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Experimental Case Study of Sonic Perception of a First-Generation Electric Truck

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Abstract

The sound generated by electric propulsion systems differs compared to the prevalent sound generated by combustion engines. By exposing listeners to various sound situations, the manufacturer can start understanding which direction to take to achieve compelling battery electric vehicle trucks from a sound perspective.

The main objective of this study is to understand what underlying aspects decide the experience and perception of heavy vehicle–related sounds in the context of electrified propulsion. Using a thematic analysis of data collected at a listening experiment conducted in 2020, factors affecting the perception of novel sounds generated by a first-generation electric truck are investigated. A hypothesis is that the experience of driving or being a passenger in electric trucks will affect the rating and response differently compared to listeners not yet experienced with this sound.

The results show that the combination of individual preference and experience, hearing function, acoustic content, time variation, signal stability, load-dependent feedback, and situation-equivalent sounds affect the outcome. The assessment and rating of quality and acceptance did not differ between battery electric truck experienced listeners and first-time listeners in general. The only driving condition clearly breaking this pattern was the auxiliary brake condition, which, besides being significantly higher rated by novel listeners, also stood out as the highest-rated and most positively commented driving operation overall.

In conclusion, several combined factors affect the assessment of electric truck sounds. Three identified aspects are removing disturbing sounds, making the sound environment smooth and silent, and providing clear functional feedback. Memory of the contextual experience is a key factor when assessing sounds from driving operations. The expected difference between listeners with and without experience with electric truck sounds will be minor unless there is exceptionally high sound quality.

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Introduction

In 2020, Scania did an extensive listening test on a first-generation battery electric truck (BEVt) to obtain reactions and evaluations of the new sounds during different driving operations. The purpose was multifaceted: finding the need for improvement, exploring the general perception of the new sounds, investigating expectations, and assessing the degree of acceptance. The test took place at a breakpoint, right at the introduction of producing electrified trucks. The sounds were still novel for most people working in the R&D department at Scania. Therefore, these data are an informative source of attitudes and expectations of vehicle sounds during an ongoing change related to driver environment. As a follow up, a renewed analysis was made of the data to investigate the qualitative outcome: What affected the experience of early explorations of sounds from an electric truck?

Previous attempts to investigate the perception of the sounds produced by electrified vehicles have had different approaches. The experience of quality related to the frequency balance of the tonal content was investigated by Lennström et al. [1] using acceleration driving conditions based on electric passenger cars. Decreasing high-frequency components and increasing mid-frequency components gave high ratings on overall satisfaction. They also investigated the influence of the test environment but found no significant difference in mean ratings between the laboratory and in-vehicle environments. However, they saw differences in the variances between the group that did the in-vehicle test first and the laboratory test after, compared to those who did the tests in the reverse order. Previous factual experiences of the sound situation gave more precise answers.

Driving a vehicle with electrified propulsion for the first time is a very different experience than driving a vehicle with a combustion engine [1, 2]. Münder and Carbon [2] conducted a listening test focused on the drivers' perception of overall quality and satisfaction to study the holistic impression of sounds generated by an electric driveline during dynamic driving operations. Four different driving scenarios were recorded in 11 different vehicles. The recordings were presented to the participants in a simulator. Two variables were investigated: how strongly the target signal (meaning the driveline) was perceived through the background sound and the overall quality of the impression. Strong perceived salience correlated with low perceived quality. Qualitative feedback from post-interviews revealed acceptance, and sometimes even preference, for load-dependent noise differences. The authors claim that auditory evaluation is individual and linked to memory associations and experiences. The ecological validity of psychoacoustic tests validating objective metrics is questionable, as they may fail to account for the complexity of real-life contextual experiences. On the other hand, real-life measurements lack replicability. The holistic experience, including the physical, emotional, cognitive, and contextual levels, is emphasized as a contributor to the sense of satisfaction, where the vibro-acoustical part is vital. Focusing on the new soundscape, Münder and Carbon investigated associations derived from the electric power train and its impact on the perceived overall product quality. The psychological aspects are considered extra important when discussing the building blocks for acoustic quality. According to Münder and Carbon, they "include affective, cognitive, and situational factors" [2].

Münder and Carbon [3] have neatly compiled the most recent research published about the perception of electrified vehicles, covering the years 2000–2020. In total, 53 articles were reviewed. They concluded that sounds generated by electric vehicles are still novel and need further investigation to guide the development and target setting. The authors request innovative study methods, such as semantic investigations and exploring associations evoked by the sounds perceived in electric vehicles. Therefore, an analysis of an explorative study on BEVt presented in this article is of significant interest. Also, very few studies have been conducted on electrified trucks, and most future truck customers still belong to the category of inexperienced listeners when it comes to electrified vehicles.

The main objective of this study is to understand, from a holistic point of view, what underlying aspects decide the experience and perception of dynamic heavy vehicle–related sounds in the context of electrified propulsion. The second objective is to investigate whether the experience of driving this kind of vehicle affects the outcome.

The Listening Experiment

Participants

In total, 52 participants (47 men and 5 women) from Scania's R&D department took part in the test. All but one reported normal self-estimated hearing. Participation was voluntary. The ages of the participants were not collected. Figure 1 shows the distribution of experience.

The Sounds and the Test Vehicle

The test vehicle was a first-generation Scania truck BEV 25 P with a P17N cabin and a wheel configuration 4 × 2 with Michelin 315/70/R22.5 tires. It weighed 29 tons and had a continuous engine power of max 230 kW.

The stimuli were different driving conditions recorded in the test vehicle on the Scania test track in Södertälje. The sound sequences were 10–30 s long, depending on the driving operation. Spectrograms for the different driving conditions are presented in Figures 2(a), 2(b), 2(c), 2(d), 2(e), and 2(f).

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FIGURE 1 The participants' experience of driving and listening.

