Treball de Fi de Màster

Màster universitari en Enginyeria d'Automoció

Study and application of the AVAS to electric vehicles for pedestrian safety.

REPORT

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Resum

Aquest treball de fi de màster (TFM) està orientat a estudiar i analitzar un dels nous sistemes incorporats als vehicles elèctrics (EV) moderns, el SAAV, o sistema d'alerta acústica vehicular. Aquest sistema que s'obliga a incorporar-se als EV sota normativa des de l'any 2019 per a la seva circulació presenta diversos models de sons ja existents en cotxes del mercat actual. Tant la normativa com diferents models de sons SAAV són analitzats per entendre la situació actual d'aquesta tecnologia. En tractar de sons, el TFM descriu també informació teòrica base que estenc els coneixements sobre els elements acústics i la seva estructura.

La substitució dels sons de propulsió vehicular que comporta l'augment de circulació d'EVs en lloc de vehicles de combustió interna (ICE) involucra una adaptació social. Per això, aquest treball busca descobrir quina és la percepció de les persones davant de diversos sons de SAAV d'EV de marques diferents. Mitjançant un Jury test realitzat a diversos estudiants es puntua diferents sons per revelar quins sons agraden més i quins fan una impressió insatisfeta. En apartats següents, s'analitzen aquests mateixos sons enquestats per establir correlacions entre els resultats obtinguts de percepció acústica i l'estructura de cada so, les freqüències, harmònics i sorolls. D'aquesta manera, es busca entendre que aspectes dels sons de SAAV són els que provoquen que siguin percebuts amb característiques més atractives que d'altres, i quins aspectes varien depenent de la categoria vehicular per a la qual va ser dissenyat el so.

Finalment, aquest TFM involucra el desenvolupament i el disseny d'un model de so per al SAAV d'un vehicle en específic. Es detalla el que va comportar la producció d'aquest so de propulsió i també se'n fa l'anàlisi acústic. Aquesta secció addicional a l'enfocament principal del treball busca proporcionar una mica d'experiència més enllà del teòric i donar a saber com seria dur a terme un projecte similar a la vida real.

Resumen

El presente trabajo de fin de máster (TFM) está orientado a estudiar y analizar uno de los nuevos sistemas incorporados en los vehículos eléctricos (EV) modernos, el SAAV, o sistema de alerta acústica vehicular. Este sistema que se obliga a incorporarse en los EV bajo normativa desde el año 2019 para su circulación, presenta varios modelos de sonidos ya existentes en coches del mercado actual. Tanto la normativa, como distintos modelos de sonidos SAAV son analizados para entender la situación actual de esta tecnología. Al tratar de sonidos, el TFM describe también información teórica base que extiendo los conocimientos sobre los elementos acústicos y su estructura.

La sustitución de los sonidos de propulsión vehicular que conlleva el aumento de circulación de EVs en lugar de vehículos de combustión interna (ICE) involucra una adaptación social. Por ello, este trabajo busca descubrir cual es la percepción de las personas ante varios sonidos de SAAV de EV de marcas diferentes. Mediante un Jury test realizado a varios estudiantes se puntúa distintos sonidos para revelar cuales sonidos agradan más y cuales dan una impresión insatisfecha. En apartados siguientes, se analizan estos mismos sonidos encuestados para establecer correlaciones entre los resultados obtenidos de percepción acústica y la estructura de cada sonido, sus frecuencias, harmónicos y ruidos. De esta forma, se busca entender que aspectos de los sonidos de SAAV son los que provocan que sean percibidos con características más atractivas que otras, y que aspectos varían dependiendo de la categoría vehicular para la cual fue diseño el sonido.

Finalmente, este TFM involucra el desarrollo y diseño de un modelo de sonido para el SAAV de un vehículo en específico. Se detalla lo que conllevó la producción de este sonido de propulsión y también se realiza el análisis acústico del mismo. Esta sección adicional al enfoque principal del trabajo busca proporcionar un tanto de experiencia más allá de lo teórico y dar a saber como seria llevar a cabo un proyecto similar en la vida real.

Abstract

This master’s thesis (TFM) is oriented to study and analyze one of the new systems incorporated in modern electric vehicles (EV), the AVAS, or vehicle acoustic warning system. This system, which is required to be incorporated in EVs under regulations since 2019 for their circulation, presents several models of sounds already existing in cars in the current market. Both the regulations and different models of AVAS sounds are analyzed to understand the current situation of this technology. When dealing with sounds, the TFM also describes theoretical background information that extends the knowledge about acoustic elements and their structure.

The substitution of vehicle propulsion sounds brought about by the increased circulation of EVs instead of internal combustion vehicles (ICE) involves a social adaptation. Therefore, this work seeks to discover what is the perception of people in front of several AVAS sounds of EVs of different brands. By means of a Jury test performed to several students, different sounds are scored to reveal which sounds are more pleasing and which ones give an unsatisfied impression. In the following sections, these same surveyed sounds are analyzed to establish correlations between the obtained results of acoustic perception and the structure of each sound, its frequencies, harmonics, and noises. In this way, we seek to understand which aspects of the AVAS sounds are the ones that cause them to be perceived with more attractive characteristics than others, and which aspects vary depending on the vehicle category for which the sound was designed.

Finally, this TFM involves the development and design of a sound model for the SAAV of a specific vehicle. It details what was involved in the production of this propulsion sound and also performs the acoustic analysis of it. This section in addition to the main focus of the work seeks to provide some experience beyond the theoretical and let you know how it would be to carry out a similar project in real life.

Content

Abbreviations and symbols

- AVAS: Acoustic Vehicle Alerting System.
- EV: Electric vehicle.
- Octave band: Frequency range where the upper frequency is twice the lower frequency, dividing the audio spectrum into logarithmic intervals for analysis and measurement purposes.
- ICE: Internal combustion engines.
- NHTSA: National Highway Traffic System Administration.
- SUV: Sports Utility Vehicle.
- Jury test: Evaluation of a product or service based on the opinions and perceptions of individuals, often involving subjective assessments and feedback.
- dB: Logarithmic unit used to express the ratio between two values of power, intensity, commonly used to measure sound level or signal strength.
- Hz: Hertz, is the unit of frequency that measures the number of cycles or vibrations per second in a sound wave, representing the pitch or tone of a sound.
- CV: From French acronym, standing for chevaux-vapeur, it is equivalent to horsepower. It is a unit of power commonly used in the automotive industry to measure the engine's output.

Figures list

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Table list

1. Introduction

The current trend of vehicle production focused mainly on electromobility has led to a decrease in the use of internal combustion vehicles (ICE) and with it, not only the production of emissions, but also of sound. This last aspect brings with it a problem that has been questioned due to the risk of being run over by pedestrians and cyclists [1]. The sounds produced by a moving vehicle are mainly produced by engine emission, the aerodynamic effect of the wind, and tire friction [2]. It has been shown that the sound identified at speeds greater than 20km/h are similar for both ICE and electric vehicles (EV) [2]. However, the risk is more evident at low speeds, where for the common cases of an ICE vehicle, the engine sound predominates over the other two, but in the case of an EV it is different. Electrically driven vehicles at low speeds emit a much lower sound that could be difficult to identify in time and even more so in scenarios where visibility is reduced [3].

In this regard, the relevant European and American organizations have presented new regulations to be complied with in the framework of the production of vehicles using both partially and fully electric propulsion [4][5]. The implementation of the AVAS, Acoustic Vehicle Alerting System, has been agreed upon, which corresponds to a vehicle sound production system that serves to alert pedestrians to the proximity of an oncoming vehicle. The sound produced by the vehicle must be continuous and with minimum and maximum volume limits or decibels (dBs) that will be emitted when the vehicle is traveling at a speed equal to or less than 20km/h for the European territory and 30km/h for the North American territory, as established by the National Highway Traffic Safety Administration (NHTSA) of the United States [6].

Since AVAS can be developed by the car manufacturer itself, and since these sounds can be designed by engineers or specialists, this adds a new aspect to the list of brand identity factors due to it is a characteristic that does not depend on the propulsion components of the vehicle such as the type of engine, displacement, or exhaust system, which are common in combustion vehicles. This creation of an audible identity of a brand and its assimilation to a visual representation of it is called sonorous branding and aims to evoke a mental image that exclusively characterizes the brand by means of a hearing process [8]. In this sense, it is intended to explore the possibility of creating sounds that can be related to the image of an electric vehicle, and at the same time meet the necessary requirements to be applied to the vehicle's AVAS system. Although several manufacturers have already presented their new models of electric cars with AVAS systems and their own sounds [9][10][11], it is also interesting to study the reaction that pedestrians get over them. The perception of listeners regarding new sounds generated by electrified vehicles may give an indication of how future auditory models should be shaped for greater attraction and social acceptance. Likewise, the analysis of the different AVAS sounds allows us to understand how they are structured and designed in order to relate them to the way pedestrians respond to them.

1.1. Motivation

The profound transformation of the automotive world towards electric propulsion has led to new mobility reforms to be pursued. Pedestrian, driver, and passenger safety must always be paramount when adapting new vehicle models to the market. In this context, the development of Acoustic Vehicle Alerting Systems designed to safeguard people's safety serves as a motivation for a study on what is involved in this new technological adoption. Analyses of people's reactions to this change as well as a study on how the regulatory gap could be exploited to design a characteristic sound into a vehicle are topics that have not yet been revealed in great detail. Therefore, this paper seeks to cover part of that study and to present a new perspective on what has been developed over the last few years.

