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MASTER'S DEGREE IN

°ICT FOR INTERNET AND MULTIMEDIA°

DIGITAL SIGNAL PROCESSING FOR ELECTRIC VEHICLES'S SUSTAINABLE MOBILITY

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Abstract

Electric vehicles are one of the new technologies that have significant advantages such as reducing dependence on fossil fuels, reducing the emission of environmental pollutants, etc. However, they also face challenges. One of the most important of which is the lack of sound production by these vehicles, which can lead to a decrease in safety and an increase in the level of road accidents. In this thesis, a method based on granular synthesis for producing different sounds is presented, the final goal of which is to use it in the performance platform and optimize sounds related to sustainable mobility. In fact, sound production in electric vehicles can lead to road safety by informing pedestrians and cyclists and preventing accidents. Parameters such as speed/rpm/torque/pedal position are considered as input parameters to change the sound. In this project, eight different sounds are played in real time and after being modulated and filtered, they are combined to make more complex sounds. The proposed method is implemented in MATLAB software. The results are considered as input for the third part of the project so that they can be used to design sound for electric vehicles.

Keywords: Electric vehicles, digital signal processing, sustainable mobility, granular synthesis, Reduce accidents, sound generation.

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Chapter 1

Introduction

1.1 Introduction

Electric vehicles can bring significant benefits such as reducing dependence on fossil fuels and reducing the amount of pollutant emissions. These advantages, along with the ability of these vehicles to provide the required energy for consumption in critical times when the power grid is facing problems, have caused them to be considered significantly. It is expected that in the coming years, the number of vehicles with gasoline engines will gradually decrease and the number of electric vehicles will increase. As shown in Fig. 1.1, there are different types of vehicles, the most important of which are gasoline vehicles, hybrid vehicles, vehicles with the ability to connect to the power grid, and battery-based electric vehicles.

1.2 The usage of the granular synthesis for the sound of electric vehicles

Electric vehicles have been able to help reduce challenges such as the emission of air pollutants by using batteries as a fuel source and eliminating fossil fuels. However, due to the lack of sound production, they have created a safety challenge on the roads. Therefore, sound production in electric vehicles has been raised as an important issue in the field of using these vehicles. Many methods and techniques have been used for this purpose. One of these methods is based on granular synthesis.

Granular synthesis is presented as a computer music technique with the aim of producing complex sounds and it can be used to produce different sounds in electric vehicles. This method uses thousands of short sound events (usually 1 to 100 milliseconds) to produce sound, each of

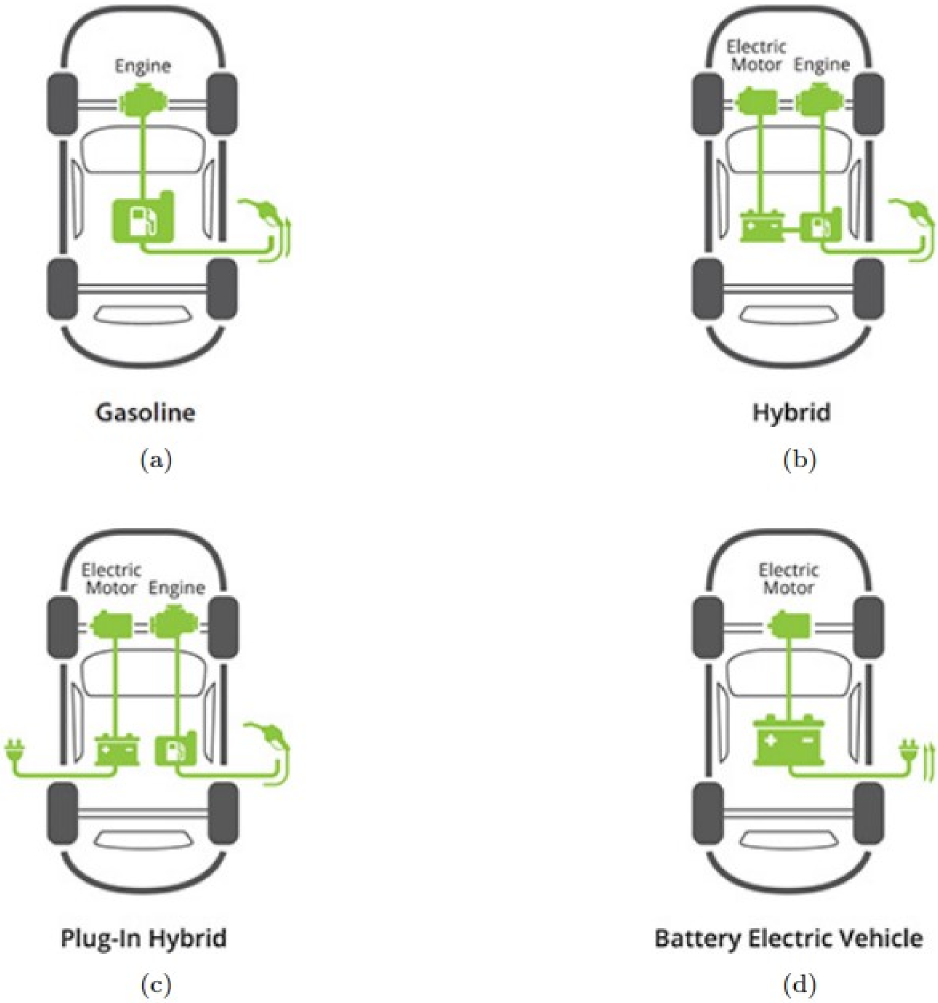

Figure 1.1: Types of vehicles [1]

which is called a ” granule”. Each granule has a specific and unique waveform and amplitude. In fact, the main idea behind granular synthesis is to break the sound into very small pieces or segments. Granular synthesis is similar to wavetable synthesis, but works on a much finer scale. Granular synthesis method is continuously evolving with the aim of producing better sounds and songs.

Each of the small audio parts or granules can have a higher or lower playback speed compared to other granules. It is also possible to repeat them. In addition, changes in the pitch of each seed make it possible to change the pitch of a sample without affecting its timing. You can also change the order of the granules to create bass or bass sounds.

The granular synthesis method makes it possible to produce different sounds for electric vehicles and change them according to the speed and acceleration of the vehicle. The goal is to be able to optimally inform pedestrians or cyclists from their presence on the roads. It should be noted that the production and distribution of this sound must be done in compliance with legal requirements to prevent noise pollution and produce a sound within the permitted range to warn.

Therefore, the general proposal of this research is to provide a system based on the granular synthesis method to produce sound in electric vehicles with the aim of reducing the number of accidents.

1.3 The FIAMM project

This study is part of a three-part project conducted for FIAMM, which is working with automotive companies. The platform, developed on Matlab + Simulink + Embedded Coder environment, implements signal processing as schematized in the Fig. 1.2.

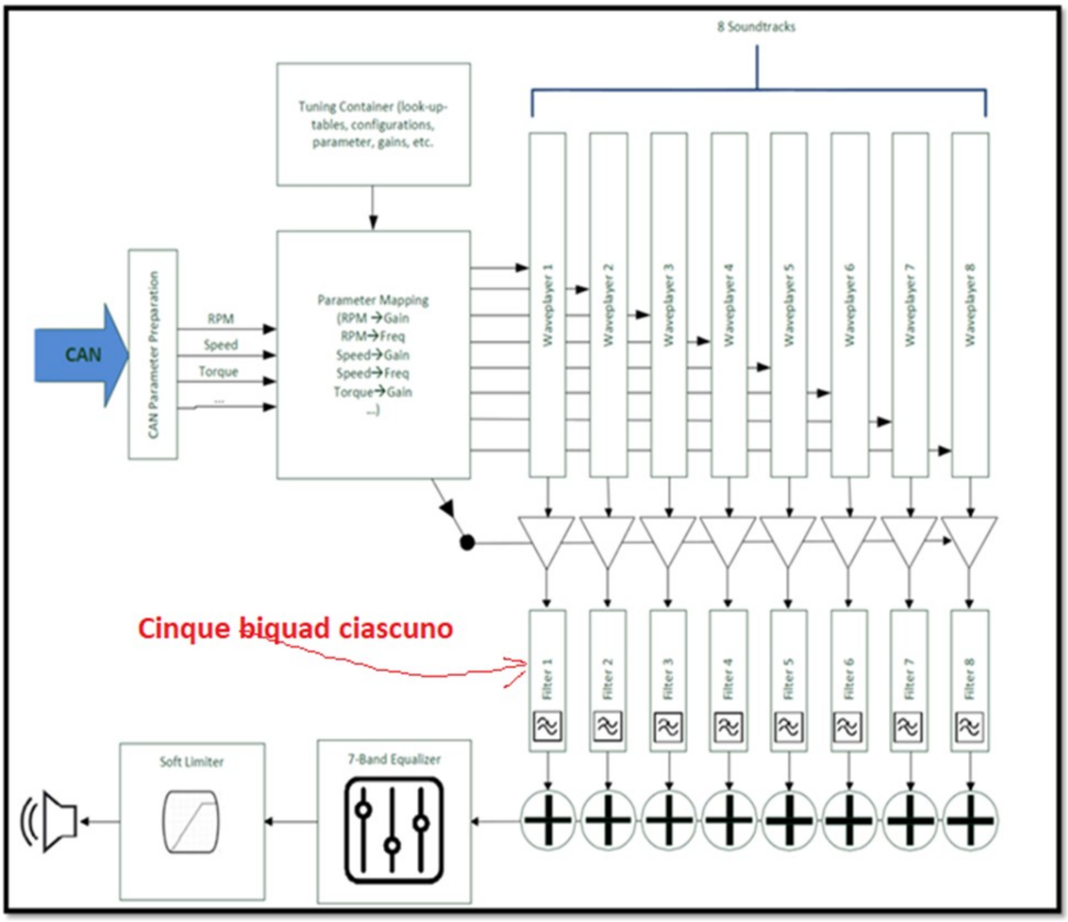

Figure 1.2: An overview of the sound production project for electric vehicles [2]

The first part of this project is the use of granular synthesis method to produce sound in electric vehicles, which is the focus of this thesis.

The second part of this project focuses on the simulation of Controller Area Network (CAN) parameters to optimize the exterior sound design of electric vehicles (EVs). This section was done by colleagues.

Using CAN simulation, the research investigates in detail how parameters such as vehicle speed and engine RPM can be processed in real-time. Also, how these data can effectively modulate the frequency and amplitude of the exterior sounds of electric vehicles.

The simulation model is able to appropriately modulate the sound outputs according to the dynamic state of the vehicle. Thus providing a rich sound palette that varies according to the speed and movements of the vehicle. The thesis highlights the critical role of the CAN system in managing the exterior sound of electric vehicles. Also, it lays the foundation for future innovative approaches in this area.

The third part of this project is focused on sound design, which actually uses the results of the two mentioned theses for sound design.

In fact, the aim of that study was enhance electric vehicle (EV) sound design using granular synthesis with PureData, improving user experience, and meeting safety standards. The research assesses EV sounds' recognizability, informativeness, pleasantness and annoyance to ensure their safe integration into urban environments, supporting sustainable mobility. In this regard, PureData was used. Also, the methodology of experiment and analysis was based on ANOVA.

1.4 Objectives

The aim of this study is to provide a granular synthesis method for producing sounds in electric vehicles, which is done with the aim of improving road safety and reducing accidents. In particular, the aim of this thesis is to provide an approach for sound production for silent vehicles. This approach should be able to synthesize sounds for all possible working conditions of the vehicle according to the parameters such as the vehicle's speed and acceleration. This can lead to a sustainable mobility.