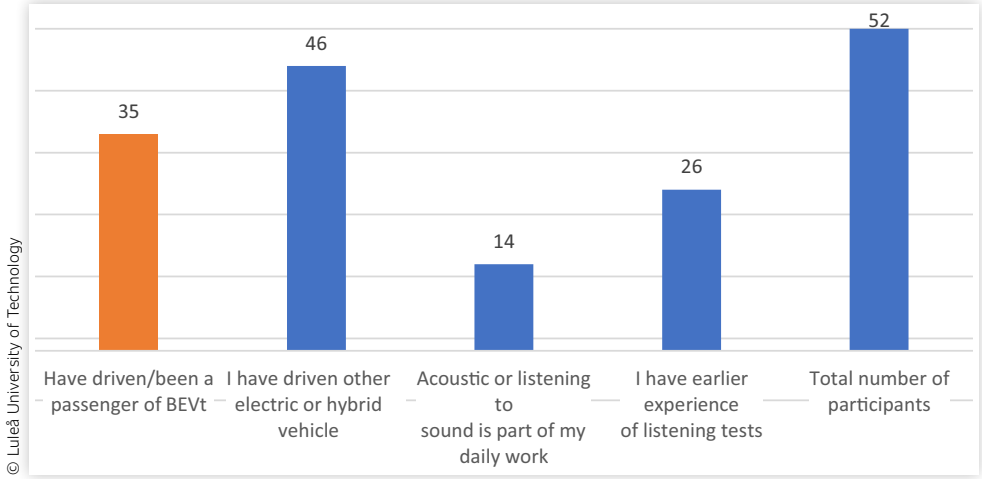

FIGURE 2(a) Spectrogram of driving condition 1. Start-up sequence. Start up the system by turning the key and then wait. The start-up sequence included noise from turning the key, followed by electric sounds ending in a constant salient tonal sound that continues throughout the sequence.

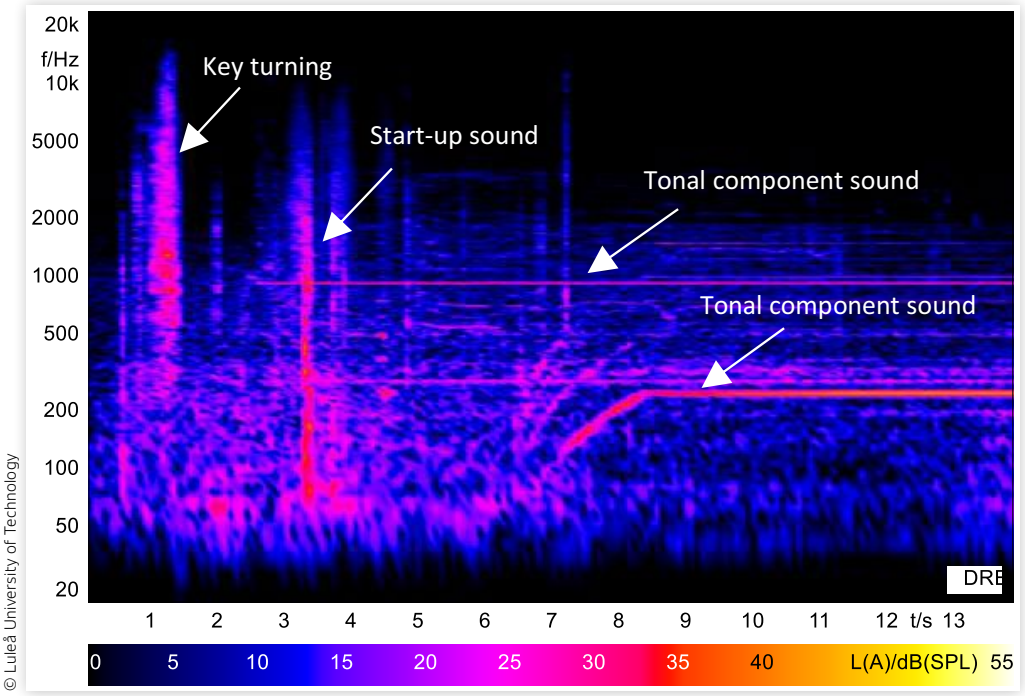

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FIGURE 2(b) Spectrogram of driving condition 2. Full acceleration from standstill to maximum speed. This sound is highly dynamic and changes with increasing speed. The wind increases with speed.

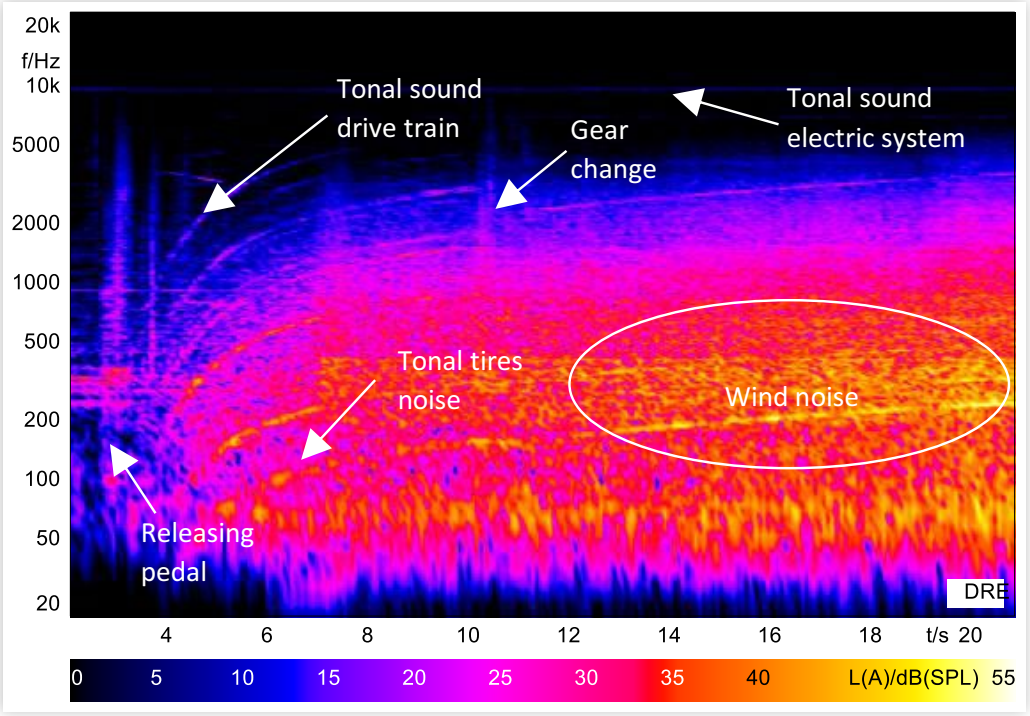

FIGURE 2(c) Spectrogram of driving condition 3. Constant speed at 80 km/h.