1.2. Project scope

The work intends to have a scope that covers the study of the state of development of AVAS by making comparisons of the different systems presented by various brands of electric vehicles. It will study the characteristics of sounds related to electric propulsion and look for combinations of sounds that have the potential to be used in electric vehicles. Through a survey conducted to people interested in the automotive sector and with some basic knowledge about electromobility, their reactions and perspectives towards the propulsion sound proposals will be studied. Based on this, we will establish the characteristics that generate the most positive reaction in the participants that can serve as a pattern for future acceleration sound designs.

Considering the sound branding studies, we will analyze how EV manufacturers can, through AVAS, take advantage of the gap generated to use new propulsion sounds and form an emotional connection with the receiver capable of associating them with special characteristics of the vehicles. The project will be limited to the analysis of the existing sound models in various electric vehicles throughout a Jury test for which the quality of these sounds will be determined. The results will be studied to demonstrate how people perceive these sounds and what characteristics are the most remarkable for future improvement in the next EV generation.

1.3. Project objectives

The general objective of this work will be the study of the acoustic vehicle alerting system for electric vehicles, AVAS, based on the current homologation regulations and taking into account the important factors that involve its correct application in modern vehicles.

The particular objectives will be the following:

- To study generally the conception of sound and its characteristics in order to understand the subject matter in relation to the acoustic part of the system.

- Analyze the AVAS that are currently available on the market and that have already been applied to various electric vehicle models in order to have a reference of the proposals that have been launched.

- To obtain information about what is the perspective and the acceptance of the people in front of this new feature of the modern electric car through a Jury test.

- To analyze the characteristics of different AVAS models in order to relate them to the answers obtained in the test and to discover which aspects are the most relevant when designing an AVAS sound.

- To present an AVAS sound proposal for a specific electric car model using as a guide the references obtained and the sound analysis.

1.4. Planification

It is necessary to define a calendar of activities that serves as a reference point to manage the availability of time effectively and complete all the proposed activities correctly. These activities should vary throughout the work as tasks are developed and difficulties are encountered in completing them on time.

Week Nº	Activity	Start date	End date
1	Get to know the AVAS regulations	8/3/2023	15/3/2023
2	Search and analyze sources of information for state of the art on AVAS	15/3/2023	22/3/2023
3	Write the literature review about AVAS	22/3/2023	29/3/2023
4	Learn about acoustic theory applicable to AVAS	29/3/2023	5/4/2023
5	Learn about acoustic theory applicable to AVAS	5/4/2023	12/4/2023
6	Write about the existing AVAS proposals on the market and their details	12/4/2023	19/4/2023
7	Search and collect AVAS sounds available on the internet	19/4/2023	16/4/2023
8	Design the Jury test format to be administered to UPC members	26/4/2023	3/5/2023
9	Refine details of the sound proposals and prepare opinion surveys	3/5/2023	10/5/2023
10	Collect data and complete the number of Jury tests desired	10/5/2023	17/5/2023
11	Collect data and complete the number of Jury tests desired	17/5/2023	24/5/2023
12	Analyze survey results and draw conclusions (radar charts)	24/5/2023	31/5/2023
13	Analyze acoustically the used sound samples	31/5/2023	7/6/2023
14	Analyze acoustically the used sound samples	7/6/2023	14/6/2023
15	Establish correlations between the acoustic analyzes and the results of th	14/6/2023	21/6/2023
16	Establish correlations between the acoustic analyzes and the results of th	21/6/2023	28/6/2023
17	Write the final results of the analyzes	28/6/2023	30/6/2023
18	Study an electric vehicle model for AVAS sound design	10/7/2023	14/7/2023
19	Design and produce an AVAS sound for the chosen EV	17/7/2023	21/7/2023
20	Design and produce an AVAS sound for the chosen EV	24/7/2023	28/7/2023
21	Design and produce an AVAS sound for the chosen EV	31/7/2023	4/8/2023
22	Analyze acoustically the final sound of the AVAS proposal	7/8/2023	11/8/2023
23	Write the results of the acoustic analysis	14/8/2023	17/8/2023
24	Carry out the economic assessment and further investigation	21/8/2023	23/8/2023
25	Write TFM report and conclusions	24/8/2023	31/8/2023
26	Tutor review and receipt of feedback	1/9/2023	7/9/2023
27	Review and latest memory corrections	8/9/2023	12/9/2023

Table 1: planning for project

2. Literature review

The Acoustic Vehicle Alerting System, AVAS, must be developed taking into account all the regulations mentioned in the standards in effect for its correct operation. However, the application of this system in the new electric and hybrid cars goes beyond just knowing the regulations but includes the study of the behavior of sound and its perception to the human ear, as well as an analysis of the current state of the developed and proposed versions related to the system.

2.1. AVAS Regulations

Although the respective AVAS regulations for both the European Union and the United States can be analyzed in their respective links [4][5][5a], it is necessary to mention the most relevant aspects to be considered for the development of this work.

2.1.1. System operation

As dictated by the Delegated Regulation (EU) 2017/1576 [4] in Annex VIII and Section III, the provisions will apply to vehicles registered as of July 1st, 2019, and to new vehicles as of July 1st, 2021. It is highlighted that, the AVAS system shall be installed on electric or hybrid vehicles, which at low speeds only use the electric motor, to generate a warning sound from the time the vehicle starts up to a speed equal to or less than 20km/h, and in reverse. Vehicles may not have AVAS for reversing if they have another acoustic warning device that meets the minimum sound level requirements [4][5a]. Similarly, vehicles whose overall sounds comply with the minimum range of levels presented in Table 2 referring to point 6.2.8 of UNECE Regulation No. 138 [5a] are not required to have AVAS. With reference to Regulation 138, any AVAS pause mechanism or function is prohibited during vehicle use, however, the sound of the system may be attenuated as long as it complies with the limits in Table 1 [5a].

2.1.2. Sound type and volume

Regarding the type of sound, it is specified that it must be a continuous sound synchronized with the speed, indicating the operation and behavior of the vehicle. It is required that the sound generated by the system be similar to that generated by a vehicle of the same category, but with an internal combustion engine. [4].

Minimum Sound Level Requirements in dB(A)

Frequency in Hz		*Constant Speed Test paragraph 3.3.2. (10 km/h)*	*Constant Speed Test paragraph 3.3.2. (20 km/h)*	*Reversing Test paragraph 3.3.3.*
Column 1	*Column 2*	*Column 3*	*Column 4*	*Column 5*
Overall		50	56	47
1/3rd Octave Bands	160	45	50	
	200	44	49	
	250	43	48	
	315	44	49	
	400	45	50	
	500	45	50	
	630	46	51	
	800	46	51	
	1,000	46	51	
	1,250	46	51	
	1,600	44	49	
	2,000	42	47	
	2,500	39	44	
	3,150	36	41	
	4,000	34	39	
	5,000	31	36	

Taula 2: Minimum sound levels to be complied with (Regulation n°138 [5a])

Table 2 shows the minimum levels that the acoustic warning should reach, i.e., the volume of the sound expressed in decibels dBs, corresponding to the frequency that is being emitted. Column 2 of the table indicates the frequencies in Hz at which the sound of the AVAS could be and columns 3 and 4 indicate the minimum decibels (dB) at which the sound should reach.

As mentioned in section 6.2 of specifications of Regulation n°138, referred to in Regulation 2017-1576, the speeds for the performance tests are 10km/h and 20km/h. In both cases the minimum sound pressure levels set out in table [2] and at least two of the third octave bands as mentioned in the table must be covered. One of these bands shall be below or between the 1600 Hz third octave band. The emitted sound is required to have a frequency shift to acoustically represent the acceleration and deceleration of the vehicle and alert bystanders. This frequency shift shall come into play from when 5km/h is reached until 20km/h is reached and shall vary proportionally with speed in the range of 0.8% of the frequency for every 1km/h increased [5th].

The AVAS sound shall be emitted stationary when the vehicle is stationary and there is the possibility for the vehicle manufacturer to provide the driver with a list of sound options that can be chosen to preference as long as they are in compliance and meet the requirements [4] [5th]. Regarding the maximum sound level, the AVAS shall not exceed 75 dB when the vehicle is in motion; this shall be measured at a distance of 2m, which corresponds to 66 dB if measured at a distance of 7.5m. [5ª].

2.2. Physical qualities of sound

Sound can be defined as the set of vibrations produced by an emitter that travels throughout air in the form of waves and that stimulates the human hearing in a range of perceptible sound pressure. The sound wave is composed by physical qualities such as amplitude, frequency, propagation time and timbre, which can be modeled in a way that generates a message or creates a desired common interpretation [8]. It is important to know how sound behaves by means of each of these attributes in order to better understand some restrictions of the regulations and even to understand how the sound could be shaped in a certain way it creates an emotional binding between the driver and the acceleration sensation, which is described in a further chapter.

2.2.1. Amplitude and intensity

Vidal (2017) defines sound amplitude as the amount of energy that is propagated that provides the audible sensation. In other words, it is the level of sound load involving the changes in pressure level [8]. Meanwhile, the intensity of the sound is related to volume the sound is being emitted at. Both factors are related to each other by the respective unit of the measurement which is decibels (dB). The human ear can generally hear sounds ranging from the threshold of hearing, which is around 0 decibels (dB), to the threshold of pain, which is typically around 120-130dB. The range of audibility covers a broad spectrum of sound intensities, with quieter sounds at the lower end and louder sounds at the upper end. To these factors it is possible to relate an extra attribute which is loudness. Loudness can be understood as how people psychologically interpret the physical quality of intensity [14]. It could be possible that a sound with the same intensity is considered as loud for some people while for others is not, and it depends on the age [14]. Intensity on the other hand, could be affected by the medium that is producing the sound, in this case, the speakers installed in the car.

