9-12 AUGUST 2015
inter.noise 2015
SAN FRANCISCO, CALIFORNIA USA

Influence of unexpected engine start sound of hybrid vehicle in cabin -Comparison between Japanese and German drivers-

Toru Ueno[a)]
Junji Yoshida[b)]
Department of Mechanical Engineering, Osaka Institute of Technology
Asahi-ku Omiya, 535-8585, Osaka, Japan

Hugo Fastl[c)]
AG Technische Akustik, MMK, Technische Universität München, Arcisstr. 21, 80333 Munich, Germany

In this study, we investigated an impression of engine automatic start sounds for charging electricity of hybrid electric vehicles having idling reduction function. Subjective evaluation test employing various idling sounds of hybrid vehicles were carried out by Japanese and German participants. As a result, uneasiness feeling was found to be increased by the automatic engine start sound in both countries. In addition, upper limit of engine rotational speed and loudness of the engine sound were analyzed not to increase the uneasiness feeling in the cabin. The analytical results indicated the upper limits of the engine start sound were 1400 rpm in Japanese, and 900 rpm in German participants. In addition, 6 sone in Japanese and 4 sone in German participants were analyzed as the upper limit loudness. Consequently, German participants were found to be more sensitive to the engine automatic start sound than Japanese.

1 INTRODUCTION

In recent years, environmental friendly vehicles have been developed. Hybrid electric vehicle (HEV) is one of the popular environmental friendly vehicles at present. This hybrid vehicle occasionally runs using only electric motor at the low speed and load like starting condition in urban streets. Accordingly, HEV does not have only good environmental performance but also have quietness in cabin. However, this quietness may endanger pedestrians who don't recognize a vehicle approaching. Hence, vehicle companies and researchers have been considering how to design sounds to inform the vehicle approaching [(1)-(8)]. On the other side, HEV is not always silent actually. Motor

[a)] email: yoshida@med.oit.ac.jp

and relevant mechanical noise become dominant because of the engine rest. In addition, HEV having idling reduction function sometimes starts engine automatically in order to charge the electricity of the battery. This sound event may cause negative feelings to drivers. Nevertheless, there are rarely previous researches investigating this influence on drivers. Furthermore, if the relationship between the negative feelings to the unexpected engine start sound and the engine rotational speed is clarified, suitable engine speed compatible with charging electricity efficiency could be considered.

In this study, we investigated how they feel the unexpected engine start sound at first. Next, if they have negative impression to the sound, upper limit engine rotational speed and noise level to inhibit the negative feeling are analyzed through subjective evaluations using various idling sound of HEV. In addition, the feeling may be difference according to the nationality because of the difference of the vehicle history and the traffic condition. Accordingly, these evaluations were carried out both in Japan, where HEV has already been popular, and in Germany, which is one of the representative advanced countries of vehicle industry.

2 SUBJECTIVE EVALUATION OF IDLING NOISE

In this section, we implemented subjective evaluation using engine automatic start sound. In general, the quietness in cabin is very high at the HEV stop condition. Hence, the evaluation to the sound at the condition has a possibility to be affected by the before (decelerating) and after (accelerating) sounds at the driving condition. Thus, we recorded a decelerating, stop, and accelerating sounds of a HEV for the presentation in the subjective evaluation as the sound sequence. In addition, there were three conditions at the HEV stop situation; engine rest, continuous engine running, and engine automatic start. The participants evaluated only sounds at HEV stop in the replayed sound sequence.