1.5 The importance of audio synthesis for EVs

Electric vehicles provide many opportunities and advantages both from the point of view of "production" and from the point of view of "consumption". So that the growing trend of investment in this field promises a world without fossil vehicles in less than 20 years. These vehicles, with their many advantages, help to create a sustainable development in the transportation sector. Meanwhile, their limited challenges, especially in the field of sound production, can be solved by using new and efficient approaches such as the granular synthesis method. In this way, while enjoying the benefits of electric vehicles, it is also possible to improve road safety.

Periodic electric signals can be converted into sound by amplifying them and driving a loudspeaker with them. One way to do this is to simply add various amplitudes of the harmonics of a chosen pitch until the desired timbre is obtained. This synthesis and production of sound is necessary to maintain road safety.

1.6 The reason for using granular synthesis

The high potential of the sound synthesis method has made this method a valuable method in sound production or design. These potential include sound design and its ability to change the speed and speed of playback.

The reason for using the granular synthesis method in this study is its high ability and advantages in producing and designing different sounds that can change according to the speed and acceleration of the vehicle.

1.7 Thesis Structure

In this chapter, first, a short introduction was presented regarding the use of granular synthesis method for sound design in electric vehicles. Then, three studies conducted in line with the implementation of FIAMM project were introduced. In the following, while introducing the objectives of the present study, the importance of using the granular synthesis method to produce sound in electric vehicles was presented. Also, the reason for using the mentioned method in this study was stated.

In the second chapter, the importance of sound production in electric vehicles and the introduction of the latest techniques and technologies presented in this regard will be discussed. In the third chapter, the literature of the subject is reviewed and the most important works done in this field are introduced and analyzed.

In the fourth chapter, the granular synthesis method for producing sound in electric vehicles will be explained.

In the fifth chapter, the discussion about the proposed method is discussed. Finally, presenting the results and suggestions in the sixth chapter is the end of this thesis.

Chapter 2

State of Art in The Electric Vehicles' Sound Generation and Regulations

2.1 Introduction

One of the industries that has always attracted the attention of experts is the transportation industry. Scientists have always been trying to produce vehicles that have better performance, lower fuel consumption and less pollution than conventional vehicles. Due to the benefits of reducing fuel consumption and greenhouse gas emissions and energy efficiency, EVs have recently received much attention and are expected that this process will continue.

In general, more than 1.4 million electric vehicles will be sold in the United States in 2023, a new annual record, accounting for 9.1 percent of all new passenger vehicle sales that year. The increase in acceptance of electric vehicles is driven by a combination of factors, including the increase in model diversity and consumer economics. The cost of fuel and maintenance of electric vehicles is much lower than gas vehicles.

Additionally, the average purchase price of a new fully battery EV is expected to drop nearly 25% over the next few years due to lower lithium prices and legal incentives to expand EVs. The drop in the price of electric vehicles means that the price of electric vehicles will be almost the same as conventional vehicles in the next two years [1].

Therefore, in recent years, a lot of research has been done about electric vehicles and the challenges caused by their widespread penetration.

On the other hand, sound is an important element in the driving experience, which can include sounds inside and outside the vehicle cabin. By reducing the size of the engine and using turbochargers, vehicle manufacturers have moved towards reducing the noise of vehicles. Also, due to the silent nature of their engine, electric vehicles do not have an audio feedback that indicates their speed and acceleration. On the other hand, this causes problems for pedestrians, cyclists and other people who pay attention to the audio signals emitted by other vehicles to move in traffic.

2.2 Electric vehicles and the importance of using them

The world is more and more involved in the destructive effects of pollution caused by fossil fuel vehicles. So, EVs have appeared as a solution for the transformation of the vehicle industry and making transportation compatible with the environment and reducing the emissions. Today, many people have realized the urgent need to reduce vehiclebon, and for this reason, the use of electric vehicles has become more popular [2]. Due to this importance, many efforts have been made to improve their performance. For example, a method based on digital signal processing is presented to improve the performance of electric vehicles. The purpose of this method is to identify vehicle problems and diagnose problems in parts such as ignition, battery, engine and brakes, etc. in an effective and fast way. The results of the implementation of the proposed method show the effectiveness of the digital signal processing in improving the performance of electric vehicles [3].

Also, the safety of these EVs on the road has always been taken into consideration. In some studies, it is focused on the detection of acoustic warning signals in urban environments to improve the safety. In this regard, a set of primary signals has been created and used in a time/frequency domain to display temporal and spectral characteristics (continuous, impulse, harmonic, etc.). The obtained results have shown that the method has high efficiency compared to other similar methods. Also, the safety level on the roads can be increased by using the method [4].

2.2.1 Reducing greenhouse gas emissions

Electric vehicles produce fewer greenhouse gases than vehicles with an internal combustion engine. Internal combustion engine vehicles emit vehiclebon dioxide and other pollutants directly from their exhaust pipe, but the amount of emissions from the exhaust in electric vehicles is very small or even zero. This is because electric vehicles rely on electric motors that are powered by batteries. As a result, zero direct emissions of harmful pollutants such as vehiclebon monoxide, nitrogen oxides, and particulate matter, leading to reduced air pollution.

2.2.2 Impact on human health and respiratory conditions

Using electric vehicles to reduce air pollution has a positive effect on human health. Reducing pollutants in the air can help improve respiratory diseases such as asthma, bronchitis and allergies.

In addition, reducing the presence of pollutants such as fine particles can reduce the risk of vehiclediovascular diseases and respiratory diseases. Ultimately it improves the overall well-being of individuals and society.

2.2.3 Integration of renewable energies

Electric vehicles have the potential to use, in addition to electricity, other renewable sources such as solar or wind energy to charge their batteries. The use of these resources makes electric vehicles more environmentally friendly. Reducing dependence on fossil fuels and using sustainable alternatives will improve the clean transportation system. Connecting electric vehicles to renewable energy networks has several advantages. For example, it can promote the growth of renewable energy infrastructure, reduce dependence on non-renewable resources, and reduce greenhouse gas emissions from electricity generation [2].

2.2.4 Economic benefits for consumers

Compared to gasoline vehicles, electric vehicles have lower maintenance costs. Even with the correct and economic modeling of the price of electricity, they can perform better in terms of fuel costs and energy consumption. These advantages, along with technical advantages such as low noise and high acceleration, have made these vehicles ideal options for consumers.

2.2.5 Saving and protecting natural resources

Battery production, including lithium-ion batteries, requires water. But the amount of water used in the battery production process is less compared to the water used in the extraction, refining and transportation of fossil fuels for vehicles with internal combustion engines. For this reason, by implementing efficient water management practices such as recycling and optimizing production processes, the sustainability of electric vehicle production will increase [5].

2.3 The challenge of not producing sound

Promoting sustainable transportation and the use of electric vehicles helps preserve natural resources. One of the critical aspects of conserving natural resources is reducing dependence on fossil fuels.

Fossil fuels such as coal, oil and gas are finite non-renewable resources that take millions of years to form. In addition, their combustion leads to the emission of greenhouse gases and pollution. For this reason, improving energy efficiency and providing sustainable solutions in the transportation industry can reduce overall energy consumption. Also, it can help to reduce pressure on natural resources.

In addition to the above advantages, reducing noise pollution is another advantage of electric vehicles compared to vehicles with internal combustion engines. However, the lack of sound produced by these vehicles has also become a concern at the same time. In fact, at the same time as the demand for the use of EVs is increasing due to their significant advantages, the various challenges of using them, should also be examined. This requires interdisciplinary collaboration between automotive engineers, acousticians, psychologists and urban planners, among others.

Sound production is one of the warning signs of the existence of vehicles that can inform other vehicles as well as pedestrians and cyclists of their existence. Therefore, noise reduction in electric vehicles has become an important challenge from the perspective of maintaining safety.

Therefore, adding the ability to produce sound to these EVs with the aim of informing pedestrians, cyclists and other vehicles of their existence is an important goal of the proposed approach. Previously, various approaches and techniques have been used to produce sound by electric vehicles with the aim of increasing safety and reducing the risk of accidents [6].

The techniques developed to add the ability to produce sound to EVs, can reduce the risk of accidents. Also, they can increase the level of driving safety. Moreover, they are examined from the point of view of the psychological effects of sounds produced on pedestrians and the use of aesthetic features.

As mentioned before, one of the faults attributed to electric vehicles is their lack of sound production. This can be dangerous, because pedestrians, cyclists or people with vision problems do not notice the presence of electric vehicles around them and accidents may occur.

To deal with such risks, the European Union has required all electric vehicle manufacturers to equip their new products with sound generators. Electric vehicles must produce at least 56 decibels of sound while traveling at a speed of 20 km or more. This sound should also reflect the increase or decrease of the vehicle's speed.

The NHTSA states that electric vehicles up to the speed of 30 km/h should produce artificial sound so that it is easy for cyclists and pedestrians to recognize them.

A speed above 30 kilometers per hour will cause noise in tires, wind noise and other things that help to recognize EVs and there will be no need to produce artificial sound [7].

Fake engine sounds in electric vehicles are usually created using a combination of software and hardware. The vehicle's internal and external speaker system plays synthetic or pre-recorded engine sounds. This technology uses various types of vehicle sensors to receive data from the propulsion systems. It then simulates or amplifies the exhaust sound while driving and delivers the desired sound.

Even after adding sound, electric vehicles are typically quieter than the standard internal combustion engines found in other vehicles. These vehicles create less noise pollution in urban environments, but they will endanger the safety of pedestrians. The intensity and depth of the simulated engine sound may vary depending on the vehicle model and manufacturer. Some vehicles make a monotonous sound that plays all the time, while others make it depending on the engine speed (RPM) and the speed of the vehicle, which is completely normal.

In addition, some vehicles allow drivers to customize the simulated engine sound. However, additive sounds can create a complex interference that may be loud in some places and very faint in others, which should also be taken into account.

2.4 Legal Requirements

Regarding the production of sound and its intensity by electric vehicles, until now, legal requirements have not been officially finalized in most countries. However, in the United States of America and the European Union, legal mechanisms and legal requirements have been provided in this regard. These legal requirements include various issues that will be introduced below [8].

2.4.1 Important indicators and driving conditions

Some of the most important indicators proposed in the legal requirements set in the United States and the European Union are shown in Table 2.1 and compared with each other.

The metric parameters differ from each other in the legal requirements developed in the United States and Europe. Table 2.2 shows the comparison of driving conditions of the examined vehicle in the legal requirements prepared in the European Union and the United States.

Table 2.1: Comparison of the most important indicators proposed in the legal requirements of the European Union and the United States

Indicators	European Union	United States of America
minimal Third Octave Bands levels	✓	✓
Tonal required 6dB above vehicle levels	✓	-
minimal Pitch Shift per km/h	✓	✓
Tonal required above 400 Hz	-	✓
Maximal overall level	✓	-
Minimal overall level	✓	-

Table 2.2: Comparison of driving conditions of the examined vehicle in the legal requirements prepared in the European Union and the United States

Conditions	European Union	United States of America
In stop mode	-	✓
Moving at a speed of 10 km/h	✓	✓
Moving at a speed of 20 km/h	✓	✓
Moving at a speed of 30 km/h	-	✓
Reverse gear movement	✓	✓

As can be seen, the legal requirements of the United States are stricter in this regard. When the vehicle is moving at speeds higher than 30 km/h, or even when the vehicle is stopped but on, it must produce sound. But according to the legal requirements approved in the European Union, when the vehicle speed increases above 30 km, it is no longer required to produce sound by the vehicle. Also, there is no need to produce sound when the vehicle is stopped.

2.4.2 Minimum overall level

The minimum intensity of sound produced to ensure the reduction of the risk of accidents in the legal requirements prepared in the United States and the European Union is determined as shown in Table 2.3 [8].