When the amplitude of the sound wave increases, so the intensity does and with it the loudness is perceived as greater, corresponding to the blue wave with respect to the red one in figure 1. When there are changes suddenly in the intensity of the sound this could generate special attention from the receiver that can link it to an emotion such as tension or amazement [8]. In this sense, if the mentioned system is designed in such a way that the alerting sound presents changes in intensity, e.g., with the increase of the motor revolutions or during the acceleration, it could result in a more impressive experience. From the point of view of the driver, the sound could lead to this link between the acceleration perception and the emotional reaction, and in the case of pedestrians, this would not only alert them to the proximity of a car but could generate a greater impression of the speed at which it is coming and its distance.

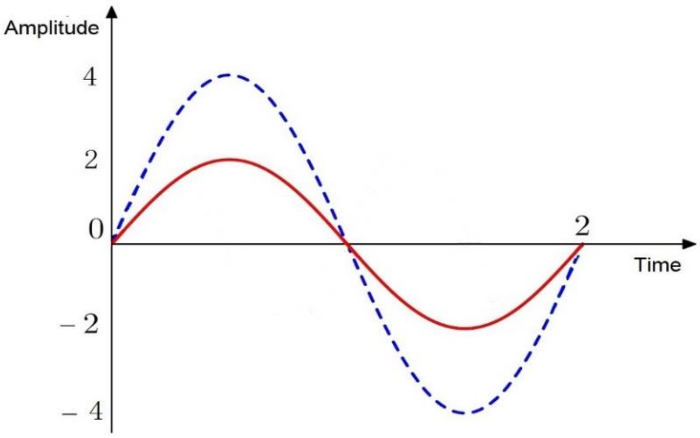

Figure 1: Two waves with different amplitude and same period.

2.2.2. Frequency and tone

Frequency is determined by how many cycles the sound wave completes in one second, which could be understood as the velocity of the wave. The measurement unit of the frequency is Hertz, Hz, and if the sound is in between the range of 20Hz to 20000Hz, it is audible for the human hearing, corresponding these frequencies to what is called infrasound and ultrasound respectively [14]. However, in practical case this range is range is more in between 50Hz and 15000Hz due to the differences in age could affect the frequency detection. When the sound increases in vibration, the frequency increases and the tone gets higher, which results in high-pitched tones [15]. In other words, tone is related to the frequency in such proportion that the higher the frequency, the higher tones, high-pitched, and the lower the frequency, the lower the tones, low-pitched. Sound is composed by harmonic frequencies, which are frequencies multiples of the main, that makes it possible to recognize the tone and the note, as in the case of hearing a trumpet and a tuba playing the same at the same frequency but a different note [15].

Similar to the case of the changes in the amplitude and intensity to create an impression in the receptor, the changes in frequency and tone could result in different emotional reactions. As tone is related to the psychological interpretation of the sound vibrating at a certain frequency, it is possible to relate high-pitched tones with excitement, and a low-pitched tone with splendor or seriousness [16]. In that sense, the alerting sound to be modeled could involve frequencies in low and high tones, also known as bass and treble, that generate in the pedestrians a reaction of precaution but at the same time some excitement or impression by the type of vehicle is passing through.

It is convenient to treat sound as a combination of frequency bands which are ranges defined by a lower and higher frequency in which depending on the purpose of the frequency range the distortion is more or less limited. An octave band is mostly defined by the frequency range between two sounds whose fundamental frequencies, the lowest vibrating frequency produced, are multiple of two. When necessary, it is possible to improve the sound quality or resolution by dividing the octave band into three pieces logarithmically equal to each other, this is called one-third octave band. The strength of the sound can be plotted in a graph known as frequency spectrum where the horizontal axis shows the frequency range in Hz and the vertical axis shows the sound level in dB, and in which most of the cases the fundamental frequency presents the highest amplitude followed by the rest of harmonics in descending order [17]. An example of frequency spectrum for interior car noise is shown in figure (2).

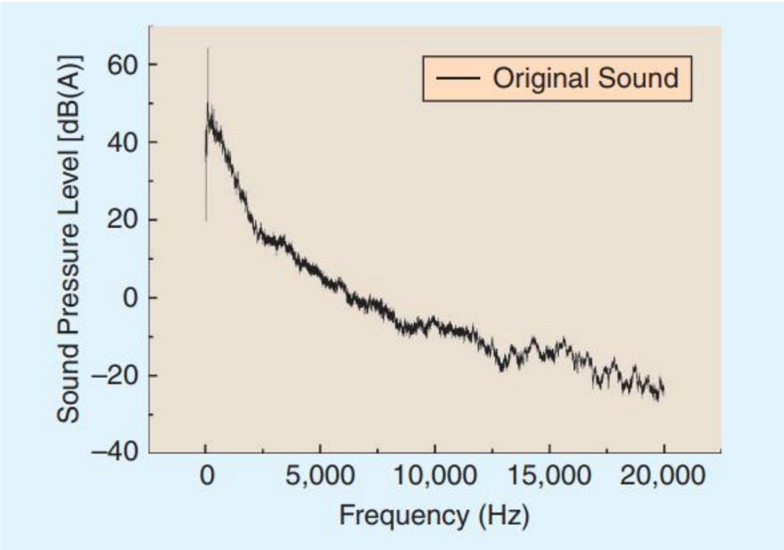

Figure 2: frequency spectrum for interior car noise.

Regarding the regulations, it is mentioned that the alerting sound in AVAS must have at least two frequencies in the range of the one-third octave bands shown in figure (2) which goes from 160 Hz until 5000 Hz. From these two mandatory frequencies at least one of them has to be in the range of 160 Hz to 1600 Hz, corresponding to 11 optional one-third octave bands. This means that the change of frequency when the sound is been simulating the vehicle acceleration, braking, or reversing must be in between the mentioned range. Choosing the one-third octave at which the initial frequency of the sound stimulates the vehicle being stationary, is very relevant as it could become a recognizable factor for people to relate it to a certain vehicle brand. It is common to relate a car noise at low frequencies with low or no acceleration, but depending on how low is that frequency it could be possible to identify the type of vehicle that is producing the sound, or at least get an idea of the size of the vehicle. In that context, the relation between the type of vehicle and the frequency at which the sound for stationary state is playing, must be studied in further chapters.

2.2.3. Propagation time and timbre

When it comes to propagation time, it indicates the duration of the sound, which at the same time could be discrete or continuous, being the last mentioned the one of interest for the aim of this project. A continuous sound is constant and in some cases hard to be identified individually, and in comparison to the discrete sound its duration is not less than 5 seconds [8]. Vidal (2017) mentions that based on the psychoacoustics, the propagation time or duration is also related to the sound intensity, as the more time a sound is being play at a constant level of decibels, the more impression of a higher intensity it will have. If this case is applied to the AVAS and it is designed in such a way that one of the frequencies has more duration over the rest of them, this will be the one perceived with the higher intensity and probably the most remember by pedestrians.

On the other hand, timbre depends more on the material of the object that is emitting the sound, the shape, and dimensions, as well as the medium by which is being transmitted the sound [15]. Timbre is determined by a composition of different harmonics that vibrate throughout a body at certain frequencies and depending on the number of harmonics the quality of the sound can increase proportionally [14]. Long (2014) describes timbre as the quality of the sound that enables to distinguish one instrument from another, or a particular characteristic that distinguishes one sound from other similar [17]. If two AVAS sounds get to be very similar to each other, the quality of the speakers or the design of the sound itself could be primordial factors for brand distinction. Timbre depends on the number of harmonics and their relative intensities, the sum of which together with other small sounds results on an auditory sensation and could facilitate the identification of a brand [8]. For the objective of this work, timbre will be considered as result of the modification of the other mentioned attributes and other influences as the type or quality of the speaker will be neglected.

2.3. Vehicle propulsion sound and its perception

The mandatory integration of the acoustic warning system in current and upcoming electric and hybrid vehicle models represents a significant change in the noise maps of cities where EVs are widely adopted. A noise map can be interpreted as a graph that globally assesses the noise exposure in a selected area based on the different noise emitters and general predictions of sounds in the zone [12]. The increase in the market of electric vehicles with AVAS may impact the living conditions of residents in high traffic areas due to the perception of the acoustic warning could change from being a means of preventing pedestrian accidents to being an irritating aspect for the human hearing when there is a large number of vehicles with this system operating and transiting at the same time in the area. Laib and Schmidt (2019) conducted a study of how AVAS could affect the soundscape and compared the sound pressure level of 7 vehicles with and without AVAS in operation [13]. In this comparison examined at speeds of 10km/h, 20km/h and 30km/h it could be evidenced that the sound pressure level of vehicles could increase from 1dB to 11dB when AVAS was activated and that this difference depended on the manufacturer and its warning system, with the VW e-Golf and Renault Zoe being at the extremes of the list respectively [13]. The relevance of this study lies in the importance of pedestrians and residents' evaluation of this increase in sound pressure when AVAS is activated, and the traffic flow is governed by EVs. It has been demonstrated throughout simulations that the fully replacement of light weight ICE vehicles by EVs with AVAS, without heavy vehicles in the traffic flow, represents a reduction of sound pressure levels of 1dB [12]. This means that, if all cars circulating at 30km/h in a zone with a real urban traffic are electric, the sound pressure levels emitted by these cars would be lower than the case of having only ICE vehicles on route and, at the same time, it could improve the acoustic environment in a noise map by 6% [12]. However, most of the people are used to the sound of cars with combustion engines and the pass-by of several EVs with AVAS may be a new scenario initially perceived as more annoying than the conventional [13].