2.1 Stimuli, Procedure, and Participants

To obtain the stimuli for the subjective evaluation, we recorded HEV interior sounds at cruising, decelerating, stop and accelerating conditions using artificial head microphones (HEAD acoustics HSU2) put on the passenger seat. The recorded sounds were edited for replaying as the sound sequence as follows; cruising (40 km/h) for 4 s, deceleration for 4 s, stop for 8 s, accelerating for 4 s and cruising (40 km/h) for 4 s. In total, duration of the sound sequence became 24 s by adding these sound elements in the order. Additionally, we prepared three engine patterns in the stop situation; engine rest, engine running and engine automatic start (engine rests for first 4 s and runs for the second 4 s). Furthermore, three engine idling rotational speeds at 1000, 1500 and 2500 rpm were prepared for the analysis of the upper limit engine speeds to inhibit the increase of that feeling. Hence, there were nine evaluation patterns composed of three idling patterns (engine rest, run, automatic start) and three engine rotational speeds (1000, 1500 and 2500 rpm) in total. Averaged A-weighted sound pressure levels (SPLs) at the cruising, decelerating and accelerating were 59.7, 49.7 and 53.6 dBA, respectively. The SPLs at the continuous running engine idling sound of 1000, 1500 and 2500 rpm at the vehicle stop condition were 44.9, 51.4 and 53.0 dBA. In the evaluation, the second half of the engine automatic start sound (engine running sound) was the exactly same with the engine continuous running sound.

In the evaluation, the sound sequence was presented to the participants from PC using playback system and headphones (SENNHEISER HD600) at a sound chamber. After listening the sound sequence, the participants evaluated only the sound at the vehicle stop condition. As the evaluation parameter, “loudness” was employed as the fundamental evaluation index[9]. In addition, “uneasiness” and “annoyance” were also used to investigate the negative feeling. In the loudness evaluation, the participants rated the loudness of the sound using integer scale from 0 to 100. In the uneasiness and annoyance evaluations, numerical evaluation seemed to be difficult and category evaluations were applied using four categories “very uneasy / annoyed,” “uneasy / annoyed,” “slightly uneasy / annoyed” and “not uneasy / annoyed.”

This subjective evaluation was carried out using original software. Vehicle conditions (decelerating, stop or accelerating) were indicated on the PC monitor synchronized with the presentation of the sound sequence to inform the evaluation timing (stop condition). Participants were instructed to evaluate the sound only at the vehicle stop condition. In case of engine completely stop condition, any sound was not presented, therefore, we prepared an option to skip the evaluation if they did not hear any sounds in the stop condition.

This evaluation test was conducted separately in each session. Nine presentation sound sequences were presented twice in each session. Thus, 18 sounds were presented and evaluated in each session. Each participant iterated this session nine times in total, hence, each sound sequence was evaluated 18 times in all sessions. In addition, all participants carried out three trials before the actual test to comprehend the evaluation procedure.

Eight Japanese male in 20’s participated in this test as the Japanese participants and nine German male and one German female from 20’s and 30’s participated as the German participants. Totally, there were 18 participants in this test. In the evaluation, their driving experience of HEV may affect the ratings, therefore, we asked them about the experience of their HEV driving after completing all evaluations. As the result, all participants in this test except for a participant in Japan did not have any experience of driving HEV. The result means this subjective evaluation was carried out to novice of HEV.

3 RESULTS

Figure 1 and 2 shows analytical results of loudness, uneasiness and annoyance in case the engine was running continuously or the engine was started automatically at the three engine rotational speeds (1000, 1500 and 2500 rpm), respectively. For the analysis of loudness, the obtained scores were averaged for all participants in each country. In the analysis of uneasiness, uneasiness ratio, which is a selecting ratio of “very uneasy,” “uneasy” or “slightly uneasy” was firstly calculated. And then, Z-value was obtained using the ratio and a normalized Gaussian distribution function. The obtained Z-value was named as uneasiness score. Annoyance score was also obtained in the same manner.