Table 2.3: Comparison of the minimum sound intensity produced in decibels in the legal requirements prepared in the European Union and the United States

Conditions	European Union	United States of America
In stop mode	-	49
Moving at a speed of 10 km/h	50	55
Moving at a speed of 20 km/h	56	62
Moving at a speed of 30 km/h	-	66
Reverse gear movement	47	52

2.4.3 Maximum overall level

In the legal requirements approved in the European Union in all driving situations, the maximum volume of sound produced is considered equal to 75 decibels. However, in the legal requirements developed in the United States, no specific limit is considered.

2.4.4 Minimum third overall band levels

The comparison of the legal requirements presented in the United States and the European Union in terms of the minimum required sound pressure levels is shown in Fig. 2.1 [8].

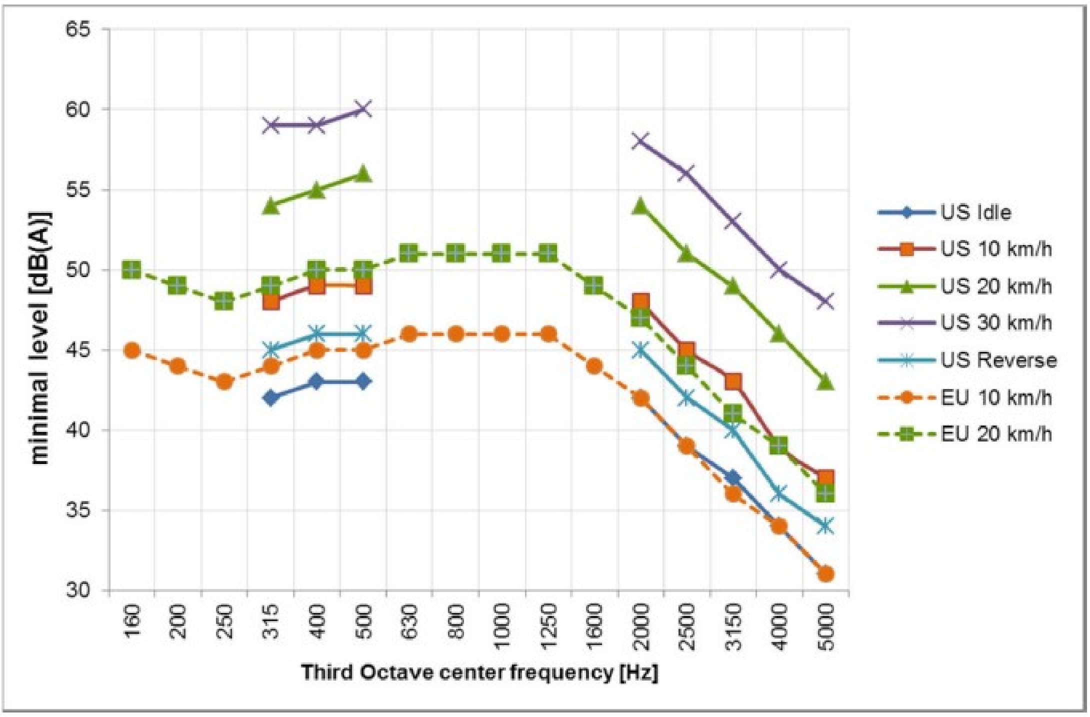

Figure 2.1: Comparison of the minimum required sound pressure levels in different driving conditions provided in the legal requirements of the United States and the European Union [8]

As can be seen, the EU proposal for minimum sound pressure levels is mostly in the range of 160 to 5000 Hz, Also, the US proposal focuses on the frequency bands between 315 to 500 and 2000 to 5000 Hz.

2.4.5 Tonals below 400 Hz

Legal requirements in the United States have prescribed a tonal below 400 Hz.

2.4.6 Pitch shift

Legal requirements in both the United States and the European Union have emphasized that tonal pitch must be related to vehicle speed. The minimum displacement in the mentioned requirements is 1% and 0.8%, respectively [8].

2.4.7 Tonal above vehicle level

US legal requirements emphasize that a tone must be 6 dB higher than the sound emitted by the vehicle in that third octave band [8].

2.5 Developed technologies and methods

So far, modern technologies and methods for producing sound in EVs have been presented with the aim of increasing the level of driving pleasure and preventing traffic accidents.

In reference [9], a new approach to sound design in electric vehicles is presented. Also, in this study, the requirements related to sound production in electric vehicles that are being used in Chinese automobile companies have also been investigated. In order to collect data, interviews with ten sound design experts were used. The goal is to highlight the insights of electric vehicle sound design professionals and extend it to address issues related to electric vehicle sound in design. These findings show that the use of methods based on digital signal processing can be effective in this regard.

In reference [10], a method based on granular synthesis for producing sound in electric vehicles is presented. Also, the effect of this method on the emotional experience of drivers has also been investigated. In the proposed model, four granular synthesis parameters including sample source, grain duration, grain coating, and RPM range are considered. By combining different values of each sound parameter in an orthogonal array, 27 different sound samples have been produced. The sounds produced by 32 participants (20 men, 12 women) were evaluated. The results showed that each granular synthesis parameter has a different effect on the user's understanding of emotion and satisfaction. In addition, the results showed that the combination of different values of each parameter may lead to the induction of a specific feeling in people. The sound design method proposed in this paper can help the development of electric vehicle sound in the future.

In reference [11], a method for designing a sound simulation system in electric vehicles is presented, which is proportional to the acceleration of the vehicles. In this study, the motion characteristics based on the acceleration of the vehicle engine have been investigated using digital audio signal processing. In this method, the data related to the status of the moving vehicle is placed online on the CAN bus of electric vehicles. According to this situation, the sound of the engine movement is simulated using the digital signal processing method. The obtained results have shown that this method can improve the performance of drivers and reduce the number of accidents.

In reference [12], a method for producing sound in electric vehicles with the aim of improving road safety is presented. The proposed approach is based on the hypothesis that the safety distance chosen by a driver can be observed by adjusting the active sound of the vehicle. To verify this hypothesis, a driving simulator based on digital signal processing was designed. In this simulator, the driving experience with the designed sound and the driving behavior resulting from it can be repeated and verified in a virtual environment. The proposed sound design is based on an additive synthesizer using Shepard-Risset and its control is done with external signals. This active sound design can be added to the latest generation of electric vehicles to improve road safety while increasing the emotionality of the driving experience. Also, the results show that emotions are changed by certain harmonic sets of pitches and this change of emotions can affect driving behavior and reducing traffic.

In reference [13], an overview of the design of a linear and directional sound production system has been discussed. This design is made using complex audio signal processing algorithms. It has been tried that the required digital functions, Hilbert transform functions, filters are performed by the powerful Spartan-6 series FPGA chip. Also, in the initial simulations, it has been shown how the audio signals entering this system will reach our ears by SSB algorithms and by using the nonlinear effect of the air integrator. By using various pre-processing steps, accurate sampling rate and application of multiple signal processing functions, we will witness the least distortion and side noises in the system. Operational samples of this system are made in different frequency modes and have commercialization capabilities.

2.6 Sound synthesis in electric vehicles

Synthesis can be defined as the combination of multiple elements to form a connected whole. Synthesizers are so named because they create and combine electrical signals to produce sound. By doing this, they synthesize the sound. Synthesizers are electronic instruments that usually take the form of keyboards – although they can also be arrangers or arpeggiators.

Synthesizers use an oscillator to generate an audio signal using different audio waveforms and frequencies. Synths come in two forms: monophonic synthesizers and polyphonic synthesizers. Synths can only play one note at a time. This makes them great for bass lines and lead synth parts. Polyphonic synths can play multiple notes.

Today, sound synthesis can be done through software or soft synthesizers without the need for physical equipment beyond your computer. While different types of sound synthesis differ in the tone emitted and the way the sound is produced, they all use specific tools to shape the sound. Generally, an audio signal is generated through an oscillator before passing through one or more filters and low-frequency oscillators (LFOs).

Sounds designed based on the sound synthesis method for vehicles from the perspective of drivers and pedestrians have been investigated. Also, the quality and intensity of the produced sounds have been evaluated from the point of view of complying with the legal requirements and relevant standards. The results show that the sounds produced can help to improve the road safety level while stimulating people's emotions. Also, the results show the manufacturers of EVs can use the method based on sound synthesis both for their customers and general public to create a good acoustic experience. The use of this technology and internal and external sound amplification allows vehicle companies to give more flexibility to their products [14]. Also, a method is presented for designing engine sound as well as creating it in noiseless vehicles. In this regard, a model has been proposed to investigate the relationship between engine noise, vehicle condition parameters and noise sources. The most important variables indicating the condition of the vehicle considered in this study include engine speed, vehicle speed, gear condition and vehicle acceleration. The proposed method consists of analyzing the sound output from the engine and extracting its harmonic content by considering random noise sources. The resulting signal represents the input of the developed algorithm, based on granular synthesis. It leads to the production of a new sound depending on the operating conditions of the engine. The evaluation of the obtained results indicates that the solution offers a completely pleasant and real engine sound that is able to increase driving safety [15].

In some studies, the theory and applications of the modified frequency modulation synthesis method for use in electric vehicles have been investigated. This technique overcomes some of the shortcomings of classical frequency modulation and provides a more complete spectrum due to changes in the modulation index. The application of the proposed method in resonance and formant synthesis has been investigated. This technique provides a means to change the symmetry of the spectral coverage. Finally, the applications of the proposed scheme are discussed. The results show the possibility of online use of this method in the production and processing of sound in electric vehicles [16].

2.6.1 Additive Synthesis

In this method, sound is produced by combining a large number of sine waves with different levels and frequencies. Combining more of the mentioned waves can lead to the production of additional harmonics. The function of sine waves in additive synthesis is similar to the function of oscillators in subtractive synthesis. In reference [17], an additive synthesis method for use in electric vehicles with LiFePO4 batteries is presented. The results have shown that the proposed plan, in addition to increasing the safety level, can also bring economic benefits compared to other methods.

In [18], a method for sound design in electric vehicles is proposed, which takes into account parameters related to vehicle movement. Also, the interactive genetic algorithm has been used to optimize the sounds. Synthesized EV sounds, based on additive synthesis and filtering, have been proposed to a set of participants during testing. An experimental protocol is proposed to evaluate the detectability of EV sounds. After the convergence of the method, the sounds obtained by the interactive genetic algorithm have been compared with different sound design proposals. The results show that the quality of sounds designed by the interactive genetic algorithm method is significantly higher than other existing methods. In addition, the sounds produced while meeting the legal requirements can also improve the level of safety. Moreover, a methods based on granular synthesis for sound production in electric vehicles have been investigated. As Fourier analysis is for additive synthesis, an equivalent method is presented as the analytical counterpart of a generalized granular synthesis in which sound is constructed by combining selected heterogeneous components. The obtained results show the effectiveness of the proposed method in sound synthesis and improving the performance of EVs from the perspective of increasing the safety level [19].

2.6.2 Subtractive Synthesis

Subtractive synthesis is a method of sound synthesis in which parts of an audio signal (often a signal rich in harmonics) are attenuated by a filter to change the loudness of the sound. The signal from the oscillator is sent to a filter and shows frequency-dependent losses and resonances in the body of the device.

In reference [20], in order to detect road traffic and reduce driving risks, a method based on modeling and subtractive synthesis is presented. The obtained results show that this model can increase the level of driving safety.