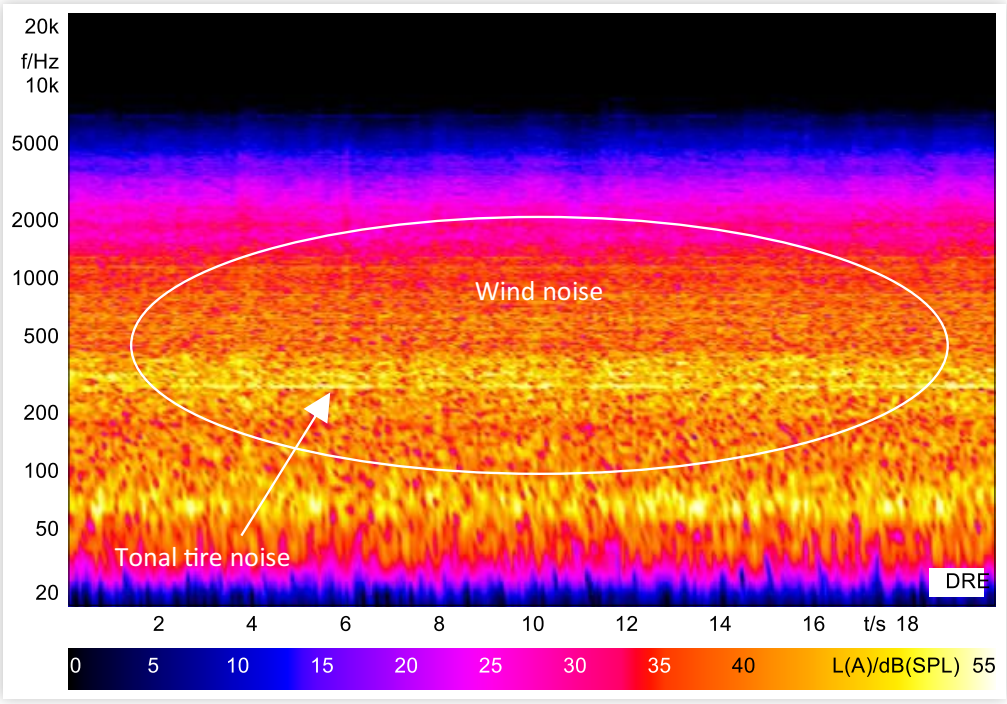

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FIGURE 2(d) Spectrogram of driving condition 4. Auxiliary brake. From 80 km/h speed, the driver engages the lever, activating the regenerative engine brake, and the vehicle slows down accordingly.

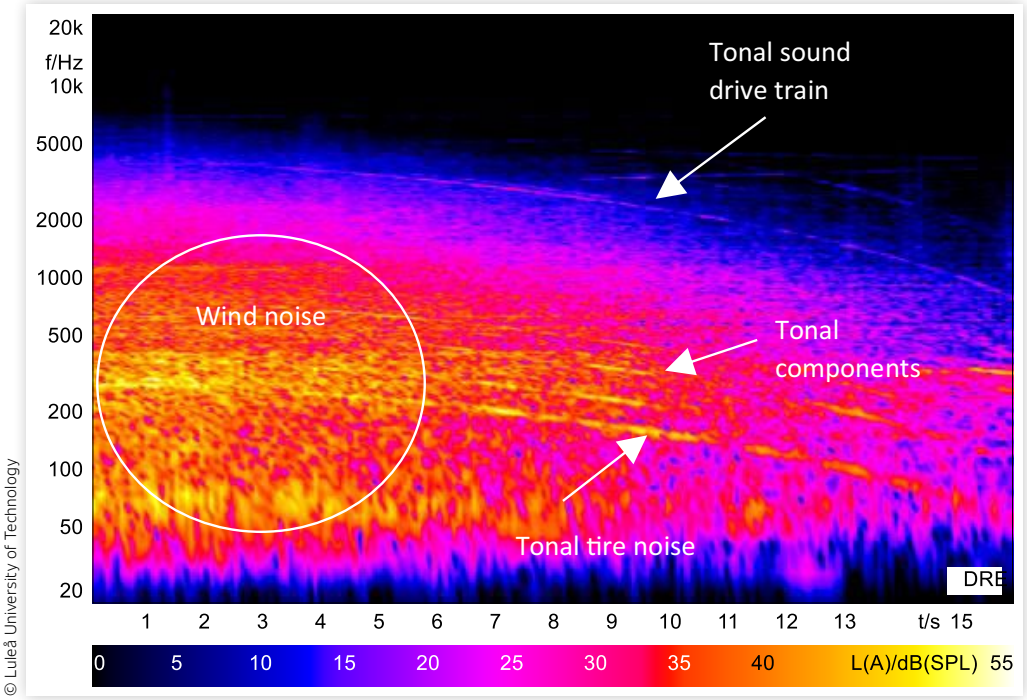

FIGURE 2(e) Spectrogram of driving condition 5. Full acceleration uphill. From standstill, the vehicle accelerates full throttle up a hill with a 16% inclination. Therefore, the sound starts with a short acceleration sequence, ending at a constant speed of 30 km/h up the rest of the hill.

