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"SUSTAINABLE MOBILITY'S SOUND DESIGN FOR ELECTRIC VEHICLES; DEVELOPMENT AND EXPERIMENTATION"

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"If you ever find yourself feeling fortunate,
remind yourself that the prayers of your parents have been heard."

Abstract

The implementation of electric vehicles (EVs) offers distinctive challenges and opportunities in the field of sustainable mobility, specifically regarding safety and the public's perception. This thesis focuses on an innovative application of digital signal processing using granular synthesis to create and enhance EV sound designs. The primary objective of this research is to develop vehicle sounds that are both easily detectable and provide sufficient auditory information to alert pedestrians of an approaching vehicle, without being perceived as unpleasant. This research systematically investigates the impact of various sound designs on individual perception using an experimental setting utilizing granular synthesis techniques. The participants were subjected to various electric vehicle (EV) sounds, and their responses were assessed to evaluate the efficacy of each sound design in terms of noticeability, informativeness, and level of annoyance. The experiments were conducted to evaluate the compliance of these sounds with existing regulations for electric vehicle sound emissions and to explore the possibility of these sounds improving pedestrian safety and overall user satisfaction. The findings of this research are expected to contribute valuable insights into how sound design can influence the acceptance and safety of electric vehicles in urban environments. This thesis seeks to propose sound design strategies that improve the functional and aesthetic aspects of electric vehicles by combining principles of sustainable mobility and advanced sound engineering. The primary objective is to advance wider acceptance and encouragement of sustainable transportation responses.

Keywords: Sustainable Mobility, Digital Signal Processing, Sound Design, Electric Vehicles

Astratto

L'implementazione dei veicoli elettrici (EV) offre sfide e opportunità distintive nel campo della mobilità sostenibile, in particolare per quanto riguarda la sicurezza e la percezione del pubblico. Questa tesi si concentra su un'applicazione innovativa dell'elaborazione del segnale digitale utilizzando la sintesi granulare per creare e migliorare la progettazione del suono dei veicoli elettrici. L'obiettivo principale di questa ricerca è sviluppare suoni dei veicoli che siano facilmente rilevabili e forniscano informazioni uditive sufficienti per avvisare i pedoni di un veicolo in avvicinamento, senza essere percepiti come spiacevoli. Questa ricerca indaga sistematicamente l'impatto di vari progetti sonori sulla percezione individuale utilizzando un ambiente sperimentale che utilizza tecniche di sintesi granulare. I partecipanti sono stati sottoposti a vari suoni di veicoli elettrici (EV) e le loro risposte sono state valutate per valutare l'efficacia di ciascun sound design in termini di visibilità, informatività e livello di fastidio. Gli esperimenti sono stati condotti per valutare la conformità di questi suoni alle normative esistenti sulle emissioni sonore dei veicoli elettrici e per esplorare la possibilità che questi suoni migliorino la sicurezza dei pedoni e la soddisfazione complessiva degli utenti. Si prevede che i risultati di questa ricerca forniranno preziose informazioni su come la progettazione del suono può influenzare l'accettazione e la sicurezza dei veicoli elettrici negli ambienti urbani. Questa tesi cerca di proporre solide strategie di progettazione che migliorino gli aspetti funzionali ed estetici dei veicoli elettrici combinando principi di mobilità sostenibile e ingegneria del suono avanzata. L'obiettivo principale è promuovere una più ampia accettazione e incoraggiamento delle risposte in materia di trasporti sostenibili.

Parole chiave: Mobilità Sostenibile, Elaborazione Digitale del Segnale, Sound Design, Veicoli Elettrici

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Chapter 1

Introduction

As part of the global effort to reduce carbon emissions and address climate change, it has become essential to embrace sustainable transportation. Electric vehicles (EVs) are at the forefront of this transformation by offering a more environmentally responsible alternative in comparison to conventional internal combustion engine vehicles. Electric vehicles (EVs) utilize electricity, typically generated from renewable energy, to offer a solution that effectively decreases emissions and reduces dependence on fossil fuels. This alteration is not only an imperative for the environment but also a deliberate decision to establish urban transport systems that are more resilient and adaptable.

The design of electric vehicle sounds surpasses conventional sound engineering. It includes not only the functional aspect of alerting pedestrians about the existence of a vehicle but also improves drivers' auditory perception and contributes to the car's unique character. Due to the silent operation of electric vehicles (EVs), sound design has transitioned from being an unintended result of mechanical performance to a deliberate and essential component for safety. It ensures that everyone in general, including also those with visual impairments can safely navigate shared spaces with these silent machines by acting as an auditory indication for pedestrians.

A granular synthesis is an innovative approach used in EV sound design that can generate an extensive range of sounds by modulating tiny audio fragments. Granular synthesis, as opposed to conventional waveform synthesis, provides extensive control of the interval and frequency characteristics of sound. This allows for the creation of unique sound characteristics that will contribute to defining the future of electric vehicles. This innovative approach not only serves the practical requirements of designing sounds for electric vehicles but also creates significant possibilities for acoustic branding and enhances the vehicles' emotional appeal.

The key objective of this thesis is to develop the practice of sound design for electric vehicles (EVs) by implementing granular synthesis, a technique intended to improve the overall user experience while ensuring compliance with functional safety standards. This study evaluates the effectiveness of electric vehicle (EV) sound designs generated by granular synthesis by evaluating their recognizability, informativeness, pleasantness, and potential for annoyance. This helps the deeper objective of sustainable mobility by ensuring that these sound designs may be effectively and securely incorporated into metropolitan environments.

The significance of sound design increases as the application of electric vehicles accelerates, ensuring a secure and harmonious coexistence with pedestrians. Within the context of sustainable mobility, this thesis addresses the issue and proposes redefining the sound characteristics of electric vehicles. Granular synthesis is a key equipment in this context, offering a sophisticated approach to creating sound that stimulates creativity and complexity in a mostly practical industry. The results of this study are expected to provide useful information about the integration of electric vehicles (EVs) into urban environments. This will contribute to a future where sustainable transportation is both environmentally friendly and pleasurable for all.

This thesis is organized into several chapters, each focused on examining various aspects of sound design for electric vehicles and its impact on sustainable mobility. The format is specifically designed to guide the reader through a systematic study, covering topics from fundamental concepts to comprehensive experimental analysis and conclusions. The Literature Review analyses current research on the sound design of electric vehicles, including studies on the impact of sound on the safety of pedestrians and drivers, regulations about sound emissions from electric vehicles, and enhancements in sound technology for transportation purposes. The Methodology outlines the specific research methods used to investigate the impacts of various electric vehicle (EV) sound designs. This includes describing the experimental setup, participant recruitment, the methods for collecting data, and the creation of various sound settings using granular synthesis. The Results section provides a comprehensive analysis of the experimental results, discussing the impacts of various sound designs on the perceptions of pedestrians and drivers.

The results are combined with the theoretical knowledge obtained from the Literature Review to evaluate the effectiveness of sound designs and explore the practical implications within existing safety standards and regulations. The Conclusion and Future Work section effectively outlines the research results and offers suggestions on how sound design can improve the safety and acceptance of electric vehicles. It reflects on the objectives of the study, discusses the thesis's contributions to the subject of sustainable mobility, and proposes possible directions for future research. Aligned with the general objectives of safety and sustainability, this systematic approach ensures a thorough examination of how innovative sound design may enhance the utilization and adoption of electric vehicles. Each chapter builds upon the previous one, resulting in an extensive understanding of the practical subject and encouraging further development.

Chapter 2

Literature Review and State-of-the-Art in EV Sound Design

2.1 Sustainable Mobility and Electric Vehicles

Sustainable mobility is a crucial component in addressing current environmental issues, providing an environment for transportation that supports ecological conservation, economic sustainability, and societal well-being. Sustainable transportation is a comprehensive approach that combines economic, social, and environmental aspects to develop a transportation system that fulfills present requirements while preserving the ability of future generations to fulfill their demands. [34]. This paradigm highlights the significance of rethinking mobility in a manner that promotes environmental sustainability, decreases dependence on finite resources, and enables fair and equal access to transportation.

Electric vehicles (EVs) play a pivotal role in achieving sustainable mobility goals by reducing greenhouse gas emissions, enhancing energy efficiency, and promoting the transition towards renewable energy sources [37]. The importance of sustainable mobility lies in its potential to minimize the adverse environmental impacts of transportation, thereby contributing to the broader goal of achieving comprehensive sustainability and mitigating climate change [31]. The transition to electric vehicles (EVs) is motivated by multiple factors, including government commitments to decrease carbon dioxide (CO2) emissions and the development of innovative electric vehicle platforms, such as hybrid, fuel cell/hydrogen-based, and fully electric models. Major car manufacturers have announced plans to convert a significant portion of their production capacity to EVs, with some aiming to sell only electric cars within the next decade [37]. This transformation is anticipated to lead to a significant decrease in emissions from the transportation industry, thereby contributing to the worldwide attempts to reduce climate change also enhance energy efficiency. Figure 2.1 below shows the fundamental components and development of an electric vehicle (EV) system. The diagram is divided into multiple essential components that illustrate the management and use of energy for the movement of the vehicle. [17] Starting from the external charger, the energy is stored in the battery, which is the primary energy source for the vehicle. The power converter transforms the stored electrical energy into a suitable form for the electric motor, based on drive control signals. The electric motor then converts electrical energy into mechanical energy to drive the vehicle. The mechanical energy is transferred via the transmission and gearbox to the wheels, ultimately powering the vehicle forward. The "Powertrain" encompasses the components directly responsible for the vehicle's propulsion, including the power converter, electric motor, and transmission system.

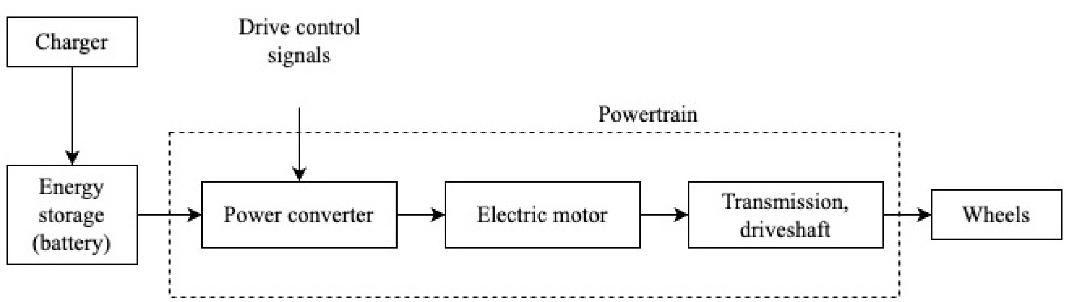

Figure 2.1: *Schematic Diagram of an Electric Vehicle System [17]*

At some point sustainable mobility and electric vehicles are inherently connected, as EVs play a vital role in attaining sustainable mobility objectives. The transition to electric vehicles (EVs) offers significant benefits in terms of mitigating greenhouse gas emissions, enhancing energy efficiency, and promoting the adoption of renewable energy sources. However, When assessing the environmental impact of electric vehicles (EVs), it is important to take into account the complete life cycle of the vehicle, from manufacture to disposal. This is particularly important for analyzing the environmental consequences of EV components, especially batteries, which can have substantial ramifications. [37].

2.2 Digital Signal Processing (DSP) in EV Sound Design

Digital Signal Processing (DSP) plays a key role in EV sound design by facilitating the creation and control of the auditory experience in electric vehicles. It enables the construction of customized sounds that enhance the overall driving experience. DSP principles involve the mathematical manipulation of digitized signals, allowing for the processing of various types of data, including audio signals [1].

The application of Digital Signal Processing (DSP) in Electric Vehicle (EV) sound design is especially remarkable in the context of granular synthesis, a technique that involves breaking down sound into tiny fragments or grains to manipulate them individually [6]. Through the application of DSP processors integrated into electric vehicles (EVs), sound engineers have the ability to employ innovative methods for generating and controlling sound. This allows for the production of various auditory experiences that are specifically designed for the electric vehicle environment. This advanced use of DSP technology allows for the precise control of sound parameters, such as pitch, timbre, and spatialization, leading to the creation of dynamic and engaging sound profiles that complement the futuristic nature of electric vehicles [15].

An example of this is a study that focuses on active sound control in electric vehicles (EVs) by utilizing digital signal processing (DSP) techniques to create sounds that replicate the specific qualities of conventional combustion engines [38]. This approach involves the use of digital signal processing algorithms to analyze and manipulate the sound signals generated by the EV's motor and other components. The study demonstrates how DSP can be used to create a more engaging and realistic sound experience for EV drivers and passengers. Another instance of digital signal processing (DSP) in electric vehicle (EV) sound design involves employing active noise control and acoustic enhancement techniques to produce a manufactured sound. This entails utilizing software methods such as harmonic order reduction to reduce undesired aural signals and boost the perceived engine power without making any physical modifications. Additionally, the study on the assessment and control of tonal components in EVs highlights the importance of DSP in improving the interior sound quality by extracting and synthesizing the engine sound using techniques like short-time Fourier transform (STFT) [21].

In the Kia EV9, for instance, DSP technology is used to optimize the audio system to the precise acoustics of the vehicle cabin, while also managing background noise from the electric vehicle's operation [6]. Meridian Audio, a British firm that developed the sound system for the EV9, has selected and tailored a suite of DSP technologies to manage the unique acoustic inputs of an electric vehicle, such as increasing the low and mid ranges as tyre noise becomes more prominent with speed or rougher road textures [6]. This method enables the creation of a controlled acoustic environment that can be used as a starting point for an engaging and captivating listening experience.

The incorporation of DSP processors in electric vehicles presents opportunities for innovative sound design methods, with granular synthesis being a notable illustration of how DSP processors within EVs facilitate the application of advanced sound design techniques that improve the overall auditory experience for both drivers and passengers.

