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Research on Integrated Virtual Component Sound System

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ABSTRACT

Unnatural noises generated by vehicles can cause anxiety and stress related to potential vehicle defects. This, in turn, can tarnish the brand image and lead to a loss of trust with customers. This is why automotive manufacturers continue to conduct research on noise reduction and are accelerating the development of related technologies.

The transition from internal combustion engine vehicles to electric vehicles has intensified the focus on noise-related issues. The absence of an engine has made it possible to recognize noises that were previously masked by the engine. As a result, vehicle manufacturers are working to strengthen regulatory standards for component operating noise.

Component manufacturers are addressing these demands through design improvements aimed at reducing noise. However, there are limitations to how much operational noise can be reduced through design changes alone. As a result, research has been conducted to change the perception of operating noise and effectively mask it, leading to the development of the Virtual Steering Sound System.

This paper explores the advancement of the Virtual Steering Sound System, focusing on the generation of virtual sounds for individual components and their harmonious integration to create a musical experience for the driver during vehicle operation.

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1. INTRODUCTION

With the increasing adoption of electric vehicles (EVs), the automotive industry is experiencing a paradigm shift from internal combustion engine vehicles (ICEVs) to EVs, driven by global carbon emission regulations and advances in battery technology. As engines are replaced by motors and transmissions are substituted by reducers, EVs exhibit significantly lower noise levels compared to traditional ICEVs.

However, this quietness has led to a new set of challenges. While engine noise in ICEVs masked the sounds of various components, this masking effect is no longer present in EVs, making component noises more noticeable to consumers. A study of customers who had purchased a new car within the last year revealed that the noise-related quality problems (PPH, Problems Per Hundred) of EVs were about 1.8 times higher than those of ICEVs.[1] As a result, vehicle manufacturers are strengthening regulations on component noises in response to these new challenges.

[Base : New Car Buyers in the Past Year / Unit : Number of Problems per 100 Vehicles]

Category	2024				2023			
	PPH(Rank)		GAP	Ratio	PPH(Rank)		GAP	Ratio
	EV	ICEV	EV-ICEV	EV/ICEV	EV	ICEV	EV-ICEV	EV/ICEV
Electrical Equipment & Accessories	33.5(1)	18.4(2)	15.1	1.8	36.2	16.6	19.6	2.2
Noise & Abnormal Sounds	31.7(2)	17.8(3)	13.8	1.8	30.2	19.8	10.4	1.5
Climate Control & Ventilation System	17.4(3)	7.6(6)	9.8	2.3	16.9	9.1	7.8	1.9
Audio & Video System	15.8(4)	15.5(4)	0.3	1.0	18.8	12.5	6.3	1.5
Steering Wheel & Steering System	15.0(5)	8.5(5)	6.5	1.8	16.6	9.1	7.6	1.8
Interior & Trim	15.0(6)	7.1(9)	7.8	2.1	12.6	7.1	5.5	1.8
Body, Paint, Molding & Water Leaks	13.9(7)	7.4(7)	6.5	1.9	13.8	8.5	5.3	1.6
Seats & Seat Belts	12.7(8)	5.6(10)	7.1	2.3	8.9	5.6	3.3	1.6
Brakes	11.5(9)	7.3(8)	4.2	1.6	15.3	7.9	7.3	1.9
Battery*	9.6(10)	2.3(12)	7.4	4.3	10.9	1.5	9.5	7.4
Powertrain**	7.8(11)	18.6(1)	-10.8	0.4	8.3	17.2	-8.9	0.5
Tires	6.3(12)	2.7(11)	3.6	2.4	4.7	2.4	2.4	2.0
Problem Experience Rate(%, Ratio)	55	38	17	1.4	52	37	14	1.4

*Electric vehicles: 'High-voltage battery (8.3 PPH)', Low-voltage battery (1.4 PPH)
**Electric vehicles: 'Electric motor, etc.', Internal combustion engine vehicles: 'Engine (13.0 PPH)', 'Transmission (5.6 PPH)'

Figure 1. Number of Quality Claims for EV and ICEV (PPH, Problems per Hundred).