It is well known that in quotidian during a person routine, most of the times the interaction with vehicles both in a driver´s perspective or passing-by as a pedestrian point of view can be easily repeatedly more than once. For that significant relationship that vehicles have in our normal life it is possible that a normal person can identify just by audible recognition if an approaching vehicle in the street is a normal car, a truck or even a motorcycle. In various studies had been demostriated that vehicle type classification can be achieved just by audio inputs recognition [22][23]. It has been demonstrated that seven types of vehicles can be identified (i.e. bus, small truck (without trailer), big truck (tractor unit with semitrailer), van, motorcycle, excluding scooters, car, tractor) and even the type motor, diesel or gasoline, could be recognized in the audio detection [22]. On the other hand, the electric car scenario could be more difficult to detect even a close distance when they are approaching at lower speed than 30km/h and the danger that can represent to pedestrian, cyclists and deceased people is the biggest motivator of the AVAS requirement in EVs. Considering the exponential increase of the AVAS application in electric vehicles of the future market, there is a big possibility that the combination of different alerting sounds and the overlay of various tunes at different durations create a cacophony which results in a harmonic disruption of the regular soundscape. For that reason, car manufacturers and system developers must take into consideration sound characteristics that could be more acceptable by road users.

2.4. State of vehicle sound distinction

There is no doubt that there is a massive group of people in the automotive field that have more experience with car sounds and have the ability to recognize the car model and in various cases even the motor type. The change in the tone of acoustic vibration when the motor is running or the vary in timbre from the exhaust system may be characteristics that car sounds connoisseurs use to identify vehicle specifications. For this specific costumer market, the change towards electric vehicles turns out trickier to achieve due to that lack of sound variety that represents an important attraction at the moment of driving. However, it is an aspect not only relevant for combustion car lovers but for most of car manufacturers as how their vehicles sound is another characteristic that they have analyzed specially for latest car models and supercars to be a point of attraction for the costumer. It is mainly the big brands of sporty, luxurious, and fast cars that care about the sound of their models to stand out from their competitors [24]. However, as the electric market gradually extends to all vehicle brands, the possibility of new vehicle models to stand out acoustically in the market without having to be one of the top brands in the industry is expanding.

The Acoustic Vehicle Alerting System (AVAS) has been developed to provide an audible warning to pedestrians when an electric vehicle is approaching. However, AVAS can also be used as an opportunity for car manufacturers to create new sounds for their electric car models as a new feature for their customers. This not only enhances the driving experience but also adds a unique feature to differentiate their electric car models from other brands. It is possible that different sound designs had a significant impact on drivers' perception of electric vehicles' safety, comfort, and performance. In that sense, car manufacturers should consider designing customized sounds to enhance the user experience. This new trend of creating sounds for electric cars is already being explored by some car manufacturers. For example, BMW's electric i4 model features an artificial sound created in collaboration with the composer Hans Zimmer, giving the vehicle a unique acoustic signature [25]. The use of AVAS to create new electric car sounds can be a unique selling point for car manufacturers, providing a new feature for customers and a way to enhance the driving experience of electric vehicles.

However, the desires and preferences of the customer regarding the sound produced by the electric vehicle of their choice, are not yet very well defined as it is an aspect that has not been evidenced for as many years as it is with combustion cars. These modifications or alternatives in the sounds that manufacturing companies are emphasizing with their experts and connoisseurs opens a range of possibilities that will be discarded or approved over time as their customers show acceptance and especially attraction to the sounds of an EV. From sounds that are perceived as robotic, electrifying, or flashy to tones that could be very similar to those produced by household appliances or devices that run on electric motors that make people question and negatively criticize the sounds of cars are already part of the existing market.

3. Methodology

For the achievement of the objectives described in the first part of the paper, it will be explained in this section all the relevant aspects from the related topics that will be used for the continue of this paper. First, the Jury test is introduced to describe how this survey methodology works and how it will be applied to the aim of the project. Secondly, an extensive search of existing AVAS sounds in the current electric vehicle market was conducted. The sounds were analyzed to identify similar characteristics and above all to compile the best sounds to be used in the Jury test detailed below. The jury test was designed with the investigated sounds. All the important aspects to be considered to perform the test are explained in their respective section. Then, with the data collected from the test, the answers were analyzed, and conclusions are presented, which will be used for the future sound proposal to be designed.

3.1. Jury Test

Technological changes and new user demands have led to the establishment of new product quality standards, one of them being the sound quality of the product. The sound emitted by a product in operation could be interpreted in different ways by the users depending on the psychological perception they have of it. What may sound sophisticated to one person may sound annoying to another, and to have a better idea of how comfortable a sound is to most of the users, the jury test comes into play. Jury test is described as a hearing evaluation made to a group of selected people to quantify the feelings, comfortability and perception produced by a sound and to determine the quality of the sound [18]. Nevertheless, since the sound interpretations are subjective, the responses could be influenced by the listener´s mood, expectations, or personal preferences. These factors are not controllable by the tester, however, a test designed in proper way may reduce the fluctuations on the responses.

In order to correctly categorize the quality of the sounds of a product, it is of vital importance that the sounds to be exposed to the listeners follow a selection criterion. The sound samples to be tested must be from a group of products that are in the same range of type, price, functionality, working condition, and they must assimilate as much as possible to how they would sound in real life when the product is being used [19]. It is also significant that the people who are going to test the sounds are from the group of potential consumers of the type of product in question. Being this an evaluation of sounds, it requires a metric that allows the assessment of its quality, so for this purpose an initial Jury test where listeners are exposed to several sounds of products of the same type allows to obtain the appropriate metric to evaluate the sound quality in a second test [20]. The mentioned scenario is applied to the aim of this work in such a way that a first Jury test is conducted to determine the metric for a second Jury test where the sound quality of AVAS is evaluated. In the first test, different sound samples from electric vehicles with the AVAS activated are presented to the listeners in order to correlate their responses with a common metric applicable for the second test. In the second test, the sound quality of the alerting sound to be later proposed is assessed using the metric obtained in the first Jury test. Both the sound proposals, and the design of the Jury test is further explained in following sections.

3.1.1. Length and loudness

When designing a Jury test, it is necessary to consider that the long exposition of the listener to a sound is more likely to shows results less concise and precise than with short sound samples due to memory fatigue. It is recommended that depending on the type of sound sample the duration of the reproduction follows this guideline [20]:

- Stationary sounds: reproduction for 3-5 seconds
- Non-stationary / Transient sounds: reproduction can be longer than 5 seconds if needed depending on the sound but trying to keep it as short as possible.
- Total test time should not take more than 40 minutes. Even better if it is less than 20 minutes [20].

On the other hand, depending on how loud the sound samples are it could be more complex to rate a sound as the psychoacoustic metric of loudness dominates in this case. In the case of benchmarking, when different types of sounds are being compared it could be better to reproduce the sound at their original loudness level to keep it as real as possible. However, when it is intended to rate some aspects of the sound and the listeners are not expert on the topic of evaluation, loudness impacts on how they will rate it, and even though if the sound is smooth and melodious, if it is very loud people will express rejection towards it. For that reason, equalizing the loudness of the sound samples to the same level helps to keep the focus of the listeners to the aspects of interest [19].

3.1.2. Jury test techniques

Within the evaluation technique of the Jury test, there are different methods that can be applied to study the subjective responses of the exposure to a sound, depending on the interest of the test.

- **Paired Comparison:** In this test method the juror simply compares the sound from two products and selects the one that he prefers. To obtain answers more reliable, the pairs of sounds can be presented in alternated order more than once. However, it could be time consuming if there are various sounds to be compared as all the combinations of pairs need to be tested [20].

- **Semantic Differential Test:** It rates a sound in a scale limited by opposites adjectives. The juror assesses the sound sample based on a subjective judgment, and for that reason the results could vary more but at the same time it provides more information from the listener perspective [19][20]. A question of this type could look like the figure shown below.

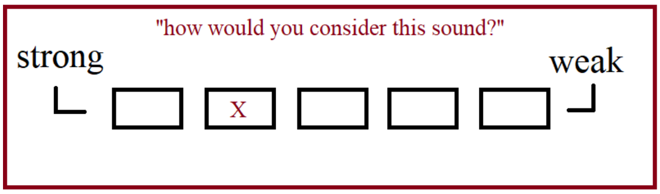

Figure 3: example of semantic differential test

It must be considered that for this Jury test technique there are some assumptions to be taken when asking the questions. The extreme adjectives must have the same meaning for all testers and been chosen wisely to avoid too many middling answers. All the responses must be in anonymous, and the tester must respond with total honesty without trying to please the test organizer with answers that they think are wanted [20].

- **Ranking:** It could be considered as the easiest Jury test as the tester listens to all the sound samples at once and ranks them in the scale of attribute asked for analysis. For example, it could be placing the sound samples from the weakest to the strongest as shown in the figure 4. This technique makes the tester to focus on more details of the sound to rank them even though in real life not much attention is put to these aspects when hearing the sounds [19].

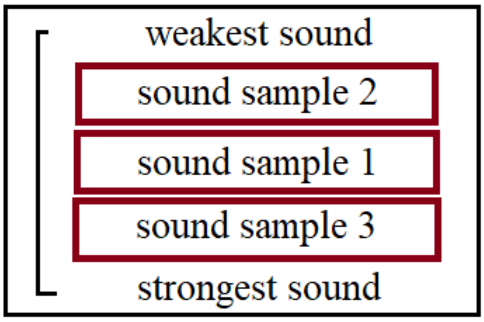

Figure 4: example of ranking technique

- **Category:** This technique is similar to the semantic differential test except that the sound sample is played once, and the tester has to rate the sound in a numeric scale for a specific attribute only. It is convenient that the jurors are highly knowledgeable in the product for the test as rating for example in a scale of strength could be tricky if they first listen to one sound that can be easily consider very strong and the next sound sample is even strongest. For that reason, the test must be answered properly [21].