2.6.3 Wavetable Synthesis

This type of synthesis is based on the use of a number of single-cycle waveforms. In reference [21], the noise problems of current motors are investigated. Sampling-based engine sound creates limitations in creating natural sounds. To solve this problem, the method based on Wavetable Synthesis has been used in this study. Also, the results of this method have been compared with additive and subtractive syntheses to extract the most similar real engine sound. The obtained results show the higher efficiency of the proposed synthesis method compared to other existing methods.

2.6.4 Active sound synthesis

Active sound production systems for electric vehicles play an important role in improving the perception and transmission of sound in the vehicle. They can meet the needs of different user groups for driving and riding experience. Active sound synthesis algorithm is the main part of ASGS.

In reference [22], a variable-range linear interpolation method is presented to design an active sound synthesis algorithm that uses frequency shift and pitch shift. By examining the performance parameters of electric vehicles such as vehicle speed, engine speed, etc., the audio signal is interpolated to change the frequency of the audio signal. Then the amplitude of the audio signal is determined. In this way, it is possible to simulate a sound similar to the sound of the engine of traditional vehicles according to different driving modes.

The obtained results show that the produced sound can quickly and accurately reflect the driving condition of electric vehicles. Finally, by analyzing and verifying the quality of the synthesized sound through various parameter settings, it is possible to obtain the engine synthesized sound. It satisfies the subjective evaluation of the sound quality. Also, the results have shown that the proposed method plays an important role in improving pedestrian safety and driving experience.

An active sound generation system is presented to simulate engine sound in electric vehicles. In this regard, a mathematical model has been proposed and implemented along with a Fourier transform technique and short-term synthesis. Also, the ASG hardware is designed along with its functional circuits and the corresponding control software is also developed. The ASG system is configured based on the speakers used by the vehicle's audio system. The designed sound changes according to the acceleration of the vehicle. The control method is also modeled based on the characteristics of internal noise and taking into account the range of engine sound changes.

The obtained results show the high accuracy of the proposed method for sound production [23].

Also, some presented methods for producing active vehicle sound are based on granular synthesis algorithm. The advantage of these methods are that they prevent mismatching of the parameters of granular sound signals. The comparison of the expression of the audio signal function and the Hilbert transform is done based on the principle of overlap. In addition, parameters such as phase, frequency and amplitude of audio signals have been interpolated using the Hermit interpolation algorithm. It can guarantee the continuity of phase, frequency and amplitude curves. The results show that the method can be used for sound production. Also, the results show that transmission sound can create a high-quality sound recovery and increase the safety level of pedestrians and cyclists by preventing accidents [24].

2.7 The importance of using methods based on digital signal processing

Digital signal processing, in its essence, involves the manipulation of signals that are represented in digital form. Unlike analog signal processing that deals with continuous signals, digital signal processing works on discrete time signals. This provides the possibility of precise control and analysis. At the heart of digital signal processing is the digital signal processor, which is a specialized microprocessor optimized for high-speed numerical computations. Digital signal processing algorithms, from simple filters to complex Fourier transforms, define the operations performed on digital signals.

Digital signal processing offers several advantages over analog signal processing, including flexibility, repeatability, and immunity to noise and distortion. Using the power of digital computing, digital signal processing enables complex signal analysis and manipulation in real time [25]. Digital signal processing has revolutionized the audio industry and enabled advanced features such as noise reduction, equalization and spatial audio processing. From smartphones to professional audio equipment, digital signal processing algorithms enhance the listening experience in a variety of environments.

In the field of image and video processing, digital signal processing algorithms enable tasks such as image enhancement, compression and pattern recognition. Applications in this field range from medical imaging and surveillance to augmented reality and computer vision.

Also, digital signal processing plays a central role in modern communication systems and facilitates modulation, demodulation and error correction. From wireless networks to satellite communications, digital signal processing algorithms ensure reliable data transmission and reception.

In addition, digital signal processing, in aerospace and defense, is part of radar and sonar systems and provides the possibility of identifying, tracking and analyzing the target signal. Real-time processing capabilities provided by digital signal processing algorithms enhance situational awareness and threat detection. Considering the significant advantages and many applications in various fields such as sound processing, image processing, etc., the development of digital signal processing systems is necessary. On the other hand, the use of methods based on digital signal processing can be an efficient approach for sound production in EVs due to their diversity and compatibility. On the other hand, the possibility of creating a high matching between the speed of the vehicle and the intensity of the generated sound can contribute to increasing the level of safety. Nevertheless, the possible challenges caused by the use of these methods, such as the environmental effects and costs of their implementation, should also be taken into consideration [25]. In many studies, the design of efficient logarithmic converters for digital signal processing applications has been discussed. In this regard, logarithmic converters based on piecewise linear approximation have been investigated and an accurate method based on linear programming has been presented to obtain optimal coefficient values. Also, the maximum error of relative approximation has been minimized, while reduced non-zero bits have been used for coefficients. This method results in a significant reduction of relative approximation error compared to the results of previous methods. Implementation details and manufacturing results in 90nm CMOS technology are also briefly described [26]. Moreover, an adder circuit is presented, which has a special application in the field of digital signal processing. The designed circuit has a suitable speed for processing signals and special attention has been paid to the power consumption. One of the applications of these circuits is in the production and synthesis of sound in electric vehicles. The obtained results show the effectiveness of the plan [27].

2.8 Sound synthesis for Electric Vehicles

Solutions based on sound synthesis can help to reduce and solve this problem. This sound synthesis in electric vehicles can generally be in two ways, which will be explained in the following. Digital audio synthesis was introduced more than 60 years ago. About 20 years later, digital music synthesizers became commercial. After that, when specifications for digital musical instrument interfaces were published and incorporated into products. This made it possible to play multiple synthesizers connected to each other or to play music synthesizers with computer control using sequencing software. In recent years, MIDI music synthesizers have found their way into cell phones. Therefore, it can be said that almost everyone uses voice synthesis in their daily life. Sound synthesis is a technology in which signal processing plays an important role [28].

In order to synthesize sound in electric vehicles, many devices have been produced so far, in addition to methods, one of these devices is called HALOsonic. This device is able to produce sound inside and outside the cabin. The core of the easy-to-implement technology is a software algorithm originally developed for fast processing of active suspension systems. Its function is that based on the speed and acceleration of the vehicle, through a central processor, a sound similar to the real engine is produced. This sound is played through the vehicle's front bumper speaker and through the vehicle's normal audio system. The reason for placing the speaker in front of the vehicle is that the sound can be easily recognized from a distance. The remarkable thing about this device is that it is able to reduce the sound faster compared to internal combustion engines. In general, there is no need to use sound synthesis at high speeds because the sound of tires and the road are considered as the main source of sound. Pedestrians and cyclists or other drivers can use them to detect the presence of a vehicle on the road.

By imitating the speed and frequency of gasoline engines, the sound processor allows pedestrians to recognize the speed, direction and distance of the vehicle. It is very important in increasing the level of safety and reducing the number of accidents.

The synthesized engine sound, which is close to the real engine sound, can help to identify it better. If the sound produced is not similar to the real engine sound, it may cause annoyance or confusion to people.

Fig. 2.2 shows a synthesis interface that is used to produce artificial sounds in electric vehicles [29]. Synthesizer programming is superior compared to sample-based algorithms, and by using several oscillators, it can create many possibilities for producing different sounds.

The key audio parameters that have the ability to create a sense of coherence between artificial and natural sounds of vehicle engine have been investigated. By analyzing the time and frequency of sounds produced, the presence of micromodulations in frequency and resonances caused by sound transmission were identified. These parameters are considered in the form of a sound synthesis model. In order to evaluate the method, experiments have been vehicleried out. The obtained results have shown that the inclusion of resonances in synthesized sounds significantly increases their naturalization properties. But the use of micromodulations does not have a significant effect on it. Also, the results have shown that from the users' point of view, the implementation of the method can lead to an acceptable level of satisfaction [30].

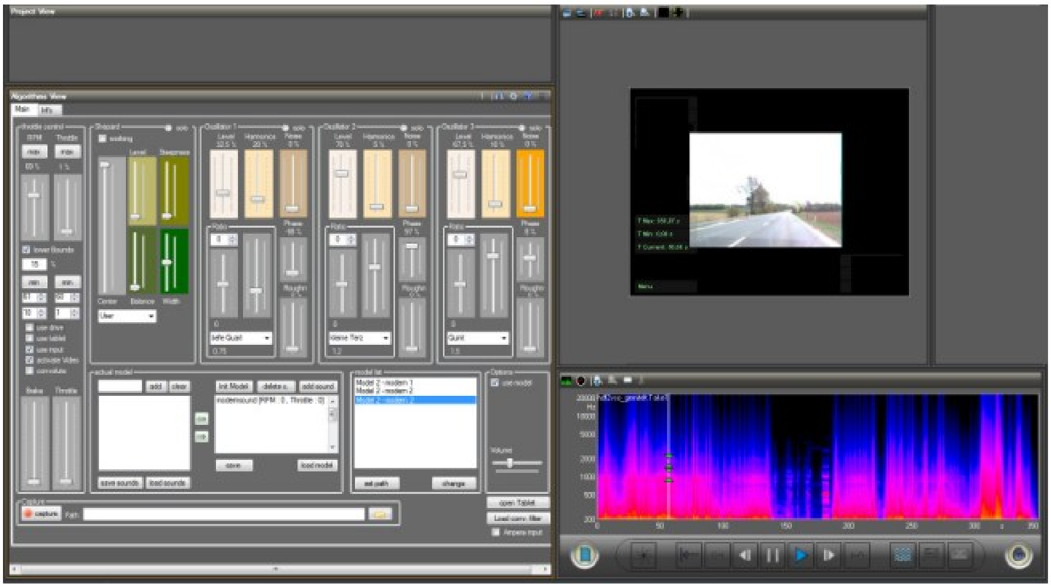

Figure 2.2: Sound synthesis tool to generate of sounds in EVs [29]

2.8.1 Internal Digital Sound Synthesis

In this case, sound contouring is activated inside the vehicle by producing sounds corresponding to the speed and acceleration of the vehicle through a standard speaker system. It should be noted that advanced synthesis tools provide complete flexibility for today's electric and hybrid vehicles in "all-electric" mode. The use of sound synthesis in the condition of engine shutdown in electric vehicles makes it easier to understand the states of the engine being on and off. The synthesis of sound corresponding to the speed and acceleration of movement inside the vehicle cabin space causes a better sensory connection between the driver and the vehicle. Many of vehicle sound design methods focus on three dimensions including engine speed, spectral energy distribution and sound amplitude in normal speed range. The focus of the design is on sound intensity parameters, calibration taking into account the characteristics of the speaker's frequency response, the accuracy of sound range control and sound quality. In this regard, ASGS control software and hardware have been developed. The results of the implementation of the proposed plan on real vehicles show that the method is able to provide the desired sound in different conditions, including constant speed and constant acceleration. Also, the evaluation results show that parameter design, selection and accuracy of calibration methods and noise evaluation determine the accuracy and effectiveness of ASGS [31].

2.8.2 External Digital Sound Synthesis

Advanced external sound synthesis technologies make it possible to design and produce a unique external sound that is unique to each brand and easily recognizable.

The diagram related to the analysis of the sound synthesis method used in electric vehicles is shown in Fig. 2.3 [30].