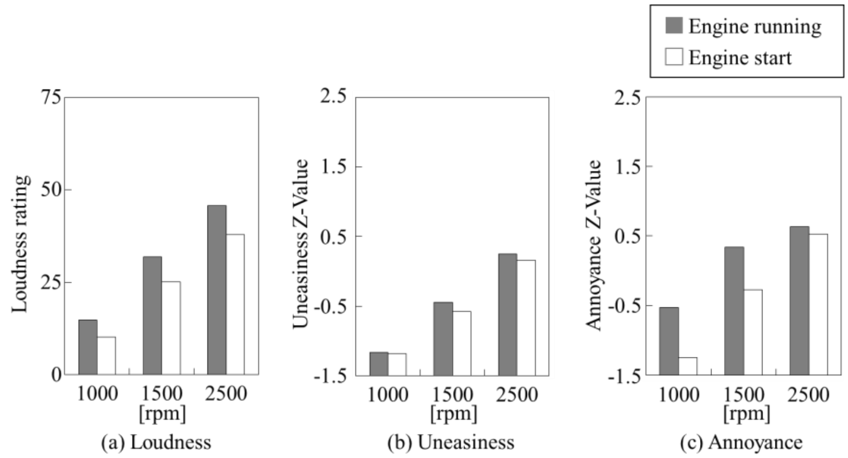

Fig. 1 – Subjective evaluations of hybrid vehicle idling sounds by Japanese participants.

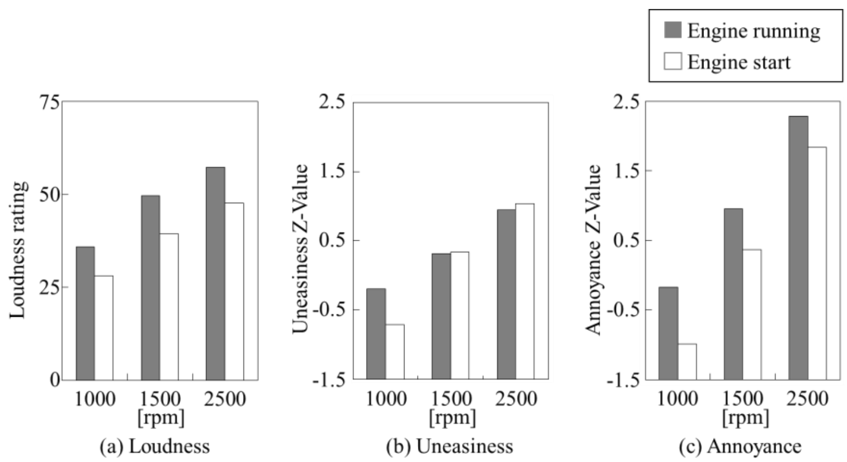

Fig. 2 – Subjective evaluations of hybrid vehicle idling sounds by German participants.

In both figures, (a), (b) and (c) show the analytical results of loudness, uneasiness and annoyance. Gray and white bars indicate the scores of engine continuous running sound and those of engine automatic start sound, respectively. From these results, loudness, uneasiness and annoyance of engine start sound are found to be larger according to the engine rotational speed. Additionally, loudness at engine start sound are observed to be smaller than those of engine continuous running sound at any rotational speed. As the reason of the loudness decrease, existence of the silent duration in the engine start sound is considered to be a main factor. In the engine start sound, a half of the presented sound was silent because of the idling reduction function. The participants were instructed to evaluate entire of the sound at the stop condition including the silence period. Therefore, the loudness is considered to be evaluated relatively softer than the engine running sound.

Uneasiness and annoyance scores of engine start sound were evaluated smaller than those of engine continuous running sound at all engine rotational speeds as same as loudness. However, the differences of uneasiness (annoyance) scores between engine start sound and engine continuous running sound are different in each engine speed although the loudness differences were almost same. This tendency indicates that uneasiness and annoyance scores didn't depend on only the loudness but another factor such as engine automatic start sound may have affected the evaluation results. Then, we tried to separate the contribution of the loudness and the contribution of engine automatic start in the uneasiness and annoyance scores. Firstly, we obtained the loudness dependency on these negative feelings. Figure 3 and 4 shows the relationship between these feelings and the loudness in each engine rotational speed at the engine continuous running condition.