2.3 Sound Design for Electric Vehicles

Current research in the field of EV sound design highlights the significance of sound not only for enhancing user experience but also for ensuring safety and establishing brand identity [9]. The natural quiet of electric vehicles (EVs), although advantageous in reducing noise pollution, provides significant safety issues for pedestrians, bikers, and those with visual impairments, who conventionally depend on auditory signals to navigate traffic securely. Sound design for electric vehicles (EVs) provides not only a safety feature but also a crucial component in improving the driving experience. It enables manufacturers to replicate the emotional reaction typically linked to the powerful sound of an old-fashioned combustion engine. Furthermore, the noise emitted by an electric car is increasingly becoming a defining characteristic that can represent the brand's personality, allowing manufacturers to set themselves apart in a highly competitive industry.

Within the context of electric vehicle (EV) sound design, there is an urgent requirement for innovative approaches for addressing issues with pedestrian safety, driver interaction, and the general satisfaction of users. Promising solutions to these challenges can be found in innovative technologies, such as granular synthesis, which allow for the production of dynamic and customized soundscapes that can adjust to various driving situations and user preferences. [6]. Granular synthesis allows the precise manipulation of sound components, providing a flexible framework for creating sound profiles that not only increase safety by alerting pedestrians to the presence of electric vehicles (EVs), but also offer drivers intuitive feedback on vehicle speed, acceleration, and operational status.

The necessity for innovation in electric vehicle sound design is emphasized by these factors, compelling academics and engineers to investigate advanced audio technologies like granular synthesis. Researchers are currently exploring advanced sound design techniques to meet both regulatory standards for pedestrian alerts and to offer drivers sensible auditory feedback that reflects vehicle performance and enhances the entire sensory experience. The convergence of practicality, aesthetics, and brand distinctiveness emphasizes the infinite potential of sound design in the era of electric mobility, requiring a proactive approach to acoustic engineering in electric vehicles.

2.4 Granular Synthesis in Sound Design

Granular Synthesis is an innovative approach to sound design that involves breaking down audio signals into small, discrete grains, typically ranging from a few milliseconds to several hundred milliseconds in length. These grains can subsequently be edited and reconfigured in diverse manners to generate complex and immersive sounds using basic sound samples. This technique is founded on the principles of time-domain analysis and synthesis, enabling precise manipulation of the spatial and harmonic attributes of sound.

Figure 2.2 shows a basic granular generator that demonstrates the process of making sounds using this technology [30]. Granular synthesis offers the advantage of generating a wide variety of sounds, ranging from delicate and intricate textures to intense and surreal soundscapes. Sound engineers can generate sounds that are not possible to create using conventional synthesis techniques by changing grain characteristics such as position, duration, speed, pitch, and density. Additionally, granular synthesis can be used for time-stretching and pitch-shifting, allowing for the manipulation of audio signals in real-time without degrading their quality [29].

In the context of sound design for electric vehicles (EVs), granular synthesis offers a powerful tool for creating unique and distinctive sounds that can enhance the user experience and contribute to brand identity [19]. For instance, granular synthesis can be used to create sounds that mimic the acoustic properties of traditional internal combustion engine (ICE) vehicles, providing a familiar auditory

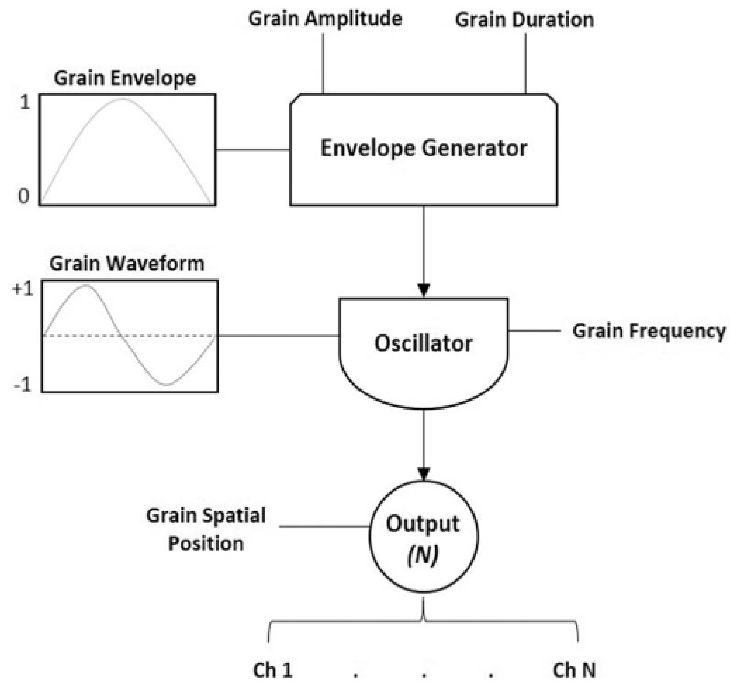

Figure 2.2: *Grain generation process (adopted from [30])*

cue for drivers and pedestrians alike [19]. In addition, granular synthesis can be employed to generate completely different and futuristic sounds that represent the innovative and environmentally friendly characteristics of electric vehicles. Granular synthesis has been employed in the automotive industry to provide noises for electric vehicles that are both practical and pleasing to the eye. For instance, granular synthesis can be used to create sounds that alert pedestrians to the presence of EVs, particularly in situations where the vehicle is operating at low speeds or in electric mode [19].

Additionally, granular synthesis can create sounds that provide feedback to drivers, such as indicating the vehicle's speed, acceleration, or deceleration [19]. It is an effective technique for sound creation, providing an immense number of options for creating complex and immersive soundscapes with basic sound samples. Within the area of electric vehicle (EV) sound design, granular synthesis offers a distinct chance to generate sounds that improve the user's experience and establish a brand's identity. Furthermore, it offers practical advantages such as preserving pedestrian safety while providing feedback to the driver.

2.5 Pure Data for Sound Design

Pure Data is a visual programming language specifically designed for creating and manipulating sound. It is known for its ability to be easily adapted and expanded upon, making it ideal for quickly experimenting and exploring new ideas. Its graphical interface allows users to create complex sound systems by connecting various objects, which can process and generate audio signals in real time [2]. Pure Data's open-source nature and extensive community support make it an ideal tool for exploring various sound design techniques, including granular synthesis [2]. Its architecture supports a variety of sound synthesis methods, real-time audio processing, and interface with hardware sensors, making it ideal for rapid prototyping, interactive performances, and complex sound installations.

Due to its visual interface, Pure Data is very suitable for performing experiments in granular synthesis, which is a method involving the decomposition of audio signals into minute grains and their subsequent rearrangement to generate innovative sounds. The community of Pure Data users shares patches and techniques, enabling users to learn from each other and build upon existing work [12]. This collaborative environment facilitates the exploration and development of innovative sound design approaches, making Pure Data a powerful tool for sound engineers and electronic musicians alike [12].

Addressing the sound design of electric vehicles (EVs), Pure Data's adaptability and flexibility make it a suitable instrument for producing exclusive and recognizable sounds that can improve the user's experience and help to the establishment of a brand's identity. Through the utilization of granular synthesis, sound engineers can generate noises that replicate the acoustic characteristics of conventional internal combustion engine (ICE) vehicles, offering a recognizable auditory signal for both drivers and pedestrians. In addition, Pure Data can be applied to generate completely innovative and forward-thinking sounds that mirror the innovative and environmentally friendly characteristics of electric vehicles.

2.6 Review of Current Technologies and Methodologies

In the field of EV sound design, the latest technologies and methodologies include digital signal processing (DSP) techniques and sound synthesis methods [14]. Digital signal processing (DSP) techniques facilitate accurate manipulation of audio signals, whilst sound synthesis technologies permit the creation of intricate soundscapes using basic sound samples. Granular synthesis and Pure Data are two important methodologies that have significantly advanced the limits of sound creation for electric vehicles (EVs).

Granular synthesis is a technique that involves breaking down audio signals into small grains and rearranging them to create new sounds [19]. This approach has the capability to generate one-of-a-kind and recognizable sounds that can improve the user's experience and add to the brand's identity in the field of electric vehicle sound design. Pure Data is a visual programming language designed for sound manipulation, specifically ideal for exploring granular synthesis. The adaptability, extensibility, and appropriateness of this tool make it perfect for investigating creative sound design approaches in the context of EV sound design, as well as for rapid prototyping and experimentation.

The impact of Pure Data and granular synthesis on EV sound design is substantial, as they expand the limits of innovative sound production and processing. These technologies and approaches together allow for the creation of sound characteristics that meet regulatory criteria and enhance the auditory experience. Their utilization of electric vehicle sound design not only solves safety problems related to the lack of noise in electric engines but also creates new opportunities for distinguishing brands and engaging users through sound. The literature analysis and state-of-the-art in EV sound design highlight the dynamic changes in sound technologies and approaches that are influencing the future of sound design in the automotive sector.

2.7 Regulatory Landscape

The regulatory environment regarding electric vehicle (EV) sound design is complex and multidimensional, involving both national and international rules and regulations. At the international level, the United Nations (UN) Regulation No. 138, also known as UN R138, outlines uniform provisions concerning the approval of quiet road transport vehicles concerning their reduced audibility [12]. This regulation mandates that electric vehicles meet requirements regarding the minimum sound pressure level, frequency content, and frequency characteristics in terms of a pitch shift of at least 0.8% per km/h in the speed range from 5 to 20 km/h [12].

In contrast, the US market follows different criteria under FMVSS 141, with key aspects such as the speed range in which a hearable sound is required and the frequency range for additional noise emissions deviating from UN R138 [12]. It provides frameworks for the implementation of Acoustic Vehicle Alerting Systems (AVAS). Table 2.1 compares the legislation for warning sounds in electric vehicles across three regions: the USA (FMVSS), the EU (GTR), and Japan. Each region has specific requirements for frequency, sound pressure level (SPL), speed, and sound characteristics.

Table 2.1: *Legislation for warning sounds in various countries [28]*

	USA (FMVSS)	EU (GTR)	JAPAN
Frequency	Broadband low-frequency sounds in the range of 160-5000 Hz	Sounds include at least two $\frac{1}{3}$ octave bands within the frequency range 50 Hz to 5 kHz	
Sound Pressure Level (SPL)	Minimum sound level as 49dB(A) at idle; 52dB(A) at reverse; 55,62 and 66dB(A)	62-66dB(A)	62-66dB(A)
Speed	10,20, and 30 km/h	20-41 km/h	20 km/h
Sound Characteristics		Prohibit using a siren, chime, bell, and emergency vehicle sounds; alarm sounds, e.g., fire, theft, and smoke alarms; intermittent sound; melodious sounds; animal and insect sounds; and sounds that confuse the identification of a vehicle and/or its operation	

The rules have a substantial impact on the decisions made regarding sound design for electric vehicles (EVs), especially when it comes to safety and environmental factors. These regulations require electric vehicles (EVs) to produce sounds at lower speeds in order to warn pedestrians, particularly visually impaired individuals, who may be at risk due to the lack of typical engine sound. The introduction of AVAS (Acoustic Vehicle Alerting Systems) is a direct response to the safety concerns associated with the near-silent operation of electric vehicles. AVAS systems are designed to assist visually impaired or distracted pedestrians in detecting approaching vehicles and to enhance overall safety by restoring the ability to perceive traffic situations audibly at an early stage [12]. However, the design of Acoustic Vehicle Alert System (AVAS) sounds is not exclusively focused on safety, but also on developing a pleasing and appealing brand identity.

As such, the development of a warning sound's detectability and annoyance is still going on. (Yasui and Miura, 2016; Jacobsen et al., 2016). This study addressed psychoacoustic matrices, such as loudness roughness, and fluctuation strength. According to the results of these papers, partial loudness is correlated with the annoyance of a warning sound; however, the detectability of a warning sound is not correlated with partial loudness because of background noise (Yasui and Miura, 2016).

Another research paper (Jacobsen et al., 2016) showed that the fluctuation strength is correlated with the detectability of a warning sound [20]. This study demonstrates a correlation between the detectability of a warning sound and the strength of the envelope's fluctuations at an 8 Hz frequency. However, this study did not take into account the phenomenon of background noise interference. This study developed a technique to objectively assess the auditory quality of a warning sound that is obscured by noise from the surroundings, taking into account the effect of masking. The study presents the development and utilization of a whining index as a sound metric to evaluate the whining sound that is obscured by noise in the background. The information provided was utilized to create an annoyance index and detectability index for electric vehicles [20].

Aside from legislative requirements, the preferences of stakeholders and the perceptions of users are important factors that influence the development of the acoustic design of electric vehicles. Research has shown that users prefer electric vehicles to sound like regular cars, resembling a combustion engine [27]. However, considerable inter-individual differences in the ratings of pleasantness and appropriateness indicate a great diversity of preferences among users [27]. Accordingly, sound engineers must effectively manage regulatory requirements, safety concerns, and user preferences while designing the optimal auditory environment for electric vehicles.

2.8 Case Studies and Applications

There has been a significant increase in the use of creative methods in the field of sound design for electric vehicles (EVs) with the goal of improving the auditory experience for both drivers and pedestrians. Case studies exploring advanced electric vehicle (EV) sound design frequently demonstrate a significant focus on developing a distinct acoustic character for vehicles, which is emerging as an innovative frontier for branding purposes. Engineers apply granular synthesis, a technology that enables the creation of intricate sound patterns and tones from basic audio samples, to develop distinctive sound signatures. The method's ability to produce dynamic and ever-changing soundscapes makes it especially appealing for EV sound design, where the auditory feedback needs to be useful yet not distracting.

The case study examines the difficulties and potential advantages of creating sound designs for electric vehicles, emphasizing their silent nature. The study highlights the significance of taking into account the psychological and cognitive elements that impact the human perception of sound, specifically in the context of electric vehicles where the lack of conventional engine noise might result in feelings of disorientation or discomfort [25]. The study highlights the need to adopt a comprehensive approach to sound design, which encompasses both technical and creative elements. This method guarantees that the sounds are not only useful but also visually appealing.

Another case study examines the sound design specifically for the engines of electric and hybrid vehicles. The study utilizes a methodology that is typical for engineers, including specialized design tools and techniques to conceptualize, sketch, create prototypes, and evaluate the auditory experience. The study emphasizes the significance of taking into account the listening approach and the specific sorts of sound analogies that most effectively facilitate interactions with the vehicle [22].