- **Scheffé´s Method**: It is a technique that combines differential test and ranking where two sounds are played twice for replication in different order, i.e., first sound 1, then sound 2, and after that sound 2 and then sound 1. It is a longer test that enables to get more information about the sounds and rank them in an attribute scale by comparing both sounds [19]. This type of test has the following appearance:

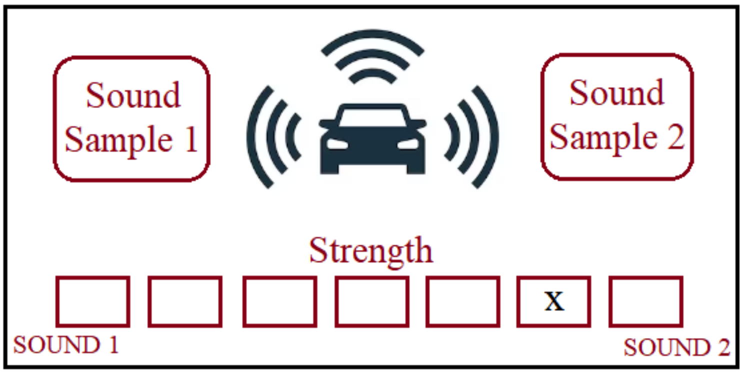

Figure 5: example of Scheffé´s method

3.1.3. Number of testers

Typically, when conducting a test, it is difficult to get a large number of jurors to take the test due to logistical or time constraints. Therefore, the most normal scenario for this kind of test is to get a group of approximately 20-30 people. However, having more than 50 people taking the test is not likely to change or considerably improve the results that would be obtained with 30 people [19]. It is important to know that around 10%-20% of the jurors will be eliminated from the test based on the quality of their answers. This could be done once the media of the answers is obtained and the standard deviation is determined for each question of the test.

3.1.4. Answers recollection mode

Based on the explanation of the webinar by Siemens [19], the test can be taken in two modes described below.

- Individual mode: In this mode, the moderator or the person in charge of conducting the test designs it, prepares the PC and hardware, and controls the juror that is taking the test. One juror at the time sits in front of the PC and takes the test, and the results are analyzed afterwards.

- Group mode: In this case, all the jurors are present at the same location and take the test at the same time in different PCs. Jurors should be in a single network from their individual PC and the audio must be reproduced by the same type of medium for all participants, i.e., headphones. The moderator or person in charge should have a software to monitor how the tests are being completed. The answers are sent to the moderator and are analyzed afterwards.

3.2. AVAS applications

As it was mentioned before, the regulations and requirements applied for the AVAS in electric and hybrid vehicles has challenged the vehicle manufacturer to take advantage of them and use the sound creation opportunity to your advantage. There have been famous brands that have achieved a good concept for their vehicle´s AVAS and others that still need to improve some aspects. In this section, it is described which brands were considered for the audio selection of AVAS sounds, and the characteristics of the car model that corresponds to the sound and brand selected.

3.2.1. BMW

- Electric vehicle: BMW i4 E
- Vehicle type: Coupé / Fastback
- Year: 2021
- Max Velocity: 190km/h
- Max Power: 340CV / 250kW
- Autonomy: 589 km/h [26]

Figure 6: BMW i4E

Taken from: https://www.bmw.co.nz/en/all-models/bmw-i/i4/2021/bmw-i4-highlights.html

3.2.2. Fiat

- Electric vehicle: Fiat 500e

- Vehicle type: compact
- Year: 2020
- Max velocity: 150km/h
- Max power: 118CV / 87kW
- Autonomy: 320km [27]

Figure 7: Fiat 500e

Taken from: www.fiat.com

3.2.3. Jaguar

- Electric vehicle: Jaguar I-Pace
- Vehicle type: SUV
- Year: 2019
- Max velocity: 200km/h
- Max power: 400CV / 294kW
- Autonomy: 470km [28]

Figure 8: Jaguar I-Pace

Taken from: https://www.electrifying.com/reviews/jaguar/i-pace/review

3.2.4. Porsche

- Electric vehicle: Porsche Taycan Turbo
- Vehicle type: Sedan / Sport
- Year: 2019
- Max velocity: 260km/h
- Max power: 680CV / 500kW
- Autonomy: 508km [29]

Figure 9: Porsche Taycan Turbo

Taken from: https://www.porsche.com/spain/models/taycan/taycan-models/taycan-turbo-s/

3.2.5. Kia

- Electric vehicle: KIA EV6
- Vehicle type: Compact SUV
- Year: 2021
- Max velocity: 185km/h
- Max power: 228CV / 168kW
- Autonomy: 528km [30]

Figure 10: Kia EV6

Taken from: https://motork.com/kia-ev6-awd-77-kwh-325-cv-electrico-oferta

3.2.6. Skoda

- Electric vehicle: Skoda Enyaq iV
- Vehicle type: SUV
- Year: 2021
- Max velocity: 160km/h
- Max power: 179CV / 132kW
- Autonomy: 397km [31]

Figure 11: Skoda Enyaq iV

Taken from: https://www.skoda.es/modelos/enyaq/enyaq-iv

3.2.7. Hyundai

- Electric vehicle: Hyundai IONIQ
- Vehicle type: Small family car (C segment)
- Year: 2019
- Max velocity: 165km/h
- Max power: 136CV / 100kW
- Autonomy: 311km [32]

Figure 12: Hyundai IONIQ

Taken from: https://www.sgcarmart.com/new_cars/newcars_gallery.php?CarCode=12246&CUR=39#gallery_start

3.2.8. Mustang

- Electric vehicle: Mustang Mach-E
- Vehicle type: SUV
- Year: 2020
- Max velocity: 180km/h
- Max power: 351CV / 258kW
- Autonomy: 550km [33]

Figure 13: Mustang Mach-E

Taken from: https://www.hibridosyelectricos.com/coches/precio-ford-mustang-mache-gt-mas-deportivo_46870_102.html

3.2.9. Audi

- Electric vehicle: Audi E-tron GT
- Vehicle type: Sedan
- Year: 2021
- Max velocity: 245km/h
- Max power: 530CV / 590kW
- Autonomy: 492km [34]

Figure 14: Audi E-tron GT

Taken from: https://modelkars.com/en/shop/gt-spirit/gt393-audi-e-tron-gt-kemora-grey/

3.2.10. Nissan

- Electric vehicle: Nissan LEAF Canto
- Vehicle type: Hatchback / Compact
- Year: 2019
- Max velocity: 157km/h
- Max power: 218CV / 160kW
- Autonomy: 396km [35]

Figure15: Nissan LEAF Canto

Taken from: https://www.motorpasion.com.mx/industria/nissan-leaf-se-actualiza

3.3. AVAS Jury Test Design

For the aim of this paper, the design of the Jury Test to measure the quality of some AVAS sound follows the recommendations from mentioned articles to be valid as much as possible. It is important to consider that the development of this project was mainly done with available material from internet such as the audio samples. The actual collection of audios and recordings represented a logistical and monetary difficulty to carry out. To do so, it would have been necessary to obtain all the car models mentioned and the appropriate recording equipment to follow the regulations. Therefore, the resources used must be considered as valid for the presentation of the results in the following sections.

Number of sound samples:

In this case, the sound samples to be evaluated are taken from platforms of the internet such as YouTube since the different vehicle brands have published promotional videos of their cars with their own AVAS system on this webpage. In the same way, audio files uploaded by some experts on the subject or car fans are used as sound samples to compare them and perform the first jury test. At the end, it was possible to collect 12 sound samples that have enough good quality to be used in the test that are distributed between the 10 vehicle brands mentioned above. For the case of the Kia EV6, depending on the drive mode set for the vehicle the AVAS changes the sound. For that reason, two sounds are used in the test corresponding to two different drive modes. Similarly, the vehicle Jaguar Pace-I was considered twice in the list of the sound samples as one sound was recorded from the interior of the vehicle and another from the exterior of it. Both sounds are from the same vehicle and even though they sound different, both can be considered as AVAS sounds.

Sample duration:

The sound samples were equalized to the similar loudness level for a better evaluation with help from a software called MixPad Multitrack. With this program the sounds samples were edited just in length and loudness so that they would all be equally long and without such a distinction in volume. The length of the samples was stablished to be between 5 and 7 seconds as there are 12 samples and a longer duration could be more annoying to listen to when the jurors are filling the Jury test. With these modifications, the test is intended to be completed in approximately 7-8 minutes. In this way, the juror does not get distracted easily or bored after having answered the first questions of the test.

Technique applied for the test:

For the objective of this work in which is intended to determine specific sound characteristics that describe the sound quality of different AVAS from diverse vehicle manufacturers, it is applied the ***category technique***. With this form of Jury Test, it is sought that jurors listen to a number of sound samples of AVAS and rank these sounds depending on the aspect or quality that is mentioned. In this case, the qualities to be ranked for will be selected in such a way that all the jurors can easily relate the aspect to the sound of the electric cars without a deep knowledge in sound characteristics or vehicle details. The aspects that the jurors are intended to rank once they listen to sound samples individually are the following:

- **Luxury:** In the context of AVAS, the term 'luxury' as a characteristic of sound refers to creating a sophisticated and premium auditory experience for the vehicle occupants and external environment. Luxury, in this sense, implies the use of high-quality and carefully designed sounds that enhance the overall perception of the vehicle's presence and contribute to a sense of refinement. The perception of how luxury an EV is, based on their AVAS, can be prioritized by a high-fidelity sound reproduction with excellent clarity, richness, and precision. The sound should be free from distortion, artifacts, or harshness. Incorporation of harmonic elements that are pleasant and musical in nature could be fundamental as well as carefully selecting and blending frequencies, the sound can evoke a sense of elegance and sophistication. The concept of luxury in AVAS sound characteristics aims to enhance the overall driving experience and aligns with the notion of luxury as a premium, refined, and sophisticated attribute.