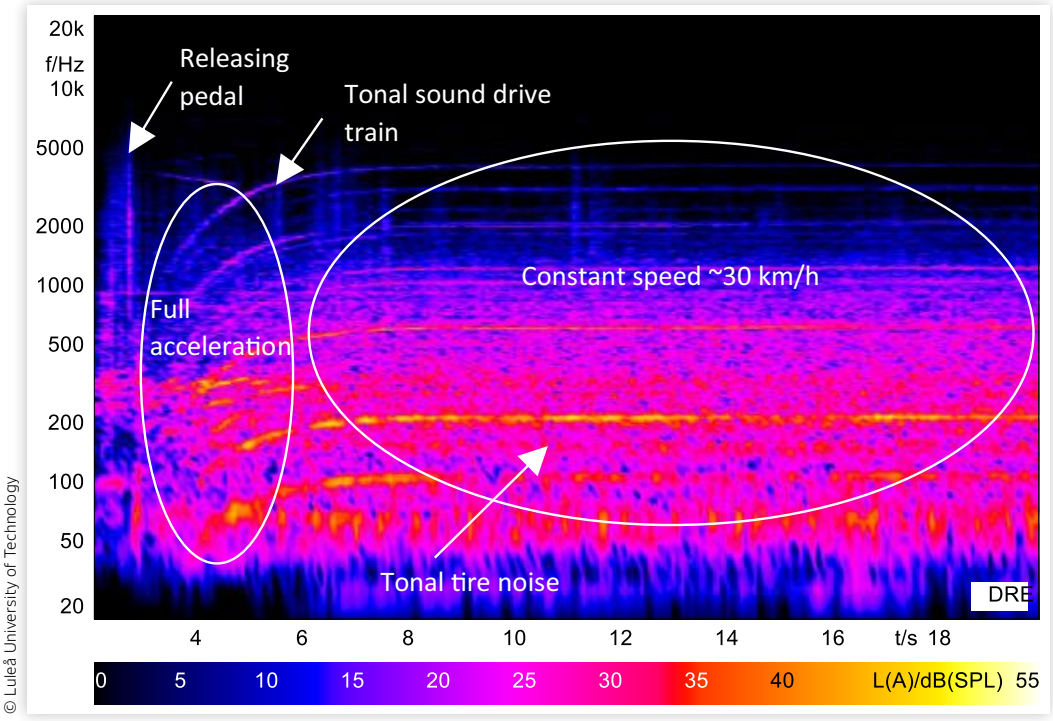

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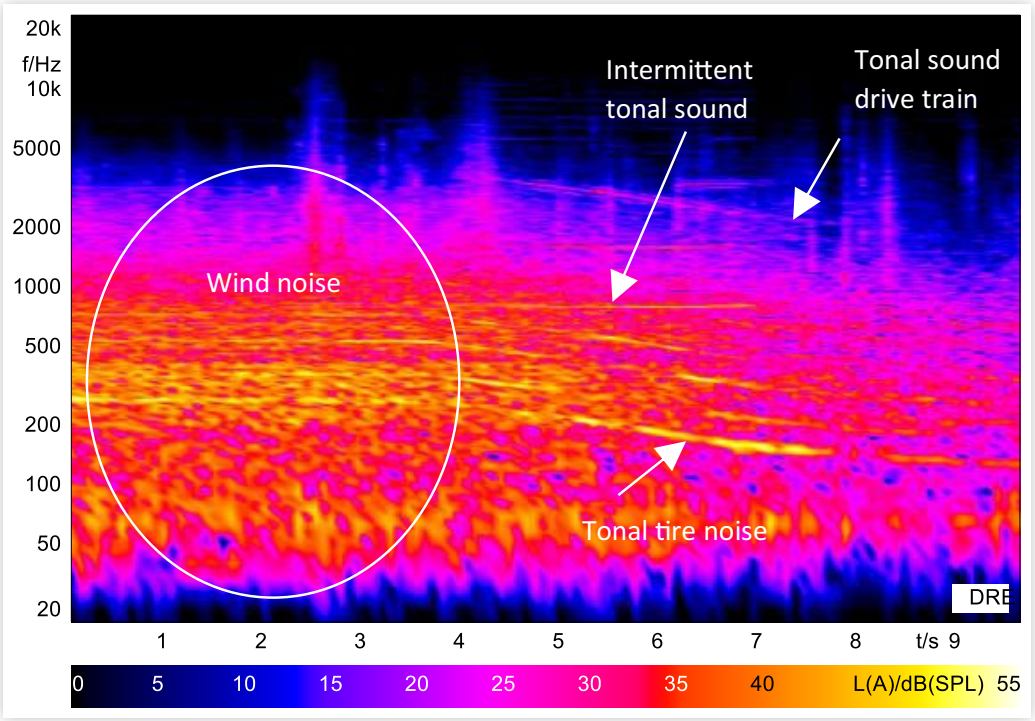
FIGURE 2(f) Spectrogram of driving condition 6. Pedal brake. From high speed, 80 km/h, the driver brakes with the pedal until reaching 40 km/h constant speed.



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The recordings were made in the cabin, according to ISO 5128 [4] using the two microphone positions at the driver's right and passenger's left ear for replay via speakers. The sound files were analyzed and edited with HEAD acoustics Artemis v11.0 software, high-pass-filtered (HP 40 Hz), and exported to wave format (48 kHz, 24 bit) for playback.

Procedure

The listening test was performed group-wise in the Listening Studio at the Scania Technical Center in Södertälje (see Figure 3). Due to Corona restrictions, only three participants could do the test simultaneously. The sound was presented through a speaker system configured from stereo to 5.1 surround sound with TC Electronic Unwrap HD.

The participants were informed that the context in the studio differed from the cabin and were encouraged to imagine driving a truck when listening. The same test leader led all the tests, which took approximately 40 min each. The different sound files were presented as a storyline to give a sense of actual driving (start-up, acceleration from a standstill, etc.).

The overall volume in the listening room was set to give a natural sound experience. Because of difficulties to reproduce the low-frequency content in a realistic manner and to increase the dynamic range for higher frequencies, the frequencies under 40 Hz were strongly attenuated. This resulted in a 7–8 dBA lower overall level compared to the level recorded in the truck cabin. The sound pressure levels above 40 Hz were similar to the levels in the truck cabin. A 7.1 loudspeaker setup was used. The three front speakers were used as main speakers. The rear speakers were adjusted to the same level as the surround speakers to give audible support to the participants sitting in the rear seats.

FIGURE 3 The listening studio at Scania Technical Center in Södertälje.

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FIGURE 4 The evaluation scale was used for the sound quality estimation in the test.

Judgment									
1	2	3	4	5	6	7	8	9	10
Unacceptable	Very poor	Poor	Insufficient	Unsatisfactory	Acceptable	Fair	Good	Very good	Excellent

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Dependent Variables

Dependent variables in the test were rating of sound quality, see Figure 4, and semantic differentials [5]. The later were used for sound profiling of the total impression and acceptance evaluation of the different driving operations [6].

The acceptance of the sounds was assessed in two dimensions, "satisfaction" and "usefulness," as seen in Figure 8(a) and 8(b), which were derived from nine different semantic differentials. Four of the semantic differentials respond to attributes related to satisfaction and the rest to usefulness. Van der Laan [6] uses a five-alternative rating scale (ranging from –2 to 2). This listening test used a modified scale with seven alternatives (corresponding to the values –3, –2, –1, 0, 1, 2, 3) instead; see Figure 5.

The study also included qualitative data collection representing:

- Expectations of the sound before the listening test.
- Free notation of impressions during the test.
- Future requirements after performing the listening test.

No specific result can be traced back to any participant, as all answers were anonymous. The data has been re-analyzed and used for publication with Scania CV AB's consent.

Method and Analysis for This Study

The method used for the analysis is an inductive thematic analysis, which is a descriptive method to generate codes and themes that describe the content of the data [7]. The strategy for generating the themes is data-driven to seek the pros and cons of sounds generated by an electrified truck within the context of driving it. The different steps in the analysis are described in Figure 6.

The following analyses were made:

- Thematic analysis of the qualitative data extracted from the two questions about expected and required sounds before and after the test.
- Thematic analysis in combination with the usability and quality estimation for the different driving conditions.
- Thematic analysis combined with the total assessment's profiling and quality estimation.