The external sound can be synthesized by combining artificial sounds. Mechanical sounds are made by considering the harmonic components that represent the sounds produced by the engine's rotating crankshaft. Harmonic components, including size and frequency phase, were obtained using the numerical integration method. Noise was simulated with random sounds and spectral characteristics similar to the measured value, and its amplitude was synchronized with the rotation speed. The synthesized sounds were evaluated for sound production through hearing tests. The obtained results show that the method has good accuracy and quality and can improve the safety of pedestrians and cyclists [32]. Also, an algorithm for the real time synthesis of internal combustion engine noise is presented. Through the analysis of a recorded engine noise signal of continuously varying engine speed, a dataset of sound samples is extracted. It allows the real time synthesis of the noise induced by arbitrary evolutions of engine speed. The sound samples are extracted from a recording spanning the entire engine speed range. Each sample is delimitated such as to contain the sound emitted during one cycle of the engine plus the necessary overlap to ensure smooth transitions during the synthesis. The proposed approach, takes advantage of the specific periodicity of engine noise signals to locate the extraction instants of the sound samples. During the synthesis stage, the sound samples corresponding to the target engine speed evolution are concatenated with an overlap and add algorithm. It is shown that this method produces high quality audio restitution with a low computational load. It is therefore well suited for real time applications [33].

2.8.3 Sound2Target

In this case, active noise cancellation and digital sound synthesis are used simultaneously to remove unwanted noise and enhance desired audio content.

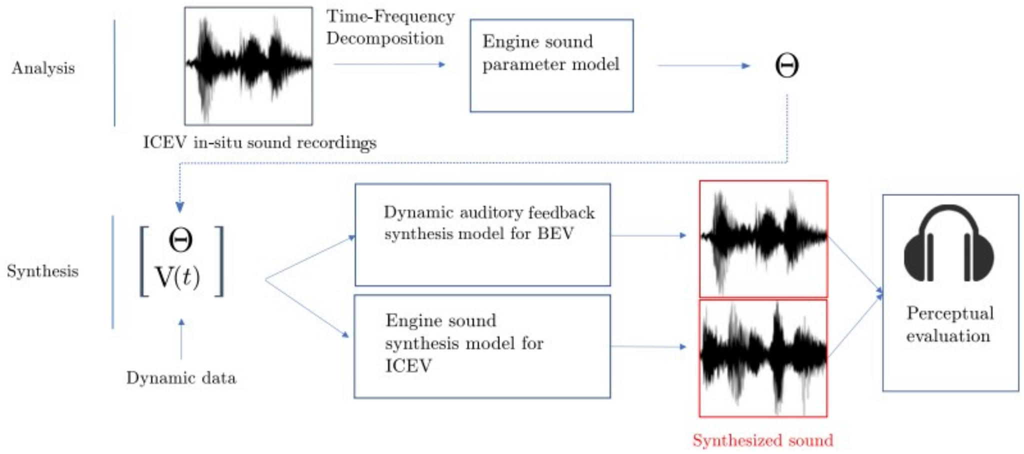

Figure 2.3: Diagram related to the analysis of sound synthesis method used in EVs [30]

2.9 Engine sound system

2.9.1 Sound sampling

The first step was sampling the original engine sound, which it was done with the REV Lotus before its petrol engine was replaced, and with a number of other vehicles. The final engine sound synthesis system is independent of the sound samples, so the driver can select the sound samples to be used to generate the engine sound he or she prefers. A high-quality directional condenser microphone was used for sound recording.

It was placed about 50 cm behind the vehicle exhaust. Audio was then recorded with an audio software suite onto a PC. Engine RPM were held constant for about three seconds during recording and this procedure was conducted at regular RPM readings, from 1,500 to 9,000 RPM [34].

2.9.2 Vehicle sensor input and sound output

There are various options for sensor input from the vehicle to control the generated engine sound, e.g., electric engine RPM sensor, vehicle speed from speedometer or GPS, etc. For the REV Racer Lotus, we used an even simpler method, utilising a drive system current sensor, which roughly corresponds to engine revs, in addition to the vehicle's GPS speed.

This allowed us to implement the engine sound system with minimal interference with the vehicle. Our goal is to run the vehicle sound system on a dedicated embedded hardware. However, we have implemented the prototype for the Lotus on our existing in-vehicle automotive PC (core 2-duo). It also serves a number of other tasks, including driver information, data logging and telemetry. Sounds are being played back through an amplifier and vehicle mounted waterproof marine speakers.

The flowchart of electric vehicle sound design is shown in Fig. 2.4.

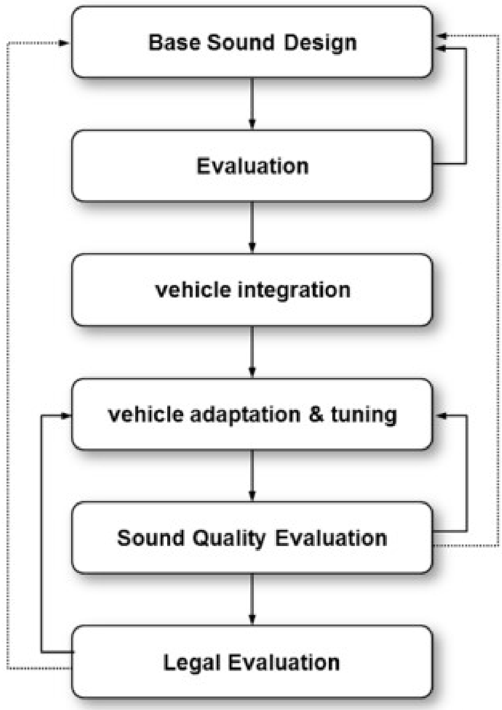

Figure 2.4: Electric vehicle sound design flowchart [34]

As it can be seen, after the design, the produced sound must be evaluated both from the perspective of quality and from the perspective of compliance with legal requirements.

2.9.3 Audio processing

Audio processing is required to increase the resolution between recorded audio samples and to blend between them. We were able to decrease the RPM increment between samples by producing interpolated samples to fill the gaps. Audio samples at 50 RPM increments are sufficient to produce a smooth engine sound. While several methods for this interpolation were available, we have explored wave synthesis, Fourier interpolation, and frequency shifting.

The wave synthesis turned out to be too compute-intense for the planned embedded hardware implementation. Hence, we will only describe Fourier interpolation and frequency shifting in this section [34].

2.10 Sound customization

As mentioned in the introduction of this dissertation, a relevant aspect in the vehicle design is represented by the opportunity to customize some aspects of the vehicle. One of this is the engine sound. This can be applied not only to EVs, which needs an acoustic system to address the lack of noise issue, but also to other categories of vehicles, which already have a clearly audible sound. Often, vehicle makers require the possibility to give more emphasis to some engine sound harmonics so to let them prevail upon the others. This allows to enhance the timbre and get a more powerful sound. Generally, the harmonics to be emphasised are the odd ones, thus the first, the third and the fifth. Also higher order harmonics can be highlighted.

This effect is obtained by inserting a tunable gain on each tracked harmonic and sub-harmonic of the original signal, before performing granular synthesis. This is quite easy, as the harmonics decomposition has already been implemented to perform noise elimination and granular synthesis.

Furthermore, such components can be either enhanced, by setting a gain bigger than 1, or attenuated, imposing a gain smaller than 1. Default gain value is set to 1, that is no correction is performed on the harmonic energy.

Vehicle perception can be modified by making it sounds like a different one in terms of cylinder configuration. Another modification on the vehicle sound can be the addition of various sound effects, so to further enrich the perceived audio. Effects include, as an example reverberation, tremolo, echo, equalization and panning.

Chapter 3

Granular synthesis for Electric Vehicles

3.1 Granular synthesis

Granular synthesis is a sound production and modulation method that works by combining micro-audio samples (granules) extracted from an audio track.

This method is an innovative technique in the field of acoustics to produce specific sounds, even in real-time applications. This method is widely used in video games and in general in the world of virtual reality to combine sound effects and animations, as well as sound production in electric vehicles. This method is growing because the sounds produced based on it are very realistic and a wide range of sounds can be created with its help. A granular is characterized by two main parameters: envelope and content, which refer to the shape of the granule's amplitude and the actual audio contribution, respectively.

Depending on the manipulations grains are subjected to and the way they are reordered, different sound textures can be created. As an example, granular synthesis can be exploited to perform time stretching of the original audio they are extracted from, altering the sound duration and letting the pitch unmodified [35].

They can be arranged randomly or according to some criteria. In this thesis, a new grains sequence is established according to a new provided vehicle parameters profile. This includes the engine speed, the gear and the acceleration information over the time. The granular synthesis steps are shown in Fig. 3.1.

3.1.1 Granule envelope

Envelope means the manipulation performed on grains amplitude, affecting their shape especially at the boundaries.

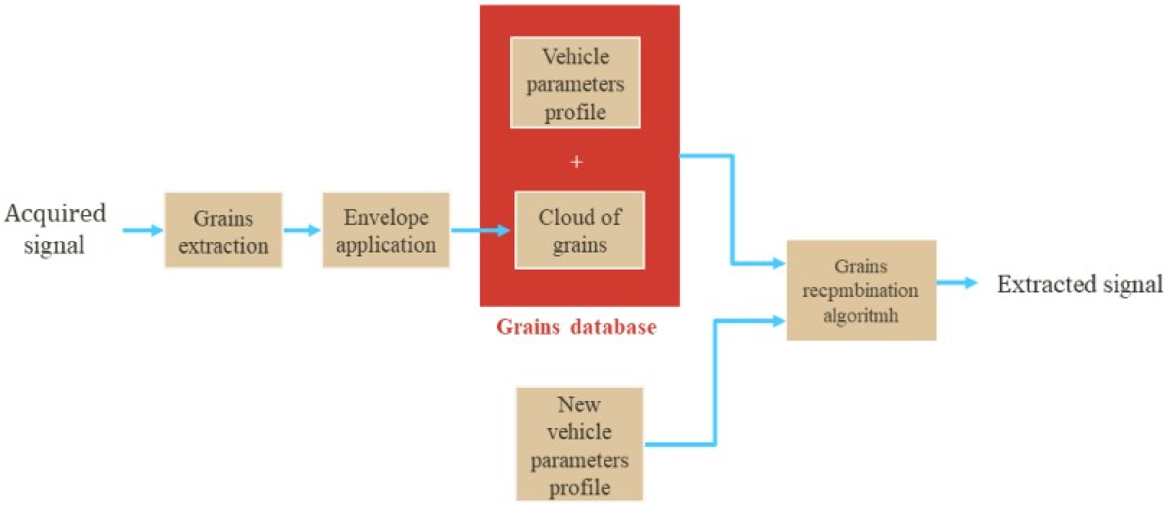

Figure 3.1: The steps of granular synthesis [35]

The transition between seeds in the recombination process should be done as gradually as possible. Thus, after they are extracted, grains are windowed, which means an envelope is applied. Basically, envelope application generates the fade-in and fadeout effects at the grains boundaries [36]. The grain shape follows exactly the one of the superimposed window. So, the envelope governs both the grains duration and amplitude. The structure of Windows is shown in Fig. 3.2, which shows the steps of Attack, Sustain and Release phases of the overall envelope duration:

Attack time: It determines the slope of the window rising part. Here the grain amplitude is modified according to the steepness of such interval. The smoother the slope, the more natural the transition between the previous and the current grains will be more. Sustain time: It means the region where the grain amplitude is unmodified with respect to the original shape it has in the starting audio sample. The sustain time: If the grain is quite long but, the sustain phase is very short, it is equivalent to have a very short grains.

Release time: It determines the slope of the window in the falling. The bigger the slope, the rougher will be the transition to the next grain in the sequence [37].

The sum of these three contributions provides the envelope length, corresponding to the grain duration. The proportion between the three phases, establishes how distinguishable the contents of the grain are: the higher the duration and the longer the sustain phase, the more the sound timbre is preserved. Thus, when going towards smaller duration, the grain sound is perceived mainly as a click, that is the timbre information is no longer intact. This means that envelope parameters are crucial for granular synthesis. Therefore, their choice must be performed vehicleefully so to achieve an optimal signal reconstruction.