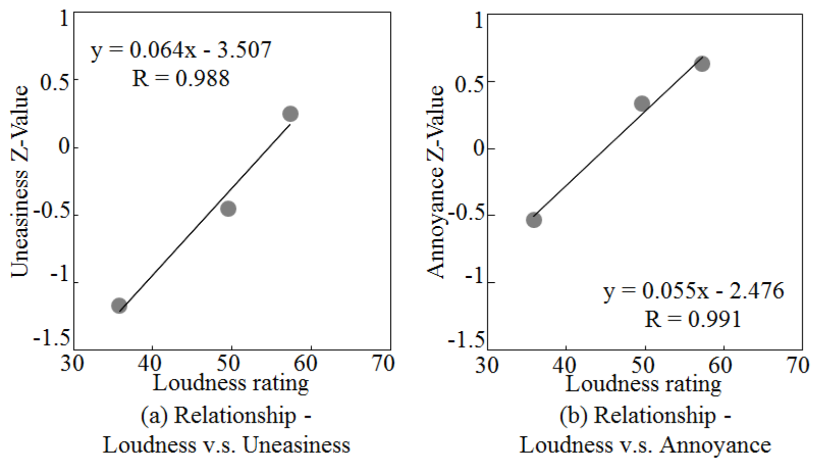

Fig. 3 – Relationship between loudness and uneasiness (a), and relationship between loudness and annoyance (b) in Japanese participants.

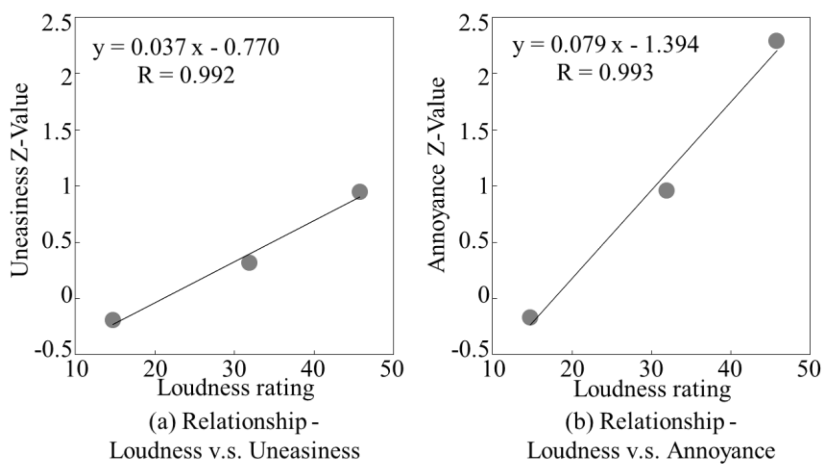

Fig. 4 – Relationship between loudness and uneasiness (a), and relationship between loudness and annoyance (b) in German participants.

These results indicate very high correlation between these negative feelings and the loudness. Then, the influence of the engine start sound on the negative feelings was investigated by compensating the loudness influence as follows. Uneasiness and annoyance by the loudness (loudness affected uneasiness / annoyance) of the engine running sound was estimated at first using the regression equations indicated in Fig. 3 and 4. As same as the loudness affected uneasiness / annoyance of engine running sound, the values of engine automatic start sound were also obtained using the obtained loudness of the engine start sound. Secondly, the loudness compensated uneasiness and annoyance scores of the engine start sound were obtained by adding the difference of the loudness affected uneasiness / annoyance scores between engine running and start sounds. Figure 5 and 6 shows the comparison of these scores of the engine running sound and the loudness compensated uneasiness (a) and annoyance (b) scores of the engine start sound in Japanese and German participants, respectively.