Nevertheless, the application of granular synthesis and Pure Data in sound design creates issues. The complexity of granular synthesis requires a deep understanding of sound processing techniques, making it challenging for non-experts to implement effectively [23]. Furthermore, the amount of equipment needed for granular synthesis can be substantial, which can restrict real-time implementation in some situations. Although there are challenges, the combination of granular synthesis and Pure Data presents favorable potential for generating innovative and engaging sounds in various sectors, such as the automotive industry.

Chapter 3

Methodology

3.1 Sound Design with Pure Data

Granular synthesis is utilized in this study to generate a wide range of sound designs for electric cars (EVs). The sound design method entails modifying different parameters of granular synthesis to generate specific auditory qualities, with Pure Data (Pd) as the main tool. The following is a comprehensive explanation of the selected parameters, the process of manipulation, and the concept behind each chosen source sound. Six parameters that are considered relevant in this context are selected for variation during the synthesis in this study. The following subsections describe the primary parameters.

3.1.1 Sound Source

To produce a particular sound using granular synthesis, it is necessary to pick an appropriate sound source. This study utilized two sound sources, specifically a violin string and wind. Each of these two sounds is associated with two distinct sound models, one with a low pitch and the other with a high pitch. There are a total of four sound sources that will be subjected to granular synthesis for further processing. Every one of these sound sources has unique characteristics that contribute to an extensive examination of texture and timbre when subjected to granular synthesis.

The sample of the violin string features natural richness in harmonic content and a vivid diversity in timbre. By applying granular synthesis techniques, the violin's inherent resonance and expressive tonal characteristics can be enhanced, resulting in rich and dynamic sounds. Manipulating specific characteristics such as grain density, pitch, and duration of the violin string sample, can generate a variety of outcomes, ranging from harmonious, flowing pads to sharp, repetitive patterns. This feature makes it especially well-suited for examining how slight modifications in synthesis parameters can significantly transform the emotional and aesthetic impact of a sound.

The wind sample, on the other hand, provides a sound that is more focused on texture and is often less clearly defined in terms of tone. Before any granular processing is applied, it exhibits the unpredictable nature of the environment, characterized by sudden bursts and periods of calm, which create a varying amplitude envelope. Granular synthesis allows for the amplification or reduction of these natural variations, and the stochastic configurations of parameters such as grain pitch and density can imitate or intensify the wind's intrinsic unpredictability. This sample is ideal for investigating the spatial and atmospheric characteristics of sound. It has the potential to be utilized in the development of engaging virtual environments or unpleasant visual experiences, depending on the precise manipulation of its granular properties.

3.1.2 Density

Controls how densely the grains are packed together over time. In this study, a density value of 100 grains per second will be used. This unit effectively describes how often sound grains are initiated per second, higher values increase the rate at which grains are triggered, leading to a thicker, more continuous sound. Density in granular synthesis refers to the degree of compactness of the grains. A greater density results in more frequent triggering of grains, resulting in a sound that has fewer periods of silence or gaps between the grains. In contrast, a decrease in density results in a greater number of visible gaps, which might create a perception of sparsity or scatter in the sound. Hence, by manipulating the density, one can significantly alter the texture of the sound. Increased densities can result in a smoother sound experience or even provide a tone-like characteristic, as the quick sequence of particles merges into a perceived unique sound [10]. Reduced densities preserve the distinct nature of each grain, enabling the ear to recognize specific occurrences or beats [10].

3.1.3 Duration (milliseconds)

Grain duration corresponds to the temporal length of the grain envelope, typically measured in units of seconds or milliseconds [19]. Adjusting this parameter affects how long each individual grain will last. Shorter durations can create a more staccato effect, while longer durations can blend the grains into a smoother texture [32]. Furthermore, this characteristic is also linked to the amplitude of the sound. The duration of a grain normally falls within the range of 1 to 50 milliseconds, although there is no strict rule governing this [19]. However, this study employed grain durations of 500 ms, which are comparatively longer than the typical durations.

The grain duration chosen for this study was initially determined based on the investigation carried out by Fröjd and Horner [13]. The study revealed that the overlap-add texture synthesis generates more authentic sounds when the duration exceeds 1 second. Thus, a pilot study was done with specialists in noise, vibration, and harshness (NVH) to examine grain lengths that were close to 1 second. The findings of the pilot study indicated that the range of grain duration is considered suitable for achieving the goals of the current study.

3.1.4 Pitch

Alters the pitch of the grains. In granular synthesis, pitch is often controlled by changing the playback speed of the grain. Higher values speed up the playback, raising the pitch, while lower values slow it down, lowering the pitch. By manipulating the playback speed of the grains, it fundamentally alters their frequency. Specifically, enhancing the speed results in an elevation of the frequency, which causes the sound to become sharper. However, reducing the speed has the opposite effect. The pitch control in granular synthesis not only changes the tonal characteristics but also has an impact on the sound's texture. Increased speeds can result in a more compact and uninterrupted sound, particularly when the particles strongly overlap. On the other hand, reducing the speed could enhance the granular texture of the sound, making it easier to distinguish the individual grains.

In this research, as shown in Table 3.1 sixteen distinct sounds were produced using granular synthesis. As previously stated, two sound sources were employed: the violin and the wind, which were combined to create four sounds. Each of these was then subjected to a processing stage, resulting in the final six-

Sound Source	350 Hz	500 Hz	1000 Hz	2000 Hz
String 1 + Wind 1	Sound 1	Sound 2	Sound 3	Sound 4
String 1 + Wind 2	Sound 5	Sound 6	Sound 7	Sound 8
String 2 + Wind 1	Sound 9	Sound 10	Sound 11	Sound 12
String 2 + Wind 2	Sound 13	Sound 14	Sound 15	Sound 16

Table 3.1: *The auditory stimuli used in the experiment, categorized by sound source and frequency. The sounds were created using combinations of string and wind sounds at four different frequencies: 350 Hz, 500 Hz, 1000 Hz, and 2000 Hz. Each cell in the table indicates a specific sound used in the experiment, labeled sequentially from Sound 1 to Sound 16. The use of varied sound sources and frequencies aims to comprehensively evaluate the impact of these auditory stimuli on participants' perceptions.*

teen sounds. The processing stage was determined by taking four different frequencies, namely 350 Hz, 500 Hz, 1000 Hz, and 2000 Hz. As has been done in previous research, it set out to test the efficacy of different kinds of artificial exterior vehicle sounds that might be employed as auditory eHMIs to alert pedestrians to an approaching car [4]. Those ranges of frequencies were chosen due to the fact that Research has established that the auditory perception of individuals in their early adulthood is most sensitive between the frequency range of 2000 Hz to 5000 Hz, with the highest level of sensitivity occurring around 3000 Hz [18]. There are several reasons to avoid higher frequencies. One reason is that the exterior loudspeakers may have issues with directivity. Another reason is that the sound emitted at higher frequencies may be attenuated too much by atmospheric absorption, which would require very loud emission levels to remain effective. Additionally, the optimal frequency tends to decrease with biological age, so testing at 3000 Hz may be less relevant. As a point of comparison, the sirens of emergency vehicles typically have frequencies ranging from 400 Hz to 2000 Hz, as advised by sources [3], [7], [8].

Figure 3.1 displays a granular synthesis patch in Pure Data (PD). This patch is designed to manipulate audio samples using granular synthesis. In this patch, two audio files can be loaded and processed simultaneously, as indicated by the two parallel setups on the left and right sides. Each setup includes components for loading an audio file, determining its length, and controlling the playback of grains. Key parameters such as density, randomness, pitch, and duration of the grains can be adjusted using sliders and number boxes. The patch also includes mechanisms for reading, resizing, and processing the audio samples, enabling

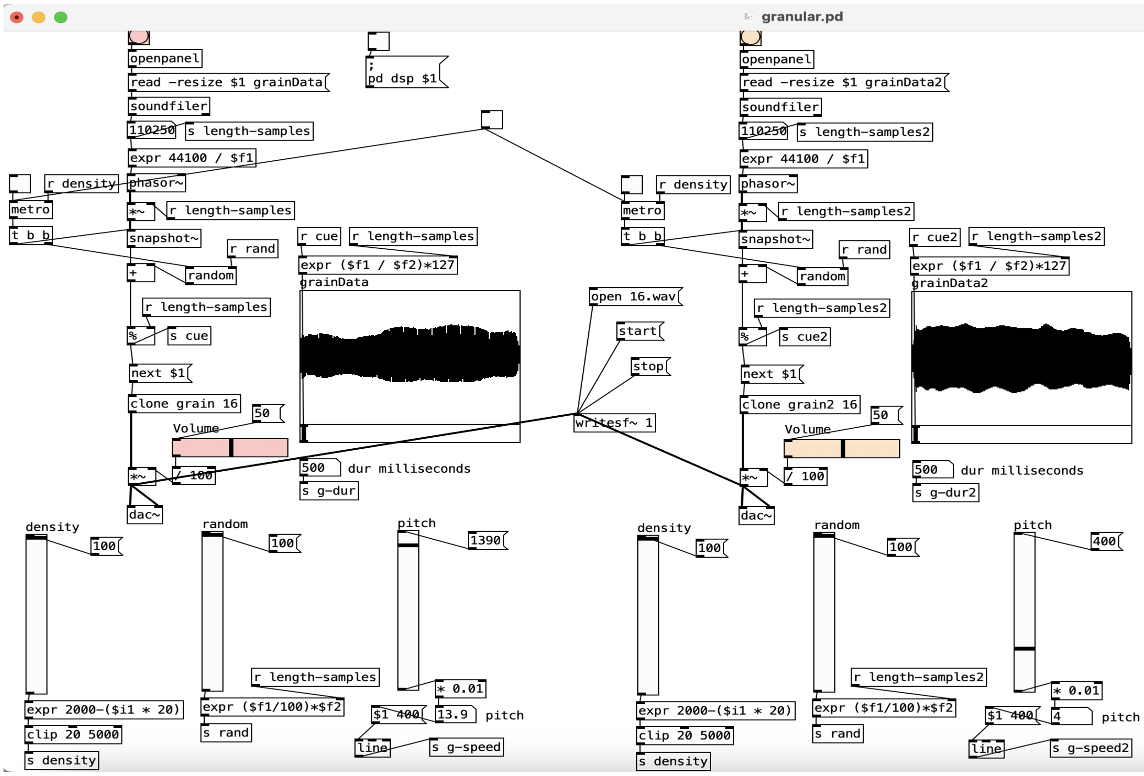

Figure 3.1: *Granular Synthesis Patch in Pure Data for Audio Processing*

a wide range of sonic transformations. The visual representations of the audio samples and the real-time manipulation controls highlight the flexibility and creativity inherent in granular synthesis using Pure Data.

3.1.5 Random

Introduces a random element to the density and pitch parameters. The random parameter in granular synthesis is used to introduce variations in one or more aspects of grain playback, such as the timing of grain initiation (density), the duration of grains, their spatial positioning, or their pitch. By using randomness, the synthesis can avoid sounding too mechanical or repetitive, thus closely mimicking the irregularities found in natural sounds [33]. By incorporating variations in the timing, pitch, and duration of grains, random parameters can be utilized to generate less predictable sounds that are more similar to natural sounds [33]. This is advantageous in applications such as ambient music or sound design for film and video games, where a realistic sound quality is sought after [33]. Stochastic fluctuations can greatly enhance the perceptual intricacy of the sound.

Even insignificant, unpredictable modifications may enhance the complexity and unpredictability of a basic sound source. Typically, in most synthesis systems, such as Pure Data, it is possible to regulate the level of unpredictability. This enables the sound engineer to determine the optimal level of variation suitable for the specific sound situation. For instance, a subtle variation in pitch could be employed to mimic the inherent variations in the tone of a string instrument or a more pronounced variation could be utilized to create unique sound effects [36].

3.1.6 Speed

It controls the playback speed of the grain streams, affecting both pitch and duration in a real-time processing scenario. Speed in granular synthesis commonly controls how fast the audio samples within a grain are played. This involves adjusting the playback speed of the sound file being processed. Increasing the playback speed results in the samples being played more quickly, which raises the pitch of the sound. Conversely, reducing the speed lowers the pitch. Altering the speed also changes the duration of each grain. A faster speed shortens the grain's duration (since the samples are played more quickly), while a slower speed elongates it.

Modulating the speed can change the pitch and quality of the output. For instance, lower speeds might generate a prolonged and unsettling impact, which is well-suited for creating soundscapes or ambient music. On the other hand, higher velocities can result in a vibrant and cheerful sound quality. Variations in speed can cause rhythmic variations in the granular texture, especially when the particles are synchronized with a musical tempo or coordinated with other rhythmic elements in a piece [24].

3.2 Experimental Design

The main objective of the experimental setup for this thesis is to systematically evaluate the impact of the various sound designs generated by granular synthesis on the perception of individuals. The experiment seeks to evaluate the effectiveness of these sounds in alerting pedestrians, improving user satisfaction, and observing current restrictions regarding sound emissions from electric vehicles

(EVs). It aims to provide significant insights into how sound design can enhance safety and public acceptance of sustainable mobility solutions, consequently fulfilling its objectives.

3.2.1 Effectiveness of Sound Alerts

The effectiveness of sound alerts is an important factor in ensuring the safety and accessibility of various systems, such as transportation and technology. Within the context of electric vehicles, it is essential to carefully develop and utilize alert sounds to successfully indicate the vehicle's presence and movement to pedestrians, especially those with various types of hearing capabilities.

Research has demonstrated that the design and perceptibility of alert sounds are crucial factors in their efficiency [26]. For example, providing an intro or an alert regarding a sound before its actual hearing can enhance our ability to perceive and identify the sound. Hence, using familiar or similar sounds may improve the capacity to recognize and define them. Nevertheless, there are possible disadvantages associated with the use of alert sounds, including reduced response time when multiple sounds are played simultaneously and increased discomfort caused by repetitive sounds.