To address this issue, noise masking technologies using virtual sounds have gained attention. Specifically, applying virtual sounds to mask the noise from various components, including the steering system, is an area of active research. However, simply masking the noise can create an artificial feeling for consumers, potentially leading to a sense of discord over time. Thus, there is a need to utilize virtual sound technology not just as a noise masking tool but as an element that enhances the driver's experience.

Similar changes have occurred in the evolution of the electric Active Sound Design (e-ASD) system for EVs. Initially, e-ASD systems focused on replicating engine sounds to reduce the perceived lack of engine noise during EV driving.[2] Over time, however, these systems have evolved into unique sound designs that maximize the joy of driving, contributing to both consumer experience and brand identity.

This study aims to apply this evolutionary direction of e-ASD to virtual component sounds. Moving beyond merely masking component noises, it proposes generating creative sounds that reflect the individual driver's emotions. By designing virtual sounds for not only the steering system but also various components of the vehicle, this research introduces a new driving experience where the sounds of different parts harmonize to form a cohesive musical experience. This approach offers an emotional experience where the driver actively creates music while driving, beyond the conventional vehicle sounds.

Furthermore, this virtual sound system can enhance the vehicle manufacturer's brand image. By developing unique virtual sounds specific to a brand, manufacturers can offer familiarity and trust to consumers while solidifying brand identity. This study explores how virtual component sounds can contribute to improving driver experience and brand value, extending beyond mere noise masking.

2. RESEARCH AND DEVELOPMENT OF INTEGRATED VIRTUAL COMPONENT SOUND SYSTEM

2.1 Virtual Steering Sound System and Its Limitations

Previous research on virtual steering sound systems focused on analyzing the noise characteristics of steering components and designing virtual sounds based on this data. Noise measurements were taken under various operating conditions in real vehicle environments, and the frequency characteristics and noise contribution of individual components were analyzed. The results showed that, regardless of steering speed, noise energy was concentrated between 60Hz and 800Hz, with RBNA (Rack and Ball Nut Assembly), motor, and belt being the primary contributors. Based on this, a virtual sound was designed to effectively mask noise in the 60Hz–800Hz range.[3]

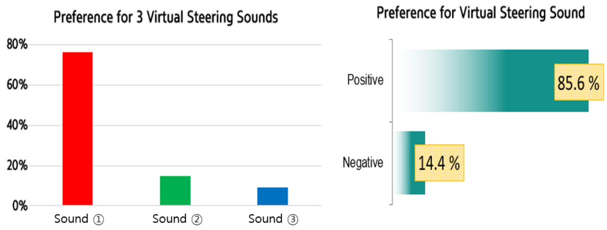

Figure 2. Virtual Steering Sound Demo Feedback Results.

The following graph shows the preference and feedback results for individual sounds. To verify the effectiveness of the designed system, both acoustics experts and non-experts participated in real vehicle demonstration evaluations, which received 85.6% positive feedback. However, 14.4% of negative feedback was also noted, including:

a. Cognitive Dissonance: "It feels more artificial than naturally occurring sounds, causing discomfort."
b. Interference with Music: "When I listen to music while driving, the steering sound interferes, creating an unpleasant experience."

These feedbacks highlighted the need to evolve the system beyond simple noise masking and focus on enhancing the driving experience. Therefore, the concept of an "Integrated Virtual Component Sound System" was introduced, where virtual sounds from various vehicle components are harmoniously combined, offering a unified sound experience for the driver.

2.2 Integrated Virtual Component Sound System

This system aims to overcome the limitations of previous virtual steering sound systems while providing a new experience for the driver. The demo results from the virtual steering sound system confirmed that designing sounds solely based on noise analysis does not guarantee consumer satisfaction. Consumers are more focused on how pleasant the sound is, rather than how effectively it masks the actual noise. Furthermore, individual preferences for sound suggest that personalized sound options are necessary.