- **Sportiness:** It refers to a sound that creates a sense of dynamic energy, performance, and excitement, reminiscent of traditional sports cars. It aims to evoke a feeling of power and sporty aesthetics through the vehicle's sound signature. The sound associated to sporty vehicles can have a lower and more aggressive tone and may feature a slightly deeper pitch to emulate the characteristic sound of high-performance engines. Also, dynamic variations in volume and intensity can enhance the sense of acceleration or engine responsiveness. It can include revving-like sound patterns that dynamically adjust the sound output based on the vehicle's speed, simulating gear shifts or engine revving. This modulation contributes to the perception of sportiness. Emulating the exhaust note of traditional sports cars can be achieved through the deliberate use of harmonics and emphasis of specific frequencies ranges that are commonly associated with sporty vehicles creating an impression of power and performance.

- **Attractive:** With this aspect it is intended that the juror ranks how attractive perceives the vehicle is by the stimuli of auditory senses. A positive emotional response in attractiveness can be determined by harmonics and frequencies carefully selected that provides a melodic quality, resembling pleasant natural sounds and a beaty appeal. An attractive AVAS sound can also be enhanced by the uniqueness and distinctive character of it, that creates a sense of exclusivity and a recognizable vehicle´s identity. Dynamic and energetic sounds, resembling musical crescendos or rhythmic patterns, can evoke a sense of excitement and engagement that increase the motivation for the juror consider a sound as attractive.

- **Futuristic:** Characteristic that involves innovation, advanced technology, and a forward-looking sonic experience with a sense of modernity. The more distinctive elements in the AVAS sound the more futuristic it could be perceived. These elements can be achieved by the addition of synthesized tones, dynamic modulations, and effects such as electronic beeps, swishes or whooshes. The integration of spatial audio can enhance the futuristic experience as well, creating similar sounds to those of spacecrafts or robots. The perception of how futuristic a sound is could be affected by the configuration of the speakers in the vehicle and in this case the quality of the sound samples recorded for the Jury test.

- **Potent:** The perception of power in an AVAS sound could be linked to the use of low-frequency tones that creates a sense of weight and a more powerful appearance. Sounds that mimics the revs of a typical powerful engine or exhaust pops can evoke a feeling of potency with the use of proper harmonics that impact the audience. As well as the other aspects mentioned above the dynamic change of the sound when the car is accelerating plays and important role for this perception, but at the same time, adding elements such as sounds that resemble roaring or growling can be associated with strength or dominance that enhance how potent the vehicle sounds.

- **Reliable:** The aspect of reliability is intended to be ranked in the sense that when the juror listens to an AVAS sound a feeling of trust and assurance is created towards the electric vehicle. Modulation in AVAS sounds in such a way that they present consistency and emits a steady and continuous pattern could increase the confidence from people on the car. Similarly, a sound that is predictable but at the same time clearly electric and distinguishes from the rest creates more reliability when deciding to use such vehicle as a means of transport. In this case, it could be possible that differences in the quality of the used sound samples influences in the perception of how reliable the vehicle is. However, the spontaneous response from the jurors will be considered as valid as if they would listen to the same vehicle sounds in the street.

Place and jurors' selection:

The facilities of the ETSEIB faculty of the UPC will be used for the test. With the due authorization of the professor and tutor of the present work, the time corresponding to the classes of active and passive security of the vehicle will be used for the tests to be answered. The people who will be part of the group of jurors in this test are students of the master's degree in automotive engineering. Therefore, they are people who have fundamental knowledge about the automotive world and what electromobility is becoming in today's world. Additionally, the test is also addressed to the students who are members of the formula student team of the UPC. This team is involved in the design and construction of an electric racing vehicle for a Europe-wide university tournament. Therefore, it also involves students who have a more direct contact with the issues related to the focus of the test. For the aim of this test, it was established that the number of jurors should not exceed 30 persons. This number is sufficient to get valid conclusions from the test without a overcharge of responses that could modify the later statistics.

Test presentation and answers collection method:

The final presentation of the test to the jurors was made in the survey platform called SurveyMonkey. The style of the Jury test was thought to be simple and aesthetic to avoid distracting the jurors when completing the test. It consists in 12 questions that starts with the sound sample shown to play followed by the 6 aspects to be ranked in a scale from 0 to 5. The jurors are intended to first listen to the audio only once, if possible, and then rank it considering that 5 is the top and best score to be placed. The sound samples are shown without any specifications of the type of vehicle involved. Otherwise, giving information about the model or vehicle brand could easily influenced the answer of the juror and persuade for a better or worst score depending on the likes and dislikes of the jurors. In the following figure the format of the test is shown with one question as it applies the same for all the questions.

Figure 16: Jury test format shown in one question.

This jury test was thought to be answered using headphones as it would be completed individual and assiduously. This means that, every juror will complete the test in the same computer and the answers will be immediately saved after the test is taken to transcribe them later to an excel file. The computer will be placed in an isolated area from the rest of the students with as few distractions and noise as possible. In addition, communication between students who have taken the test will be limited so that they do not influence the missing answers of the rest of the group.

3.4. Sound metric

In addition of the analysis to be done with the results of the Jury test, a correlation between the sound samples better ranked and a determined sound metric improves the interpretation. In that sense, the metric of relevance for this case is divided into three parts as follows.

3.4.1. One-third octave bands

As it is mentioned previously in initial sections, a one-third octave band is a frequency range where the upper frequency is twice the lower frequency and at the same time this frequency range is divided into three equal parts. The use of one-third octave bands is common in sound measurement and equalization. Its analysis is particularly useful in evaluating audio systems, noise pollution, and designing sound reinforcement systems. It helps in identifying specific frequency components, analyzing frequency response, and assessing the overall sound quality in various applications [35].

In this case, the one-third octave band analysis of the sound samples used in the test is aimed to find the pressure levels (dBs) at which the frequencies are registered for every AVAS case. In this way, it is possible to check if the minimal requirements mentioned in the regulations are met. On the other hand, similarities in frequency ranges between the AVAS models can be detect. This makes it possible to discover how the sound of AVAS of different brands is shaped and to serve as a reference for future research.

3.4.2. Sharpness (check properly from here)

Sound is characterized by its modulation and this, at the same time, is characterized by amplitude and frequency. The more remarkable the modulation of the sound the higher the level of sharpness it can have [37]. Sounds with modulations above 3000 times per second are considered as high frequencies sounds and are suitable for the measurement of sharpness. In that sense, sharpness measures the high frequency annoyance or prominence of the sound, i.e., the perceived presence of higher harmonics in the sound [36]. It expresses the quality of the sound with how cutting it is, related to how pleasant we perceive the sound. If there are high frequency energy in a sound, then the sound will be sharper than sounds with no strong high frequencies present [38]. To obtain the sharpness value, sounds with frequencies higher than 3kHz are summed and weighted according to frequency. The same behavior happens with tone, as the higher the tone the higher the sharpness of the sound [36, 38]. The higher the sharpness of the sound, the worse the sound quality.

In essence, sharpness is a measurement of high frequencies content in a sound, which means that if in this case two different AVAS sounds are taken, and sharpness is calculated for both of them it possible to know the difference of their high frequency content. The unit of the sharpness is acume and this is defined as 1kHz @60dB.

3.4.3. Roughness

Sounds that have modulations between 20 and 300 times per second are considered for roughness measurements. This is because the human ear stops detecting individual modulations after 20 modulations per second, and a perception of a rough, stationary tone appears until 150 modulations per second are reached. For modulations from 150 to 300Hz, hearing three separate tones is described as a common sensation [37]. In that sense, roughness measures the modulations of sounds at mid frequencies in the range initially mentioned. The highest sensation of roughness is reached when the modulation occurs at a frequency of 70Hz [36]. The roughness unit is asper, and produces a sensation equivalent to a tone of 1kHz at 60dB sound pressure level, with a modulation frequency at 70Hz, modulated at 100% of amplitude [39].

Therefore, roughness can be simply seen as a perceptual attribute that describes the sensation of irregularity, or rapid fluctuations in the auditory experience. It is often associated with sounds that have rapid variations in amplitude or frequency, resulting in a perceived rough or gritty texture. The modulation effects in a sound increase the level of roughness and can be caused by the interaction of closely spaced frequency components or rapid changes in amplitude. The intensity and frequency range of the modulation contribute to the strength and prominence of the roughness sensation. Within the automotive scenario, it is possible to evidence an auditory case with a higher content of sharpness and roughness in sport vehicles, while the vehicles considered luxurious seek to achieve a softer sound and without so much background noise.

3.4.4. Prominence ratio

When measuring sound, common metrics such as decibels and tones may be insufficient to fully characterize it. Therefore, the prominence ratio metric allows to detect audible tones and quantify them within a sound at their corresponding frequencies. To calculate the prominence of a tone within a sound, the level of the tone relative to the background sound is considered. Within this metric, a tone is considered to be prominent at 9db or above, and the critical band containing the tone in question is compared with the two critical bands that surround it [40]. In other words, the prominence ratio measures and compares the energy or amplitude of a particular frequency to the overall energy or amplitude of the entire sound signal. The higher the prominence ratio, the more salient or prominent the tone is within the sound sample. This analysis can be valuable for identifying key elements or detecting specific features of interest in a sound, such as fundamental frequencies, harmonics, or transients.