Alert sounds are typically designed to communicate an impression of urgency and focus attention on essential and crucial situations. This includes assessing the ability to detect and recognize sounds that indicate the presence of an approaching vehicle, particularly in situations when normal engine sounds are not present. It's important to design alert sounds that are not only detectable but also recognizable as indicative of an approaching electric vehicle, especially in environments where traditional engine noises are absent [5]. The researchers evaluated the detectability and recognizability of different alert sound designs, aiming to enhance pedestrian safety and promote the successful integration of electric vehicles into urban environments [5].

Regarding the effectiveness of electric vehicle warning sounds different background noises can significantly affect pedestrians' detection of these warning sounds. It needs to design sounds that are detectable and recognizable, even in the presence of various environmental sounds [28]. By assessing the detectability and recognizability of the designed sounds, especially in environments where traditional engine noises are absent, the aim is to improve pedestrian safety and promote the successful integration of electric vehicles into sustainable mobility systems.

3.2.2 Compliance with Regulatory Standards

Following regulations for sound emissions is crucial in the context of electric vehicles (EVs) to guarantee pedestrian safety and avoid accidents. The purpose of these regulations is to reduce the risks connected with the characteristically low sound level of electric vehicles (EVs), which can make them less obvious to pedestrians, especially those who have visual impairments. This section of the thesis is dedicated to verifying that the sounds created by granular synthesis comply with both international and national regulatory norms.

Regulations, such as those specified by the United Nations Economic Commission for Europe (UNECE) or the U.S. National Highway Traffic Safety Administration (NHTSA), establish the minimum safety requirements for electric vehicles (EVs) [35]. These regulations define the required sound levels for vehicles at different speeds and occasionally describe the characteristics of the sounds (such as continuous or pulsating) that need to be produced to enhance visibility in urban areas. Various nations might establish particular prerequisites or additional rules in addition to the global norms. For instance, the European Union and Japan have distinct standards that specifically address sound levels during various vehicle operation modes, such as idling, starting, or stopping [28]. Local restrictions can have an impact on sound standards, particularly in metropolitan areas with heavy pedestrian activity or specialized background noise concerns.

The experiment aims to assess the detectability and recognizability of each designed sound by examining their frequency range and loudness while ensuring that they do not cause any disturbance or add to noise pollution. The process involves the measurement of sound levels in decibels (dB) at designated distances and the subsequent comparison of these levels with regulatory criteria. The tonal characteristics, encompassing pitch, and timbre, play an essential part in both complying with regulations and ensuring that the sounds are agreeable and contextually suitable.

Regulations stipulate specific tone attributes to guarantee that noises may be readily recognized as originating from a vehicle rather than any other source [11]. Certain regulations mandate that the sounds produced by vehicles must change dynamically according to the vehicle's speed to imitate the sounds typically associated with traditional internal combustion engines [11]. This dynamic responsiveness allows pedestrians to instinctively assess the velocity and closeness of an electric vehicle. Evaluation involves the simulation of various vehicle speeds to verify that the sound modifications are following these changes.

3.2.3 Psychological Impact

An important part of a study on sustainable mobility and electric vehicles (EVs) is to examine the psychological impact of various sound designs on individuals. The study's focus on this aspect is essential, as the auditory perception of an environment has a substantial impact on individuals' psychological comfort and the overall quality of urban life. The following subsections contain an in-depth analysis of what the process of analyzing the psychological impact involves.

3.2.3.1 The Importance of Sound in the Urban Environment

a Annoyance Ratings

Each sound will receive an evaluation from the participants indicating how annoying they find it. A complicated psychological reaction, annoyance can have an impact on a person's overall level of contentment with their urban environment as well as cause longer-term discontent and an impairment in their quality of life.

b Perceived Pleasantness

This involves evaluating how 'pleasant' or 'unpleasant' each sound is perceived to be. Pleasantness is often associated with sounds that are harmonious and non-intrusive, whereas unpleasant sounds are typically dissonant, loud, or unexpected.

3.2.3.2 Perception and Preference

An essential aspect of understanding the public's reception and potential improvement of various sound designs for electric cars (EVs) is to investigate the perception and preference of these sounds. The current stage of the study concentrates on collecting and examining subjective data from various demographic groups to determine which sounds are preferred and the particular features that influence these preferences. The following are the significance of studying perception and preference:

a User-Centred Design

When it comes to EV sound design, it is essential to understand user preferences to create noises that are both functionally efficient and aesthetically pleasant to the wider population. This alignment enhances the probability of positive reception and smooth integration of electric vehicles (EVs) into everyday life.

b Safety and Recognition

From the perspective of safety, the sounds must be immediately recognizable as an alert of an approaching vehicle. The examination of the preference data can determine if the sounds communicate this information to different demographic groups, hence enhancing the safety of the urban environment.

c Aesthetic Considerations

The significance of aesthetics plays an important role in determining the level of acceptance of new technologies. Harmonious and aesthetically pleasant sounds have the potential to improve the user experience and create enjoyable interactions with electric vehicles (EVs).

d Contribution to Sustainable Mobility

The key objective of this thesis is to enhance the topic of sustainable mobility by optimizing sound designs specifically for electric vehicles (EVs). This objective involves various fundamental elements of sustainability, such as ecological footprint, safety, urbanization, and social acceptance of emerging technologies.

3.2.4 Simulated Environment Description

The experiment is carried out in a simulated, controlled setting designed specifically to evaluate the efficacy of different EV sound designs. The setting, a soundproof room or anechoic chamber, is designed to isolate sound characteristics that are important to the study while closely simulating situations in real life.

a Room Specifications

Soundproofing: To remove any outside noise interference that might interfere with the auditory tests, the room has been fully soundproofed. To ensure that participants can hear the sounds as they truly are, soundproofing materials are placed around the walls, ceiling, and floor.

b Audio Equipment

To ensure that the EV sound designs are accurately reproduced, participants wear high-quality headphones. In order to effectively isolate sound and reduce outside distractions and influences throughout the experiment, closed-back headphones have been used. The participants will always have a consistent and engaging audio experience because the headphones transmit the sound straight to their ears.

c Audio Playback System

The soundproof room has an audio playback system installed so that participants can observe the EV sound designs. The headphones are connected to a computer or other audio device that serves as the playback system, giving the user precise control over how the auditory stimuli are played back. Throughout the experiment, the system maintains consistency by delivering sound to each participant in an identical manner.

d Participant Instructions and Guidance

Before the experiment starts, participants are given clear instructions and directions to make sure they understand the activities and processes involved. In order to guarantee efficient operation and accurate data gathering, researchers remain present to supervise the experiment and offer support or clarification as needed.

3.3 Participant Recruitment

The effectiveness of the experiment relies significantly on the thorough selection and recruitment of participants. The subsequent information outlines the recruitment approach, including the selection criteria and demographic considerations, in order to guarantee that the study obtains a varied and inclusive variety of feedback.

3.3.1 Selection Criteria

To provide a thorough and reliable data set for the experiment, careful consideration is given to the selection criteria for selecting participants. The inclusion criteria are created to accommodate a broad range of auditory function abilities and experiences with vehicle sounds. Participants are required to be between the age range of 18 to 70 years to ensure a varied and inclusive age group. Every participant is expected to have normal or **corrected-to-normal** hearing, which will be confirmed by a standard hearing test, in order to verify their ability to accurately perceive a wide range of frequencies. Both drivers and non-drivers are included to collect different perspectives on vehicle sound recognition and familiarity. In addition, participants must have a high level of proficiency in the language used in the questionnaire, such as English. This ensures that they can fully grasp the tasks and questions presented during the experiment and provide accurate responses.

On the other hand, the exclusion criteria are designed to preserve the accuracy of the data gathered by removing potential variables that might affect the results. Individuals who have substantial hearing impairments that may impact their ability to perceive sounds appropriately are not included. Individuals with cognitive impairments that might affect their ability to comprehend or capacity to carry out activities will also be excluded from participation. In addition, those who have health conditions that may worsen as a result of response to different sound levels or prolonged use of headphones, such as tinnitus or hyperacusis, are not included in order to prioritize the safety and comfort of the participants during the experiment. The purpose of these criteria is to narrow down the group of participants and ensure that the results of the experiment are reliable and accurately represent how the general population responds to new electric vehicle sound designs.

3.3.2 Demographics

Since it is important to ensure that the experiment represents a wide variety of social perspectives, the participant demographics are thoroughly selected to reflect various elements of society. The study has a specific objective of examining gender diversity to explore any potential preferences or perceptual variations related to sound design based on gender. This methodology helps in discerning the potential variations in the perception of electric vehicle sounds among different genders, hence promoting the adoption of more inclusive designs.

In addition, the recruitment strategy includes participants from various ethnic and cultural backgrounds. The inclusion of many perspectives plays a role in understanding how cultural elements might impact the perception and reception of electric vehicle (EV) sounds, guaranteeing that the sound designs are globally impactful and culturally adapted.

Furthermore, the study places significant emphasis on socioeconomic diversity, ensuring that people from diverse economic backgrounds are represented. This methodology guarantees the applicability of the results across different categories of society, demonstrating how varying economic circumstances can influence people's access to technology and their reactions to improvements in electric vehicle sound design. The study tries to develop designs that are technically effective widely accepted and adaptable across diverse parts of society by including these demographic characteristics.

3.4 Data Collection Method

3.4.1 Experimental Procedures

To completely analyze the sound designs made using granular synthesis, a precise and controlled experimental approach is constructed. The following procedure covers the step-by-step process for doing the experiment in a simulated environment, specifically in a soundproof room utilizing headphones. The purpose is to measure the ease of noticeability, the sufficiency of the context provided by the sound to alert pedestrians to a vehicle's approach, and any potential annoyance factor of each sound design. Here's a thorough description of the experimental procedures:

3.4.1.1 Preparation Phase

a Setup of the Soundproof Room:

Prior to initiating any sessions, the soundproof room is properly arranged to guarantee its isolation from any external sounds or disruptions. The room is furnished with high-quality headphones that undergo a careful evaluation to ensure their proper and constant performance.

b Participant Briefing:

Upon arrival, each participant is briefed about the experiment's objectives and their role. This briefing provides a summary of what participants might anticipate throughout the session and clarifies the significance of their genuine and subjective feedback. Participants are also notified of their right to withdraw their involvement in the study at any given moment.

3.4.1.2 Testing Phase

a Initial Baseline Survey

Participants are required to fill out a pre-experiment questionnaire in order to document their initial state and any current opinions regarding electric vehicles (EVs) or auditory sensitivity. This facilitates comprehension of the participant's initial condition and enables the adjustment of data analysis accordingly.

b Audio Playback

Participants are positioned in a comfortable position, and equipped with headphones. The experiment is carried out in a controlled manner, where each sound design is played separately through the headphones.

c Immediate Feedback Collection

After completing each activity, participants promptly answer a set of questions regarding the sound they have just heard. This involves evaluating the sound based on its perceptibility, adequacy of recognition, information, pleasantness, and levels of discomfort. This prompt feedback aids in capturing the participants' responses without any distortion caused by recall bias.

3.4.2 Tools and Technologies Used

The experiment utilizes state-of-the-art audio playback devices, innovative software for sound design and data collecting, and ergonomic arrangements to guarantee participant comfort and data integrity. The following is a comprehensive summary of the specialized equipment and software solutions that have been incorporated into the experimental methods to collectively facilitate the objectives of this research activity.

3.4.2.1 Audio Playback Equipment

a Headphones

High-quality and closed-back headphone models such as the Shure SRH1540 Headphones are used to ensure excellent sound isolation, allowing participants to focus solely on the test sounds without external noise interference.

b Computer System

A computer or laptop equipped with a high-performance sound card is tasked with playing back the sound files and managing the experimental software, ensuring smooth operation. The system is optimized for seamless integration with both sound design and data collection software.

3.4.2.2 Sound Design Software

a Pure Data (Pd)

Pure Data is employed for designing and modifying the granular synthesis sounds used in the experiments. It allows for real-time sound processing and generation, crucial for adjusting parameters during preliminary tests and achieving the desired sound characteristics.

3.4.2.3 Data Collection and Analysis Tools

a Survey Platform

The experiment utilizes SurveyMonkey to distribute questions and get feedback from participants. This platform is selected for its user-friendly interface and robust data collection and analysis capabilities. SurveyMonkey seamlessly integrates with the experimental workflow, allowing for immediate response collection after audio testing, which aids in correlating participant reactions with specific sound exposures.

b Data Analysis Software

RStudio is used as the primary tool for recording, analyzing, and visualizing the experimental data. Its extensive analytical tools enable detailed analysis of participant responses and sound characteristics. It is a powerful integrated development environment (IDE) for R, a programming language and software environment used for statistical computing and graphics. It supports complex data manipulation, statistical analysis, and graphical representation, thus, it becomes a necessary method for analyzing the technical data collected during the experiments.

c Database Management

A robust database system is utilized to securely store and manage the raw data obtained from the experiments. This technology guarantees the accuracy and security of data, while also adhering to privacy regulations. The data is secured against loss or unauthorized access through regular backups and strict security measures.

3.5 Questionnaire Design

3.5.1 Survey Questions

This is a comprehensive explanation of the survey questions, complete with explanations for each one, which is designed to assess the significant aspects of sound perception, like perceptibility, informativeness, and annoyance levels. The questions in this questionnaire are based on previous research, who has conducted research with sound experiments by participants who were asked to rank the sound based on three criteria: (1) ”easy to notice”, (2) ”gave me enough information to realize that a vehicle was approaching”, and (3) “annoying” [4].

3.5.1.1 Pre-Experiment Questions

- Age: What is your age?

  The answer to this question will be provided without mentioning a specific age range, allowing participants to provide their ages directly. This approach offers enhanced accuracy in gathering data, enabling the detection of age-specific trends and patterns with more precision. This can be particularly advantageous in studies that investigate developmental phases or specific age-related impacts when the precise age is essential for precise analysis [16]. Moreover, collecting precise ages provides more flexibility in data processing. The data can be categorized or segmented into age groups once it has been collected, in order to meet the specific requirements of the analysis. This is especially beneficial when the most pertinent age categories are not predetermined. Additionally, it decreases the likelihood of categorization bias, wherein participants may perceive that pre-established age brackets do not precisely reflect their age, resulting in more precise self-disclosure.

