DOI: 10.61782/fa.2025.0216

FORUM ACUSTICUM EURONOISE 2025

Comparative Analysis of Acceleration Sounds from Electric and Internal Combustion Vehicles Using Discomfort Indices

Misaki Nitta[1] **Shunsuke Ishimitsu**[1*]
[1] Graduate School of Information Sciences, Hiroshima City University, Japan

ABSTRACT

Contemporary Japanese society relies heavily on vehicles for transportation and leisure. This has led to environmental concerns owing to vehicle emissions, prompting a shift toward environmentally friendly alternatives, such as clean diesel and electric vehicles. Clean diesel vehicles aim to reduce harmful emissions, whereas electric vehicles are favored because of their minimal emissions and quiet operation. However, the lack of engine noise in electric vehicles can make it difficult for drivers to perceive speed changes, potentially increasing the risk of accidents, and simply amplifying all sounds is not viable because it may cause discomfort. Therefore, this study explored how deviations from expected engine sounds affect the perceived sound quality and vehicle performance assessment. Unlike traditional gasoline-powered and clean diesel vehicles, electric vehicles produce very little running noise, which makes road surface noise more prominent. Given the novelty of electric vehicles and the challenges associated with their driving noises, this study focused on acceleration sounds, analyzing whether incorporating typical engine noises, such as rumbling and humming, could enhance realism. The comfort levels of the participants with various acceleration sounds were examined based on their driving experience, highlighting the complex relationship between sound expectations and vehicle operation.

Keywords: *rumbling, booming, humming, engine sound, wavelet.*

[*]***Corresponding author***: *ishimitu@hiroshima-cu.ac.jp*

1. INTRODUCTION

Contemporary Japanese society relies heavily on vehicles for daily activities, and is transitioning from transportation to leisure activities. However, the popularity of vehicles has raised environmental concerns owing to exhaust emissions, prompting a shift toward eco-friendly alternatives in response to tightening regulations in Europe. Clean diesel vehicles (DVs) aim to reduce harmful emissions, whereas electric vehicles (EVs) have gained traction owing to their low emissions and lack of engine noise during operation [1]. The absence of discernible acceleration noise may compromise the driver's ability to sense speed changes accurately, potentially leading to unsafe driving conditions or accidents. However, the uniform amplification of sounds is not a solution because it can cause discomfort. The perception of sound quality is grounded in human expectations regarding the sound of an engine, which influences drivers' comfort during operation. In this study, we explored the impact of engine sound deviations from expected standards on the perceived sound quality, which affects the assessment of vehicle performance.

In contrast to existing internal combustion engine vehicles, such as gasoline and DVs, the running noise of EVs is low.

One characteristic of EVs is that the sound that occurs from the vehicle while driving is low so that the driving noise on the road surface can be heard. EVs are new, and many challenges are associated with driving noise.

Consequently, this study focuses on DV and EV acceleration sounds to determine the presence of sensations such as rumbling, booming, and humming in acceleration sounds, similar to their existence in steady-state, low-speed sounds. Moreover, we investigated whether integrating these sensations into the EV acceleration sounds could enhance realism. During the auditory experiment, the participants were categorized based on their driving experience and their perceived "comfort" with different types of acceleration sounds was examined.

2. DISCOMFORT INDEX

2.1 Rumbling sounds

The sounds that induce the rumbling sensation comprise low-frequency tones (with frequencies below 100 Hz), which undergo temporal modulation in amplitude at low modulation frequencies (below 20 Hz) [2]. The prototypical sound involves a 40 Hz pure tone, which undergoes temporal modulation at a frequency of 8 Hz and is mathematically defined as:

$$s(t) = a \cdot \sin(2\pi \cdot 40 \cdot t) \cdot (1 + m(t) \cdot \cos(2\pi \cdot 8 \cdot t)) \quad (1)$$

with time t denoted in seconds and the amplitude denoted as a. The sound pressure level of the carrier $a \cdot \sin(2\pi \cdot 40 \cdot t)$ was 83 dB SPL. The function *m(t)* describes the temporally varying modulation depth as:

$$m(t) = \frac{t}{T_r} \quad (2)$$

for $0 < t \leqq Tr$,

$$m(t) = 1 \quad (3)$$

for $Tr < t \leqq T\text{-}Tr$,

$$m(t) = 1 - \frac{t - (T - T_r)}{T_r} \quad (4)$$

for $T\text{-}Tr < t \leqq Tr$, with a total duration *T (=10 s)* and ramp duration *Tr (=3 s)*. Rumbling is the sensation of low-frequency spectral components with audible temporal level Fluctuations [3]. It could originate from vortex shedding at the wheel wells, the trailing edge or the floor pan [4]. The most important source of rumbling is the combustion engine. Especially during a run-up operating condition, fluctuations occur with a period of two engine revolutions [5], eliciting a strongly audible rumbling sensation in the vehicle interior [6].

2.2 Booming Sounds

Doleschal et al. [2] revealed that signals evoking the sensation of booming comprised a low-frequency tonal component with a frequency ranging from 10 to 50 Hz, accompanied by higher-frequency components that underwent temporal amplitude modulation at a frequency matching that of the low-frequency component. The lowest higher-frequency component had a frequency between 100 and 200 Hz, whereas the other higher-frequency components extended up to a frequency of approximately 1 kHz. Based on these findings, the prototypical sound for booming combines a low-frequency pure tone with amplitude-modulated high-frequency components. The modulation frequency was the same as that of the low-frequency tone and the higher-frequency components were selected as integer multiples of this frequency. The prototypical sound is expressed as follows.

$$s(t) = a \cdot (\sin(2\pi \cdot 38 \cdot t) + m(t) \cdot c(t) \cdot (1 + 0.5 \cdot \cos(2\pi \cdot 38 \cdot t))) \quad (5)$$

with the modulated carrier.

$$c(t) = \sin(2\pi \cdot f_c \cdot t) + 0.3 \cdot \sin(2\pi \cdot 2f_c \cdot t) + 0.2 \cdot \sin(2\pi \cdot 3f_c \cdot t) + 0.1 \cdot \sin(2\pi \cdot 4f_c \cdot t) \quad (6)$$

and frequency fc (=152 Hz) for the first modulated component. Amplitude a was chosen to obtain a low-frequency component sound pressure level of 73 dB. Function m(t) was applied only to the higher-frequency components to clarify that the interaction between the low-frequency component and modulated higher-frequency components is crucial for booming. Genuit [3] describes a sound as booming if it contains an unmodulated low-frequency pure tone and tonal components with higher frequencies that are modulated at a modulation frequency equal to the frequency of the low-frequency pure tone.

2.3 Humming sounds

Contrary to rumbling, humming sounds feature pronounced, unmodulated, and low-frequency components (frequencies below 150 Hz) [2]. The humming prototypical sound comprises a single 50 Hz pure tone. The signal is expressed as:

$$s(t) = a \cdot \sin(2\pi \cdot 50 \cdot t) \cdot m(t) \quad (7)$$

Function m(t) is the same as that for rumbling and serves as a time-varying amplification. Without *m(t)*, the sound pressure level of the prototypical humming sound was 88 dB. Sounds containing unmodulated low-frequency tonal components are perceived as humming [3]. Common sources for humming are tire-cavity vibrations [7] and the excitation of interior resonance frequencies due to emissions from the combustion engine [8].

3. CORRELATION ANALYSES BASED ON DISCOMFORT INDEX

3.1 Wavelet Transform

Wavelet transform (WT), a powerful tool for analyzing signals characterized by irregular, noisy, intermittent, and non-stationary phenomena, differs significantly from traditional methods such as short-time Fourier transform [9]. An analysis with the WT involves the use of a wave-shaped function called the mother wavelet (MW). This transformation involves computing values by varying the MW scale and location of the signal. In particular, this plane is filled with transformation values. Performing such calculations continuously yields a continuous WT, whereas performing them discretely yields a discrete WT. The goal of obtaining WT values is to determine the correlation between the MW and signal at various scales and locations. In this study, we used continuous WT as an analytical method. This method is effective for analyzing time-series signals because of its ability to provide information on both frequency components and their corresponding positions and times.

