound image, and preference. Effects of each signal processing method are compared and advantages and disadvantages of each method are discussed.

Keywords: Electric vehicle (EV), Additive sound, Acoustic feedback, Sound image

1. INTRODUCTION

The advent of electric vehicles (EV) has brought many acoustical issues to automobile industry. One important problem is ironically the quietness of interior sound. EV drivers are not able to grasp of driving speed adequately due to the lack of acoustic feedback, and this leads drivers to drive faster and to commit more driving violations as reported by E. Heller (1). Also, some drivers have claimed that they miss the sensation of acceleration formerly provided by the powerful roaring sounds of combustion engines. This phenomena results from the excessive reduction of dynamic impression.

Acoustic feedback and dynamic impression of EV sound both can be simultaneously strengthened by playing virtual sound through internal speaker. This concept, namely active sound design, has been proposed by many researchers as the most efficient method to solve acoustical problems of EV (2, 3). However, this has not been widely applied to electric vehicles because proper additive sounds and their effects are not sufficiently verified yet. A large number of investigation on virtual sounds and their influence is required to set a guideline of virtual sound selection.

Norio Kubo proposed four types of signal processing methods for EV exterior sound based on questionnaire results: sinusoidal wave composition, compress-stretch method in time signal, adjustment method of time gap, sound play by event (4). The proposal seems also appropriate to enhance acoustic feedback of EV interior sound in that derived sound contain information of driving state in certain way. In this study, effects of two of his proposal on acoustic feedback and sound image are investigated. Test stimuli were produced as described in Sec. 2, and a listening test was conducted with the procedure presented in Sec. 3. With the evaluation results, effects of each signal processing method on subjective evaluation are discussed in Sec. 5.

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2. STIMULI

2.1 Base Sound

The signal recorded in the previous study (5) was used again to obtain the base sound. 10 seconds of signal was extracted and rattling noise was deleted by GENESIS LEA software.

2.2 Additive Sound

2.2.1 Category 1 – Subharmonics of high frequency component

Additive tones whose frequencies vary with motor RPM can enhance acoustic feedback. Focusing on the existing high frequency tonal component of EV sound, addition of its lower harmonics was suggested by Gwak et al. (5). This strategy is basically one case of "sinusoidal wave composition" or "compress-stretch method in time signal" of Kubo's proposal (4). Four virtual sounds were produced by this manner and the relative frequencies and the levels of artificial tones are presented in Fig. 1. Sound 1 and Sound 2 are two successful cases in the previous study. Relative frequencies of two tonal components to the existing tonal component are 1/3 and 1/5 in Sound 1, and 1/16, 1/8 for Sound 2. Sound 3 and Sound 4 contain more tonal components so that they essentially make sound much louder. However, it was expected that acoustic feedback would be more strengthened. The interval between added tones is octave for Sound 3, and perfect fifth and perfect fourth for Sound 4.