Results

Expectations

From the derived thematic analysis and the identified themes presented in Table 1, the participants expected

FIGURE 5 An example of one of the semantic differentials used in the test with a seven-alternative scale. The participants were presented with a "blind" scale without numbers, with a neutral middle rating.

Pleasant	o	o	o	o	o	o	o	Unpleasant

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FIGURE 6 The steps in the thematic analysis.

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TABLE 1 Thematic analysis of the qualitative data from the question: "Describe how you imagine what an electric truck sounds like."

Themes	Subcategories	Character	Example of statements
Relate to another sound source	An animal Toy car Passenger car Sewing machine Commuter train Home appliance Not as an internal combustion engine (ICE)	Tonal High frequency Following speed	*"Generally quieter but whining high frequency. As an insect instead of a roaring lion."* *"As a sewing machine. The sound will be more connected to speed than acceleration."*
Futuristic		Swift Fast	
Powerful		Clean Not too loud	
Silence as a positive feature	Tonal Buzzing Deep humming Load-dependent Speed-dependent	Muffled Smooth Soft Faint Low level	"Buzzing and tonal sound, but at very low levels." "Silent, but with some tonal sounds at high load."
Silence as a negative feature	Tonal Disturbing	High pitch Whining Constant frequency Coming and going Other sources than the power train	"Quiet, but with a transmission sound and other sounds that are disturbing (heard more)."
Silence as a neutral feature	No sound compared to ICE	Quiet	"I imagine it to be very silent and smooth compared to one with ICE."
Consistent			"One sound. Not 27 different."

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that the sounds would be soft and smooth but tonal, leaning toward high pitch, emphasizing silence, and not too loud. Clean and powerful are other attributes mentioned. A few participants expressed an expectation of disturbing or unpleasant high-pitched sounds. Some participants related the expected sound to another sound source, such as a commuter train or a sewing machine. These are sources characterized by high-frequency tonal components that alter with speed. Most people who related to other sound sources had experience driving a BEVt.

Driving Operations

As shown in Figure 7, the quality assessment for the different driving operations was similar, ending up at an average value of 7–8. The result means that the participants assessed the sounds presented to be somewhere between fair and good, which reflects a generally positive reception, with room for improvement, as the comments reveal.

Start-Up Sequence As shown in Table 2, the participants found this sound unpleasant and indeterminate. A monotone tonal character contributed to annoyance as well as confusion. When was the vehicle ready to go? The expected "clear to go" message, starting up the vehicle, never came.

No trends are seen in the acceptance evaluation, which points to diverse meanings of this sound.

Full Acceleration Function-connected feedback from the driveline accelerating was highly appreciated, but opinions about the tonal character were dispersed, as seen in Table 3. A third of the participants thought the high-pitched tones were annoying, but the sound was rated as acceptable overall. However, the impression was that the driveline lacked power and did not communicate the brand it represents. At higher speeds, the wind noise was dominant and disturbing.

The acceptance assessment showed that the majority found this sound useful, but a third were unsatisfied. One of the novice listeners wrote, "The whining is good that it rises with RPM. You understand that the electric

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FIGURE 7 Boxplot of the quality assessment for different driving operations. The black staples represent participants who have driven or been passengers in a BEVt before. The gray staples represent those who have not. The box represents the middle 50% of the data. Each whisker extends to the furthest data point in each wing, within 1.5 times the interquartile range (Q1–Q3). Any data outside this range is an outlier, marked as a ring. The cross indicates the average value, and the line indicates the median.

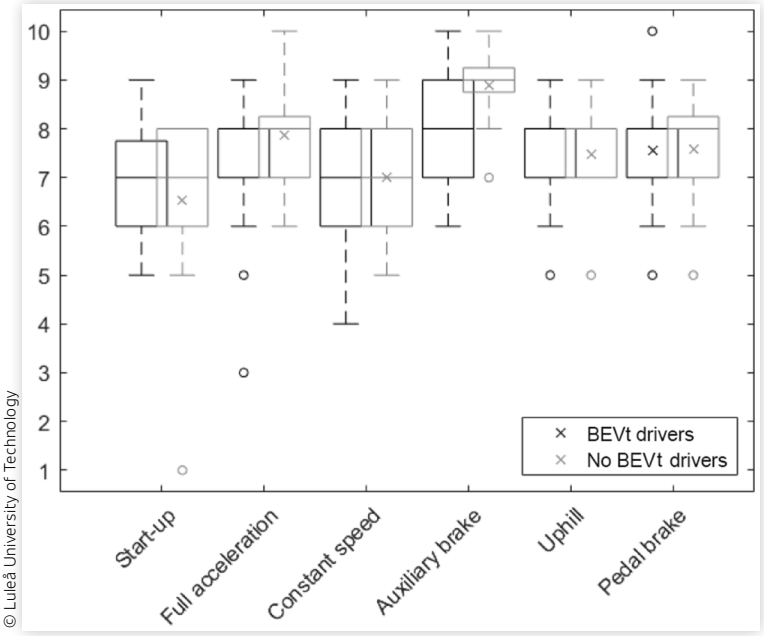

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TABLE 2 Thematic analysis of qualitative data from the free comment field of the start-up sequence.

Themes	Subcategories	Character	Example of statements
Necessary	Bearable Unpleasant Annoying	Too loud Tonal Monotone	"*Something to get used to. Bearable.*" "*Good that you hear something, so that you know that the vehicle has started. The sound is annoying though.*"
Tonal	Confusing Intrusive Annoying Disturbing	Whining Dull Tiring Constant	"*Would like a more distinct notification that the vehicle is ready to go.*"
Not important			"No special sound that I react to starting the vehicle. Have other things to think about. Not disturbing"

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TABLE 3 Thematic analysis of qualitative data from the free comment field of the full acceleration sequence.

Themes	Subcategories	Character	Example of statements
Disturbing noise—low speed	Tonal	Howling Whistling High pitch	"*Very high-pitched sound increasing in frequency, unpleasant. It is ok when the wind takes over.*"
Disturbing noise—high speed	Wind noise	Loud Dominant	"*At high speed becomes the road and wind noise dominant and very distinct/disturbing.*"
Effective functional feedback	Tonal	Nice Even Annoying	"*Soft and nice with even rise. Tonal.*" "*Generally quiet. The wind sound gives a positive feeling that the truck is moving fast. High tone noise is a little bit annoying but overall good.*"
Lack of functional feedback	No power Disconnection	Silent	"*The character of the sound is not really connected to the function. Want a clearer and more powerful sound.*"

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TABLE 4 Thematic analysis of qualitative data from the free comment field of the constant speed sequence.