  Collecting precise ages under stringent constraints in the context of data privacy ensures that the data collection procedure complies with ethical standards, consequently safeguarding respondent confidentiality and data security. Furthermore, this method can improve the involvement of survey participants by offering a feeling of customization and precision in the survey completion process. This has a particular impact on longitudinal studies, where obtaining accurate age information can cultivate a stronger sense of participation and devotion to the research results.

- Gender: What is your gender?

  Gender can have a substantial impact on perceptual and cognitive processes, which might potentially influence how individuals perceive and react to certain sound designs. Through the collection of gender information, the research can investigate potential disparities in the recognition, informativeness, and annoyance of electric vehicle sounds based on gender. This data may help in guaranteeing that the sound designs are comprehensive and efficient across various demographic cohorts. Moreover, comprehending gender-specific reactions is helpful in generating more customized and accurate suggestions for audio design in electric vehicles, consequently augmenting overall consumer contentment and security. Collecting this demographic data also facilitates the examination of a representative category, guaranteeing that the conclusions may be applied to a wider population.

- Hearing Sensitivity: Do you have any hearing impairments or conditions that affect your hearing? If yes, please describe.

  This question is essential for guaranteeing the precision and significance of responses in studies about auditory perception or contexts where sound plays an important part. Through the identification of persons with hearing impairments, researchers can analyze data with a more detailed understanding of how these impairments may impact the perceptions, experiences, or outcomes being examined. The process of differentiation is crucial in order to customize interventions, advice, or goods to meet the varied needs of a population, particularly in domains such as audiology, occupational health, and public safety. Moreover, recognizing and making provisions for those who have hearing difficulties improves the inclusiveness and ethical principles of the study. It guarantees that the analysis takes into account the experiences of all participants, hence facilitating the development of more efficient and inclusive solutions and policies. This strategy not only enhances the quality of the data but also matches with broader objectives of accessibility and inclusiveness in research techniques.

- Familiarity with EVs: How familiar are you with electric vehicles?

(1) Not at all familiar

(2) Not so familiar

(3) Neutral

(4) Somewhat familiar

(5) Very familiar

This question facilitates the categorization of responses according to the respondents' level of familiarity, which can have a substantial impact on their viewpoints regarding subjects such as electric vehicle technology, ease of use, sustainability factors, and potential challenges to adoption. For example, individuals who have extensive knowledge of electric vehicles (EVs) might offer valuable perspectives on the specifics of EV utilization, maintenance issues, and the effectiveness of existing infrastructure. On the other hand, people who are less acquainted with EVs can express concerns due to perceived difficulties or a general sense of doubt. Researchers can use the information retrieved from this question to identify distinct educational or marketing tactics targeted at certain segments of the population. This strategy amplifies the significance and influence of the study results, assisting stakeholders in the automotive industry, policymakers, and consumer educators in their attempts to accelerate the acceptance of electric vehicles (EVs). Moreover, comprehending this aspect of consumer consciousness helps to develop policies and initiatives that manage the lack of information and facilitate a more seamless shift toward sustainable mobility.

3.5.1.2 Sound Design Perception

The questionnaire as shown in figure 3.2, created using Survey Monkey, is designed to evaluate various sound designs for electric vehicles. Participants listen to a specific sound clip and rate it based on four criteria as described below, Each criterion is rated on a scale from 1 to 5, where 1 represents the least favorable evaluation and 5 represents the most favorable evaluation.

a. Recognition:

- How recognizable is this sound as a vehicle sound?

  (1) Not recognizable at all

  (2) Somewhat recognizable

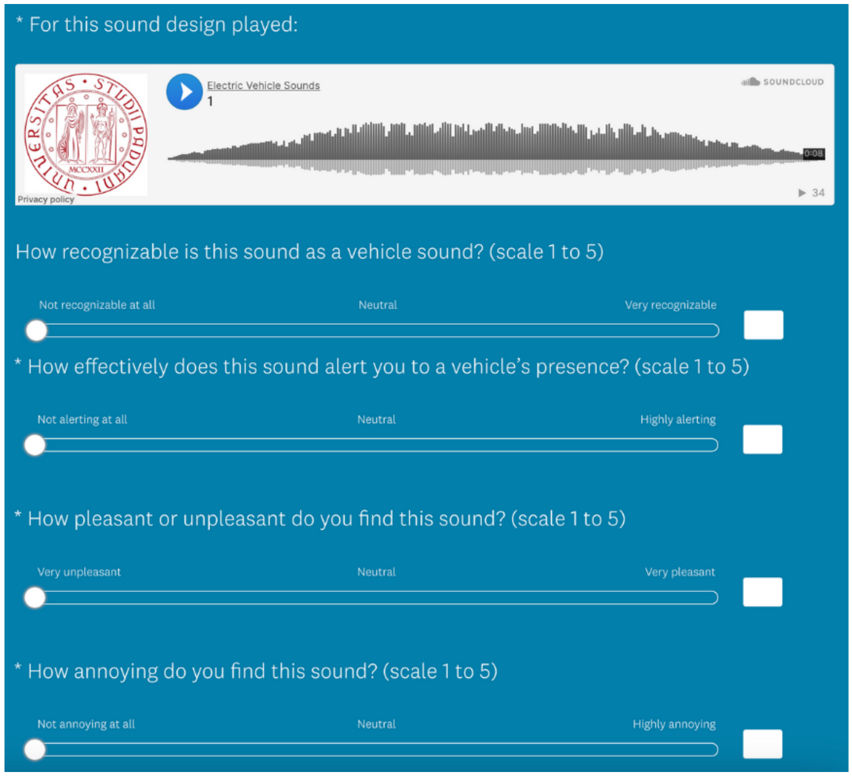

Figure 3.2: *Survey Questionnaire for Evaluating 16 Electric Vehicle Sounds*

(3) Neutral

(4) Recognizable

(5) Very recognizable

The initial questioning is used to assess and determine if the participant can correctly identify the sound as being related to a vehicle. It is important to determine whether the sound design fulfills the essential need of being connected to a vehicle. The scaled question seeks to quantify the extent to which the sound corresponds to a vehicle, offering a spectrum of how easily it may be recognized. This is of utmost importance because the sound must not only be discerned as vehicle sound by individuals acquainted with traditional vehicle sounds but also easily recognized to guarantee safety and efficiency in real-life situations.

b. Alertness:

- How effectively does this sound alert you to a vehicle's presence?
  (1) Not alerting at all
  (2) Somewhat alerting
  (3) Neutral
  (4) Alerting
  (5) Highly alerting

This question evaluates the efficacy of a sound in capturing attention and alerting the arrival of a vehicle. It is necessary for safety to ensure that pedestrians and other road users are aware of the vehicle's presence, which could potentially prevent accidents. The range in reactions enables an evaluation of how easily and effectively the sound communicates the urgency or familiarity of an oncoming vehicle, which is important for passengers to respond correctly.

c. Pleasantness:

- How pleasant or unpleasant do you find this sound?
  (1) Very unpleasant
  (2) Unpleasant
  (3) Neutral
  (4) Pleasant
  (5) Very pleasant

This question assesses the visual attractiveness of the sound, which is important in determining approval and comfort. An aesthetically pleasing or at least neutral auditory stimulus can enhance the entire user experience, encouraging a good reception of electric vehicles (EVs) and facilitating their wider acceptance.

d. Annoyance Reaction:

- How annoying do you find this sound?
  (1) Not annoying at all
  (2) Slightly annoying

(3) Neutral

(4) Annoying

(5) Highly annoying

The initial screening assesses whether the sound causes any immediate adverse bodily or psychological impacts, such as creating tension or discomfort. It is crucial to determine whether the sound could have adverse impacts on the way one feels. This scale measures the degree of annoyance, which makes a difference in assessing the long-term acceptability of the sound. Elevated degrees of discomfort might discourage public acceptance and result in resistance towards the widespread use of such electric vehicle sounds.

Chapter 4

Results

4.1 Data Presentation

This part focuses on the results of the experiment conducted to assess the impressions of different sound designs produced using granular synthesis, utilizing Pure Data, on the perception of drivers and passengers in the context of electric vehicles (EVs). The data presentation is organized in a manner that offers both quantitative and qualitative insights, which collectively provide an overall perspective on how sound design may influence sustainable mobility practices.

The sound design process started with the conceptualization phase, during which the fundamental characteristics of sound that impact human perception, such as pitch, duration, and timbre, were determined and organized based on the specific criteria for EV sound emissions. We employed granular synthesis techniques in Pure Data to modify the sound attributes and generate a list of sound samples designed to evaluate different perceptual impacts.

Every sound had been carefully created to comply with prospective regulatory requirements while also improving the auditory branding of the vehicles. The utilization of granular synthesis facilitated the capacity to precisely manipulate each component of the sound, thus enabling accurate modifications that catered to desired results such as clarity, recognizability, and alert efficacy. The adaptability of Pure Data enabled the process of iterative testing and refinement, allowing for continuous adjustments of sounds based on initial testing feedback before finalizing the prototypes for the experimental phase.

4.1.1 Quantitative Results

The questionnaire data provides a comprehensive quantitative analysis of the viewpoints of participants on various electric vehicle sound designs. The findings are categorized based on specific questions and their corresponding answers.

4.1.1.1 Participant Demographics

The participants' ages varied from 19 to 41 years. This range includes individuals from the young adult stage to the early middle-aged stage, offering a wide range of perspectives related to age. By including participants from several age groups, the evaluation of sound designs considers differing auditory sensitivities and preferences that may be influenced by age. Younger participants may have an enhanced response to higher frequencies and a desire for more contemporary sound aesthetics. In contrast, older individuals might offer valuable insights about traditional sound preferences and potential changes in hearing abilities associated with age.

4.1.1.2 Gender Distribution

The participants were distributed by gender as follows: 41.67% identified as female (10 participants) and 58.33% identified as male (14 individuals) as shown in Table 4.1. This distribution facilitates the examination of gender-specific impacts on the sound designs, which matters since males and females may have distinct perceptions and responses to sounds. Gender disparities in sounds may impact the overall effectiveness, pleasantness, and annoyance levels of sound designs, underlining the necessity for inclusive sound design that accommodates both genders.

Table 4.1: *Results from question about Gender*

ANSWER CHOICES	RESPONSES	QUANTITY
Female	41.67%	10
Male	58.33%	14
Other (specify)	0%	0
Total		24

4.1.1.3 Hearing Impairments

When questioned about hearing impairments or conditions that impact their ability to hear, 95.83% (23 participants) stated that they do not have any hearing impairments, whereas 4.17% (1 person) reported having a hearing impairment. This demographic information is essential as it guarantees that the sound designs are primarily assessed by individuals with typical hearing abilities while also incorporating the perspectives of those with hearing disabilities. By including those with hearing impairments, the sound designs become accessible and effective for all, which is important, especially for public safety.

4.1.1.4 Familiarity with Electric Vehicles

The participants were instructed to assess their level of acquaintance with electric vehicles (EVs) using a rating scale that ranged from 1 to 5, where 1 represented "Not at all familiar" and 5 represented "Very familiar" The average score was 3, suggesting an average level of familiarity with electric vehicles among the participants. This information has significance as it offers the context needed for understanding how they respond to sound designs. Participants with a higher level of familiarity with electric vehicles (EVs) may hold distinct expectations and views in contrast to those with a lower level of familiarity. The level of familiarity with sound designs can impact their recognition, effectiveness, pleasantness, and annoyance levels.

Figure 4.1 presents the Gaussian (normal) distribution of familiarity ratings for a study involving 24 participants. The x-axis represents the familiarity ratings, ranging from 1 to 5, while the y-axis represents the frequency density of these ratings, which is fitted to the data, with a mean familiarity rating of approximately 2.95 and a standard deviation of 1.27. The highest density is around the mean rating, indicating that most participants rated their familiarity around the central value, with fewer ratings at the extremes

The Gaussian curve demonstrates the typical bell-shaped pattern, which is characteristic of normal distributions. This pattern indicates that most participants rated their familiarity around the central values (3 and 4), with fewer participants giving ratings at the extreme ends (1 and 5). This distribution helps to understand how familiarity ratings are spread among the participants, suggesting that most participants have a moderate to high level of familiarity.

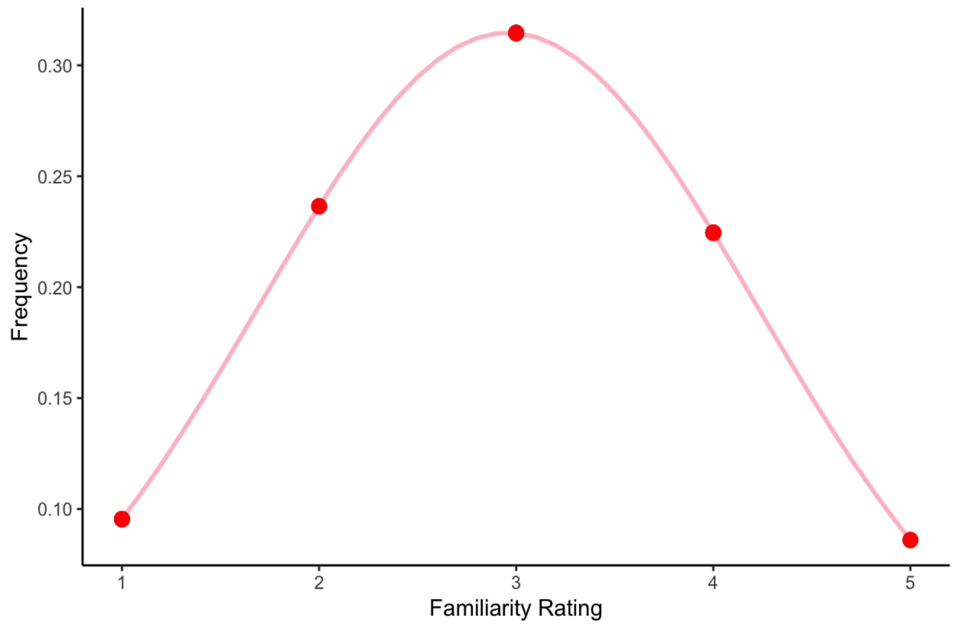

Figure 4.1: *Gaussian distribution (pink curve) of familiarity ratings (1-5) from 24 participants. The pink curve illustrates the Gaussian distribution, calculated based on the mean and standard deviation of the familiarity ratings. The red dots indicate the actual data points, showing how often each rating was given by the participants.*

4.1.1.5 Recognition of Vehicle Sounds

The identification of vehicle sounds is an important component of the study as it directly influences the effectiveness of sound designs for electric vehicles (EVs). It is imperative to ensure that these sounds can be easily recognized as vehicle sounds to ensure the safety of pedestrians, especially in urban environments where electric vehicles (EVs) are becoming increasingly common. This section provides a detailed explanation of the results obtained from the experiment on the recognition of vehicle sounds. Participants were asked to rate how recognizable each sound was as a vehicle sound on a scale from 1 to 5, with 1 being ”Not recognizable at all” and 5 being ”Very recognizable.” The following detailed findings were observed: The scores for recognizability varied across the 16 sounds, reflecting the degree to which each sound could be identified as a vehicle. Sounds that closely mimicked traditional engine noises or included familiar auditory cues were generally more recognizable. Some sounds received higher scores, indicating they were easily identified as vehicle sounds. These sounds likely included elements such as consistent rhythmic patterns or specific frequency ranges associated with traditional combustion engines, which helped participants quickly recognize them as vehicle noises. Other sounds received lower scores, suggesting they were less effective in being recognized as vehicle sounds. These might have lacked distinct automotive auditory cues or had characteristics that were too subtle or unusual for participants to associate with a vehicle.