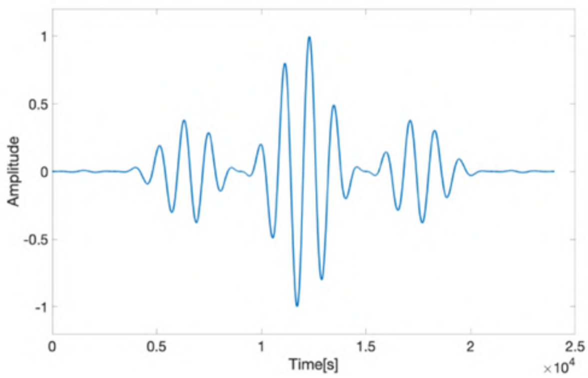

Figure 1. MW of Rumbling.

3.2 MW based on discomfort index

In this study, the reference sounds of rumbling, booming, and humming were used as the MW. Using these MWs in a wavelet analysis (WA) made it possible to display the degree to which the reference sound correlated with the evaluation sound. The MWs were waveforms of the reference sounds cut out for four cycles and then windowed with a Blackman window to provide continuity to the cut-out intervals. To prevent differences in the intensity of the color map from one reference sound to another when comparing the analysis results, all the reference and evaluation sounds were normalized with the maximum value set to one. One of the MWs created, Rumbling's MW, is shown in Figure 1.

3.3 Scale to frequency conversion

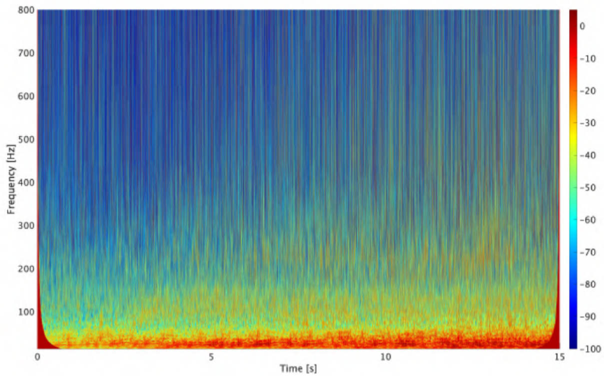

Figure 2. WA of EV Rumbling

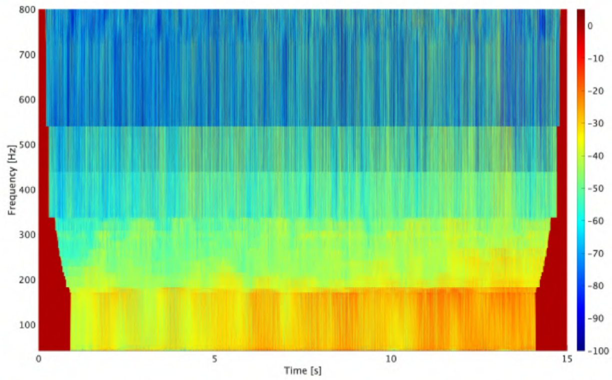

Figure 3. WA of EV Booming.

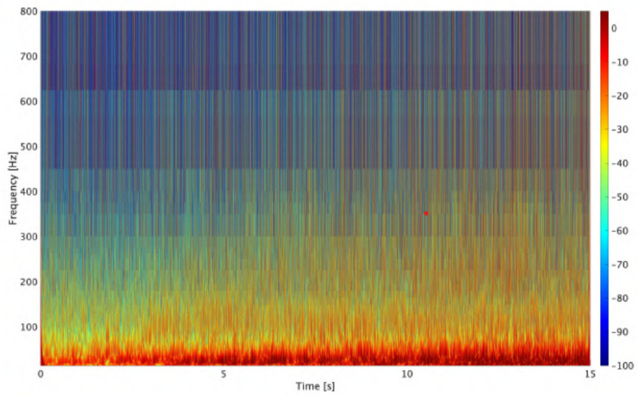

Figure 4. WA of EV Humming.