Themes	Subcategories	Character	Example of statements
Lack of feedback	Dominant wind and road noise	Soothing	"*Can hear the tires and the air drag, no sign of the engine!*"
Masking as a positive feature	Wind noise	Powerful	"*Good, only wind noise.*"
Masking as a negative feature	Wind and tire noise	Boring Tiring Constant	"*Tiresome sound in the long term. Probably, I perceive it as louder in the silent studio than it really is?*"

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machine is pulling, but it's irritable. Might as well be lower. The wind noise is more disturbing."

Constant Speed It was obvious that the wind noise was dominant. It was experienced as unproportionally loud in the studio compared to the cabin. The lack of feedback from the propulsion was mentioned, as seen in Table 4. The constant audible low pitch from the tire noise was eventually mentioned as tiring and annoying. From the van der Laan test [6], it could be seen that the majority rated the sound as not acceptable.

Auxiliary Braking This sequence was the highest rated in sound quality and acceptance. The sonic feedback to the driver enhanced the impression of linear braking, matching the expected sound from a vehicle slowing down. However, some listeners thought the sound character was too sharp and should drop in frequency (see Table 5).

The rating of acceptance reflects the opinion that the sound is highly usable. The majority were also satisfied with the sound.

Uphill This sound was perceived as informative but too tonal and annoyingly constant. The oscillation when reaching a steady state uphill was found disturbing. The high-pitched content of the sound was irritating and tiring (see Table 6).

The majority estimates this sound as useful, but the participants' satisfaction with it is divided in half between those who find it satisfying and those who do not.

Pedal Brake Table 7 presents the thematic analysis of the pedal braking driving operation. The sound was perceived as informative, signaling that the vehicle was slowing down. But it was also vague. Some annoying high-frequency content and extra sounds made this sound disturbing and signaled the product to be non-premium.

Comparing the pedal brake to the auxiliary brake sequence shows that more assessments end up on the unacceptable side in the van der Laan diagram for the pedal brake case. Still, the sound is regarded as useful. See and compare Figures 8(a) and 8(b).

Total Sound Impression

Table 8 supports the obvious lack of masking compared to previous experience with combustion engines. Dominating wind noise at high speed was stated as disturbing, and tire noise was more apparent than before. Reducing noise from components previously masked by the combustion engine, now clearly audible, was pointed out as necessary. A silent vehicle eluded from high-pitched whining noises was preferred.

TABLE 5 Thematic analysis of qualitative data from the free comment field of the auxiliary braking sequence.

Themes	Subcategories	Character	Example of statements
Informative feedback	Signaling retardation Expected Useful Confirmation	Futuristic Movie like Linear	"*Got a good feeling about what was happening.*" "*Good audio feedback about how much you are slowing down.*" "*The sound meets my expectations.*"
Informative feedback with reservation	Unclear Strange/new sound Annoying	Sharp High frequency Whining	"*Sounds like an airplane shutting off its engines. Gives enough information to the driver.*" "*I hear the brakes as a high-frequency whining and think that it is good that I hear that it is working and doing what it is supposed to do. Even if the noise by itself is not too nice.*"
Not brand typical	Tonal Wind noise		"*Could as well have been the commuter train arriving at the station. Would be good if we could develop a more Scania-specific sound, less sound from the electric machine.*"

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TABLE 6 Thematic analysis of qualitative data from the free comment field of the going uphill sequence.

Themes	Subcategories	Character	Example of statements
Functional feedback	Informative Indefinable Tonal Annoying Acceptable due to the load	Monotone Weak High frequency	"*I must admit that I like hearing the electric machine working hard, but at the same time, does it sound weak.*" "*Get a feeling of what is happening, struggles up the hill.*"
Disturbing	Tonal Irritating Tiring Oscillating at a steady state	High pitch Sharp Constant Howling Inconsistent	"*Irritating frequency. When the rpm is constant. Nicer at acceleration.*" "*Sounds a little too much as a commuter train; would rather hear lower-frequency tones.*"

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TABLE 7 Thematic analysis of qualitative data from the free comment field of the pedal braking sequence.

Themes	Subcategories	Character	Example of statements
Functional feedback	Informative but vague Acceptable	Nonlinear	"*Why does it vary so much when driver input is constant?*" "*Get the feeling of deceleration and no downright annoying sound.*" "*Not a nice sound, but neither unpleasant. Acceptable.*"
Disturbing sound	Tonal Extra sounds Annoying Masking wind noise	Howling High frequency Wheezy Cheap	"*Can give the wrong signal of truck shutting down!*" "*Sounds a little bit like brake screeching. Feels unnecessary. Disturbing.*"

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FIGURE 8(a) Scatterplot of the usability indexes for pedal brake.

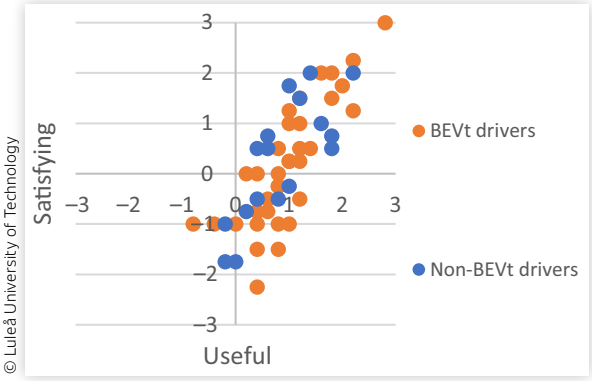

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FIGURE 8(b) Scatterplot of the usability indexes for auxiliary braking.

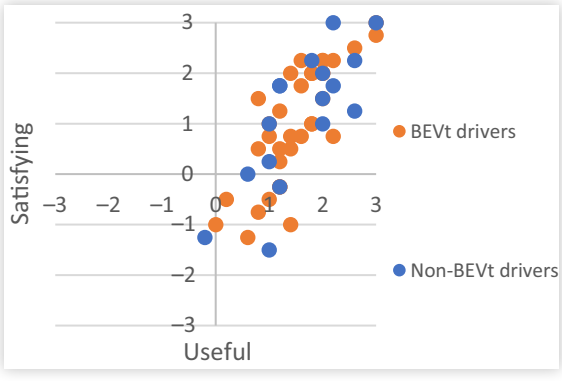

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TABLE 8 Thematic analysis of qualitative data from the free comment field of the total evaluation.