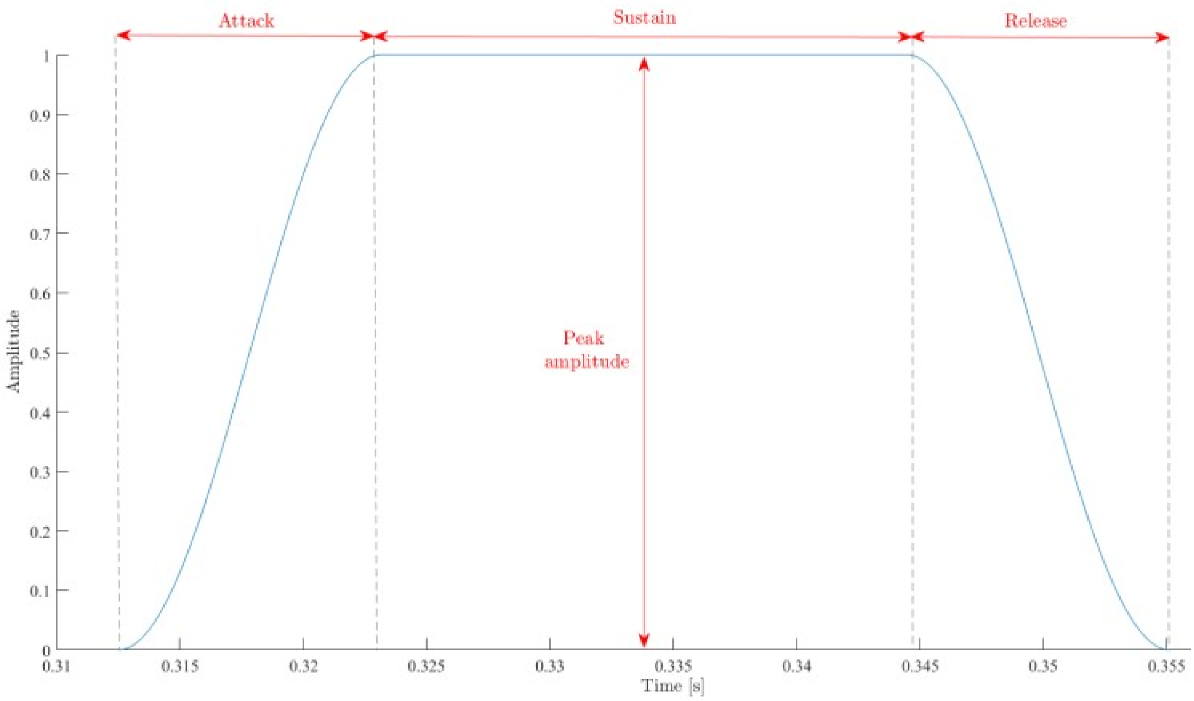

Figure 3.2: Window structure [37]

An example of how the grain shape changes after windowing is shown in Fig. 3.3. As can be seen, applying the window creates a smoothing effect at the grain boundaries. The reason is that its amplitude at the edges is reduced to zero due to the lateral damping caused by the coating.

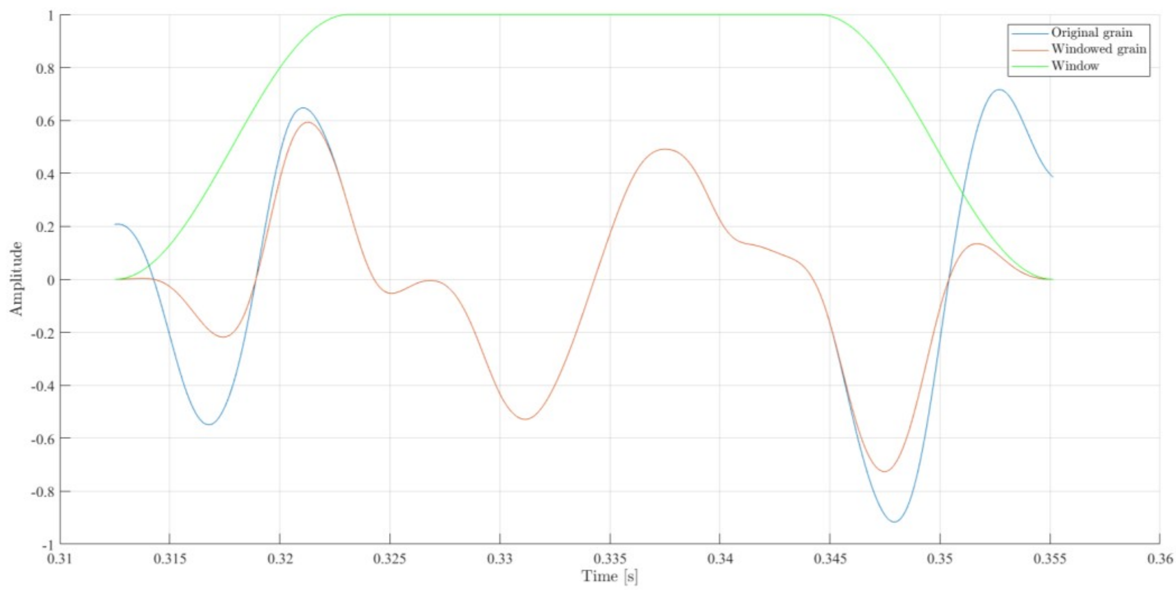

Figure 3.3: Examples of grain windowing [37]

Some possible envelopes are shown in Fig. 3.4. The most suitable for sonic content preservation is an envelope with trapezoidal profile. The sustain phase has a width that allows to maintain a considerable part of the grain unchanged from the amplitude point of view, preserving the acoustic fingerprint.

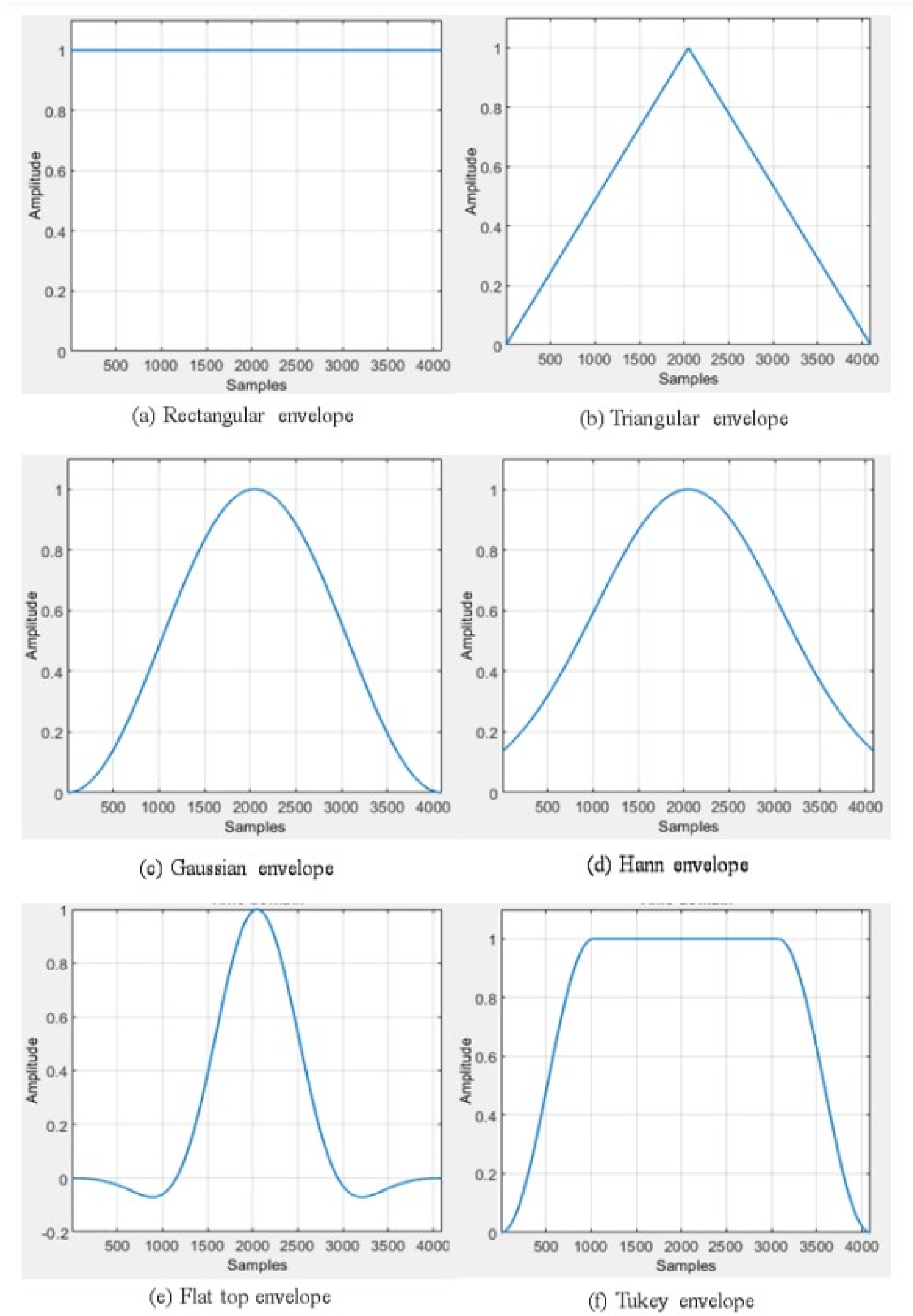

Figure 3.4: Examples of different envelope shapes [37]

3.1.2 Granules extraction

The extraction and windowing of granules can be expressed with the help of the following equations

$$\text{Grains} = \sum_{i=1}^{N} g_i \tag{3.1}$$

where

$$g_i = x\left((i-1).L + 1 : i.L\right).win(L) \tag{3.2}$$

where, Grains is the matrix of grains belonging to $R^{(L,N)}$ which grains are arranged one after the other along the columns: N is the number of grains to be extracted, whose length is equal to L. In addition, gi represents the ith grain extracted. Also, x shows the original input from which grains are derived. win is the applied envelope, which can be, for example, one of those proposed in Fig. 3.3. The outcome of this step is a collection of grains with the corresponding amplitude profiles and a set of associated vehicle state variables. In this way, each grain is characterized by its set of vehicle parameters. Such data set is the starting point for a recombination phase [38].

The richer the data set, the more accurate the synthesized signal and the higher the number of possible combinations of grains. Even if not all the vehicle operating conditions are covered, the more similar grain to the needed one in terms of RPM at a given gear value can be considered, without producing a big error. Thus, if the database is quite rich, a missing grain can be approximated with one of the two closest ones with a negligible error. Generally, the acoustic difference between a recording at a certain RPM value p1 and one at p1 + k, where k is a very small variation in the engine speed, is not appreciable. Thus we can avoid to generate a new grain, which requires in additional computational effort.

Eventually, if the data base in not full enough, grains can be created according to the needed vehicle parameters set from the existing ones, performing frequency modulation of the most similar grains. The resulting database structure reflects the one in Fig. 3.5.

Grains database

	Grain #1	Grain #2	Grain #3	Grain #4	Grain #5	…
Sonic content						…
Engine speed [rpm]	2200	2201	2203	2204	2205	…
Gear	4	4	4	4	4	…
Acceleration [m/s²]	1.21	1.21	1.22	1.22	1.22	…

Figure 3.5: The structure of grains database [38]

3.2 The motivation of choosing Granular synthesis

Granular synthesis is a compelling and innovative approach to sound design and music production, with several unique characteristics and advantages. At its core, granular synthesis involves breaking down sound into tiny grains or particles that can then be manipulated and reassembled in creative ways. This method offers sonic possibilities that are not easily achieved with traditional synthesis methods.

