EXPLORING SONIC FEEDBACK IN A TRUCK DRIVING SIMULATOR

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Abstract

The quiet sound profile of electric trucks can reduce auditory cues related to speed and acceleration, potentially affecting the driver's sense of feedback and control. Therefore, it is relevant to examine whether active sound design can optimize the driver experience. A simulator study was conducted to explore whether adding complex tonal sounds can improve the driving experience and change drivers' sense of feedback, and whether biometric measurements can capture human responses to the sounds. Sixteen participants experienced three different sound treatments during simulated driving. Two treatments provided enhanced sound feedback depending on vehicle speed and accelerator pedal position. Besides biometric measurements, subjective ratings and written comments were collected. Qualitative analyses of the results indicated that enhanced sound feedback can increase perceived sense of feedback and control for some drivers. Approximately half of the participants appeared to appreciate the added sound feedback. Galvanic skin response revealed a significant difference between the treatments and is recommended for further investigations of human response to sound feedback. Although attitudes toward and perceived need for active sound design vary considerably, the demand is still sufficiently pronounced to justify further research.

Keywords: *auditory display, sound feedback, electric heavy vehicle, biometric measurements*

1. Introduction

For first-time users, the quiet sound profile of an electric truck may feel like an improvement, but the lack of sonic feedback risks reducing the sense of control and accessible power [1]. This is an exploratory study in which the perception of sound stimuli was investigated in a simulated driving situation, using subjective inquiries together with biometric measurements. Different sound treatments were presented where complex tones were used to reinforce feedback when applying pressure to the accelerator pedal in a simulator setup. Tonal sounds are one of the properties associated with electric propulsion [2]. By emphasizing such sounds the usefulness of enhanced sound feedback was studied. The results will guide future work and investigations of active sound design [3] for heavy trucks.

1.1. Aim and purpose

The following research questions were addressed:

1. Will adding tones when changing speed improve the driving experience?
2. Can the sense of feedback and control be altered by adding tones when demanding power during driving?
3. Are biometric measurements sensitive enough to detect responses to increased sound feedback?

The hypothesis connected to the first research question was that the majority would show a more positive experience with active sound design. The hypothesis related to the second question was that enhanced dynamic sounding sequences would increase the perception of control of the driving situation. The hypothesis connected to the third question was that we would see different physiological responses for different sound treatments.

1.2. Background

In a systematic review of the auditory experience of vehicles Song et al. [4] identified several articles investigating characteristics of the electric vehicles. They state that the driving experience depends on user-machine interaction during task execution, where sound is an important factor. They call for further methodological development to identify emotions elicited by electric vehicle-specific sounds and

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to establish links between acoustics, psychoacoustics and emotional responses. Lanslots et al. [5] evaluated sound quality based on preference of recordings of acceleration from 0-50 km/h in an electric vehicle for four different sound concepts. They promote psychoacoustic metrics to find parameters usable for adjusting a listening test.

The perception and impact of sound are commonly measured using listening tests in a laboratory setting [1], [6]. The evaluation is typically done *after* the listening is performed. But it can also be done in real time [7], [8]. Sensors measuring biometric responses give the possibility to monitor reactions in real time without interfering with the driving task. The use of biometric measurements can give useful insights of human responses to sensory stimuli [9]. Facial muscle movements signal different kinds of emotions [9], [10], [11]. Measuring eye movements [12], [13], [14], [15] can give insight into internal state such as stress and cognitive load. Galvanic skin response (GSR) measurements capture physiological responses to external stimuli through micro sweating [16], [17], [18]. This metric can also give a hint of emotional reactions to sound [16]. Heart rate and heart rate variability (HRV) [19] signals effects of mental stress and workload [8].

Studies covering evaluation of sound feedback in electric vehicles during driving are uncommon. The use of biometric measurements to assess sound impact is even less common.

2. Material and Methods

2.1. Design of experiment

This experiment used a repeated measures design to assess sound perception across three different sound treatments in a truck driving simulator. Both quantitative and qualitative data were collected during the tests. After the driving session, the participants were asked "What treatment did you prefer?", and "Why?". Kahneman[20] and Västfjäll [21] claim that in retrospective sensory judgments the peak and end of the experience determine the outcome. Retrospective judgment of an experience seems to follow the same pattern, regardless of modality. Based on these findings the peak and last minute of the test rounds were of special interest.

2.2. Participants

Recruitment was conducted through an informative email distributed to the department, inviting voluntary participants, as well as through direct contact. 16 participants (8 female and 8 male) with self-reported normal hearing participated in the test. One male participant was excluded because of slow driving style, never engaging the extra sound applied and therefore not applicable to the test. The average age of the remaining 15 participants was 38.9 ($\sigma = 9.8$) years. 82% had experience of driving electric vehicles. All participants were employed by, or students at Luleå University of Technology in Sweden.