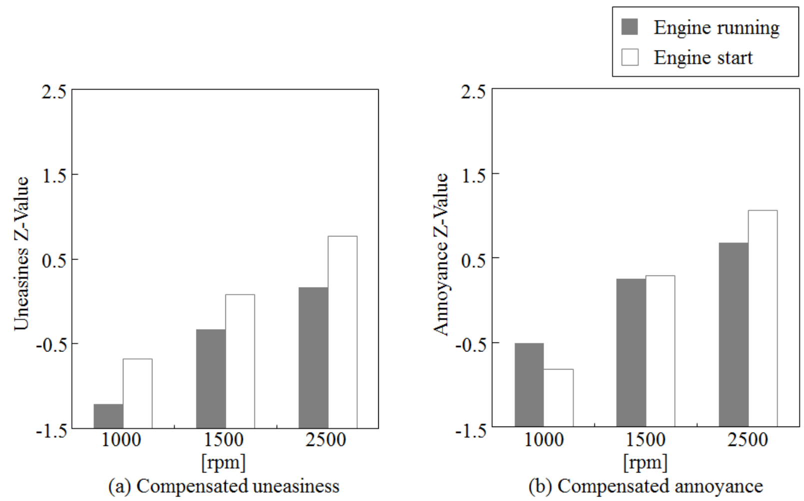

Fig. 5 – Compensated uneasiness and uncomfortableness in Japanese participants

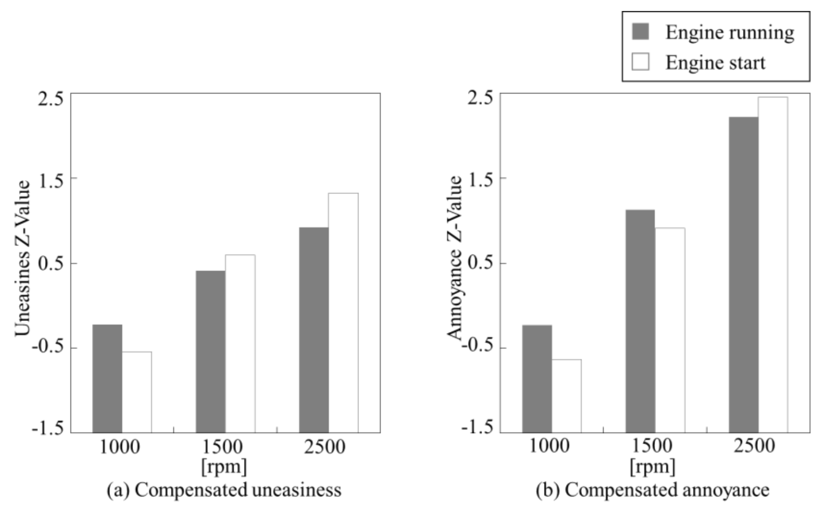

Fig. 6 – Compensated uneasiness and uncomfortableness in German participants.

Gray bars in these figures indicate the scores of the engine running sound and white bars are the compensated scores of the engine start sound. From the results, uneasiness of the engine start sound was found to be larger than those of the engine running sound in all engine rotational speeds in Japanese participants. On the other hand, annoyance was not changed uniformly. This tendency reveals that the engine automatic start sound of HEV increased uneasiness feeling. Likewise, this tendency was observed in German participants. The engine automatic start sound increases uneasiness in most engine rotational speeds except for at 1000 rpm, and uniform change was not observed in the annoyance evaluation as same as Japanese participants.

From these analytical results, uneasiness feeling was found to be increased by the engine automatic start sound of HEV in both countries.

4 ANALYSIS

Engine automatic start sound was revealed to increase the uneasiness feeling in the previous section. Then, we considered an upper limit engine rotational speed and loudness level for Japanese and German to inhibit the uneasiness feeling. Figure 7 and 8 shows the relationship between engine rotational speed and the easiness ratio which was calculated by subtracting the uneasiness ratio from 100% in Japanese and German participants.