To address this, the system was designed to focus on creating emotionally satisfying sounds without relying on component noise analysis, offering a wide range of sound options. This allows the driver to choose a sound that matches their personal taste, enhancing the personalized driving experience.
To resolve cognitive dissonance and interference with music, the study introduces an "Integrated Virtual Sound Creation Mode." Similar to existing driving modes such as Sport, Comfort, and Eco, this mode allows the driver to generate unique music during driving. When activated, this mode ensures that the sound is perceived as part of the overall driving experience, minimizing the sense of artificiality and interference with music. This enables the driver to experience a driving environment that goes beyond noise control, offering new enjoyment.

3. METHODOLOGY

3.1 System Overview

The Integrated Virtual Component Sound System is implemented based on the Hyundai Ioniq 5 vehicle. The system utilizes the Steering and Braking components, and three main inputs—Vehicle Speed, Steering Angle, and Brake Pedal Pressure—are used to adjust the virtual sound in real time, which is then output through the car's built-in speakers. Fig. 3 and Fig. 4 show the system schematic and the real vehicle system configuration, respectively.

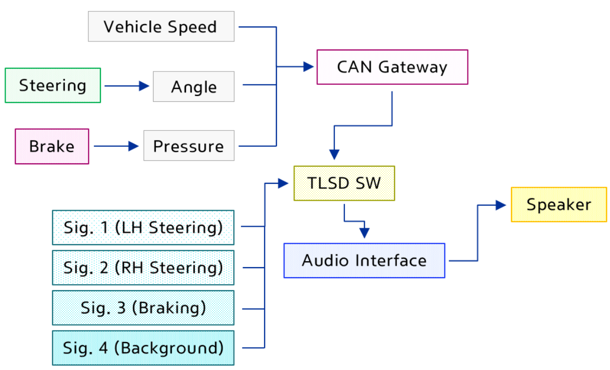

Figure 3. Virtual Component Sound System Schematic Diagram.

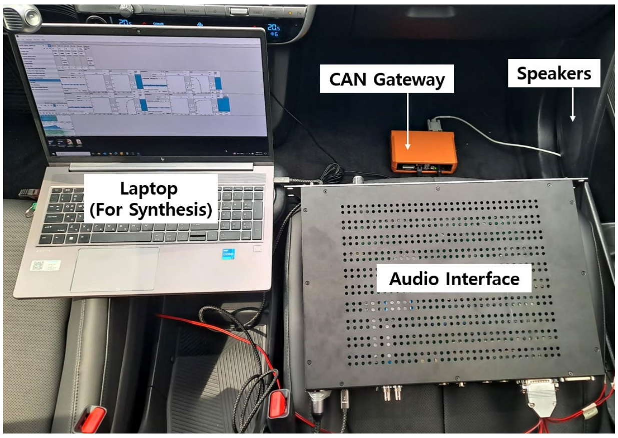

Figure 4. Virtual Component Sound System Configuration in Hyundai Ioniq 5 Vehicle.

3.1.1 Hardware and Signal Transmission

To synthesize Virtual Component Sounds, key vehicle parameters—Vehicle Speed, Steering Angle, and Brake Pedal Pressure—are collected from the vehicle's internal CAN network (R-EPS CAN network)[4] and transmitted to a PC via a CAN Gateway. The CAN Gateway converts the voltage difference between CAN High and CAN Low into digital values and translates them into a protocol readable by the PC.

On the PC, these signals are decoded using a CAN dbc file and processed in Testlab Sound Designer (TLSD) software. TLSD utilizes Sound Signatures for variation and synthesis, generating a virtual sound in real-time. The synthesized sound is then output through an audio interface, which features a high-quality Digital-to-Analog Converter (DAC) superior to the PC's built-in DAC.

To create a three-dimensional in-cabin sound experience, the system employs a total of three speakers: two built-in speakers positioned at the front on both sides and an external speaker placed centrally at the rear. This setup ensures an immersive auditory experience within the vehicle.

3.1.2 Sound Design

In this study, virtual sounds were created using Logic Pro software. As shown in Fig. 4, four thematic sound designs were developed, each consisting of four Sound Signatures. Each Sound Signature varies depending on background sound, clockwise steering, counterclockwise steering, and brake pedal activation, forming a loop structure to ensure natural repetition. The background sound also includes variations to prevent monotony.