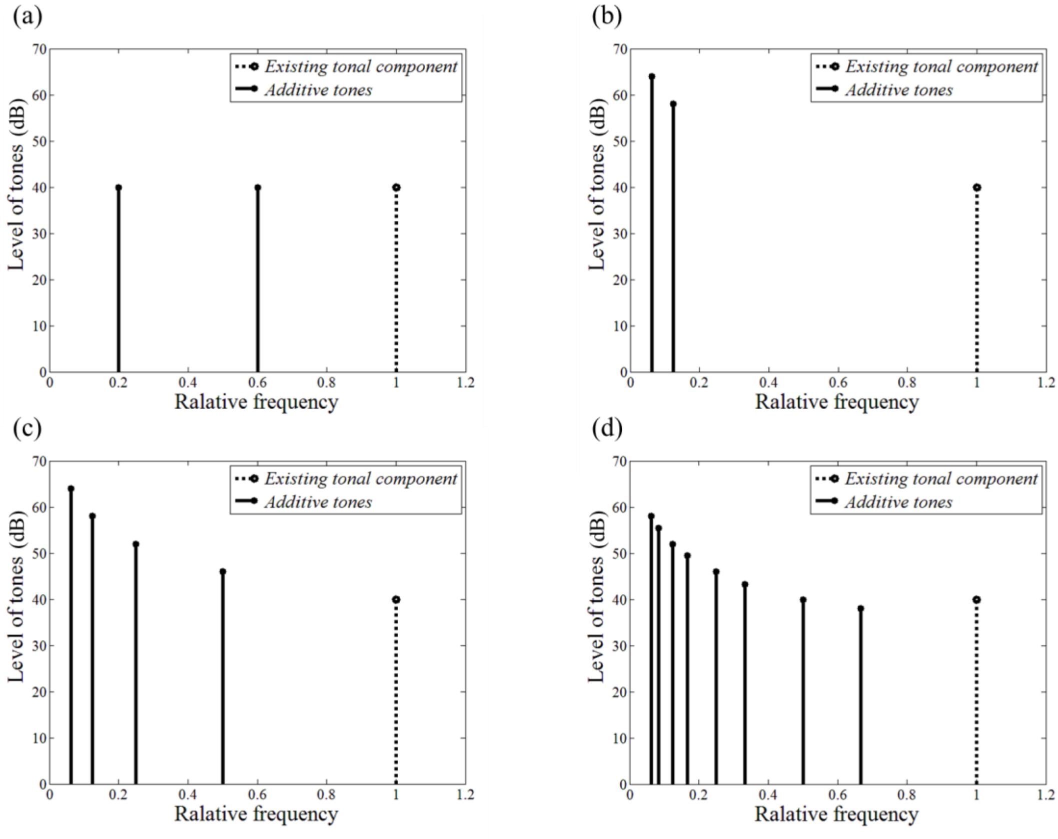

Figure 1 – Frequency components of additive tones for test stimuli in Category 1

(a) Sound 1 (b) Sound 2 (c) Sound 3 (d) Sound 4

2.2.2 Category 2 – Adjustment method of time gap

The second category adopted the method of controlling time gap between virtual event sounds. To design additive sound with this method, three main variables should be determined: type of event sound, duration of event, and gap adjustment.

Event sound could include a meaning or not. Sound of 'horse running', 'bird twittering', and 'water dropping' are examples of sound with meaning. In this study, after several pilot tests, sound of 'maracas' was chosen as the event sound to be evaluated (Sound 5).

In General, sound without meaning such as a tone is considered more proper for automobile sound design. It was also a tone used in Kubo's suggestion. Therefore, the section of Sound 1 and Sound 2 were selected as the event sound for Sound 6 to 9. Consequently, the stimulus is such that amplitude of Sound 1 or Sound 2 is modulated with the modulation frequency varying with motor speed. These four stimuli fully contain Sound 1 or Sound 2 as the basis, and the section of Sound 1 or Sound 2 was additionally inserted after -6dB of adjustment. Sound 6 and Sound 7 consist of Sound 1 as the basis, and Sound 8 and Sound 9 contain Sound 2. The event sound is the section of Sound 1 for Sound 6 and Sound 8, and that of Sound 2 for Sound 7 and Sound 9.

Duration of each event is set to be 200ms for all stimuli. 200ms has come from the fact that human perceive sound intensity in every 200ms and that consistent masking threshold is obtained only if the duration of masker is longer than 200ms (6).

The gap between sound events was set such that the longest time gap is 200ms and it becomes shorter as motor RPM increases. After the motor RPM is normalized to be 1 at the max speed, the time gap was set to be proportional to '1-normalized motor RPM'.

3. Experiment

3.1 Participants

60 Korean drivers (30 men and 30 women) were participated in the listening test. Listeners were divided into 6 groups and each group evaluated different sets of sound stimuli. One person evaluated 5 or 6 stimuli including the basis. Each stimulus except the basis was consequently evaluated by 30 participants (15 men and 15 women).

3.2 Test Procedure

First of all, participants were asked to check intensity of sensation of acceleration in 0 to 10 numerical scale for played sound. Each stimulus was played twice for this evaluation. Next, image of sound was assessed by selecting proper adjectives to explain the stimulus. Multiple choice was allowed for this assessment, and the selection items are as shown in Fig. 2. Each stimulus was played repeatedly until participants inform the end of decision.

☐ Fun to play	☐ High-tech	☐ Future	☐ Sophisticated
☐ Classic	☐ Agility	☐ Luxury	☐ Ecological
☐ Pretty	☐ Powerful	☐ Friendly	☐ Empty
☐ Metallic			

Figure 2 – Selections for sound image assessment

Overall preference of each stimulus was then tested. 0 to 10 numerical scale was used for this test, and each stimulus was played twice.

3.3 Apparatus

Listening test was preceded in a half-frame of a real car. Stimuli were played via headphone. A video of driving was reflected on the screen while evaluating the sound image and its preference. No image was reflected when the sensation of acceleration was judged.

4. Results

4.1 Sensation of acceleration

Fig. 3 shows the increment in the ratings of the sensation of acceleration. Subjective ratings increased for all stimuli. Statistically, one stimulus in category 1 and three stimuli in category 2 showed significant difference from the base sound. Generally, sounds in category 2 are evaluated to provide stronger sensation of acceleration.

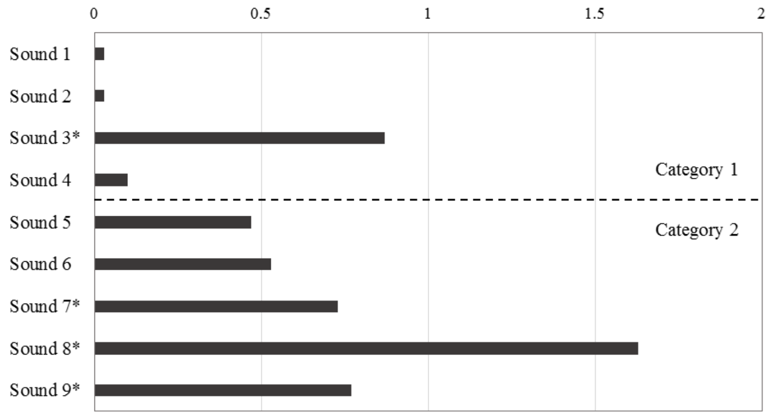

Figure 3 – Increment in the ratings of the sensation of acceleration

The star indicates that the increment is statistically significant.