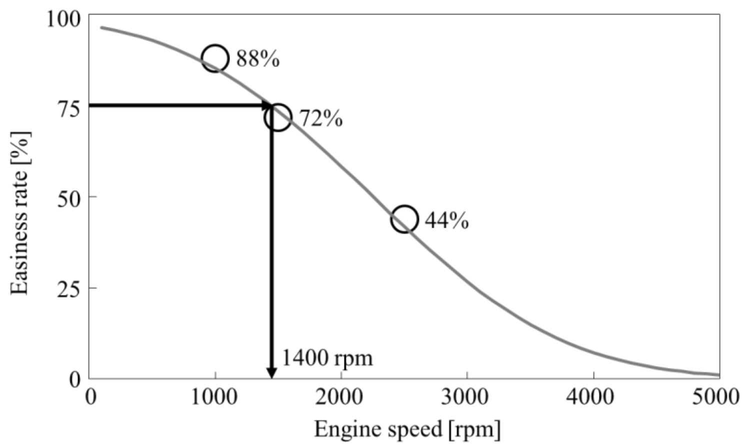

Fig. 7 – Easiness ratio to engine start sound in each engine speed in Japanese participants.

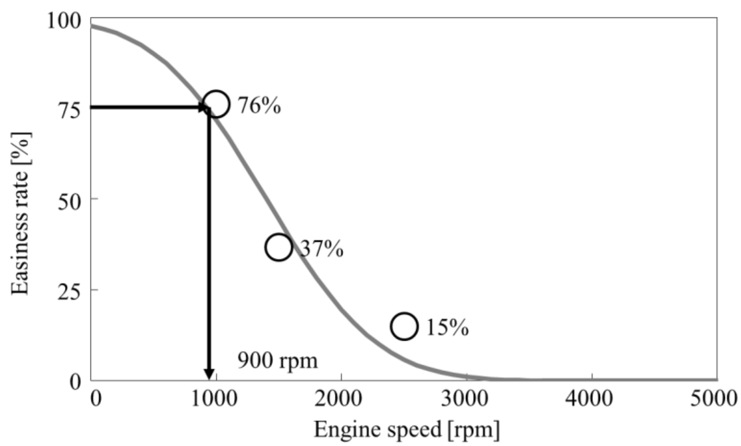

Fig. 8 – Easiness ratio to engine start sound in each engine speed in German participants.

From these figures, the easiness ratio was observed to decrease generally depending on the engine speed in both countries. Also, the ratio could be estimated to asymptotic to 100% along the increase of engine speed, and 0% along the decrease. We then obtained a cumulative Gaussian distribution curve in each country to fit the easiness ratio in each engine speed as shown in solid curve in Fig. 7 and 8. Here, we defined 75% point of the cumulative Gaussian curve as the upper limit easiness ratio and obtained the engine speed from the curve. As the result, the engine speed was found as 1400 rpm in Japanese participants and 900 rpm in German participants. This means the engine rotational speed of the vehicle used in this study had better to be under 1400 rpm for Japanese, and 900 rpm for German at the idling to inhibit the increase of the uneasiness feeling by the engine start sound.

These upper limit engine speeds could be used for only the employed vehicle in this study. If the other hybrid vehicles have softer / louder engine sound, the upper limit could be supposed to increase / decrease. On the other side, the loudness was found to relate the uneasiness feeling very much. Therefore, the upper limit level is expected to be applicable in various situations by setting the level using loudness. Then, we applied the loudness value by ISO 532B to express the loudness feeling quantitatively and considered the upper limit using the loudness value. Figure 9 and 10 shows the dependency of the easiness ratio on the loudness value in Japanese and German participants, respectively. Horizontal and vertical axes denote the loudness value and the easiness ratio. Solid lines in both figures show cumulative Gaussian distribution curves fitted to each loudness value.

