Relationship between frequency shifting of vehicle sounds and acceleration impression

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1. Introduction

The use of vehicles that are propelled in whole or in part by electric motors, such as electric vehicles (EV) or hybrid electric vehicles (HEV), is becoming increasingly common in urban fleets. Many types of EV/HEVs emit less sound than conventional internal combustion engine vehicles (ICEVs), particularly when they are driven at a low speed. It has been a matter of concern that the quietness of EV/HEVs may create dangerous situations for pedestrians, because they sometimes cannot hear the sound of such vehicles in an urban sound environment [1]. Hence, regulations and recommendations that will mandate or recommend the installation of additional sound-emitting devices in quiet vehicles are being considered by some governments/organizations, such as the United States, Japan, and the World Forum for Harmonization of Vehicle Regulations (UNECE/WP.29). According to a guideline [2], a warning sound should be automatically generated when the vehicle is driven at a speed of less than 20 km/h. This is because the difference between the sound level of an EV/HEV and an ICEV is significant in this speed range and the tire-road noise becomes dominant at higher speeds.

When the sound is designed, it should not be a simple imitation of a conventional gasoline engine sound. According to a questionnaire on the sound of EV/HEVs [3], conventional engine sounds are not the best means to identify a vehicle’s presence and behavior in an urban sound environment. In the survey, more than 50% of the respondents who drove their cars daily replied that, as drivers, they had experienced a sense of danger owing to pedestrians’ lack of awareness of their cars. In contrast, only 1.6% of the respondents owned and drove HEVs.

It is crucial to reveal the appropriate design of the sounds. For pedestrians, it is important to know the necessary sound level to give sufficient warning of an approaching vehicle in an urban environment. The authors have conducted a series of studies [4–6] to discuss the feasible sound level of the sound. There has also been some research concerning the temporal and spectral properties of such a sound. (e.g., [7,8]).

Another concern is the frequency shifting of the sound. The regulations and recommendations on additional sounds for quiet vehicles may specify requirements concerning the variation in the frequency of the sounds as a function of the vehicle speed. The goal is to make it easier for pedestrians to recognize vehicle behavior such as acceleration [2]. The relationship between frequency shifting and a pedestrian’s impression of a vehicle’s acceleration (hereafter referred to as “acceleration impression”) needs to be clarified in order to design the additional sounds and to develop appropriate legislation. Although the frequency shifting of the sound of a conventional vehicle is primarily caused by the change in the engine revolutions per minute, the additional sounds can be designed independently of the vehicle’s propulsion mechanism. As mentioned above, merely a simple imitation of a conventional engine sound is not the best method of designing a sound that can be easily detected in an urban sound environment. Additionally, imitation of the engine sound may not be the best means for pedestrians to recognize vehicle acceleration. Moreover, designing a new sound with a changing frequency that is independent of the vehicle propulsion mechanism could also result in a novel driving experience for drivers and passengers in vehicles.

To determine the relationship between frequency shifting and acceleration impression, the authors conducted Scheffe’s paired comparison test using audio and visual stimuli in a laboratory. The visual stimulus was a vehicle traveling on a road, monotonically accelerated from its stopped state. This was recorded from two perspectives: from the cabin as the view of a passenger, and from the road as the view of a pedestrian. The audio stimuli were a combination of three 1/3-octave band noises. The central frequencies of the band noises were shifted independently. The effect of frequency shifting on acceleration impression was analyzed using relative impression scores, which were defined as the differences relative to the stimulus without frequency shifting.

2. Method

The acceleration impression of the vehicle and the harmonization of the audio and visual stimuli were assessed through a paired comparison experiment.

2.1 Stimuli

Combinations of audio and visual stimuli were used in the experiment. The visual stimuli were videos of a vehicle traveling on a road, monotonically accelerated from its stopped state. Two scenes were recorded from the interior
and exterior of the vehicle on the road, as shown in Fig. 1. The vehicle was accelerated to attain a speed of 20 km/h in 5.0 s at a distance of 13.9 m from the starting position. The internal video was recorded using a camera mounted on the vehicle’s passenger seat. The external video was recorded using a camera on the road at 1.5 m height.