The sound design utilized Logic Pro's built-in plugins, such as Alchemy, ES2, and Sampler, to create diverse timbres and textures. Harmonic elements were incorporated to ensure harmony between the background sound and steering or braking actions. In particular, when steering is combined with the background sound, an Em chord is played, while braking combined with the background sound triggers an Emdim7 chord, reinforcing the melancholic atmosphere of the war-themed soundscape. Additionally, considering India as a target market, a thematic Sound Signature was created using traditional Indian instruments.

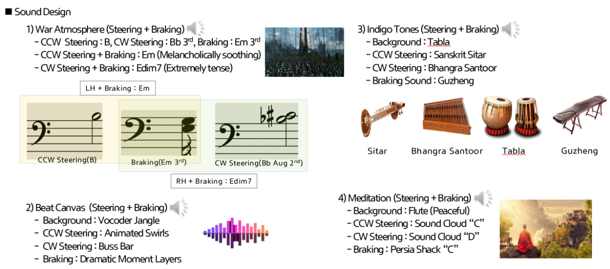

Figure 5. Four thematic sounds composed of four sound signatures.

3.1.3 Sound Synthesis Approach and System Refinement

The sound synthesis process employs Siemens TLSD software, utilizing granular synthesis, pitch modulation, and gain modulation techniques. When the synthesis approach from the comprehensive virtual sound system was applied to the integrated virtual component sound system, issues such as dissonance and unnatural sound characteristics arose. To address these challenges, an alternative method was adopted to ensure seamless auditory integration.

Virtual Steering Sound System

The Virtual Steering Sound System generates auditory feedback related to steering by processing steering speed signals. Specifically, it dynamically modulates pitch and gain in response to steering speed variations, providing intuitive auditory cues for the driver. At the steering end, where the steering angle reaches its predefined limit, the system outputs a consistent sound signature without modulation, ensuring auditory coherence.

Improvements over Previous Systems

a. Introduction of Background Sound Signature
To ensure a harmonious integration of background and component sounds, the gain of the background sound signature is adjusted based on vehicle speed.

b. Sound Adjustment Based on Steering Angle
Instead of modifying both pitch and gain according to steering speed, the refined system adjusts only the gain based on steering angle. This approach results in a smoother and more natural auditory experience.

c. Minimized Pitch Adjustment for Enhanced Harmony
To prevent disharmony between multiple sound elements, pitch adjustments are minimized. Instead, the system prioritizes gain-based sound control, improving overall sound cohesion and ensuring a more immersive auditory experience.

The following Fig. 6 illustrates the TLSD tuning process.

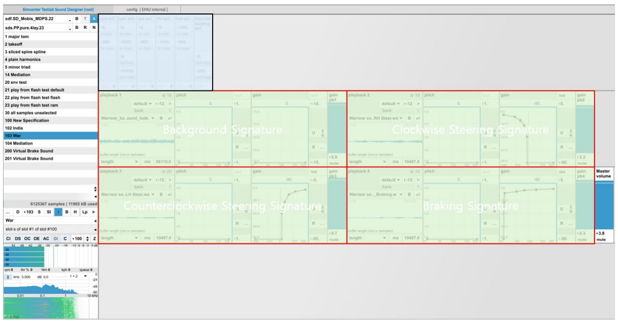

Figure 6. Tuning and Sound Synthesis on TLSD.

4. CONCLUSION

This study proposes an Integrated Virtual Component Sound System that overcomes the limitations of existing virtual steering sound systems, focusing on providing a more natural and emotionally engaging driving experience. The system, which dynamically changes sounds using CAN signals, can be applied to various vehicle components beyond steering and braking. This approach introduces a novel direction in virtual sound generation linked to component operations.

As the transition to Software Defined Vehicle (SDV) accelerates, this system can be enhanced through AI-based personalized sound creation and Over-the-Air (OTA) updates. Future research will explore expanding the system to other vehicle components, providing drivers with richer auditory experiences.

5. ACKNOWLEDGMENTS

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