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OPTIMIZING IN-CABIN ACOUSTIC COMFORT: PSYCHOACOUSTIC EVALUATION OF ENGINE SOUND PROFILES

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ABSTRACT

Achieving acoustic comfort inside the vehicle cabin typically requires a combination of Passive and Active Noise Control techniques, methods that have been effective at modifying the resulting sound field in a closed enclosure. [1] From a subjective point of view, not all noise sources are equally disturbing to passengers, and engine and road noise are often perceived as the most unpleasant noise sources, due to the presence of low-frequency components. This paper presents a subjective evaluation test designed to determine the most effective filter configuration that could improve the perception of engine noise inside a vehicle. Filtered engine noise samples are rated using the Bradley-Terry pairwise comparison method, allowing participants to express their preference between the original sound and three filtered versions of it. Recordings were captured under different operating conditions, including: driving state, gear shift and engine RPM configuration. Three perceptual attributes were chosen along with preference by default: pleasantness, power and naturality. This work aims to contribute to the development of Sound Quality Evaluation strategies that improve in-cabin acoustic comfort.

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1. INTRODUCTION

Numerous efforts have been made to study and deal with the acoustic comfort and driving experience of users over time. Relevant publications in this field include [2], [3], [4], [5], [6], [7], [8]. Psychoacoustics in the automotive industry plays a crucial role in reflecting the audible preferences of drivers and passengers to ensure sound quality subjectively; this along objectively indices are the two ways noise experienced in the car can be assessed. [9] Through subjective evaluation methods, researchers can determine the level of comfort in the driving experience, having in mind a positive outcome for it. [10] In the beginning, the interior development of the vehicle was mainly focused on achieving objective indices and quantitative metrics given by airborne and structure-borne noise paths. [11] However, this idea has gradually evolved over time, as a result of different challenges faced by manufacturers due to trends such as lighter and more efficient automobiles, but also the integration of Electric Vehicles (EV). [12] Sound Quality Design (SQD) is introduced in this field when engineers on customized solutions, including comfort and power. Various approaches such as digital signal processing and adaptive algorithms have been explored, more recently through Deep Learning (DL). [13]

2. METHODS

The following section briefly describes how the audio recordings were obtained, selected, analysed, processed and presented.

2.1 Data acquisition

Data were acquired with a four-cylinder gasoline engine research vehicle on public roads of Neue Gautinger Strasse, Germering, Germany. Audios were provided by researchers at Müller-BBM Active Sound Technology GmbH. All windows were kept closed during the measurements. Eight microphones were strategically placed in the vehicle compartment at the following positions: microphones 1 to 4 were placed on the ceiling of the car in the front left (FL), front right (FR), rear left (RL), and rear right (RR) positions, while microphones 5 to 8 were placed on the inner side of the headrests at the same locations. The sampling frequency was set to 8192 Hz. Each individual operating point was set and measured for approximately 1 minute and 30 seconds.

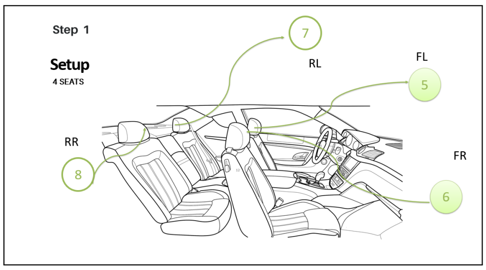

Figure 1. Setup Arrangement. M5-M6: Front seat microphones placed at the inner side of the headrests. M7-M8: Rear seat microphones.

2.2 Auditory Stimuli

From the original dataset, a total of 5 measurements were thoroughly selected for the test. Each driving operating mode was measured under different conditions: the first one reflects a smooth and constant ramp-down during the transition from 3rd to 4th gear. The second was recorded at constant speed while shifting from 3rd to 4th gear, starting at 1300 RPM (revolutions per minute). The third recording represents a smooth and continuous ramp-down in 5th gear. The fourth captures the initial ramp-up phase and, lastly, the fifth corresponds to a gradual ramp-down. All audio recordings were presented to participants in.wav format, through stereo reproduction and with normalized amplitude.

