Impression of automatic start sound of engine of hybrid vehicle under idling condition

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1. Introduction

Hybrid electric vehicles are environmentally friendly vehicles. They do not only have good environmental performance but are also quiet since the engine is often at rest. However, this may endanger pedestrians who do not hear an approaching vehicle. Hence, vehicle companies and researchers have been considering how to design sounds to inform pedestrians that a vehicle is approaching [1–5]. Strictly speaking, a hybrid vehicle is not silent since motor and relevant mechanical noise become dominant when the engine is at rest. In addition, the engine of a hybrid vehicle with an idling reduction function sometimes starts automatically when the battery needs to be charged. This mechanism (automatic engine start) occurs in engines of some vehicles having this function. However, the sound of this mechanism may cause negative feelings, especially to the drivers of hybrid vehicles, because hybrid vehicles are basically quieter than other vehicles at a low load since the engine is often at rest and drivers can be expected to pay more attention to a sound in a quiet hybrid vehicle. Nevertheless, the investigation of how drivers react the engine start sound has not been carried out until now.

In this study, we investigated the reaction of drivers to the unexpected engine start sound. Furthermore, we considered limit for the engine speed and engine noise level that inhibit the negative feeling.

2. Subjective evaluation using engine start sounds

A series of sounds recorded in the interior of a hybrid vehicle under cruising, decelerating, stopped and accelerating conditions were presented to the participants, and subjective evaluation tests were carried with the participants focusing on the sound under the stopped condition. The sounds were recorded in the following situations:

(1) Cruising at 40 km/h (4 s),
(2) Decelerating from 40 to 0 km/h (4 s),
(3) Stopped (8 s),
(4) Accelerating from 0 to 40 km/h (4 s),
(5) Cruising at 40 km/h (4 s).

These recorded sounds were combined (total 24 s) and presented as a sound sequence. In the presented sound sequence, the participants only evaluated the sound under the stopped condition. For the evaluation, we prepared a reduced idling condition, a condition with the engine continuously running and an engine start condition (with the engine stopped in the first 4 s and running in the last 4 s) under the stopped condition. In addition, we prepared three engine idling speeds of 1,000, 1,500 and 2,500 rpm for the engine running condition. Hence, there were nine presentation patterns (three engine idling conditions × three engine speeds) in total. The average A-weighted sound pressure levels (SPLs) under the cruising, decelerating and accelerating conditions were 59.7, 49.7 and 53.6 dB, respectively. The SPLs under the engine was continuously running at 1,000, 1,500 and 2,500 rpm were 44.9, 51.4 and 53.0 dB, respectively.

In the evaluation, the sound sequence was presented to the participants from a PC using a playback system (HEAD acoustics HPS4) and headphones (Sennhieser HD600) in a sound chamber where the background noise was under 30 dB. After listening to the sequence, the participants evaluated the sound under the stopped condition. As the evaluation terms, “uneasiness” and “discomfort” were employed in addition to “loudness.” In the loudness evaluation, the participants rated the loudness of the sound using an integer scale from 0 to 100. In the uneasiness and discomfort evaluations, four categories, “very uneasy/uncomfortable,” “uneasy/uncomfortable,” “slightly uneasy/uncomfortable” and “not uneasy/uncomfortable” were given.

These subjective evaluations were carried out using original software. The vehicle condition (decelerating, stopped or accelerating) was indicated on the PC monitor synchronized with the sound presentation to inform the participants of the timing of the stopped condition. The participants were instructed to evaluate the entire sound for 8 s during the stopped condition. This evaluation test was conducted separately in each session. Nine sound sequences were presented twice in each session. There were, therefore, 18 tests in each session, and each session lasted almost 15 min. Each subject participated nine sessions in total, hence, each sound sequence was evaluated 18 times in all sessions.

Eight males in their 20’s having normal hearing acuity participated in the test. Since their driving experience of hybrid vehicles or understanding of the purpose of the engine start may have affected the evaluation, questionnaire was devised to assess these factors, which was filled in after completing all tests. The results showed that all but one of the participants had no experience of driving hybrid vehicles and did not know the reason for the engine start. This means that this subjective evaluation was carried out to people with minimal experience.
Results

Figures 1(a)–1(c) shows the analytical results for loudness, uneasiness and discomfort in the case that the engine was running continuously or the engine started automatically at the three engine speeds (1,000, 1,500 and 2,500 rpm), respectively. For the analysis of loudness, the obtained scores were averaged for all participants. For the analysis of the uneasiness ratio, the selection ratios of “very uneasy,” “uneasy” and “slightly uneasy” were first calculated. Then, Z-values were obtained by using the ratios and the normalized Gaussian distribution function. The obtained Z-value was named the uneasiness score. The discomfort score was also obtained in the same manner.

The gray and white bars in Fig. 1 indicate the scores for the continuously running condition and the engine start condition, respectively. From these results, the loudness for the engine start condition was observed to be smaller than that for the continuously running condition at all engine speeds. As the reason for the reduced loudness, the silence for 4 s, that was included under the engine start condition, seems to be the main factor. Under the engine start condition, the first half of the presented sound was silent because of the idling reduction function. The participants were instructed to evaluate the sound in the 8 s duration of the stopped condition including the silence for 4 s. Therefore, the loudness was evaluated to be lower than under the continuously running condition. Uneasiness and discomfort scores for the engine start condition were also evaluated to be smaller than those for the continuous running condition. According to these results, negative feelings were not observed to be increased by the engine start sound.