Themes	Subcategories	Character	Example of statements
Improvement (in comparison with ICE)	No masking More wind and tire noise	Quiet	"*Relatively, the ICE driveline is quiet. I have not listened to any of our competitors' BEV trucks yet. What is seen as a reference?*" "*There is noise from other sources such as wind and tires.*"
Not premium	No masking To loud Tonal Wind noise Invariability	High pitch Loud Tiring Whining Buzz	"*Stronger connection to the effect of the driveline at acceleration with pedal and inclination, e.g., Power steering/compressor, contribute negatively. Wind noise at higher speeds must be reduced.*" "*I am very irritated by high-pitched tonal sounds, and I need variety in the sounds around me for a pleasant experience.*" "*The sound brings directly electric driven forklifts and commuter trains to mind = not premium.*"

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After listening to the complete "sound story"—all sound samples in a row after each other—the total impression resulted in a quality assessment rating of 7 (see Figure 9).

The resulting sound profile showed an almost neutral response but with a tendency to be "tonal" and harmless, see Figure 10. The difference was not significant for any of the variables in the sound profile ($p > 0.05$), and the effect size ($r < 0.27$) was small throughout the data. Nor did the mean of the sound quality index differ significantly between the groups for the total evaluation. However, the driving-experienced group's variance was smaller (see Figure 9).

Using a Pearson correlation analysis for the variables "annoyance" and "tonal," there is no significant difference from zero ($R = 0.02$, $p = 0.87$).

There is a significant difference between the BEVt-listening-experienced and non-experienced group rating the auxiliary brake condition ($p < 0.01$) and medium-sized effect ($r = 0.43$). This condition was, on average, higher rated than all the other conditions for both groups, see Figure 7. The other driving conditions did not show any significant difference between the groups. However, from the comments, it could be deciphered that those who had driven this type of vehicle beforehand used the memory of their experience, sometimes disregarding the sound heard in the test and just using their already obtained sound experience from the cabin context.

Suggestions for "Top Results"

The thematic analysis of the written comments given after the test, answering the question: "How would an electric truck sound like to get top values?" shows three themes, see Table 9. A silent, steady vehicle with expressed functional feedback is preferred.

FIGURE 9 Sound quality evaluation of the total sound impression presented as boxplots.

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FIGURE 10 The sound profile is derived from semantic differentials. The black solid line represents the experience of driving or being a passenger of BEVt, and the gray dashed line represents novice listeners.

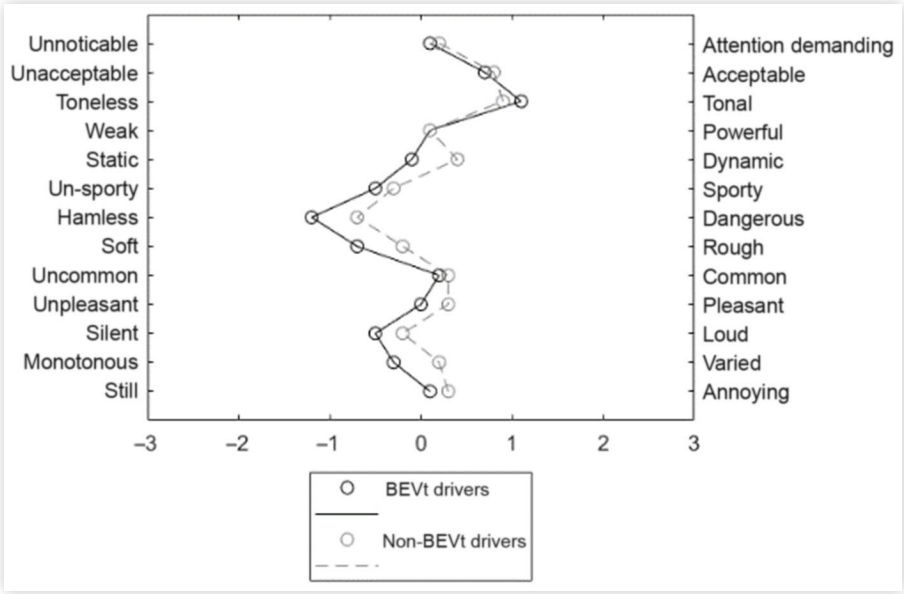

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TABLE 9 Thematic analysis of qualitative data from the last question: "How would an electric truck sound like to get top values?"

Themes	Subcategories	Character	Example of statements
Reduce/remove sound source	Wind noise	Loud Tiring	"It would be quieter with regards to wind noise."
	Tonal sounds	High frequency Constant Tiring Irritating	"Silent at idle (no constant frequency whine)" "To get top grades, I would like to remove or alternatively soften up the tonal part. The sound is acclimatizing and tiring, especially if you travel long."
	Squeaks Pumps	Annoying	"*It should be quieter regarding other noise sources that 'disappear' on a truck with ICE.*"
Quality attributes	Silence	Pleasant Smooth Soft	"*Silent when cruising.*"
	Stability	Clean Linear Even	"Continuous sound rather than sudden & unexpected."
	Variation		"More variations in sound."
	Power	Empowering Strong	
	Vigorous	Sporty Distinct Tight Alert High tech	
	Trust	Safe	
Functional feedback	Communicative tonal information	Informative Guiding Intuitive	"Wakes up, give warning, talks with you." "The tone from the electric machine can be there."

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Discussion

Underlying Aspects

The study's first objective was to understand what underlying aspects decide the experience and perception of a dynamic heavy vehicle–related sound in the context of electrified propulsion. Like the task of interpretation, the result is influenced by the researcher's subjective comprehension and understanding of the concept.

Individual values are among the underlying aspects that contribute to positive and negative experiences. Measuring individual values means measuring attitude. Values change over time and with society. At the time of the test, the closest reference source was an internal combustion engine (ICE) truck, which is an inaccurate reference since the sounds from ICE and BEVt are completely different in character. With the removed masking effect of the combustion engine and the driveline replaced by electric propulsion, the listeners need to readjust their sonic reference. The listener must relate to "silence" and former masked as well as completely new sounds in the driving context, which results in a new experience. This result is reflected in the comments with words such as "strange" or statements such as "might be something that has to get used to" or "might be annoying in the long run." The interpretation of such a statement is prevailing perplexity over the new listening situation. People do not know how to assess the sounds while they have no experience of using them yet [8].