2.3. Equipment

For this experiment a desktop driving simulator was built using the game audio middleware FMOD Studio v2.02.27 and the game engine Unreal Engine v5.3.2. The driving simulator consisted of a desktop steering station with a wide screen connected to a game steering wheel and pedals (Logitech), see Figure 1. The participants listened to the sound via headphones (Sennheiser HD 650).

Figure 1: The test setup. A desktop driving simulator with sound presented via headphones.

Biometric measurements were collected via the software iMotions v10.1.0.12 on a separate computer. A camera mounted above the screen recorded the participants' facial responses, while Shimmer3 EXG and GSR sensors measured heart rate and GSR. Tobii Glasses (3 RU), equipped with dual cameras, captured eye movements and pupil size, along with an outward facing camera that synchronized gaze data with the visual screen. An additional camera recorded the screen from behind the participant. The simulator's sound output was recorded in real time to enable alignment between auditory events and physiological reactions. The biometric data were analysed using iMotions v10.1.0.16 and MATLAB.

2.4. Testing procedure

After signing the consent form and completing the demographic questionnaire on age, gender, self-rated hearing, and experience of electric vehicles and computer gaming driving as well as participation in simulator driving studies, participants were fitted with sensors and eye-tracking glasses and seated at the desktop simulator. Before starting the test, participants were given a few minutes to familiarize themselves with the driving situation, without any sound applied. During the test they drove the simulator with three different sound treatments (A, B, and C) for five minutes each. These were presented in a pseudo-randomized order, following a Latin square sequence, to avoid order effects. After each driving round, they were asked to fill out a questionnaire evaluating the specific sound treatment. Following the complete test drive, the test leader conducted a short interview about sound treatment preferences. The test lasted one hour.

2.5. Dependent variables

2.5.1. Subjective variables

After each five-minute driving round the participants evaluated their experience of the sound treatment according to the following aspects: Acceptance was evaluated following the method proposed by Van der Laan et al. [22]. Sound quality was assessed using a 10-point rating scale, where 10 corresponded to "excellent" and 1 to "unacceptable". The properties "Powerful", "Congruent"[1], "Natural", "Expected", "Suitable at acceleration / braking / constant speed" was evaluated using a 7-point scale, where 1 corresponded to "not at all" and 7 to "extremely". The emotional ratings of valence, arousal and dominance were assessed using the method based on self-assessment manikins [23]. The scale dimensions were described using the terms happiness, vigilance, and control. To capture thoughts and attitudes of the participants, written comments were also collected.

2.5.2. Physiological and physical variables

During the driving rounds, the following responses were measured: pupil size, number of blinking, number/duration of fixations, number/duration of saccades, heart rate, HRV, and GSR. Facial expression video recordings were also made to analyse emotional reactions.

2.6. Stimuli

The test stimuli consisted of a sound bank implemented in the game audio middleware FMOD, based on stationary recordings made inside an electric truck. The parameters "Load" and "Speed" controlled the sounds. "Load" corresponded to the position of the accelerator pedal. "Speed" corresponded to the velocity of the simulated vehicle. Extra sound layers were added to two of the treatments. Three different sound treatments[2] were presented to the participants:

A Based on original recorded sounds

B Treatment A + added sub-tones

C Treatment A + added down-pitched cello tones

Treatment A consisted of a selection of stationary recorded sounds from an electric truck with different load cases (about 3-5, depending on gear, evenly distributed from low to high) and engine speeds (250-4000 rpm). In addition, gear change and start up sounds were recorded and added. The measurements were conducted on a dynamometer (rolling road), with microphones placed in the cabin at ear positions. Wind noise recordings were done separately in a still standing truck using a wind tunnel. Using the function pitch automation in FMOD, the stationary pitch of the recorded files were adjusted by ear to achieve pitch continuity, to ensure seamless transition between sound assets. These presets then followed the predefined traces in real time during driving, triggered by the pedal input (load). The objective of the sound design was to create a fictive truck sound that was convincing to experienced drivers while also eliciting a response.

Treatment B was based on Treatment A, but included a complex two frequency tone with -6 dB/octave amplitude relation. Inspired by Gwak et al. [24], who investigated adding sub tones with a musical interval to a specific order, the interval between the sub-tones were 1/5 and 1/3 in relation to the frequencies 350 Hz, 950 Hz, and 1750 Hz. These were manually adjusted in pitch to follow the speed. The purpose with the active sound design was to to mimic and enhance the character of the mechanically generated sound from an electric truck using clear tonal sounds, but with a low frequency character.