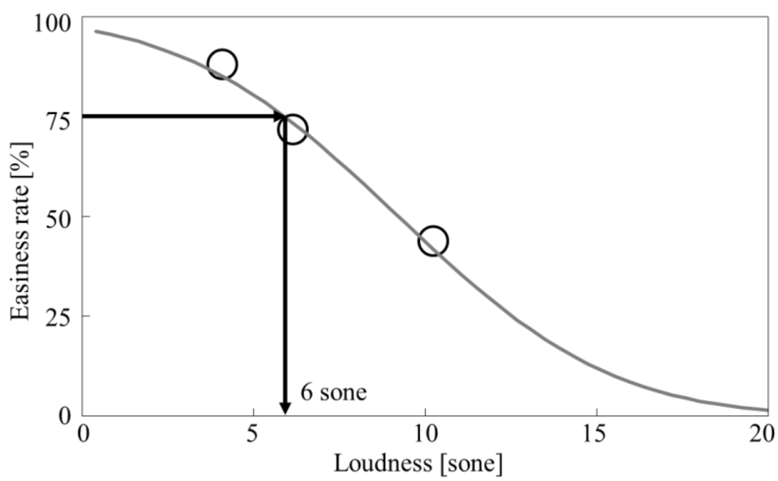

Fig. 9 – Dependency of easiness ratio on loudness in Japanese participants.

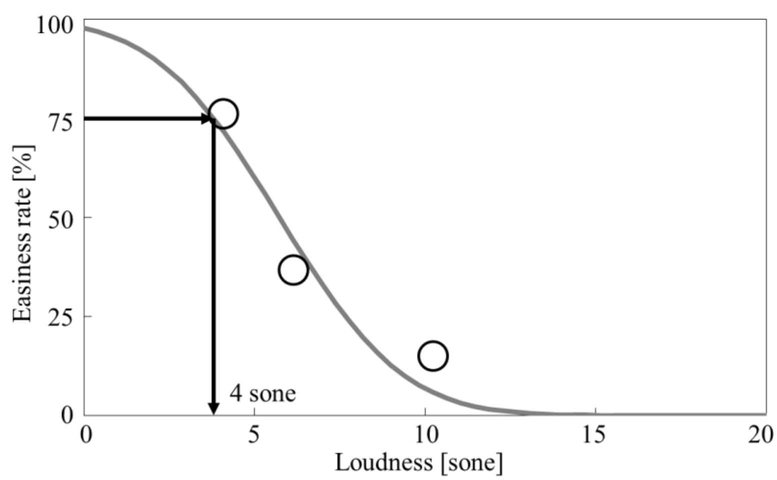

Fig. 10 – Dependency of easiness ratio on loudness in German participants.

The upper limit loudness value for the 75% easiness resulted in 6 sone in Japanese participants and 4 sone in German participants. From these obtained upper limit loudness, we can set the appropriate limit level to inhibit uneasiness feeling by the automatically started engine sound in various vehicles.

At last, we compare the tendencies of the uneasiness feeling to the engine automatic start sound between Japanese and German participants. Figure 11 show the comparison of the easiness ratio along engine speed in both countries.

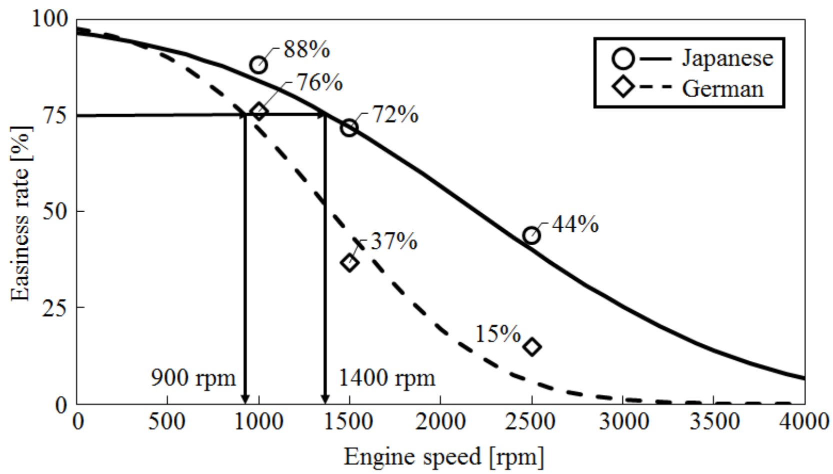

Fig. 11 – Comparison of easiness ratio to engine start sound in each engine speed between Japanese and German participants.