2.2.1 FIR Filters

Finite impulse response (FIR) filters are digital filters that are used to shape the frequency content of audio signals with high precision and stability. Due to their linear phase response, FIR filters keep the original shape of audio signals, which is ideal for applications such as equalization and noise reduction. Traditionally, are widely used in professional audio systems and digital audio workstations to ensure transparent sound processing without introducing phase distortion. FIR filters are also beneficial for loudspeaker correction and room compensation, where accurate control over both magnitude and phase is essential. Authors in [14] validate the effectiveness of FIR filters in modifying the frequency content of the noise signals. [15]

2.2.2 Frequency-based analysis

Power Spectral Density (PSD), also known as the power spectrum, describes how the power of a signal is distributed between different frequencies. It is widely used in signal processing applications because it helps identify dominant frequencies, noise levels, and other important signal characteristics. [16] The normalized cut-off frequency is determined based on the Nyquist theorem, which states that the maximum frequency that can be accurately represented is half the sampling rate. For the purpose of this study, 3 FIR filters were designed using the Hamming windowing method: a low-pass filter of order 800 and two high-pass filters of order 500.

2.3 Questionnaire

2.3.1 Evaluation Method

The pairwise comparison method was selected due to its effectiveness in facilitating listener evaluations by limiting judgments to two stimuli at a time, S1 and S2. This approach improves sensitivity to perceptual variations while minimizing cognitive load and individual bias, thereby increasing the reliability and consistency of the collected data. In contrast to rating scales or direct ranking procedures, pairwise comparisons are particularly well-suited for experiments aiming to establish a robust preference structure and to detect small differences in sound quality with more accuracy. [17] The order in which comparisons are presented has been manually configured based on a specific criterion: ensuring that the two most similar signals were not evaluated consecutively. This deliberate

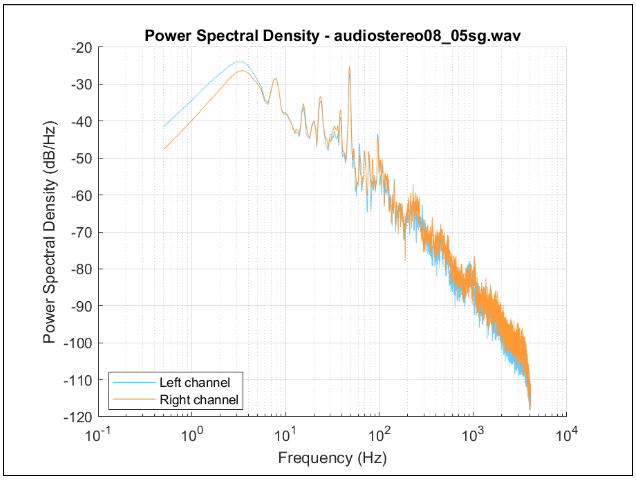

Figure 2. Power Spectral Density (PSD) of signal No. 08, measured at microphones 5 (Front Left) and 6 (Front Right). Driving operation condition: 5th gear, ramp-down. Length: 5 seconds. Sampling rate: 8192Hz.

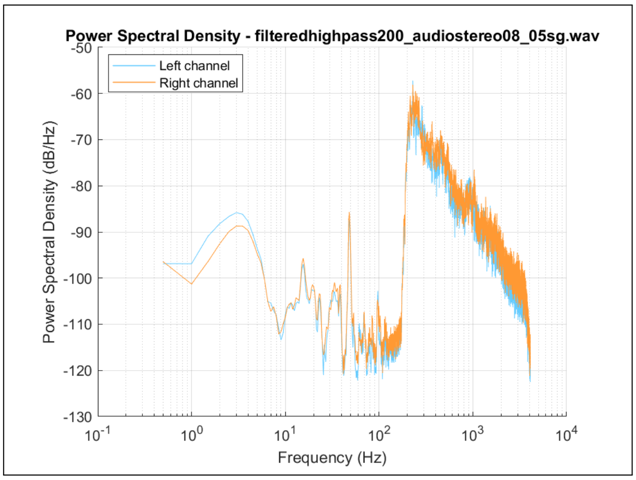

Figure 3. Powerspectral density (PSD) of signal No. 08, measured at microphones 5 (Front Left) and 6 (Front Right). Driving operation condition: 5th gear, ramp-down. Length: 5 seconds. Sampling rate: 8192Hz. Filter: High-pass, Cut-off frequency: 200Hz, Order: 500.

separation prevented potential listener bias and facilitated a more accurate and robust auditory assessment.