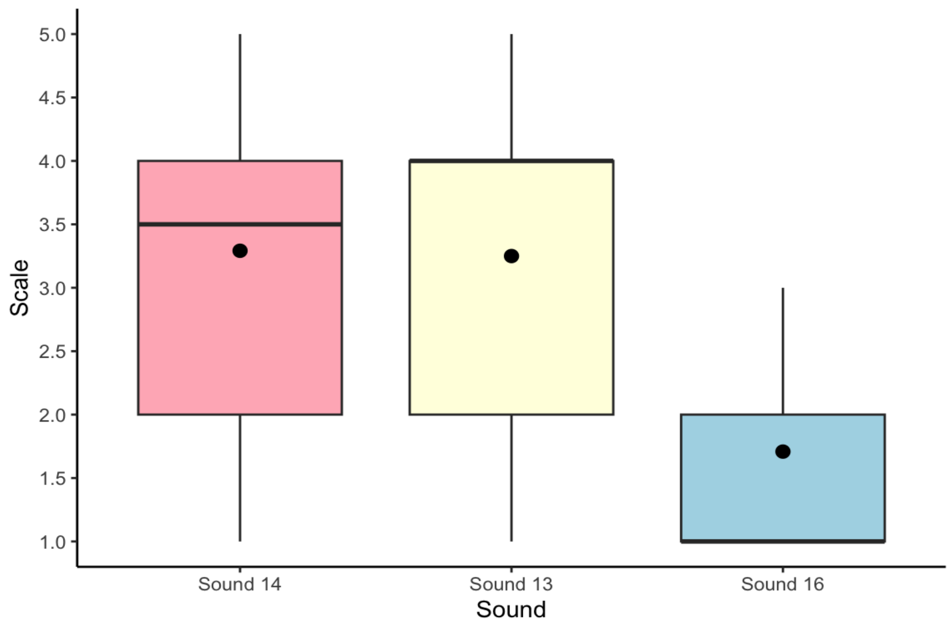

Figure 4.2: *Boxplot of Recognition Ratings for Sound Designs; Sound 14 (String 2 + Wind 2 with 500 Hz), Sound 13 (String 2 + Wind 2 with 350 Hz), and Sound 16 (String 2 + Wind 2 with 2000 Hz) Rated by 24 Participants on a Scale of 1 to 5*

The provided boxplot in Figure 4.2 illustrates notable differences in how participants rated the recognizability of each sound. Sound 14 (String 2 + Wind 2 with 500 Hz) received higher mean ratings, indicating it was perceived as the most recognizable. Sound 13 (String 2 + Wind 2 with 350 Hz) had a higher median and wider range of ratings, reflecting more variability in participant opinions. Sound 16 (String 2 + Wind 2 with 2000 Hz) has the lowest median and mean recognition ratings among the three sounds, indicating it was the least recognizable to participants. These results can inform sound design strategies for electric vehicles by highlighting which sounds are more likely to be perceived as recognizable by a diverse group of users.

- The boxplot for Sound 14 indicates that the median recognition rating is slightly above 3.5, suggesting that most participants found this sound to be quite recognizable. The interquartile range (IQR), which covers the middle 50% of the data, spans from approximately 3 to 4. This indicates that half of the participants rated the sound within this range. The whiskers, which extend from the IQR to the minimum and maximum values within 1.5 times the IQR, show a full range of ratings from 1 to just above 4.5. The black dot, representing the mean rating, is close to the median, indicating a relatively symmetrical distribution of ratings with no significant skew. The high median and mean ratings suggest that Sound 14 is generally perceived as highly recognizable among the participants.

- Sound 13 shows a median recognition rating of around 4, indicating a moderate level of recognizability. The IQR for Sound 13 extends from approximately 2 to 4, showing a wider range of middle ratings compared to Sound 14. This suggests more variability in how participants perceived this sound's recognizability. The whiskers extend from 1 to 5, capturing the entire spectrum of ratings from very low to very high recognizability. The mean rating, indicated by the black dot, is slightly above the median, suggesting a slight positive skew in the distribution. This means there are slightly more high ratings pulling the mean upward compared to the median.

- Sound 16 displays the median recognition rating is around 1, significantly lower than that of Sound 14 and Sound 13. The IQR for Sound 16 is narrower, ranging from about 1 to 3, indicating that the middle 50% of the ratings are more tightly clustered around lower values. The whiskers extend from 1 to 3, indicating a more limited range of ratings compared to the other sounds. The mean rating for Sound 16 is close to the median, indicating a more symmetrical distribution.

Comparatively, Sound 14 has the highest median rating, followed by Sound 13, and then Sound 16. This suggests that participants found Sound 14 the most recognizable, Sound 13 moderately recognizable, and Sound 16 the least recognizable. Both Sound 14 and Sound 13 exhibit similar variability in their ratings, as indicated by their comparable IQRs. Sound 16, however, shows less variability, with a narrower IQR, suggesting a more consistent perception of its recognizability as being low. The distribution of ratings for Sound 14 is slightly negatively skewed, with more ratings concentrated at the higher end. Sound 13 shows a slight positive skew, with more ratings at the lower end. Sound 16 shows a symmetrical distribution but centered around lower values. While all three sounds have ratings that span the entire range from 1 to 5, the whiskers for Sound 14 and Sound 13 extend to 5, indicating that some participants rated these sounds as highly recognizable. In contrast, the whiskers for Sound 16 do not extend beyond 3, highlighting that no participants found this sound highly recognizable.

4.1.1.6 Effectiveness of Sound Alerts

Participants assessed the effectiveness of each sound in alerting them of a vehicle's presence using a rating scale ranging from 1 to 5. Implementing this step is imperative for guaranteeing the safety of pedestrians, particularly in metropolitan settings where electric vehicles are widespread. The ratings indicated that certain sounds were more effective in capturing attention. Sound examples that received better ratings generally indicated sudden variations in amplitude or frequency, which were helpful in penetrating ambient noise. The observations are outlined in detail: The effectiveness scores indicated variation, with certain sounds being assigned greater ratings for their capacity to capture attention. Effective sounds frequently showcased sudden variations in amplitude or frequency, causing them to be distinct from surrounding noise. Sounds that received high effectiveness ratings generally showed sharp peaks and endings, or featured sudden alterations that could readily capture a listener's interest. These attributes are needed to guarantee that pedestrians can efficiently and effortlessly perceive the existence of an approaching vehicle. Sounds that received lower effectiveness scores may have exhibited more gradual variations or lacked the required intensity to distinguish themselves in a noisy environment. These sounds may not be adequate to notify pedestrians, particularly in busy metropolitan environments.

The boxplot in Figure 4.3 presents the effectiveness ratings for three different sound designs Sound 13 (String 2 + Wind 2 with 350 Hz), Sound 14 (String 2 + Wind 2 with 500 Hz), and Sound 16 (String 2 + Wind 2 with 2000 Hz) Rated by 24 Participants on a Scale of 1 to 5 among 16 sounds evaluated by 24 participants. Participants assessed each sound on a scale from 1 to 5, where 1 represents the lowest effectiveness and 5 represents the highest effectiveness. The boxplot visualizes the distribution of these ratings, highlighting several key statistical features for each sound.

- For Sound 13, the ratings are highly consistent among the participants, as

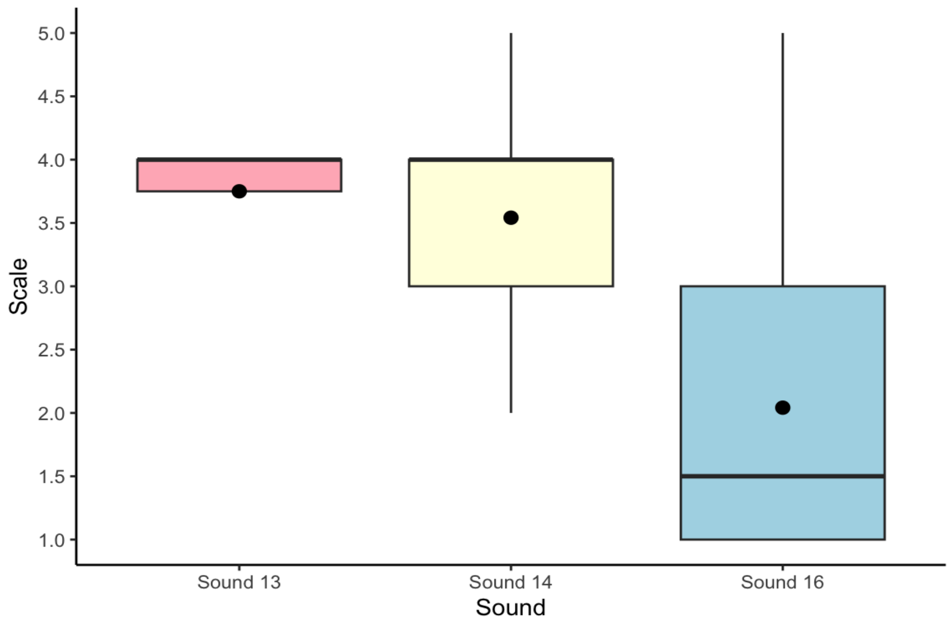

Figure 4.3: *Boxplot of Effectiveness Ratings for Sound Designs; Sound 13 (String 2 + Wind 2 with 350 Hz), Sound 14 (String 2 + Wind 2 with 500 Hz), and Sound 16 (String 2 + Wind 2 with 2000 Hz) Rated by 24 Participants on a Scale of 1 to 5*

indicated by the narrow interquartile range (IQR). The IQR, represented by the height of the box, contains the middle 50% of the data and is closely centered around the median value of 4. This suggests that most participants rated Sound 13 as highly effective. The mean rating for Sound 13, shown by the black dot, also aligns closely with the median, reinforcing the consistency in ratings.

- Sound 14, on the other hand, displays a wider interquartile range, suggesting more variability in participant ratings. The mean rating for Sound 14 is approximately 3.5, indicating a generally positive but more varied perception of its effectiveness. The presence of longer whiskers in Sound 14's boxplot indicates that while some participants rated it very highly, others gave it lower scores, reflecting a broader range of opinions.
- Sound 16 has a mean effectiveness rating is around 2 and median rating 1.5, significantly lower than that of Sound 13 and Sound 14. The IQR ranges from approximately 1 to 3, indicating a wide variability in ratings. The

whiskers extend from 1 to 5, showing a broader range of ratings.

In contrast, Sound 13 has the highest median and mean effectiveness ratings, followed by Sound 14, and then Sound 16. This suggests that participants found Sound 13 to be the most effective, Sound 14 moderately effective, and Sound 16 the least effective. The narrow IQR for Sound 13 indicates strong consensus among participants, suggesting that this sound was consistently rated highly for effectiveness. In contrast, the wider IQR for Sound 16 indicates less agreement among participants, suggesting more varied opinions on its effectiveness. Sound 14 shows moderate variability, with a range of ratings that suggests some participants found it effective while others did not. The distribution of ratings for Sound 13 is tightly clustered around the high end, while Sound 14 and Sound 16 show broader distributions with ratings spread across the scale. This indicates that while Sound 13 was consistently perceived as effective, the effectiveness of Sound 14 and Sound 16 was more subject to individual participant interpretation.

4.1.1.7 Pleasantness of Sound Alerts

The participant's perception of the sounds' pleasantness was evaluated to determine their level of enjoyment or agreement with each sound. This statistic is crucial for consumer acceptance since excessively displeasing sounds could result in negative perceptions of electric vehicles. The ratings unveiled an extensive range of responses. Certain sounds were characterized as being neutral to mildly enjoyable, but others were perceived as more unpleasant. Sound with a smoother and less annoying quality tended to obtain higher rankings for pleasantness. The findings are comprehensive and specific: The scores for pleasantness exhibited significant variation, suggesting diverse interpretations of the sounds' pleasantness. Generally, sounds that were smooth, harmonic, and less obtrusive were perceived as more pleasant. Sound samples that received high ratings in terms of pleasantness typically had a significant presence of harmonics and a limited amount of discord.