The audio stimuli were a combination of three 1/3-octave band noises. The central frequencies of the band noises were 100, 400, and 2,000 Hz. These frequencies were determined with reference to a commercially available design [7], which was intended to improve the detectability in consideration of the ear frequency sensitivity and hearing loss due to aging. The levels of the three band noises were equal. The central frequencies of all or one of the three band noises were independently shifted, whereas the others were unchanged (A1–A12). The central frequencies were linearly shifted to levels 120%, 150%, and 180% of the original frequency at the end of the stimuli (Table 1). A controlled stimulus A0 was also a similar combination of band noises, but without a shift in their frequencies. Altogether, 13 types of audio stimulus were prepared for each video scenario.

When the audio stimuli were combined with the external video stimuli, they were linearly attenuated by −23.5 dB to 0 dB from the start to the end of the stimuli. This was intended to simulate a geometrical attenuation in a free sound field. The presented sound levels were constant, with no attenuation, for the internal video stimuli.

### 2.2. Subjects
Ten subjects, comprising five males and five females, of ages ranging from 19 to 48 years participated in the experiment. None of them reported any auditory abnormality.

### 2.3. Procedure
The experiments were conducted in a soundproof room. The subjects sat on a chair at a distance of 1.6 m from a 42-inch plasma display panel and loudspeakers, as shown in Fig. 2. A pair of audio-visual stimuli were presented sequentially with a 1.5 s interval, as shown in Fig. 3. The subjects were asked to rate their impression of the second stimulus with respect to the first on a five-point scale during the 4.0 s rating phase. For combinations of the stimuli with the internal or external video scenarios, the subjects were told that they were in the passenger seat of a vehicle or on a road, respectively. The presented sound level of the audio stimuli at the location of the subjects’ heads was set at 55 dB prior to attenuation.

There were two tasks for each visual stimulus condition: one was to rate the acceleration impression of the second stimulus with respect to the first on a five-point scale, and the other was to rate the harmonization of the audio and visual impressions. The order of the four experimental sessions, comprising two visual scenarios and two tasks, was counter-balanced between the subjects.

The audio stimuli were divided into three groups according to the shifting rate (described in Table 1). Every group included the control stimulus. Half of the permutations of the five stimuli in the groups (5P2 = 10) were allocated to the acceleration rating task, and the other half were allocated to the harmonization rating task. Therefore, there were 30 audio stimuli in each experimental session. The allocation of stimuli was counterbalanced. The 30 audio stimuli were combined with the visual stimuli in pseudorandom order in each session.

### 3. Results
The rate values were analyzed using Scheffe’s paired comparison method with Nakaya’s variation. The rating scores for each of the scenarios and frequency shifting rates
were estimated. Figures 4 and 5 show the relative rating scores as differences with respect to the control scenario.

In the case of the acceleration impression, the relative rating scores were positive in all scenarios (Fig. 4). All frequency shifting scenarios were perceived as having a greater acceleration than the scenario with no frequency shift. The relative rating scores for each of the all-band and the majority of the high-band frequency shifts were significantly higher than the baseline. The increases in scores for the mid-band and low-band scenarios were relatively small.

The relative acceleration scores tended to be higher for larger frequency shifting rates. This trend was particularly evident in the scenarios using the internal video. In the case of conventional engine vehicles, the shift in the pitch of the vehicle sound is primarily caused by the change in the engine speed. As a consequence of this relationship between sound and acceleration, it is believed that a wider frequency shift is perceived as representing acceleration.

Figure 5 shows the relative rating scores for the harmonization impression. The relative harmonization scores of virtually all stimulus conditions were close to that of the baseline. The acceleration of the vehicle in the video stimuli was relatively steady. In the case of a steady acceleration, frequency shifting did not have an effect on the harmonization impression. In the case of the external video scenarios, excessive frequency shifting did not harmonize with the visual acceleration impression. Similar trends were observed in the case of internal video scenarios.

4. Summary

A paired comparison test using audio and visual stimuli was conducted to examine the relationship between frequency shifting and the acceleration impression of vehicles. The results showed that frequency shifting can enhance the vehicles’ acceleration impression for both pedestrians and passengers in the vehicles. It was also shown that the acceleration impression is affected by not only the rate of shifting but also its band. The majority of the stimulus conditions that contained a 2,000-Hz-band component had a positive effect on the acceleration impression. The band and rate of frequency shifting also had an effect on the harmonization between the impression of audio and the visual acceleration.

In the future, our aim is to investigate a comprehensive impression and to explore the capabilities of a designed application. Moreover, the actions of a driver may potentially have an effect on the acceleration impression, and hence, an examination using a driving simulator is also a part of our future work.

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References