Treatment C was based on treatment A with added cello sounds. The cello sounds consisted of bow-played open string recordings, corresponding to the musical notes C, G, and D. These recordings were lowered an octave and then pitch adjusted to follow speed and aligned to match the adjacent cello-sound asset. The aim of using the string generated sounds was to add complex tonal sounds, and at the same time create a clearly different character compared to Treatment B, Creating an eventful and exploratory tonal sound. A result of the octave pitch lowering in FMOD in combination with the bow on a string generated sound (stick-slip) created an unintended two-stroke engine like sound.

2.6.1. Statistics and thematic analysis

Repeated-measures ANOVA and post hoc Tukey adjusted t-test were applied using the statistical software R v4.5.1.

A thematic analysis [25] was applied to the written comments, allowing themes and conclusions of the different sound treatments to be identified. Copilot[3] was used to produce a conclusive summary of the conclusions using the prompt: "Write a narrative summary of the text with letters within parenthesis as base", referring to (A/B/C) which denoted the respective sound treatments. The interview transcriptions were categorized into positive and negative statements about sound preference. Copilot was prompted to "write a technical summary of the content". All AI-generated outputs were reviewed by the author, comparing the input to the output to ensure that they accurately reflected the input material.

[1] This word was explained as consistent or harmonized.

[2] Listening and video examples are available at: https://doi.org/10.5281/zenodo.19186606.

[3] Copilot is an AI-powered digital assistant integrated directly into Microsoft 365 apps.

3. Results

3.1. Subjective ratings

Acceptance is composed of two dimensions: satisfaction and usefulness [22]. The results indicate that neither satisfaction nor usefulness was significantly affected by the different sound treatments. Sound quality ratings were not significantly affected by the different sound treatments. Although, the inter-quartile range is smaller for Treatment A compared to the other treatments, see Figure 2.

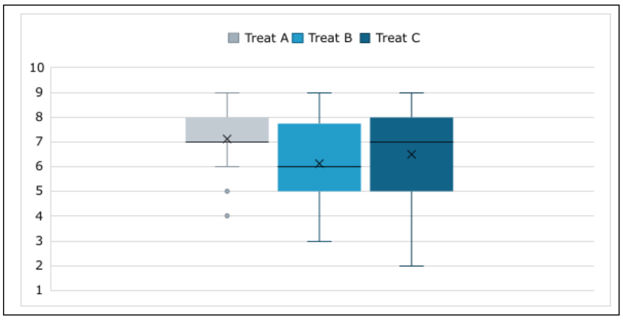

Figure 2: Box plot of rating of sound quality

The evaluation of the sound properties shows that there are no significant effects of the different sound treatments for any of the properties. Nor does the rating of emotional feelings show any significant effects.

3.2. Observable measurements

The analysis of eye movement data did not result in any significant effects. The observations of facial expression were connected to driving skill and not perception of sound. All but one participant maintained a neutral face in response to the sound. One participant started smiling when hearing Treatment C because he thought the sound was funny.

3.3. Physiological measurements

The skin conductance was evaluated using the normalized accumulated values according to Nourbakhsh et al. [17] for the whole measurements session (five minutes driving) as well as the last minute. The last minute evaluation indicated that there was a difference, $F(2, 26) = 3,30$, $p = 0.053$, $\eta^2 = 0,16$. A post hoc contrast analysis using the Tukey method gave significantly higher results comparing Treatment C to Treatment A, $p = 0.045$.

The evaluation of heart rate and HRV measurements [19] showed no significant results.

3.4. Qualitative results

From the written comments, four themes of importance were derived, see Table 1.

The interview-based sound preference analysis showed that 60% of the participants preferred enhanced sound feedback. Within this subgroup, 40% (6 participants) chose Treatment B or C, whereas 20% (3 participants) preferred the possibility to switch between Treatment A and B or C during driving. See Figure 3. The participants were asked to motivate their preferred choice of treatment. This resulted in important information about underlying aspects of preference.

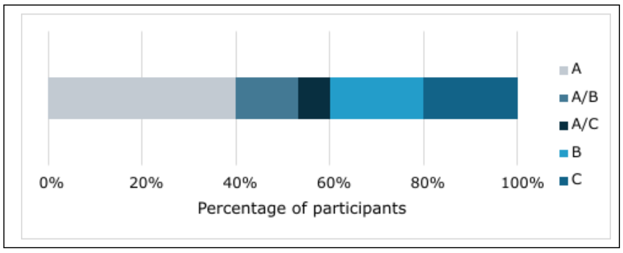

Figure 3: Resulting outcome in percentage of the question of sound treatment preference to the 15 included test participants.

3.4.1. Summary of positive comments

A The sound profile offered a modern and luxurious feel. It provided clear feedback through proportional acceleration sound and wind noise cues for speed, enhancing both comfort and driver awareness.

B The feedback provided when pressing the gas and brake pedals felt natural and realistic. It accurately reflected driving activity and made the experience easier and more intuitive with the added sound feedback.