4.2 Sound image

The percentages of participants' selection for sound stimuli are shown in Fig. 4. The black line represents the results of the base sound. Sounds in category 1 show higher selection rate of 'agility'. Characteristics of 'future' and 'sophisticated' are increased in Sound 1, and Sound 2 was evaluated to be more classic. There is no noticeable change for other adjectives.

High deviation in adjectives of 'high tech' and 'future' can be found for sounds in category 2. Because Sound 6, 7, and 8 include Sound 1, it can be inferred that Sound 1 helped interior sound have image of 'high tech' and 'future'. This effect seems to be larger when Sound 1 is added as the event sound. Results of Sound 5 indicate that the event sound with a meaning makes interior sound more friendly and fun to play, but is not proper for luxury automobile sound.

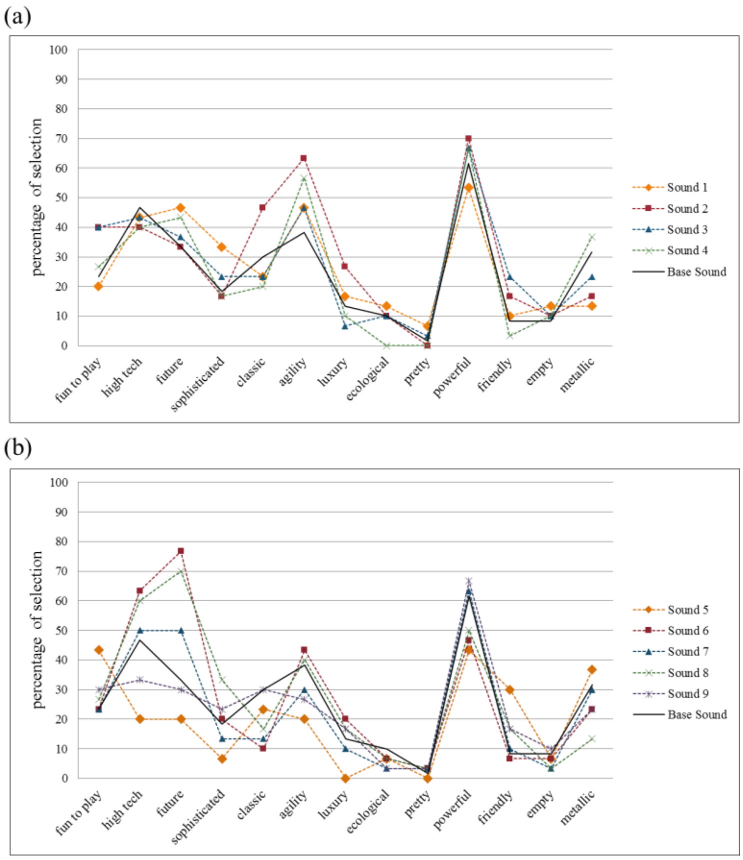

Figure 4 – Percentage of adjective selection for stimuli (a) Category 1 (b) Category 2

4.3 Preference

The mean values and standard deviations of preference scores are presented in Table 1. Despite of increase in the sensation of acceleration and changes of sound image, preference of most stimuli were reduced. Sound 1 and Sound 2 were more preferred to the base sound, and statistically significant difference was found for each sound. Results for sounds in category 1 are consistent with the result of Gwak et al (5). Loudness increment of Sound 3 and 4 seems to result in reduction of preference. Sound 5 has the lowest preference score, indicating that insertion of event sound whose meaning is irrelevant to the automobile sound should be abstained.

Table 1 – Mean values and standard deviations of preference scores for test stimuli

	Base Sound	Sound 1	Sound 2	Sound 3	Sound 4
Mean	5.0	5.2	5.7	3.8	4.3
Std	2.2	2.2	2.7	3.0	2.8
	Sound 5	Sound 6	Sound 7	Sound 8	Sound 9
Mean	2.4	3.9	3.7	3.4	4.1
Std	2.3	2.3	2.1	2.3	2.1

5. Discussion

In terms of sensation of acceleration, method of ‘adding subharmonics’ and ‘adjustment method of time gap’ are both effective in some degree. However, it seems to take large amount of loudness increment to increase acceleration sensation with the former manner. Only Sound 3 showed significant increment in acceleration feeling and this sound received the worst score in the preference among stimuli in category 1. The latter way is more effective to increase the acoustic feedback with less loudness increment, but sounds in this category were even more poorly appreciated. From the results, increasing sensation of acceleration and customers’ preference at the same time seems to be impossible.

Effects of additive sound on sound image and preference are also important results of this study. For example, Sound 1 itself makes interior sound more future and sophisticated so more preferred by drivers. With other sounds, it can also increase image of high-tech and future. However, the specific reason how this kind of additional sound affects the target sound in such way still remains unknown.

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