Originally, after the WT, the spectrum was represented in a time-scale plane using WT-specific scales; however, using MWs that are localized in time and frequency, the spectrum can be displayed in an approximate time-frequency distribution [10]. In this study, the amplitude spectrum was calculated using the Fourier transform of the MWs at each scale, and the frequency of the maximum peak in the spectrum at each scale was used as the pseudo-frequency. Figure 2 to 7 show the results of WA, in which the evaluation sound was analyzed using each reference sound as the MW. The color bar indicates the correlation between the MW and signal. Since the MW is a real signal, each has distinct characteristics. Therefore, normalization is performed using the maximum value obtained after calculating the inner product with the MW, and the dB values ranging from 0 to 100 are derived from the ratio to this maximum value. As a result, 0 dB corresponds to the maximum value. This normalization was implemented to examine the distribution of mutual similarity.

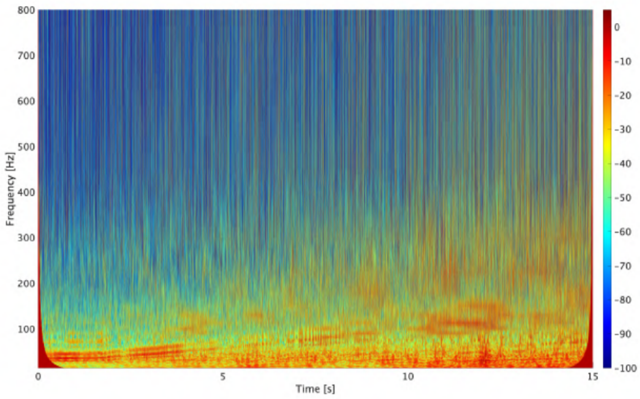

Figure 5. WA of DV Rumbling.

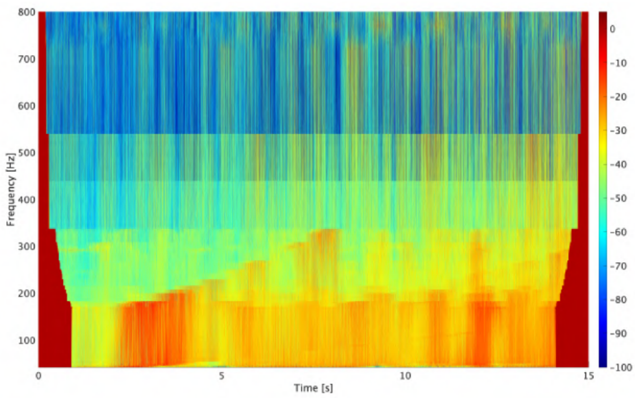

Figure 6. WA of DV Booming.

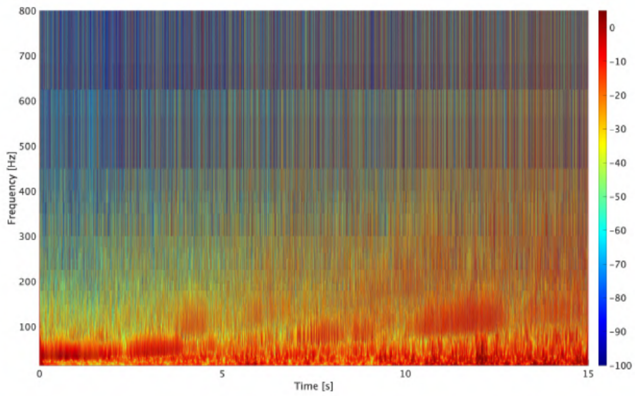

Figure 7. WA of DV Humming

4. EXPERIMENT ENVIRONMENT

Eighteen participants, comprising six women and 12 men with a mean age of 21.2 ± 1.08 years, were included in this study. An experiment was conducted to recognize the differences in driving experience by dividing nine participants into two groups distinguished by higher and lower driving frequencies, set at a threshold of at least thrice a week, with each driving session lasting approximately 30 minutes.

The participants were tasked with marking the axes shown in Figure 8 for each reference sound and indicating the duration for which they perceived the reference sound within the evaluation sound. This evaluation used a seven-point scale ranging from 0 (no perception) to 6 (hearing only the reference sound). The participants could control playback, pausing, and sound source selection for all reference and evaluation sounds, allowing them to conclude the evaluations at their discretion. The sound presentation method also considered potential sequential effects.