C The sound experience was generally adequate and aligned with driving actions, with clear distinction of engine sound. It provided good feedback when using gas and brake pedals and felt brisker compared to other sound treatments. Acceleration feedback was as expected, some aspects felt unnatural though. Adding what was perceived as motor sounds improved speed perception and created the desire to drive faster.

A/B The participants would like the option to switch between A and B to stay alert.

A/C The participant thinks that Treatment C works best for short distances and Treatment A for long distances.

3.4.2. Summary of negative comments

A The vehicle lacks sufficient auditory feedback, making the driving experience feel too quiet and uneventful. Drivers lose the sense of speed and connection, especially during acceleration. Wind noise is excessive and masks engine sounds. There is a strong desire for clearer, more engaging sound feedback when pressing the gas pedal, to confirm that the vehicle is running and responsive.

B The sound was perceived as dull and not engaging, described as spacey and monotonous over time. It induced sleepiness, became irritating, and lacked responsive feedback during acceleration.

C The sound was perceived as unsuitable for an electric vehicle. It was described as annoying, stressful, and overly alerting — more appropriate for a game than real life. While initially amusing, it became irritating and artificial over time. Users disliked the fake combustion engine sound, noting that the vibrations did not match the audio, making the experience feel unnatural.

Table 1: Thematic analysis of comments in questionary. Themes of importance.

Feedback	Vigilance	Realism	Sound Quality
A: Missing feedback. Low volume, vague impression.	A: Associated with both positive (pleasant, calming) and negative (boring, sleep inducing) feelings.	A: Feels natural and realistic with a distinct electric sound.	A: Strong positive impression; aligns with quality expectations
B: Info available about speed.	B: Has the widest range, including positive (pleasant, relaxing) and negative (stressful, annoying).	B: Comes across as natural yet weird, UFO-like, and not truck-like.	B: Significant weaknesses; needs major refinement
C: Info available about power, sense of control.	C: Is linked to stimulating or irritating effects (alerting, exciting, annoying).	C: Appears natural and realistic with some familiarity but still feels odd and not truck-like.	C: Comfort present but offset by artificiality and poor quality

A/B Wind intensity exceeded acceptable levels in both experimental treatments (A and B).

4. Discussion

Overall, the results indicate that enhanced feedback can be an important factor for user preference and that some users appreciate the increased feedback provided. However, this effect appears to apply only to a subset of the drivers. In this case, this applied to 60% of the participants. Therefore, the recommendation is to offer enhanced sound feedback in vehicles as an optional and customizable feature. Furthermore, the qualitative analysis of the participants' written comments indicated that users were able to better understand speed, perceived more feedback, and experienced a higher sense of control when enhanced sound feedback was used, compared to the original interior sound based solely on original electric truck recordings. These findings do not support the first hypothesis that a majority will show a more positive experience with active sound design but they support the second stated hypothesis that enhanced sound feedback using tones can increase the sense of control.

The study also investigated whether biometric measurements are sensitive enough to detect the impact of increased sound feedback on the drivers when using tonal signals. In total, the results showed no general or significant differences between the different treatments, suggesting that these measurements have limited usefulness when assessing the user experience for this type of sound. One exception was GSR, which showed a significant difference for the last minute of the driving sessions. A recommendation is therefore to further investigate the potential of this measurement method and how its results should be interpreted in order to better understand how users are affected. One challenge with GSR is that it reflects activity in the sympathetic nervous system, which is associated with arousal, making it difficult to determine whether an observed effect is due to stimulation from the sound itself or the emotional experience that arises when the level of feedback or sense of control changes. Thus, the measurement method likely needs to be complemented with other methods to provide a more comprehensive understanding of drivers' experiences.

4.1. Limitations

The test group consisted of employees and students at Luleå University of Technology, and few had previous experience of truck driving. The simulator used was a desktop setup featuring a passenger car driving scenario on racing track, although the car's exterior body was not displayed and the weight of the car was altered to mimic a truck. Increasing the realism of the context by using a truck driving simulator, with digital mirrors and correctly responding inertial motion, might yield different results. Using experienced truck drivers could further influence the outcomes. The sound treatments were deliberately chosen to provoke a response and to be clearly distinguishable. The design of the added sounds can, in many ways, be refined and tuned to better blend with the original sound environment and thereby gain increased acceptance.

5. Conclusion

The results of the study suggest that the driving experience, as well as the sense of feedback, can be altered by adding complex tonal sounds during speed changes in electric trucks. GSR indicated an impact of sound and should be studied further. Attitudes toward, and perceived need for, active sound design are divided among the participants. However, the demand is sufficiently pronounced to merit further investigations.

6. Acknowledgments

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6.1. Ethical declaration

This study was approved by the Swedish ethics review authority "Etikprövningsmyndigheten" in 2025, approval number 2025-02732-01.

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