2.3.2 Perceptual attributes

According to [17], Pleasantness refers to the overall subjective acceptability or enjoyment of a sound, often influenced by tonal balance, loudness, and the absence of disturbing elements. Power is associated with the perceived strength or intensity of a sound, and is often linked to attributes such as loudness and spectral content that convey a sense of engine performance. Meanwhile, naturality refers to how realistic or lifelike a sound appears and whether it aligns with the listener's expectations based on prior experience with similar auditory events. These attributes were chosen based on the frequency components of the audio samples prepared. For instance, a filtered engine sound that is more pleasant may reduce listener fatigue during driving, while maintaining sufficient power ensures that the vehicle still provides a sense of performance. Additionally, preserving naturality is crucial, as overly artificial-sounding modifications can lead to user dissatisfaction, even if the sound is technically improved. Together, these attributes allow for a holistic evaluation of sound quality that balances subjective enjoyment with perceptual fidelity. [18]

2.4 Experiment

2.4.1 Tools

To avoid external and internal noise sources were perceived by listeners during the playback step, the experiment was carried out in the anechoic room of the GTAC Laboratory at UPV. Due to the low-frequency content of the noise signals, Senheiser HD600 headphones with a frequency response ranging from 12 to 40500 Hz were employed, as well as the M-Audio Track Quad sound card connected to an ASUS laptop.

2.4.2 Process

To ensure consistency, a total of 30 participants (25 Male and 5 Female) with normal hearing abilities were invited to participate in the test. Since 5 audios with different configuration were selected, 5 sets of stimuli were presented consecutively, one set of stimuli per driving mode. First, each jury was explained the step by step of the experiment and was given an example. The software application was then launched, and the subjects were asked to read the disclaimer that describes the task to be completed and their agreement to it. As the test started, volunteers were asked to listen to two signals and rate them according to their perceptual auditory preference. During every comparison, signals S1 and S2 are continuously played until the jurors tick the available checkboxes. The instruction provided to volunteers was: "Between signal one (S1) and signal two (S2), please select the one that you find to be most pleasant/powerful/natural, than the other based on the rating scale provided".

Figure 4. Jury inside the anechoic room, reading the agreement disclaimer prior to beginning the test.

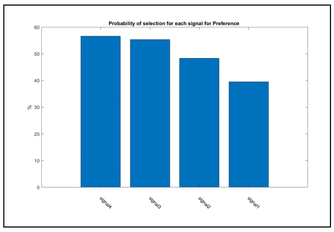

Figure 5. Probability of selection for each signal based on Preference attribute. Signal1 (original audio) was the least preferred, followed by Signal2 (low-pass filtered at 50 Hz). Signal3 and Signal4, processed with high-pass filters (200 Hz and 100 Hz respectively), received the highest preference scores.

3. RESULTS

3.1 Ratings

3.1.1 Preference ratings

The original audio signal, Signal1 received the lowest rating, indicating that it was the least preferred among the 4 available. Signal2, corresponding to the low-pass filtered signal (50 Hz, order 800), also received a negative rating, though less severe than the original, suggesting a slight improvement in perceived preference. Signal3 and Signal4, both processed with high-pass filters, demonstrated a significant increase in preference. Signal3 (high-pass filter at 200 Hz, order 500) achieved a positive rating, while signal4 (high-pass filter at 100 Hz, order 500) received the highest overall score. These results suggest that attenuating lower frequencies and preserving higher frequency content, particularly above 100 Hz, contribute positively to the subjective perception of the signal, making high-pass filtering a promising approach to improving sound quality in this context. Interestingly, this result has revealed that improved perceptual assessments can be obtained through FIR Filtering.

3.2 Acoustic EQ profile

Active Noise Control (ANC) and Active Noise Equalization (ANE) are similar schemes. While ANC focuses on reducing unwanted noise by generating anti-noise signals, ANE aims to shape the sound field to achieve a desired profile. ANE is based on ANC by not only canceling noise, but also enhancing sound quality through spectrum shaping. Relevant publications have focused on shaping the spectral content of engine noise in the vehicle interior cabin. At the same time, they highlight the importance of designing and choosing the suitable filters for the algorithms implemented in this systems. [19], [20], [21] The ultimate goal after obtaining the test results of this subjective test is to use the most pleasant filter as our Shaping filter: $C(z)$ inside the Adpative Noise Equalization algorithm.

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