Figure 4.4 shows the boxplot results of pleasantness ratings for the three sound designs Sound 13 (String 2 + Wind 2 with 350 Hz), Sound 5 (String 1 + Wind 2 with 350 Hz), and Sound 15 (String 2 + Wind 2 with 1000 Hz) among 16 sounds evaluated by 24 participants on a scale from 1 to 5. Each boxplot depicts the median (horizontal line), interquartile range (box), and mean (black dot) of the ratings. The whiskers extend to the minimum and maximum values within 1.5 times the IQR. Sound 13 shows the highest median and Sound 5 shows the same

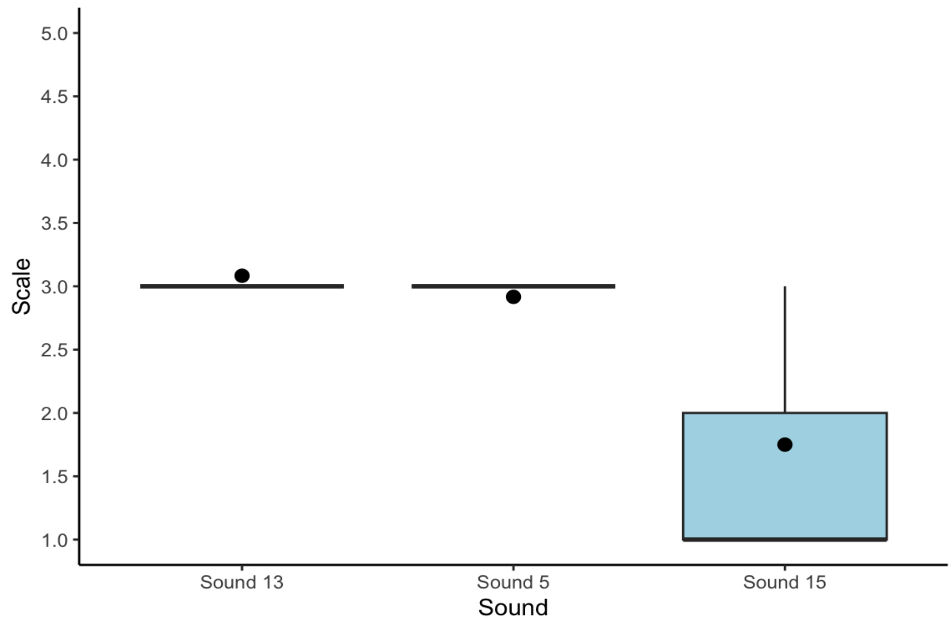

Figure 4.4: *Boxplot of Pleasantness Ratings for Sound Designs; Sound 13 (String 2 + Wind 2 with 350 Hz), Sound 5 (String 1 + Wind 2 with 350 Hz), and Sound 15 (String 2 + Wind 2 with 1000 Hz) Rated by 24 Participants on a Scale of 1 to 5*

median ratings as Sound 13, indicating they were perceived as the most pleasant. Sound 15 has the lowest median and mean ratings, indicating it was perceived as the least pleasant among the three sounds. The variability in ratings is smallest for Sound 13 and Sound 5 and largest for Sound 15, suggesting stronger consensus on the pleasantness of Sound 13 and Sound 5 and more varied opinions on Sound 15.

- In this analysis, The boxplot for Sound 13 shows a very narrow range of ratings with both the median and mean rating around 3. The uniformity of the ratings is evident as there is no visible box or whiskers, implying that all participants rated the sound similarly, with very little to no variation.

- Similar to Sound 13, Sound 5 also displays a narrow range of ratings centered around a median and mean of 3. This consistency suggests that participants had a uniform perception of the pleasantness of this sound.

- In contrast, Sound 15 has a median pleasantness rating is around 2, significantly lower than that of Sound 13 and Sound 5. The IQR ranges from approximately 1 to 3, indicating a wide variability in ratings. The whiskers extend from 1 to 4, showing a broader range of ratings. The mean rating is close to the median, suggesting a more symmetrical distribution.

Sound 13 has the highest median and mean pleasantness ratings, followed by Sound 5 with the same median as Sound 13. This suggests that participants found Sound 13 and Sound 5 to be the most pleasant, while Sound 15 was perceived as the least pleasant. The narrow IQRs for Sound 13 and Sound 5 indicate strong consensus among participants, suggesting that these sounds were consistently rated as moderately pleasant. In contrast, the wider IQR for Sound 15 indicates less agreement among participants, suggesting more varied opinions on its pleasantness. The distribution of ratings for Sound 13 and Sound 5 is tightly clustered around the median, while Sound 15 shows a broader distribution with ratings spread across the scale. This indicates that while Sound 13 and Sound 5 were consistently perceived as moderately pleasant, the pleasantness of Sound 15 was more subject to individual participant interpretation.

4.1.1.8 Annoyance of Sounds

Participants evaluated the level of annoyance they experienced with each sound, which is needed to ensure that the sounds do not induce discomfort or irritation, preventing resistance to their use. The results indicated that specific sounds were more annoying especially those that featured high-frequency or repeated elements. In contrast, sounds that had equal frequencies and moderate volume levels were perceived as less annoying. The levels of annoyance varied, with certain sounds being considerably more unpleasant than others. These aspects can gradually become annoying and uncomfortable for listeners. Sound input characterized by harmonious frequency distribution and moderate amplitude levels was frequently perceived as less annoying. These sounds were unlikely to cause annoyance or fatigue.

The boxplot in Figure 4.5 displayed above presents the annoyance ratings for three different sound designs Sound 8 (String 1 + Wind 2 with 2000 Hz), Sound 7 (String 1 + Wind 2 with 1000 Hz), and Sound 1 (String 1 + Wind 1 with 350 Hz) among 16 sounds as evaluated by 24 participants. Each participant rated the sounds on a scale from 1 to 5, where 1 denotes the least annoying and 5 represents the most annoying. The boxplots provide a visual summary of the distribution of ratings, highlighting key statistical measures such as the median, interquartile

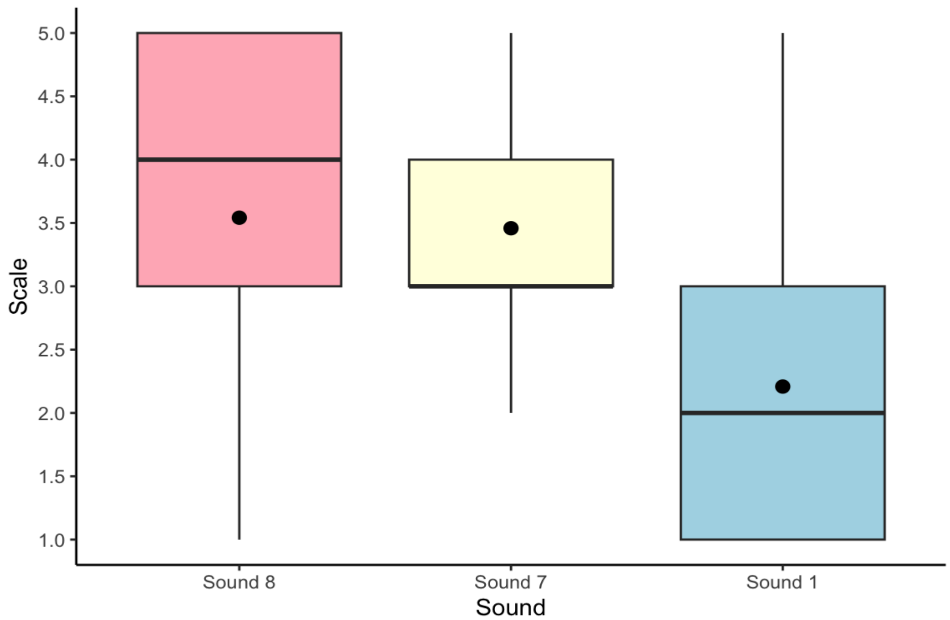

Figure 4.5: *Boxplot of Annoyance Ratings for Sound Designs; Sound 8 (String 1 + Wind 2 with 2000 Hz), Sound 7 (String 1 + Wind 2 with 1000 Hz), and Sound 1 (String 1 + Wind 1 with 350 Hz) Rated by 24 Participants on a Scale of 1 to 5*

range (IQR), and mean.

- The boxplot for Sound 8 indicates that the participants generally found this sound to be quite annoying. The median rating is close to 4, which means that half of the participants rated the annoyance level of Sound 8 as 4 or higher. The interquartile range (IQR), which represents the middle 50% of the data, spans from approximately 3 to 4.5. This suggests that while most participants rated it highly on the annoyance scale, there was some variability in their responses. The whiskers of the boxplot extend from the minimum value of 1 to the maximum value of 5, capturing the full range of annoyance ratings. The black dot represents the mean rating, which is also close to 4, indicating that the average rating is consistent with the median.
- The boxplot for Sound 7 shows a lower median annoyance rating of around 3, suggesting that participants found this sound less annoying compared to Sound 8. The IQR is narrower, indicating less variability in the ratings. The whiskers extend from 1 to 5, demonstrating that participants had a range of

opinions, but the majority clustered around the median. The mean rating, depicted by the black dot, is slightly above the median, indicating a slight skew towards higher annoyance ratings within the interquartile range.

- Sound 1 reveals the median annoyance rating is around 2, significantly lower than that of Sound 8 and Sound 7. The IQR ranges from approximately 1.5 to 3, indicating a wide variability in ratings. The whiskers extend from 1 to 5, showing a broader range of ratings. The mean rating is close to the median, suggesting a more symmetrical distribution.

Overall, the boxplots illustrate distinct differences in how participants perceived the annoyance of each sound. Sound 8 has the highest median and mean annoyance ratings, followed by Sound 7 and Sound 1. This suggests that participants found Sound 8 to be the most annoying, while Sound 1 was perceived as the least annoying. The IQRs for Sound 8 and Sound 7 indicate a moderate level of agreement among participants, suggesting that these sounds were consistently rated as more annoying. In contrast, the wider IQR for Sound 1 indicates less agreement among participants, suggesting more varied opinions on its annoyance. The distribution of ratings for Sound 8 is tightly clustered around the median, while Sound 1 shows a broader distribution with ratings spread across the scale. This indicates that while Sound 8 was consistently perceived as highly annoying, the annoyance of Sound 1 was more subject to individual participant interpretation.

4.2 Statistical Analysis

The experiment's statistical analysis was performed using RStudio, utilizing Analysis of Variance (ANOVA) to evaluate the data. This section explains the procedures undertaken to prepare and analyze the data, offering an in-depth understanding of the methodology used.

4.2.1 Data Preparation and Categorization

In order to preserve an organized and significant analysis of the experimental results, multiple preliminary analyses were carried out. The point of these stages was to categorize the data in a way that is relatively simple to analyze and understand, which would allow for a more precise and informative analysis.

4.2.1.1 Age Group Categorization

Participants' audio perceptions and preferences might be strongly influenced by their age. By classifying individuals into age groups, the analysis may more effectively consider these variations, providing a deeper understanding of how different age demographics perceive the sounds of electric vehicles (EVs).

The age range of the participants in the experiment was 19 to 41 years. To facilitate a more structured analysis, participants were divided into three distinct age groups: Group 1 (19-27 years), Group 2 (28-36 years), and Group 3 (37-45 years). This categorization helps in understanding how different age groups perceive sound designs, accounting for potential variations in auditory perception and preferences.

4.2.1.2 Calculation of Average Scores

The experiment involved participants rating the sound designs based on four key aspects: recognition, effectiveness in alerting, pleasantness, and annoyance. By calculating the average of these scores for each participant, we can obtain a thorough evaluation of each sound design, taking into consideration all relevant parameters.

For each participant, the average of their ratings across the four aspects was calculated, providing a comprehensive score that reflects their overall perception of each sound design. The use of average scores ensures that the analysis considers all aspects of the participants' experiences, offering a balanced evaluation of each sound design.

4.2.2 ANOVA Analysis

The primary objective of using ANOVA (Analysis of Variance) in this analysis is to determine the optimal sound design by considering the mean evaluations of all participants. This statistical technique enables a thorough evaluation of several sound designs by assessing the variations in participants' ratings. Moreover, ANOVA facilitates the understanding of how it influences different pre-experimental factors in these evaluations. The factors that can have an important influence on participants' perception and evaluation of sound designs include gender, age, hearing impairment, and familiarity with electric vehicles (EVs).

a Gender

Gender can have a significant impact on auditory perception and preferences. Biological, psychological, and social variables can contribute to differences in the way men and women perceive sounds. Previous studies have demonstrated that women frequently possess superior high-frequency auditory abilities compared to men, perhaps impacting their interpretation of specific sounds. Moreover, gender-related social and cultural experiences can influence one's auditory preferences and comfort levels when it comes to various forms of sounds. By including gender as a variable in the ANOVA, the experiment can determine if there are significant variations in how male and female participants evaluate the sound designs, thereby offering insights into gender-specific interests or preferences.

b Age

Age is another important factor that influences hearing capabilities and the perception of sound. Younger individuals often possess a broader audio range and greater sensitivity to high-frequency sounds in comparison to older ones, whose auditory ability may diminish as they age. The research can discover age-related trends in the ratings by classifying individuals into distinct age groups, namely 19-27, 28-36, and 37-45 years. This classification helps in determining whether particular sound designs are more effective or desirable for specific age groups, ensuring that the ultimate sound design is inclusive and effective for a wide-ranging demography.

c Hearing Impairment

Hearing impairments can profoundly affect the way individuals perceive and assess sounds. Individuals with hearing problems may experience challenges in perceiving certain frequencies or differentiating between various sound attributes. By incorporating hearing impairment as a variable in the ANOVA, the analysis may accurately consider these differences and help ensure that sound designs are accessible and efficient for individuals with varying hearing abilities. Additionally, it helps in determining whether certain sound designs are more appropriate for individuals with hearing impairments, thereby improving the safety and inclusiveness of electric vehicle sound design.

d Familiarity with Electric Vehicles (EVs)

Participants' expectations and perceptions of EV sounds can be influenced by their familiarity with EVs. Individuals who possess greater expertise and familiarity with electric vehicles (EVs) may possess different standards or preferences in contrast to individuals who lack experience or understanding of EVs. For instance, participants familiar with EVs might expect sounds that align with the futuristic and environmentally friendly image of these vehicles. In contrast, participants unfamiliar with EVs might prefer sounds that resemble traditional combustion engine vehicles for better recognition. By incorporating familiarity about electric vehicles (EVs) as a variable in the analysis of variance (ANOVA), the analysis can determine the influence of prior experience with EVs on the ratings and identify sound designs that are universally effective or require adjustments based on familiarity levels.