1. Granular synthesis allows extremely detailed manipulation of sound at a microscopic level. By changing the characteristics of individual grains sound designers can create complex textures and evolving soundscapes that are rich in detail.

2. New avenues of creativity and exploration are opened up by this synthesis technique. Granular synthesis does not rely on conventional harmonic structures or rhythmic patterns. It encourages experimentation with sound in a more abstract and unbounded context. This makes it particularly attractive for sound art and experimental sound design.

3. Granular synthesis can transform ordinary sounds into something completely unrecognizable and new. By processing sounds through a granular engine, sound designers can extract and magnify micro sounds within the source material, discovering hidden sonic qualities. It can inspire new compositions or soundscapes.

4. Granular synthesis provides exceptional control over sounds in real time performance scenarios. It is critical for electric vehicle sounds to adapt to instantaneous traffic conditions or driver inputs. For example, if a vehicle suddenly stops or accelerates, the sound produced using granular synthesis can be quickly modified to reflect these movements. This makes the sound design more interactive and responsive, making it possible to create a reactive sound environment for pedestrian safety.

5. Granular synthesis can improve the way drivers and pedestrians perceive the movement of the vehicle, thanks to its ability to integrate multi-layered sound palettes. For an EV, this creates parallel sound waves in multiple frequency bands, providing acoustic feedback that is sensitive to the driver's changes in speed and acceleration. In addition, sounds designed to harmonise with or contrast with the surrounding sounds can help pedestrians to be more aware of the vehicle's presence.

6. Granular synthesis enables the creation of personalised sound designs for driver-environment interaction. For example, it can create sound profiles that dynamically change based on

factors such as the driver's driving style or the environment in which the vehicle is located. This personalization allows brands to enrich the customer experience and better cater to user preferences.

3.3 Development and Application of Granular Synthesis in EV Sound Design

3.3.1 Components of the sound

The EV sounds were synthesized using the mathematical modeling software Matlab and the additive synthesis technique. In order to generate different but plausible sounds for an electric vehicle, four main components of the sound were considered. The components are also named design factors here.

1. Component C1 "A thermic motor sound". This component synthesizes the first harmonics of a classical 4-stroke internal combustion engine (H0.5, H1, H1.5, H2, H4, H6),
2. Component C2 "A Harmonic Sound". This component synthesizes different musical 'notes', harmonic, that constitute a chord (chord with 2, 3, or 4 notes),
3. Component C3 and C4: "A broad band Noise" (granular synthesis). These components synthesize two filtered noises.

The final temporal signal s(t) is simply a weighted sum of the different components (equation 3.3).

$$s(t) = a_{C1}C1(t) + a_{C2}C2(t) + a_{C3}C3(t) + a_{C4}C4(t) \tag{3.3}$$

In addition to this, different parametric filters were applied to the final sound: (1) A sweeping filter (envelop filter), which changes the harmonics amplitude in function of time. (2) A flanging filter (swept comb filter effect), which produces time variations of the frequency spectrum.

It is out of the scope of this paper to describe all the parameters of the synthesizer (there are more than 70 independent parameters to define a sound). So, we can mention that all the frequencies and amplitudes of the components are adjustable, to create credible and original sounds, as well as the filters parameters.

The sound is not constant but ‘played’ by a control parameter of the vehicle: the speed. To make the sound evolve with the speed of the vehicle, we choose to adjust the frequencies and the amplitudes of the different components according to the speed with parameterized patterns.

3.3.2 Design variables of the EV sound

Among the different synthesis parameters of the sounds, it is necessary to define which one are manipulated by the IGA and coded in the genome (space of exploration of the genetic code). After several experiments, the following 6 variables, and their corresponding levels, were chosen as factors to get a large diversity of sounds (table 3.1).

Table 3.1: Definition of the 6 factors (design variables) and their levels

Factor	Variable	Level1	Level2	Level3	Level4
C1	Fundamental frequency of C1	70 Hz	100 Hz	130 Hz	160 Hz
C2	Fundamental frequency of C2	100 Hz	150 Hz	200 Hz	250 Hz
C3	Fundamental frequency of C3	100 Hz	200 Hz	300 Hz	400 Hz
C4	Fundamental frequency of C4	500 Hz	600 Hz	700 Hz	800 Hz
Amp	Amplitude of C1, C2, C3, C4	$a_{C1} = 2$ $a_{C2} = 1$ $a_{C3} = 0.7$ $a_{C3} = 0$	$a_{C1} = 0.5$ $a_{C2} = 0.75$ $a_{C3} = 1.5$ $a_{C3} = 0.33$	$a_{C1} = 0.25$ $a_{C2} = 0.5$ $a_{C3} = 1$ $a_{C3} = 0.25$	$a_{C1} = 0$ $a_{C2} = 0.1$ $a_{C3} = 0.1$ $a_{C3} = 0.5$
Filter	Type of filter	None	Sweeping filter	Flanger	Sweep + Flanger

The four first factors (C1, C2, C3, C4) control the frequencies of the components C1, C2, C3, C4. The factor Amp control the relative amplitude of the different components, and the Filter controls the use of different filters to alter the global sound. 4 levels were chosen for each factor. The setting of the levels of the factors required many adjustments (not reported here) to obtain audible differences between sounds, but with still convenient sounds. With these six factors and four level, the design space counts 64=4096 possible designs (all the possible combinations of the full factorial) [39].

The four first factors (C1, C2, C3, C4) control the frequencies of the components C1, C2, C3, C4. The factor Amp control the relative amplitude of the different components, and the Filter

controls the use of different filters to alter the global sound. 4 levels were chosen for each factor. The setting of the levels of the factors required many adjustments (not reported here) to obtain audible differences between sounds, but with still convenient sounds. With these six factors and four level, the design space counts $6^4 = 4096$ possible designs (all the possible combinations of the full factorial) [39].

3.4 Implementation of Granular synthesis system in MATLAB codes

1. First, the desired noisy signal is loaded.

```
[noisyAudio, Fs] = audioread('sn-001.wav');
```

2. Then, this signal, which has a sinusoidal state, is drawn.

```
rp = noisyAudio;
r = sin((1:length(noisyAudio))*0.0001);
plot(r)
rp = r' + noisyAudio;
```

3. In the next step, using the sound command, this noisy sound is played.

```
sound(rp,Fs);
```

4. In the next step, the parameters are defined, including the size of each frame, the overlap percentage between the frames, and the size of the FFT.

```
% Parameters
frameSize = 1024*2; % Size of each frame
overlap = 0.01; % Overlap percentage between frames
nfft = frameSize; % FFT size
```

5. In the next step and according to the following command, the size of the overlaps is calculated.

```
% Calculate the overlap size
overlapSize = floor(frameSize * overlap);
```

6. In the next step, spectral subtraction is performed.

```
% Perform spectral subtraction
denoisedAudio = zeros(size(noisyAudio));
```

In this direction, a loop of length (noisyAudio/overlapSize - 1) is defined in which, first, the current frame is extracted. Then, the magnitude spectrum of the frame is calculated. In the following, the noise spectrum is estimated using a simple statistical minimum method. In the next step, spectral subtraction is performed.

Then, the inverse FFT is calculated to get the deleted frame. Finally, overlay and addition are performed to reconstruct the removed sound.

```
for i = 1:(length(noisyAudio)/overlapSize - 1)
    % Extract current frame
    frame = noisyAudio((i-1)*overlapSize + 1 :...
            (i-1)*overlapSize + frameSize);

    % Compute the magnitude spectrum of the frame
    frame_fft = fft(frame, nfft);
    frame_magnitude = abs(frame_fft);

    % Estimate the noise spectrum using a simple minimum
    statistics approach
    if i == 1
        noise_spectrum = frame_magnitude;
    else
        noise_spectrum = min(noise_spectrum,...
                             frame_magnitude);
    end

    % Perform spectral subtraction
    denoised_frame = frame_magnitude - noise_spectrum;
    denoised_frame(denoised_frame < 0) = 0;
    % Ensure non-negativity
```

```
    % Inverse FFT to get denoised frame
    denoised_frame_time = ifft(denoised_frame, nfft);

    % Overlap and add to reconstruct the denoised audio
    denoisedAudio((i-1)*overlapSize+1:(i-1)*overlapSize...
                  + frameSize) = ...
        denoisedAudio((i-1)*overlapSize + 1 :...
                      (i-1)*overlapSize + frameSize) +...
        denoised_frame_time(1:frameSize);
end
```

7. After the end of this loop and in the next step, noiseless sound is extracted and played.

```
sound(denoisedAudio, Fs);
```

8. Finally, the sound is drawn in two modes with noise and without noise.

```
% Plot the original noisy audio
t_noisy = (0:length(noisyAudio)-1)/Fs;
subplot(2,1,1);
plot(t_noisy, noisyAudio);
title('Noisy Audio');
xlabel('Time (s)');
ylabel('Amplitude');

% Plot the denoised audio
t_denoised = (0:length(denoisedAudio)-1)/Fs;
subplot(2,1,2);
plot(t_denoised, denoisedAudio);
title('Denoised Audio');
xlabel('Time (s)');
ylabel('Amplitude');
```

3.5 Implementation of Granular synthesis system in MATLAB Simulink

The proposed Simulink design is as shown in Fig. 3.6, which includes 4 subsystems.

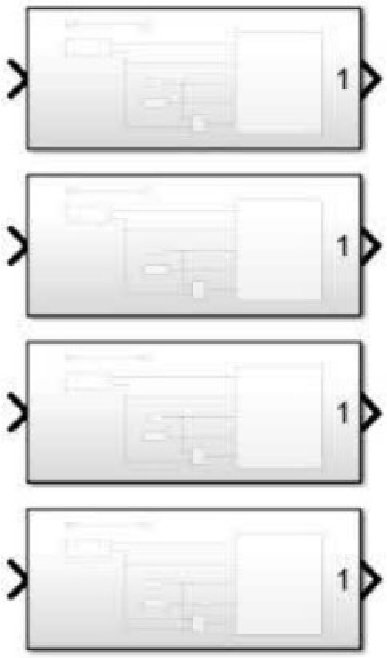

Figure 3.6: The proposed Simulink design for granular synthesis

The reason for using 4 subsystems instead of one subsystem is to improve the sound quality. These 4 subsystems work simultaneously and in real time. An input audio file is separated into many grains. Then, by changing the parameters of these microphones, including their pitch and volume, finally, new sounds are produced for use in EVs, the process of which is shown in Fig. 3.7.

In the following, the code inside the Audioread block shown in Fig. 3.7 will be explained. The decision to use four subsystems instead of a single subsystem was driven by the goal of achieving a more natural and higher-quality sound. These four subsystems operate simultaneously and in real time, enhancing the overall audio processing capability.