This metric will be used as a complementary analysis for the AVAS sounds that presents a more complex composition and in which sharpness and roughness analysis are not that suitable or enough. It aids in understanding key elements, extracting relevant features, evaluating quality, and detecting important events, contributing to a comprehensive analysis of sound characteristics and behavior.

4. Results

After conducting the jury test at the UPC, it was possible to get a total of 26 jurors, most of them between 20 and 24 years old, all students of the university. In addition to having mentioned that the test would be answered in total anonymity, only two extra questions other than those involved in listening to and scoring the sounds were asked. One of them was the age and the other question asked them to answer whether they were just unemployed, students with a job related to the automotive sector or students with a job outside the automotive sector. The results for these questions are shown in the following table.

Juror Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
AGES	24	24	24	22	24	23	23	23	23	24	22	22	23	22	19	23	21	24	20	21	20	23	20	23	22	24
I´m student only. I do not work		X	X				X			X		X	X													
I'm student and I work in the automotive sector				X	X	X		X	X		X			X	X	X	X	X	X	X	X	X	X	X	X	
I´m student and work in a different sector	X																									X

Table 3: Ages and occupations of jurors

The group of participants was distributed in such a way that the first 13 jurors are students from the master in automotive engineering of the UPC and the last 13 jurors are members of the Formula Student of the UPC. The occupation question was added with the intention of knowing how related to the automotive world and its engineering development the jurors were. From the table it can be seen that most of them have some relation with vehicles and have an idea of what the project topic involved.

4.1. Category Test results

The Jury test was conducted in such a way that, after every juror completed the test, all ranking numbers were registered in a table. That is, for every sound sample from all vehicle brands there are 26 columns corresponding to every juror with their given value respectively. Table 4 to table 16 show these values and for every table the sample standard deviation and its superior and inferior limits were calculated. In this case, as it is intended to estimate the ranking for the six mentioned characteristics of the AVAS sound in a population of young adults from 19 to 24 years old, the sample standard deviation is applied. This is due to a statement for an entire population would be drawn from a sample of people belonging to that niche. To obtain this value, the following equation was used.

$$S = \sqrt{\frac{\sum(X-\overline{X^2})}{n-1}} \qquad \text{(Eq. 5.1.1)}$$

To determine a mean value closer to the possible real value of the population it was decided to filter the standard deviation to the 65%. This means that only values in the range limited by the mean +- one standard deviation are considered for further study. After this, a spider chart was obtained for every table in order to visualize how the ranking results were distributed for the corresponding vehicle brand and its sound sample.

<u>Nissan Leaf Canto results:</u>

Nissan Leaf Canto																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	2	2	3	3	3	4	4	3	2	2	4	3	3	1	1	1	3	3	2	0	4	3	1	0	0	0	1.327	0.865	3.520	**2.28**
SPORT	1	1	1	2	4	3	3	1	1	2	1	2	3	1	1	0	2	2	1	0	4	1	0	0	2	0	1.175	0.325	2.675	**1.38**
ATRACTIVE	4	4	4	5	5	5	5	4	4	5	4	5	4	1	1	4	5	5	4	0	4	5	4	3	5	3	1.354	2.569	5.277	**4.35**
FUTURIST	3	3	2	4	3	3	4	1	1	2	1	0	2	0	1	1	2	1	1	0	1	1	2	0	1	0	1.208	0.331	2.746	**1.68**
POTENT	2	1	2	4	3	4	3	4	1	4	3	2	4	1	4	2	2	3	1	0	1	3	2	0	3	0	1.343	0.926	3.613	**2.18**
RELIABLE	2	4	3	3	2	3	3	3	5	3	3	1	4	0	3	1	2	0	1	0	2	2	1	0	3	3	1.357	0.835	3.549	**2.32**

Table 4: Jury test results for Nissan Leaf Canto

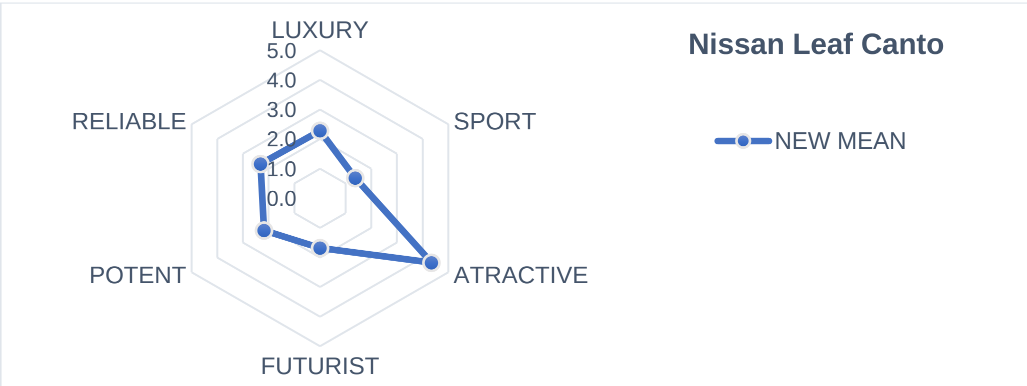

Figure 17: Spider chart for Nissan Leaf Canto

<u>Fiat 500e results:</u>

Fiat 500 e																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	4	1	4	4	4	1	3	4	4	3	5	4	2	3	3	3	2	0	4	3	2	4	2	2	3	3	1.183	1.779	4.144	**3.18**
SPORT	2	0	0	0	3	1	3	4	1	0	0	3	1	2	2	1	0	0	0	1	1	0	3	0	1	0	1.243	-0.128	2.359	**0.62**
ATRACTIVE	3	2	1	3	2	1	4	3	4	2	5	5	4	3	1	2	0	1	4	1	4	2	3	2	3	0	1.421	1.079	3.921	**2.38**
FUTURIST	4	1	4	4	3	2	4	5	3	3	5	1	2	4	3	4	2	5	3	0	2	4	3	1	5	0	1.509	1.452	4.471	**3.18**
POTENT	1	0	1	1	3	1	3	3	1	1	2	1	3	3	2	0	1	0	1	0	2	0	2	0	1	0	1.079	0.190	2.348	**1.29**
RELIABLE	1	2	1	4	3	0	3	3	4	1	4	1	2	3	1	4	1	1	2	3	2	3	2	0	3	0	1.294	0.783	3.371	**2.00**

Table 5: Jury test results for Fiat 500e

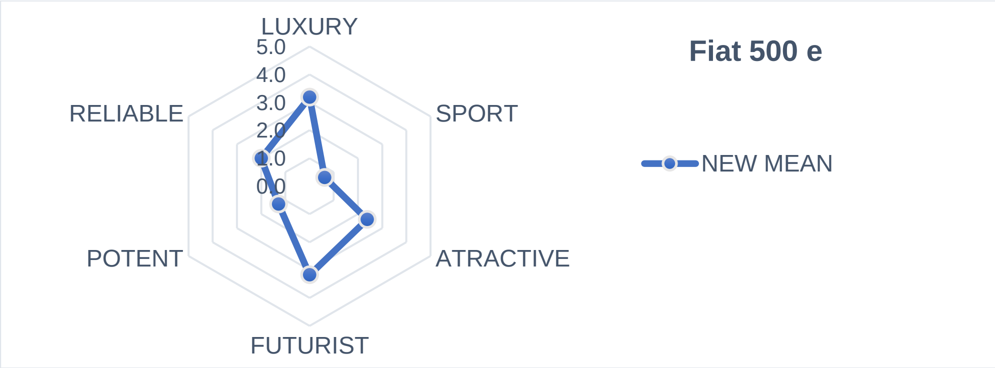

Figure 18: Spider chart for Fiat 500e

KIA EV6 results:

KIA EV6 sound1																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	3	2	2	5	3	3	4	4	3	2	4	2	5	4	3	3	3	3	3	4	4	4	3	1	1	3	1.033	2.083	4.148	**3.39**
SPORT	4	5	4	5	5	3	5	5	5	1	4	2	3	4	3	4	4	1	3	4	3	4	4	3	4	5	1.151	2.580	4.882	**3.63**
ATRACTIVE	3	4	4	5	4	1	4	5	4	2	5	2	3	4	3	3	4	3	3	4	4	4	4	2	3	5	1.029	2.510	4.567	**3.61**
FUTURIST	3	4	5	5	5	3	5	3	4	5	5	4	5	5	3	4	5	3	5	3	4	3	4	4	4	5	0.834	3.320	4.988	**4.00**
POTENT	3	4	2	5	5	2	5	5	4	3	4	3	4	4	2	3	4	2	1	5	4	5	4	1	5	5	1.299	2.317	4.914	**3.67**
RELIABLE	2	4	4	5	4	1	4	2	4	3	3	5	3	4	2	4	5	2	4	4	2	1	4	1	3	5	1.282	1.987	4.552	**3.26**

Table 6: Jury test result for KIA EV6 (sound sample 1)