The comparison shows the easiness ratio of German participants are less than Japanese participants in most engine speeds. In addition, the limit engine rotational speed of German participants (900 rpm) was 500 rpm lower than that of Japanese participants (1400 rpm). These results indicate that German participants have a tendency in which they are more sensitive and felt more uneasy to the automatic start engine sound than Japanese participants. The reason why German participants are more sensitive to the engine start sound is discussed as follows.

The German participants in this study rated more uneasy to the engine start sound than the ratings of Japanese participants in all engine speeds as shown by the white bars in Fig. 1 (b) and Fig. 2 (b). On the other side, the ratings to the engine continuous running sounds in German participants were also higher than Japanese participants as shown by the gray bars in Fig. 1 (b) and Fig. 2 (b). This indicates that German participants didn't have more uneasiness feeling only to the engine automatic start sound but also to the engine running sound at the idling condition than Japanese. Hence, the higher sensitivity to the continuous engine sound at the vehicle stop condition is considered to be a main factor increasing the uneasiness feeling to the engine start sound in German participants.

5 SUMMARY

In this study, we investigated the impression of automatic engine start sound of HEV in Japanese and German participants. Subjective evaluation was carried out using HEV idling sounds at various rotational speeds and engine conditions. "Loudness," "Uneasiness" and "Annoyance" were used as the evaluation terms in the test. As the result, uneasiness feeling was found to be increased by the engine automatic start sound in both countries. In addition, upper limit engine rotational speed and loudness value were analyzed to inhibit the increase of uneasiness in each country. The results were 1400 rpm and 6 sone in Japanese participants, and 900 rpm and 4 sone in German participants, respectively. Accordingly, the tendency of the uneasiness feeling was clarified to be different between these countries and German participants were more sensitive to the HEV engine start sound. From these experimental and analytical results, it was clarified to be better to set different engine idling rotational speeds for compatible the negative feeling with the electricity charging efficiency according to the target country.

6 REFERENCES

(1) P. Nyeste and M. S. Wogalter, “On Adding Sound to Quiet vehicles”, *Proc. of Hum, Factors Ergonomics Soc. 52nd Annu. Meet.*, 1747-1750, (2008)

(2) P. Goodes, Y. Bai and E. Meyer, “Investigation into the Detection of a Quiet Vehicle by the Blind Community and the Application of an External Noise Emitting System”, *SAE Technical Paper*, 2009-01-2189, (2009)

(3) K. Yamauchi, Y. Sakabe, K. Ito, S. Inoue and S. Iwamiya, “Questionnaire Survey on the Sound of Quiet Vehicles”, *Proc. of Inter Noise 2012*, CD-ROM, (2012)

(4) K. Yamauchi, ”Current Trends on the Audible Vehicle Alerting Sounds for Hybrid and Electric Vehicles”, *Acoustical Science and Technology*, **68**(1), 31-36, (2012)

(5) S. Kerber, “The Importance of Vehicle Exterior Noise Levels in Urban Traffic for Pedestrian - Vehicle Interaction”, *ATZ Worldwide* **108** (7-8), 19-21, (2006)

(6) S. Kerber and H. Fastl, “Perceptibility of Approaching Vehicles in Urban Background Noise”, *Proc. of INTER-NOISE 2013*, 981-988, (2007)

(7) S. Hong, K. Cho and B. Ko, “Investigation of Probability of Pedestrian Crash Based on Auditory Recognition Distance Due to a Quiet Vehicle in Motormode”, *International Journal of Automotive Technology*, **14**(3), 441-448, (2013)

(8) K. Yamauchi, T. Shimizu, F. Tamura and Y. Takeda, “Effect of Frequency Shifting on Acceleration Impression for Designing Additional Sound for Quiet Vehicles”, *Proc. of INTER-NOISE 2013*, CD-ROM, (2013)

(9) H. Fastl and E. Zwicker, Psycho acoustics – Facts and Models, 3rd edition, Springer, Berlin, (2007)