The headphones used were K812 Superior Reference (AKG) paired with a labP2-V1 (Head acoustics) playback amplifier. These amplifiers enabled the preservation of consistent volume levels during both recording and playback processes.

This experiment was conducted with the approval of the Ethics Committee of Hiroshima City University.

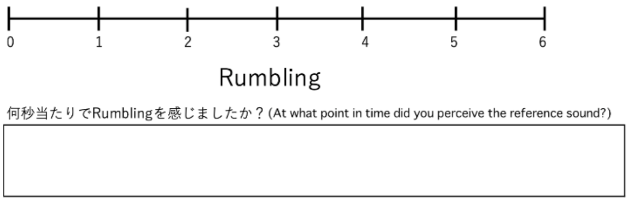

Figure 8. Evaluation Scale.

5. RESULTS

The range in which the majority of these perceived sounds (the RWM) was defined as the position where the reference sound was recognized.
The mean scores and variances of the ratings provided by the participants are presented in Tables 1 and 2 for each driving experience level.
The gray background in Tables 1 and 2 indicates that the participants did not recognize the reference sound.
First, we focused on EVs. The mean score of rumbling was lower than that of the other reference sounds in both participant groups, indicating that rumbling was the least perceived sound, irrespective of driving experience.
Next, we focused on DVs. The mean booming score was >1.5 points higher in the group with less driving experience. The group with more experience perceived booming less frequently than the other reference sounds, whereas the group with less experience perceived booming more frequently.
In this study, the noise is categorized based on the characteristics of each sound, so the differences are not expected to be significant enough to produce clear statistical significance. The analysis was conducted to observe the overall trends rather than to identify distinct differences.

Table 1. Regular driver (RD) group.

	EV			DV		
	Rumbling	Booming	Humming	Rumbling	Booming	Humming
mean	1.33	2.00	2.22	3.33	2.44	2.89
variance	2.00	3.00	3.94	2.00	1.03	2.11

Table 2. Infrequent driver (ID) group.

	EV			DV		
	Rumbling	Booming	Humming	Rumbling	Booming	Humming
mean	1.44	1.78	1.22	1.89	4.11	2.44
variance	1.28	2.44	2.19	1.86	2.61	3.78

5.1 Auditory experiment

In the auditory experiments, we observed that the sounds of rumbling, booming, and humming, previously documented only during steady-state low-speed driving conditions in earlier studies [2], were also perceptible during the acceleration phases. This extends the context in which these sounds are relevant, and may influence driver perception and vehicle design considerations.
The analysis revealed distinct differences in the perception of these sounds between EVs and DVs. In EVs, all sounds—rumbling, booming, and humming—were perceived with a lower intensity, as indicated by the mean rating scores falling below the median value of three. This suggests a quieter operational profile for EVs compared with DVs in terms of these specific auditory outputs.
Furthermore, DVs displayed a particular deficiency in the recognition of humming sounds across all levels of driving experience based on the RWM results. This implies that humming is less perceptible in DVs than rumbling and booming, which may reflect the acoustic properties and insulation standards specific to DVs. The perceptibility of booming was notably higher among participants with less driving experience, suggesting that novice drivers may be more sensitive to or less accustomed to filtering this type of noise than their more experienced counterparts. Conversely, more experienced drivers reported lower perception levels of booming sounds compared with other reference sounds, indicating a possible acclimatization effect over time or a better ability to ignore this sound during driving.

5.2 Correspondence between auditory experiment and WA

In correlation with the findings of the auditory experiments, our examination of the WA results allowed us to delineate the areas in which the auditory evaluations were contingent. Although these mappings revealed distinct variations according to the level of driving experience, they provided a structured understanding of how auditory perceptions aligned with the WA characteristics.
Unlike rumbling and booming sounds, which showed clear correlations with specific temporal segments within the WA results, humming was characterized by a notable lack of correlation with any distinct temporal direction. Participants generally perceived humming as either imperceptible or as a sound that was vaguely dispersed across the entire auditory field. This suggests that humming, unlike rumbling and booming, does not have a

localized temporal impact, but rather influences the acoustic environment in a more diffused and less distinguishable manner. This difference in perceptual localization may influence the evaluation of vehicle noise in both design and testing protocols.