Evaluating tonal sounds as such does come down to individual preferences. Some of the participants clearly show that they do not like the tonal contribution at all. Others quite like it. However, the majority do assess high-pitch tonal content as irritating, so dependency on frequency height or sharpness is valid. The evaluation also depends on whether the tone is presented continuously or as a dynamic sweep. Tonal noise related to and following changes in load or speed is accepted to a much greater degree, functioning as a carrier of information to the driver about the propulsion and status of the vehicle. As the "no-correlation" result shows, comparing the variables "tonal" and "annoying," tonal noise is not annoying per se. Constant tonal noise is perceived as tiring in lower-frequency ranges and annoyingly intrusive in the higher-frequency range. There are also attributes in this study that seem not to depend on individual preference but are more connected to hearing function, such as a sense of sharpness, for example.

The auxiliary brake was accepted and rated higher than the operation where the braking was made with the pedal. Comparing the outcome from the listening test, the difference lies in the expressed linear and nonlinear attributes. The auxiliary brake sound gives a stable signal and confirmation of the input (braking), which aligns with what is expected. The pedal braking includes extra tonal sounds that are not coherent with the other sounds, giving the sense that the product is non-premium. As one of the comments said regarding expectation: "One sound, not 27 different." Tonal noise that is expected to be constant and linear but is instead nonlinear or fluctuates is perceived as annoying. The outcome must be in line with the expectation.

Aspects related to "functional feedback" were recurrently raised by the participants, and the results support its importance as a factor in perceived sound quality. The thematic analysis shows that the priority of good sound feedback is important, reflected in the high ratings and evaluations of the auxiliary brake sequence. The feedback is meant to give the driver information to the extent necessary for the driver to act and adjust behavior. Genuit and Fiebigand [8] claim that added sounds without a clear purpose lower the perceived quality. In accordance with their study, our study resulted in positive comments with loudness adaptive load feedback. At the same time, low acceleration conditions require smoothness. Govindswamyu and Eisele [9] compared load-dependent interior noise between ICE and electric engine vehicles and found a mismatch between the impression of power and the actual torque of the electric engine, which also is seen in this study where we see statements as "weak," even though the power is higher than expected from a conventional powertrain.

Emotional feedback of sound is expressed through different attributes of character. The same attributes, as seen in this study, were noticed by Maunder and Munday [10] when investigating conventional expectations evaluating interior electric vehicle noise. "Familiarity" and comprehension of the "cleanness" of the sound were preferred. Attributes such as futuristic were linked to a positive experience, while references to established transportation, such as trams and the like, were negative. The response in the study conducted by Münder and Carbon [2] is similar to the findings of this study. A quiet character with clear operational feedback is important for high satisfaction and quality assessment. What differs compared to our study is references to long haulage, which do not appear in the study related to passenger cars.

The literature suggests other underlying aspects, which are presented in Table 10.

Novel vs. Experienced Listeners

The study's second objective was to investigate whether driving experience affects the outcome. The hypothesis was that people who had driven or been passengers in this type of truck before the test would rate the sound quality with less variance than novice listeners.

There was no general difference in evaluation between those with experience driving BEVt and those without, except for one driving case. However, the variance was smaller for the driving-experienced group when evaluating the total assessment, as seen in Figure 9.

The one case that stood out was the auxiliary brake driving condition, which differed significantly from the sound quality estimation, where the novel listeners rated this condition higher and with a smaller variance. Probably,

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TABLE 10 Underlying aspects presented by other authors.

The individual	Fundamental hearing function	Psychological aspects	Fundamental acoustics and physics	The function relation of the sound
• Gender [11]	• Gestalt theory [2] • Auditory scene analysis [12]	• Risk assessment and personality [13] • Situational factors—real or studio driving [13] • Expert listening experience [2] • Technical authenticity [10]	• Subharmonics [14, 15]	• Characteristics of the road environment [13] • Branding [9, 16]

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those who had been driving before the test related to their memory of the driving situation when answering, which gave access to factual connection between perception and sound source, the so-called memory-based evaluation [2]. This phenomenon might explain the difference, meaning the experienced drivers could include more aspects than just the sound when answering.

"Memory-based evaluation" might also have influenced the participants' ability to associate the sound with other sources, as the majority who referenced or used examples of other sound sources when discussing their expectations had prior experience driving or being a passenger in a BEVt. They described the expected sound using a similar sound source reference.

Limitations of the Listening Experiment

One limitation was that the test form was written in English and that the participants used both English and Swedish when commenting, which could have caused language confusion when translating the content.

To get representative sound files for replay the low-frequency content was cut out by HP filtering. This means that the measured sound pressure levels in the cabin and the studio differed. Also, the studio room itself and the rendering system affected the sound acoustically. Despite this, the participants complained about unnaturally palpable low-frequency contribution and high wind noise when the vehicle reached high speeds. Getting a subjectively realistic sound reproduction demanded changes in the low-frequency acoustic content.

Conclusion

The underlying aspects that affect the listening experience in both positive and negative senses are presented in Table 11.

This study, along with previously identified aspects, highlights the complexity of understanding what determines sound perception and how to design sounds that users appreciate. The findings complement prior research by identifying aspects that manufacturers should consider in BEVt development. They also support further studies that can deepen the understanding of these aspects and ultimately guide requirement setting and evaluation of BEVt operational sounds.

The general conclusion of the thematic analysis was that absolute silence is not the goal. Instead, three clear objectives emerged: removing disturbing sounds, creating a smooth and silent environment, and providing clear functional feedback.

TABLE 11 Identified underlying aspects of quality assessment.

The individual	Fundamental hearing function	Psychological aspects	Fundamental acoustics and physics	The function relation of the sound
• Individual preference • Contextual experience • Frame of reference • Values • Memory	• Frequency sensitivity • Loudness perception	• Affective and emotional factors	• Time variations • Linearity, stability, coherence • Frequency content	• Confirmation of input • Load-dependent loudness adaption
Research implying other underlying aspects:				
• Gender [11]	• Gestalt theory [2] • Auditory scene analysis [12]	• Risk assessment and personality [13] • Situational factors—real or studio driving [13] • Expert listening experience [2] • Technical authenticity [10]	• Subharmonics [14, 15]	• Characteristics of the road environment [13] • Branding [9, 16]

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There is no clear general difference between those who have experience driving BEVt and those who have not when assessing sounds. The total evaluation of the sound story shows less variation for the experienced group than the novice listeners, but the average value is the same.

However, regarding sound quality assessment, the auxiliary brake operation did show significant difference between the listening-experienced and non-experienced groups. The novice listeners gave higher and less varied ratings than those with previous sound experience with BEVt. This implies that experienced drivers use the memory of the driving situation when answering, giving access to the factual connection between perception and sound source.

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Abbreviations

BEV - battery electric vehicle
FFT - fast Fourier transformation
RPM - revolutions per minute
SPL - sound pressure level

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