The process begins with an input audio file, which is divided into numerous small segments called grains. Each grain undergoes individual processing where various parameters, such as pitch and volume, are adjusted. By fine-tuning these parameters, the system can create a wide array of new sounds. This granular synthesis technique allows for a greater degree of control and flexibility, resulting in a more realistic and refined audio output. Ultimately, the new sounds generated through this method are intended for use in electric vehicles. The improved sound

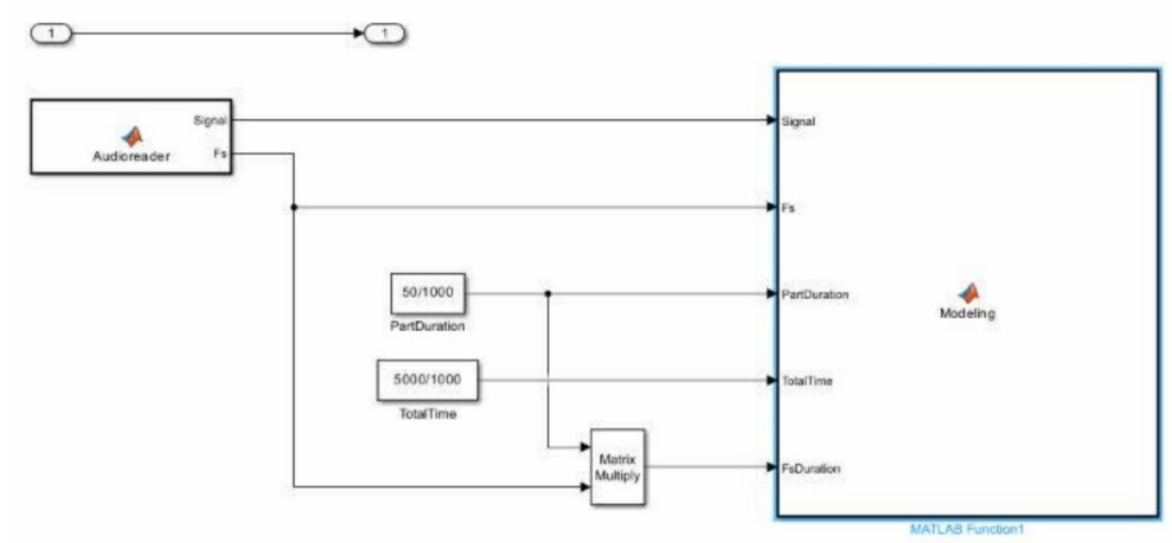

Figure 3.7: Granular synthesis plan to generate new sounds for use in electric vehicles

quality achieved by using four subsystems ensures that the auditory experience is both pleasing and natural, contributing to a more enjoyable and immersive environment for vehicle occupants.

```
function [Signal, Fs] = Audioreader ()
coder.extrinsic('audioread');
```

In the next step, the name of the studied audio file is defined.

```
FileName = 'sn-001.wav';
```

In the next step, the number of samples that must be allocated in advance for the signal array is defined. This value should be set manually based on the actual length of the audio file.

```
SampleNumber = 110250;
```

Next, the number of audio signal channels is defined. It should be noted that in this case, if the audio signal has 2 channels (stereo), the number of channels is set to 2, otherwise the value of this parameter is set to 1 (mono).

```
Channel = 1;
```

In the next step, the signal array is already allocated and the sampling frequency is also initialized. At this stage, based on whether the number of channels is equal to 1 or 2, the allocation of arrays and initial space is defined. It can be seen that the initial values of the arrays are considered equal to zero using the zeros command. In both cases, the initial sampling frequency is set to zero. Finally, by executing the corresponding block and code, the signal and sampling frequency are calculated as the output of this function.

```
    if Channel == 1
        % For mono audio, pre-allocate a stereo Signal array with zeros.
        Signal = zeros(SampleNumber, 2);
        % Pre-allocate a mono Signal array with zeros.
        Signal_n = zeros(SampleNumber, 1);
        Fs = 0; % Initialize sampling frequency to zero
        % Read the mono audio file.
        [Signal_n, Fs] = audioread(FileName);
        % Duplicate the mono signal to create a stereo signal.
        Signal = [Signal_n Signal_n];
    else
        % For stereo audio, pre-allocate the Signal array with zeros.
        Signal = zeros(SampleNumber, 2);
        Fs = 0; % Initialize sampling frequency to zero
        % Read the stereo audio file.
        [Signal, Fs] = audioread(FileName);
    end
end
```

In the following, the description of the code related to the modeling block shown in Fig. 3.7 will be discussed. As can be seen, the signal and sampling frequency obtained in the previous step and in the audioread block are used as inputs to the modeling file. In addition, PartDuration, TotalTime and FsDuration are other input parameters of the modeling file.

```
function Modeling (Signal, Fs, PartDuration, TotalTime, FsDuration)


coder.extrinsic('sound');
coder.extrinsic('audiowrite');
```

In the next step, the value of Volume and pitch parameters is determined.

```
Volume = 3;
pitch = 0.2;
```

In the next step, the number of iterations is calculated. As can be seen, for this purpose, TotalTime is divided by PartDuration, and then the fix command is used to round the obtained value. The value of the RandPart parameter is also a vector with the number of one row and the number of columns equal to Iteration, all of which are integers.

```
Iteration = fix(TotalTime/PartDuration);
RandPart = randi([1 length(Signal)],Iteration);
```

In the next step, a loop with the number of repetitions equal to Iteration is defined. In this step, first the audio file with noise is defined. Then, the size of each frame and the overlap percentage between the frames as well as the FFT size are defined.

```
for j = 1:Iteration

PartSignal = Signal(RandPart(j) : RandPart(j)+FsDuration);

%% Denoising Setup
noisyAudio = PartSignal;
frameSize = 1024; % Size of each frame
overlap = 0.05; % Overlap percentage between frames
nfft = frameSize; % FFT size
```

In the next step, the overlap size and spectral subtraction are performed.

```
% Calculate the overlap size
overlapSize = floor(frameSize * overlap);
% Perform spectral subtraction
denoisedAudio = zeros(size(noisyAudio));
noise_spectrum = 500;
```

Next, a loop is defined in which, first, the current frame is extracted.

```
for i = 1:(length(noisyAudio)/overlapSize)
    if ((i-1)*overlapSize + frameSize) > length(noisyAudio)
        continue
    end

    % Extract current frame
    frame = noisyAudio((i-1)*overlapSize + 1:...
                        (i-1)*overlapSize + frameSize);
```

Then, the frame size spectrum is calculated as follows.

```
frame_fft = fft(frame, nfft);
frame_magnitude = abs(frame_fft);
```

In the following, the noise spectrum is estimated using a simple minimum statistics approach.

```
if i == 1
    noise_spectrum = frame_magnitude;
else
    noise_spectrum = min(noise_spectrum, frame_magnitude);
end
```

In the next step, spectral subtraction is performed.

```
% Perform spectral subtraction
denoised_frame = frame_magnitude - noise_spectrum;
denoised_frame(denoised_frame < 0) = 0; % Ensure non-negativity
```

Then, in order to obtain a frame without noise, Inverse FFT is performed.

```
% Inverse FFT to get denoised frame
denoised_frame_time = ifft(denoised_frame, nfft);
```

In the next step, overlapping and adding is done with the aim of reconstructing the deleted sound.

```
    % Overlap and add to reconstruct the denoised audio
    denoisedAudio((i-1)*overlapSize + 1 : (i-1)*overlapSize + ...
                                          frameSize) = ...
        real(denoisedAudio((i-1)*overlapSize + 1 :...
                           (i-1)*overlapSize + frameSize) + ...
        denoised_frame_time(1:frameSize));
end
```

Finally, the new sound is extracted based on the initial sampling signal and frequency, and parameters such as pitch and volume are obtained.

```
    PartSignal = denoisedAudio;
    sound(PartSignal*Volume,Fs*pitch)
    % audiowrite('Export1.wav',PartSignal*Volume,Fs*pitch)
end
end
```

Chapter 4

Discussion

4.1 Introduction

This study is part of a three-part project conducted with FIAMM, which is working with automotive companies. The first part of this project is the use of granular synthesis method to produce sound in electric vehicles, which is the focus of this thesis. The other two parts have been done by other researchers (Miray and Sheena), which will be explained in the following.

4.2 Miray's research

Miray developed the CAN bus in electric vehicles for the design and management of exterior noise. The CAN simulation investigates how parameters such as vehicle speed and engine speed can be processed in real-time and how the exterior sounds can be modulated appropriately based on this data. In Miray's research, advanced CAN simulation techniques used to realize sound outputs modulated according to the dynamic states of electric vehicles.

This simulation demonstrated how the sounds emitted by the vehicle can be dynamically adjusted in response to variables such as vehicle speed and engine speed. The results of the research highlighted the critical role that CAN systems play in the design and management of sound in electric vehicles. The simulation model examined in detail how vehicle dynamics over the CAN bus, in particular key parameters such as vehicle speed and engine speed, can be used to modulate exterior sounds.

The model showed how the audio outputs are appropriately adjusted as vehicle speed increases or decreases, resulting in an exterior sound that better reflects the current state of the vehicle. The simulation results showed that the frequency and amplitude of the sound outputs increased as the speed of the electric vehicles increased, producing a louder and more intense external sound reflecting the current state of the vehicle. These sound modulations responded sensitively to changes in vehicle motion, making the external presence of the vehicle more prominent.

4.3 Sheena's research

The aim of this research is electric vehicle sound design using granular synthesis with PureData, improving user experience, and meeting safety standards. This research assessed EV sounds' recognizability, informativeness, pleasantness and annoyance to ensure their safe integration into urban environments, supporting sustainable mobility. In this regard, PureData was used. Also, the methodology of experiment and analysis was based on ANOVA.

4.4 The present study

In this thesis, a method based on granular synthesis for producing different sounds is presented, the final goal of which is to use it in the performance platform and optimize sounds related to sustainable mobility. In fact, sound production in electric vehicles can lead to road safety by informing pedestrians and cyclists and preventing accidents. Parameters such as speed/rpm/torque/pedal position are considered as input parameters to change the sound.

In this project, eight different sounds are played in real time and after being modulated and filtered, they are combined to make more complex sounds. The proposed method is implemented in MATLAB software. The results are considered as input for the third part of the project so that they can be used to design sound for electric vehicles.

The proposed method based on Granular synthesis allows extremely detailed manipulation of sound at a microscopic level. By changing the characteristics of individual grains - such as their duration, pitch, and volume - sound designers can create complex textures and evolving soundscapes that are rich in detail.

The proposed method does not rely on conventional harmonic structures or rhythmic patterns. It encourages experimentation with sound in a more abstract and unbounded context. This makes it particularly attractive for generation sound in EVs. Granular synthesis can transform ordinary sounds into sound completely new and without noise.

Granular synthesis provides exceptional control over sounds in real time performance scenarios, which is critical for electric vehicle sounds to adapt to instantaneous traffic conditions or driver inputs. For example, if a vehicle suddenly stops or accelerates, the sound produced using granular synthesis can be quickly modified to reflect these movements. This makes the sound design more interactive and responsive, making it possible to create a reactive sound environment for pedestrian safety. The proposed method can improve the way drivers and pedestrians perceive the movement of the vehicle, thanks to its ability to integrate multi-layered sound palettes.

The proposed method can create sound profiles that dynamically change based on factors such as the driver's driving style or the environment in which the vehicle is located.

Chapter 5

Conclusion and further development

5.1 Summarize the thesis

The most important results obtained in this research are as follows:

1. The proposed method can create sound profiles that dynamically change based on factors such as the driver's driving style or the environment in which the vehicle is located.

2. The proposed method can improve the way drivers and pedestrians perceive the movement of the vehicle.

3. If a vehicle suddenly stops or accelerates, the sound produced using granular synthesis can be quickly modified to reflect these movements.

4. Granular synthesis can transform ordinary sounds into sound completely new and without noise.

5. The outputs from the implementation of the proposed method are the input of the third part of the FIAMM project.

5.2 Further development

In this section, in order to conduct further studies in the field of digital signal processing for electric vehicles sustainable mobility in the future works, the following suggestions are made:

1. Presenting an artificial engine sound synthesis method in order to modify the acoustic characteristics of electric vehicles

2. Presenting a method for predicting the interior sound quality of pure electric vehicles based on transmission path synthesis
3. Designing an interior and exterior acoustical brand identity for electric vehicles by means of sound synthesis

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