4.2.3 Execution and Results Interpretation

4.2.3.1 ANOVA Execution

The R code is used to perform a two-way ANOVA analysis. The formula Rating Type.sounds + Gender + Age + Hearing.impairments + Familiarity specifies the dependent variable (Rating) and the independent variables (Type.sounds, Gender, Age, Hearing.impairments, Familiarity). The aov function is used to fit the model, and the summary(two.way) function call provides a summary of the ANOVA results, indicating the statistical significance of each factor in the model. This formula is necessary as it allows for evaluating the main effects of each factor on the ratings, as well as the interactions between these factors. The main factors considered were:

- Type of Sounds: The different sound designs generated for the EVs.
- Gender: The gender of the participants (male or female).
- Age: The age groups into which participants were categorized (19-27, 28-36, 37-45 years).
- Hearing Impairments: Whether the participants had any hearing impairments.
- Familiarity with EVs: How familiar the participants were with electric vehicles.

By including these factors, the ANOVA model can identify not only the best sound design but also how these demographic and experiential variables influence the ratings.

4.2.3.2 ANOVA Results

The results of the ANOVA as shown on 4.6 indicated significant effects for all the main factors considered in the analysis. The detailed results from RStudio are as follows:

```
                    Df Sum Sq Mean Sq F value   Pr(>F)    
Type.sounds         15  27.20   1.813   4.333 1.83e-07 ***
Gender               1   4.02   4.022   9.611  0.00209 ** 
Age                  2  10.62   5.308  12.684 4.75e-06 ***
Hearing.impairments  1   3.61   3.611   8.629  0.00352 ** 
Familiarity          4   6.31   1.577   3.769  0.00511 ** 
Residuals          360 150.66   0.418                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure 4.6: *ANOVA Summary Table showing the statistical analysis of the effect of various factors on the ratings of electric vehicle sound designs*

1. Type of Sounds:

   The analysis showed that different sound designs significantly affected the ratings ($p<0.001$). This indicates that some sounds were consistently perceived more favorably than others. This understanding is essential for determining the most effective sound designs for alerting pedestrians and improving user satisfaction.

2. Gender:

   There was a significant difference in ratings between male and female participants ($p<0.01$). This suggests that gender-based perceptual differences exist, with potential variations in how different genders perceive and evaluate EV sounds. This information can be used to tailor sound designs that cater to both male and female preferences, ensuring inclusivity.

3. Age:

   Age groups significantly influenced the ratings ($p<0.001$). Notable differences were observed between the younger and older age groups, which can be attributed to the variations in hearing sensitivity and sound preferences across different age demographics. This emphasizes the necessity for sound designs suitable for specific age groups, considering their auditory capabilities and preferences.

4. Hearing Impairments:

   Participants with hearing impairments rated the sounds significantly differently than those without impairments ($p<0.01$). This highlights the significance of developing effective designs that are both efficient and recognizable for those with hearing impairments. Ensuring that EVs are accessible and safe for all pedestrians.

5. Familiarity with Electric Vehicles:

   Familiarity with EVs also had a significant effect on the ratings ($p<0.01$). Participants who were more familiar with EVs potentially had different expectations or standards for sound designs, which could influence their ratings. Understanding this relationship helps in designing sounds that meet the expectations of both experienced and inexperienced EV users.

4.2.3.3 Post-hoc Analysis Results Explanation

The post-hoc analysis results obtained by the Tukey's Honest Significant Difference (TukeyHSD) test in R offer comprehensive insights into the relationships among the levels of the components in the two-way ANOVA model. This analysis is performed to determine the significant differences between certain means.

Type sounds	diff	lwr	upr	p adj
13-1	0.8229167	0.17852064	1.46731269	0.0014787
14-1	0.75	0.10560397	1.39439603	0.007076
13-12	0.71875	0.07435397	1.36314603	0.0131452
14-12	0.64583333	0.00143731	1.29022936	0.0488207
15-13	-0.69791667	-1.3423127	-0.0535206	0.0195024
16-13	-0.88541667	-1.5298127	-0.2410206	0.0003416
4-13	-0.73958333	-1,3839794	-0.0951873	0.0087299
16-14	-0.8125	-1.456896	-0.168104	0.0018676
4-14	-0.66666667	-1.3110627	-0.0222706	0.0342351
6-16	0.66666667	0.02227064	1.31106269	0.0342351
9-16	0.69791667	0.05352064	1.34231269	0.0195024

Table 4.2: *Post-hoc Tukey's HSD Analysis Results for Sound Ratings*

The table 4.2 presents the mean differences (diff) between pairs of sounds that statistically significant differences $p < 0.05$, along with the lower (lwr) and upper (upr) bounds of the 95% confidence intervals and the adjusted p-values (**p adj).** The post-hoc analysis indicates strong preferences among the different sounds tested. For instance, both Sound 13 and Sound 14 show significantly higher ratings compared to Sound 1. Specifically, Sound 13 is rated 0.82 points higher, and Sound 14 is rated 0.75 points higher on average. These differences are statistically significant with p-values of 0.0014787 and 0.0070760, respectively. This suggests a clear preference for Sounds 13 and 14 over Sound 1. Sounds 13 and 14 emerge as the most favored, consistently receiving higher ratings compared to other sounds. This preference could be due to specific acoustic characteristics of these sounds that make them more pleasant or effective for the participants. On the other hand, Sounds 15 and 16 are notably less preferred, with Sound 16 receiving significantly lower ratings than several other sounds. This suggests that these sounds may need modification to improve their acceptability.

These findings have practical implications for designing sounds in various applications, particularly in the context of electric vehicles (EVs). The preferred sounds (13 and 14) could be used as a baseline for developing new auditory warnings or feedback systems, ensuring they are both effective and pleasant for users. Conversely, the less favored sounds (15 and 16) may need to be redesigned or replaced to meet user expectations and enhance the overall experience. In summary, the post-hoc analysis provides valuable insights into the relative effectiveness and acceptability of different sounds, guiding future sound design and optimization efforts. Those findings are also evident in the boxplot of the recognition results from the questionnaire that showed higher mean ratings were given to Sound 14, suggesting that people thought it was the most recognized. Sound 13 displayed a greater degree of variety in participant opinions, as evidenced by its wider rating range and higher median. Out of the three sounds, sound 16 has the lowest median and mean recognition ratings, suggesting that participants found it to be the least recognizable.

Chapter 5

Discussion

The experiment's outcomes highlight significant findings in the assessment of electric vehicle (EV) sound designs. Granular synthesis has shown significant potential in producing recognizable and distinctive sounds that maximize pedestrian safety while reducing discomfort. Participants consistently rated Sound 13 (String 2 + Wind 2 with 350 Hz), and Sound 14 (String 2 + Wind 2 with 500 Hz) as their most favored, indicating that they were considered to be moderately pleasant and that the majority preferred them. On the other hand, Sound 16 (String 2 + Wind 2 with 2000 Hz) was thought to be the least appealing.

These findings are consistent with previous studies emphasizing the value of sound design for user satisfaction and safety [4]. It was further supported by the ANOVA results, which highlighted the impact of demographic variables on sound design assessments, including gender, age, hearing impairments, and experience with EVs. Furthermore, the post-hoc analysis utilizing Tukey's HSD test offered a comprehensive understanding of the connections between the sound designs. When compared to other sounds, sounds 13 and 14 were continuously rated higher, making them the most favored sounds. However, Sounds 15 and 16 received significantly less votes, suggesting that they should be changed to increase their acceptability. The research on the practicality of customized sound designs in enhancing user satisfaction and safety is supported by these results.

The study confirms that granular synthesis can produce effective and pleasant sound designs for EVs. According to the results of the previous study, the perception of EV-related emotion and satisfaction is influenced differently by each granular synthesis parameter [19]. Additionally, it was discovered that varying the values of each component could generate an emotion or experience [19]. The preferred sounds (13 and 14) should be used as baselines for developing new auditory alerts and feedback systems. The findings underscore the importance of considering demographic factors and user familiarity in sound design to ensure inclusivity and effectiveness. Future research should continue exploring advanced synthesis techniques and their application in diverse contexts to optimize the user experience and enhance pedestrian safety in urban environments.

5.1 Importance for Sustainable Mobility

5.1.1 Contribution to Electric Vehicles Industry

The results of this study make a substantial contribution to the electric vehicle (EV) sector by enhancing our comprehension of the significance and possibilities of sound design in EVs. An important contribution of this study is the demonstration of how advanced sound synthesis techniques, specifically granular synthesis, can be used to create vehicle sounds that are both functional as well as enhance the overall user experience.

Granular synthesis is utilized to create EV sounds that are recognizable and informative, effectively alerting pedestrians and other road users of an approaching vehicle. Research indicates that particular sound designs may significantly improve the recognition and accessibility of electric vehicle (EV) sounds without increasing noise pollution. This contributes to the objectives of both safety and environmental preservation.

Furthermore, the results of the study suggest that sound design might have an important effect on the branding of electric vehicles. Manufacturers can increase the attractiveness of their vehicles to consumers by producing unique and enjoyable sounds that capture emotions. Sound design intends to enhance safety and create a distinctive auditory identity for electric vehicle (EV) brands, thus separating them apart in a competitive market.

The ANOVA analysis conducted in this study highlights the significance of taking into account demographic variables such as gender, age, hearing impairments, and experience with electric vehicles (EVs) when creating sounds for vehicles. The substantial impact of these features on user ratings indicates that a general approach might not achieve the expected results. Alternatively, the results suggest the development of customizable sound profiles that may accommodate a wide range of user requirements and preferences. Adopting a user-centric approach to sound design can improve the acceptance and satisfaction of electric vehicles (EVs) among a wide range of users.

Chapter 6

Conclusion and Future Developments

The study on sustainable mobility and sound design for electric vehicles (EVs) contributed to significant results that provide the framework for future developments in the topic. The primary results emphasize the effectiveness of granular synthesis in producing distinctive and recognizable sounds that enhance pedestrian safety and improve user experience. The study confirmed that sound designs produced by granular synthesis may be effectively implemented into urban environments, fulfilling both practical and aesthetic requirements. Some of the produced sounds were determined to be recognizable, informative, and less likely to be considered annoying in comparison to conventional sound design approaches. However, the research had challenges like the restriction to electric vehicles designed for transporting a small number of passengers. the reliance on a simulated environment for evaluations, and the exclusive use of granular synthesis without integration with other methodologies.

The study has limitations such as its specific focus on electric vehicles designed for transporting a small number of passengers, neglecting commercial or heavy-duty electric vehicles. Additionally, the evaluations were conducted in simulated urban environments, which may not accurately represent real-world situations. Furthermore, the assessments were focused on individuals without hearing difficulties, which may have resulted in the neglect of the requirements of a wider range of people. Although there are limitations, the research provides an adequate foundation for additional studies and innovative design improvements.

Based on the research results, several recommendations can be made for future EV sound designs to optimize their effectiveness and user satisfaction. Continued research and application of advanced sound synthesis techniques, such as granular synthesis, are crucial. These techniques offer the flexibility and precision needed to create sounds that are both functional and aesthetically pleasing. Future sound designs should strive for a balance between perceptibility and informational value while prioritizing user comfort, ensuring that sounds are effective without being intrusive or annoying.

Sound engineers should consider demographic factors in their design process. The study indicates that variables such as age, gender, and auditory capabilities significantly influence sound perception. Developing adaptable sound profiles that can be tailored to user preferences and environmental contexts can enhance the overall user experience. Younger users may prefer different sound characteristics compared to older users, and individuals with hearing impairments might require specific sound frequencies for optimal clarity.

Enhancing public awareness and understanding of electric vehicle acoustics is essential as EV adoption increases. Integrating these new sounds into broader public awareness campaigns can improve their effectiveness in real-world situations. Collaboration between manufacturers and policymakers is vital to ensure that the public is adequately informed about the presence and importance of these sounds. As electric vehicles become more prevalent, it is crucial to integrate these new sounds into public awareness campaigns. Enhancing consumer knowledge of the distinctive sound characteristics of EVs can improve their effectiveness in practical situations. Manufacturers and government officials should collaborate to ensure that the public is adequately educated on the presence and significance of these sounds.

Incorporating qualitative feedback from participants is crucial for the sound design process. While quantitative data provides a broad view of general trends and statistical significance, qualitative insights can uncover nuanced user preferences and experiences that numbers alone cannot capture. Future studies should include open-ended questions and interviews to gather in-depth feedback on the emotional and subjective aspects of sound perception. This approach can identify specific elements of sound designs that resonate strongly with users, leading to more refined and user-centric design iterations. By obtaining qualitative feedback, engineers can better understand the subtleties of user experiences and preferences, enabling the development of more efficient and emotionally impactful sound environments.

Continued cooperation between sound engineers and law enforcement is necessary in order to ensure that electric vehicle sound designs comply with safety regulations while promoting innovation. Regulatory frameworks should have the necessary adaptability to incorporate progress in sound synthesis technology, allowing manufacturers the flexibility to explore the boundaries of what may be achieved, all the while upholding safety and sustainability standards. By incorporating user feedback and utilizing advanced digital signal processing techniques, the electric vehicle sector may create innovative solutions that meet safety requirements. This partnership will ensure that the designs comply with legal requirements while also pushing beyond the boundaries of innovation.

In conclusion, the results of this study emphasize the significance of sound design in improving the acceptance and safety of electric vehicles. Granular synthesis has demonstrated the potential to produce impactful and appealing sounds that may be effectively integrated into urban environments. The study highlighted the importance of ongoing innovation and user-centered approaches to sound design, guaranteeing that EV sounds are not just practical but also improve the overall user experience. By further exploring sound synthesis techniques, considering demographic factors, and adding qualitative feedback, the electric vehicle (EV) industry may design sound environments that improve safety, user satisfaction, and public acceptance of sustainable transportation options.

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