5.3 Influence of driving experience

The influence of driving experience on the perception of vehicle acceleration sounds was notably different between the two groups of participants. The regular driver group demonstrated the ability to identify the reference sounds at the onset of acceleration. However, once this auditory recognition was interrupted, the participants struggled to immediately re-identify the reference sound. This suggests the potential for the disruption of auditory perception continuity among regular drivers.

In contrast, the infrequent driver group, which did not engage in daily driving activities, appeared to interpret acceleration sounds more generically. This may indicate a less nuanced perception of vehicle sounds owing to their limited driving experience. Their evaluation reflected a generalized auditory response rather than detailed or specific recognition, potentially influencing the overall sensory interpretation of the driving experience.

6. CONCLUSIONS

In this study, the acceleration sounds of DVs and EVs were recorded, and auditory experiments were conducted using the discomfort index of steady-state low-speed driving sounds, such as rumbling, booming, and humming. The physical characteristics of the acceleration sounds were compared with those of the WA and auditory impressions of the acceleration sounds. The WA results showed the correlation of the reference sound with the acceleration sound as the WA was performed using the MWs of rumbling, booming, and humming as reference sounds in this study rather than using general MWs. Pursuing realistic EV driving sounds and establishing an acoustic index can be useful for designing future vehicle driving sounds. Although the results of the auditory experiment corresponded with the results of the WA, specific factors leading to discomfort or pleasantness could not be identified from the results of the auditory experiment. However, regardless of whether the sound is perceived as pleasant or unpleasant, the transition to electric vehicles under Noise Regulation Phase 3 demands a level of realism in feedback sounds, particularly during acceleration. It can be argued that the sense of realism is often found more in unpleasant sounds than in comfortable ones, and the ability to simulate this realism based on the results of auditory experiments proves to be valuable. In the future, further analysis of the results of this study and research on comfortable vehicle acceleration sounds can help to clarify their characteristics.

7. REFERENCES

[1] Japan Automobile Manufacturers Association, “Next-Generation Vehicles (Passenger Cars) in Japan”, *https://www.jama.or.jp/library/publish/mioj/ebook/2022/MIoJ2022_j.pdf,* 6 December 2023, (in Japanese)

[2] F. Doleschal, G. Badel and J. Verhey, “Rumbling, humming, booming - Perception of vehicle interior noise at low engine speeds”, *Applied Acoustics,* 197, 2022, 108915, doi:10.1016/j.apacoust.2022.108915.

[3] K. Genuit et al., “Bewertung von Fahrzeuggeräuschen,“ in Sound-Engineering im Automobilbereich, 109-182., 2010.

[4] K.-U. Nam et al., ”Windgeräuschminderung am Unterboden durch akustische Holografie“, Automobiltechnische Zeitschrift 110 (6), 480-488, 2008.

[5] T. Wakita et al.,”Objective Rating of Rumble in Vehicle Passenger Compartment During Acceleration”, SAE Technical Paper 891155, 1989.

[6] K. Tsuge, K. Kanamaru, T. Kido und N. Masuda, “A study of noise in vehicle passenger compartment during acceleration”, SAE Technical Paper 850965, 1985.

[7] K. Genuit et al., “Analysis of Annoyance of Low-Frequency Beat inside a Vehicle”, ICA, 2849-2850, (1998).

[8] M. Pflüger et al. “Akustik des Fahrzeugantriebs,“ in Fahrzeugakustik, Wien, Springer, 2010.

[9] S. Shin and K. Nakano: *The Illustrated Wavelet Transform Handbook*. Tokyo:Asakura Publishing Co, 2005, (in Japanese).

[10] S. Ishimitsu, H. Kitagawa, S. Horihata and N. Hagino, “Correlation analyses of Time-Varying Signals with wavelet and application to Ship interior noise analysis”, *Transactions of the JSME*, 69-682(02-1218), 1529-1535, 2003 (in Japanese).