On the other hand, loudness, uneasiness and discomfort increased with the engine speed. Furthermore, the uneasiness and discomfort scores for the engine start condition were evaluated to be smaller than those for the continuously running condition at all engine speeds, similarly to the loudness scores. This tendency indicates that the uneasiness and discomfort scores are related to the loudness, and the lower uneasiness and discomfort scores under the engine start condition are considered to be due to the reduction of loudness owing to the silent interval. This may hide the effect of the sound event of an engine start on the uneasiness and discomfort. Figure 2 shows the relationship between these evaluations and the loudness at each engine speed. Figure 2(a) shows the dependence of the uneasiness on the loudness and Fig. 2(b) shows the dependence of the discomfort.

These figures show a very strong relationship between these evaluations and the loudness. Next, we analyzed the effect of the sound event of an engine start on the negative feelings by compensating for the effect of loudness between the two conditions as follows. First, the uneasiness and discomfort caused by the loudness under the continuously running condition were estimated using the regression equations in Fig. 2. Here, we defined the calculated value as the effect of loudness on uneasiness/discomfort. Secondly, the effect of loudness on uneasiness/discomfort under the engine start condition were also obtained using the same equations. The difference between the effect of loudness on uneasiness/discomfort under the continuously running condition and those under the engine start condition is considered to originate from the difference in loudness resulting from the different times for which the engine was running (8 s under the continuously running condition and 4 s under the engine start condition). Then, we added this difference to the uneasiness/discomfort score under the engine start condition to compensate for the effect of loudness caused by the difference in the duration of silence between the two conditions. Figures 3(a) and 3(b) show a comparison of these scores under the continuously running condition and the compensated uneasiness and discomfort scores under the engine start condition, respectively.

Gray bars indicate the scores under the continuously running condition and white bars indicate the compensated scores under the engine start condition. From these results, the uneasiness under the engine start condition was found to be larger than that under the engine continuously running condition at all engine speeds. On the other hand, the discomfort did not change uniformly. This tendency reveals that the engine start sound of a hybrid vehicle increased the feeling of uneasiness.

In addition, since the loudness under the continuously running condition was observed to have a strong effect on uneasiness, we analyzed the contribution of the loudness and of the sound event on the uneasiness.
the sound event of an engine start on the feeling of uneasiness. Figure 4 shows the uneasiness ratio under the continuously running condition re-calculated from the Z-value (gray bars), and the ratio under the engine start condition calculated from the loudness-compensated Z-value (white bars). The difference between these values indicates the degree to which the feeling of uneasiness was increased by the sound event of an engine start. The right side of Fig. 4 shows the average uneasiness ratio for all engine speeds. The average uneasiness ratio under the continuously running condition was 35%, increased by about 17%, to 52% in the case of a sound event. This result indicates that the contribution of the sound event of an engine start to the uneasiness was not negligible.

Subsequently, we considered the upper limits of the engine speed and loudness level at which the feeling of uneasiness was inhibited. Figure 5 shows the relationship between the engine speed and the at ease ratio, which was calculated by subtracting the uneasiness ratio from 100%, before compensation under the engine start condition. From the figure, the at ease ratio was observed to decrease with increasing engine speed. Also, the ratio appeared to asymptotically approach 0% with increasing engine speed, and 100% with decreasing engine speed. We then obtained a cumulative Gaussian distribution curve by fitting the easiness ratio at each engine speed to observe the relationship between the engine speed and the at ease ratio, although the estimated relationship is considered to include a certain amount of error since only three results were used in the estimation. The obtained curve is the solid curve in Fig. 5. Here, we defined the 75th percentile of the cumulative Gaussian curve as the upper limit of the at ease ratio and obtained the engine speed from the curve. The percentile could be set by the manufacturer according to their development strategy. In this study, we used the 75th percentile because it has been used to determine the differential limen of a sense in general [6]. For the 75th percentile, the engine speed was found to be about 1,400 rpm. This means that the engine speed of the hybrid vehicle used in this study should be under 1,400 rpm during idling to inhibit the increase in the feeling of the uneasiness caused by the engine start sound.

This upper limit for the engine speed can only be used for the vehicle employed in this study; if a hybrid vehicle has a quieter engine sound, the upper limit is expected to increase. Therefore, if we set the upper limit as a loudness value, this value could be applicable in various situations. To express stationary loudness quantitatively, the loudness value in ISO 532B is known to be a suitable index. We next considered setting the upper limit as a loudness value. Figure 6 shows the dependence of the at ease ratio on the loudness value.
The solid curve in the figure shows the fitted cumulative Gaussian curve. The result indicates that the upper limit of the loudness value for a 75th percentile at ease ratio was about 6 sone. This means that the loudness of the automatic start sound of an engine should be under 6 sone so as not to increase the feeling of uneasiness.

4. Summary

In this study, we investigated the impression of the automatic start sound of the engine of a hybrid vehicle. The results showed that the sound increases the feeling of uneasiness of drivers. Furthermore, the upper limits of the engine speed and loudness that inhibited the feeling of uneasiness were considered. As the results, it was found that the engine speed should be under 1,400 rpm and the loudness should be under 6 sone.

References