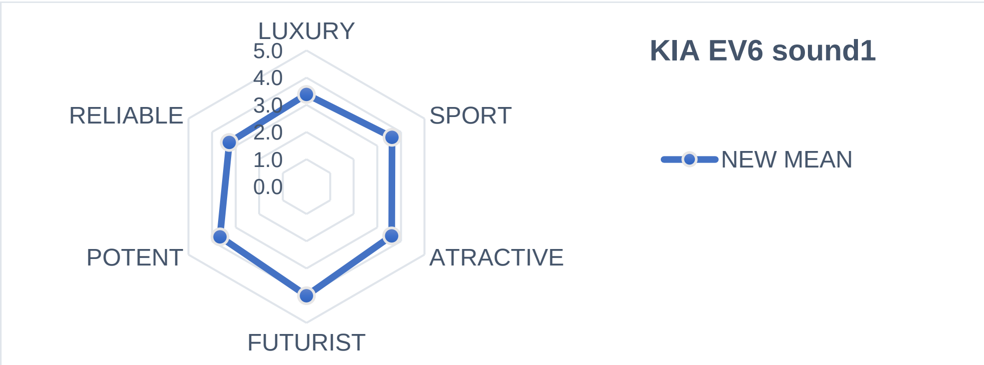

Figure 19: Spider chart for KIA EV6 sound sample 1

KIA EV6 sound 2																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	4	2	3	5	4	3	4	4	3	3	3	3	5	4	3	3	4	3	4	5	5	1	5	1	2	4	1.140	2.322	4.601	**3.47**
SPORT	4	4	5	5	5	3	5	5	4	1	4	3	5	4	4	4	5	2	5	5	4	5	5	4	5	5	1.032	3.199	5.263	**4.59**
ATRACTIVE	4	4	5	5	5	3	5	5	4	2	4	1	4	4	3	3	4	3	4	5	4	5	5	3	3	5	1.055	2.868	4.978	**3.60**
FUTURIST	2	4	5	5	2	4	4	1	4	5	3	3	4	4	3	3	4	3	2	4	5	1	4	1	3	3	1.225	2.082	4.533	**3.56**
POTENT	4	3	3	5	4	3	5	5	3	2	4	2	4	5	4	3	5	2	4	5	3	4	5	4	5	5	1.033	2.852	4.917	**3.57**
RELIABLE	3	4	4	4	4	3	5	3	4	3	4	2	3	3	3	3	4	2	4	4	3	3	5	1	3	5	0.945	2.478	4.369	**3.45**

Table 7: Jury test results for KIA EV6 (sound sample 2)

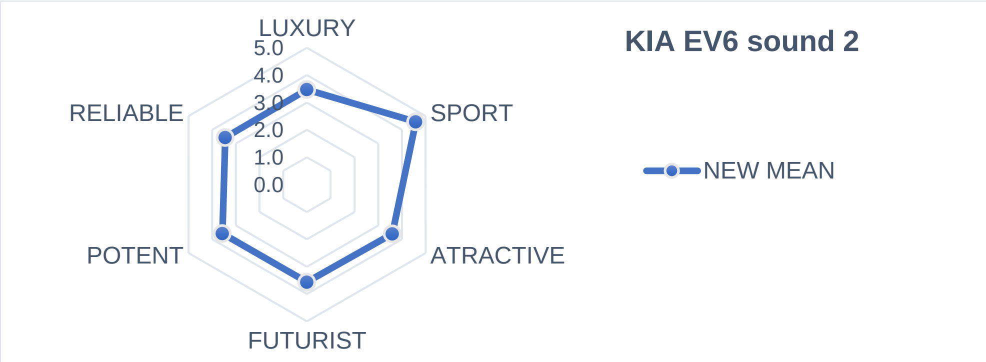

Figure 20: Spider chart for KIA EV6 sound sample 2

<u>BMW i4 E results:</u>

BMW i4 E																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	4	1	2	5	4	4	3	1	3	2	3	1	4	3	2	3	3	5	4	5	4	2	4	1	2	2	1.280	1.682	4.242	**3.05**
SPORT	5	4	5	5	5	4	5	3	2	3	5	1	5	4	3	5	5	5	5	5	5	4	5	4	4	5	1.079	3.190	5.348	**4.71**
ATRACTIVE	5	3	4	5	4	3	4	1	3	2	5	0	4	4	3	4	5	5	4	5	3	4	4	2	3	4	1.270	2.307	4.847	**3.63**
FUTURIST	2	3	4	5	3	4	4	2	3	4	5	2	4	5	3	2	3	2	2	5	5	2	4	3	4	2	1.129	2.217	4.475	**3.54**
POTENT	5	5	3	5	5	4	5	2	3	3	5	2	4	5	3	3	5	4	5	5	4	5	5	3	4	5	1.033	3.083	5.148	**4.72**
RELIABLE	3	3	4	4	4	4	5	3	5	2	2	3	4	4	2	4	4	4	4	4	3	3	4	1	3	5	0.990	2.510	4.490	**3.63**

Table 8: Jury test results for BMW i4E

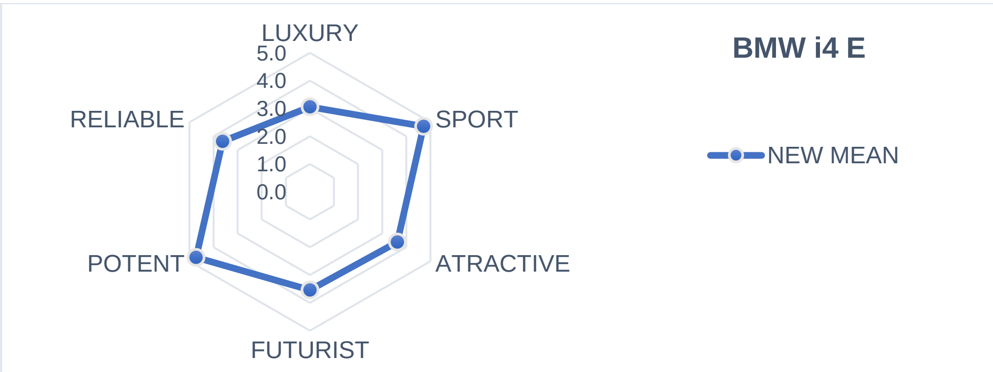

Figure 21: Spider chart for BMW i4 E

Audi E-tron GT results:

Audi E-tron GT																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	2	0	2	3	2	2	3	2	1	2	2	3	3	3	1	1	2	5	1	4	2	3	2	0	1	0	1.200	0.800	3.200	**2.05**
SPORT	3	1	4	4	2	3	2	5	1	3	4	4	5	3	2	2	4	5	4	5	2	4	3	2	2	3	1.223	1.931	4.377	**3.00**
ATRACTIVE	1	1	2	3	3	2	2	4	1	2	3	3	3	3	1	2	3	2	2	2	1	5	2	1	2	0	1.084	1.070	3.238	**2.41**
FUTURIST	1	0	4	3	1	4	3	2	3	4	3	1	3	4	2	2	2	2	1	2	3	1	2	2	3	0	1.177	1.054	3.407	**2.47**
POTENT	4	0	4	4	2	3	4	5	3	3	4	5	4	5	4	3	4	4	5	4	4	4	2	3	2	5	1.169	2.447	4.784	**3.71**
RELIABLE	2	1	3	4	2	4	3	3	5	2	2	4	3	4	3	2	3	3	2	1	3	2	2	1	2	3	1.018	1.636	3.671	**2.50**

Table 9: Jury test results for Audi E-tron GT

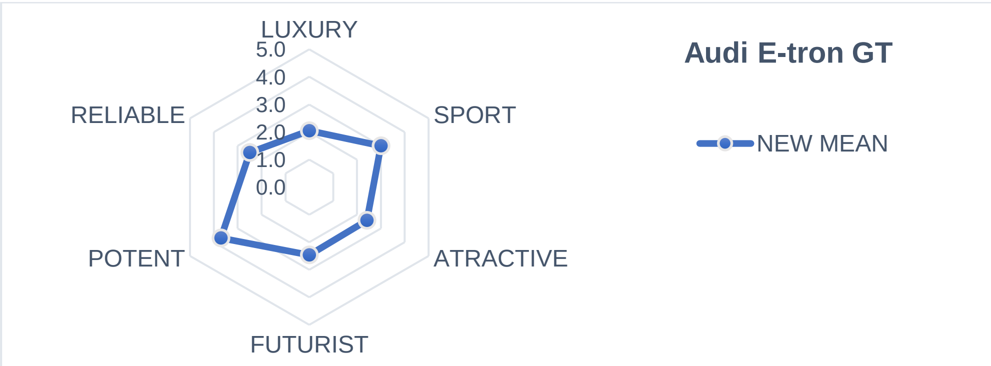

Figure 22: Spider chart for Audi E-tron GT

Jaguar Pace-I results:

Jaguar Pace-I																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	4	4	3	4	4	4	4	2	4	2	2	3	5	5	3	3	5	3	4	5	3	4	4	3	3	3	0.902	2.675	4.479	**3.53**
SPORT	5	1	4	4	5	5	3	5	5	3	4	2	4	4	4	5	5	3	5	3	5	2	3	3	4	4	1.120	2.726	4.967	**3.57**
ATRACTIVE	5	3	3	3	4	4	3	4	5	2	5	2	5	4	4	3	5	4	3	3	4	4	3	2	3	2	0.989	2.549	4.528	**3.56**
FUTURIST	3	3	3	5	4	5	4	3	5	3	5	5	3	5	4	3	4	2	1	5	4	4	3	1	4	0	1.364	2.136	4.864	**3.47**
POTENT	5	2	4	4	5	4	4	4	5	2	5	2	4	5	4	4	5	2	4	4	4	4	2	3	5	4	1.047	2.800	4.893	**3.93**
RELIABLE	2	4	3	3	3	4	3	2	5	2	3	3	3	4	4	3	4	4	3	4	3	5	3	2	3	3	0.827	2.442	4.097	**3.35**

Table 10: Jury test results for Jaguar Pace-I (Sound sample 1)

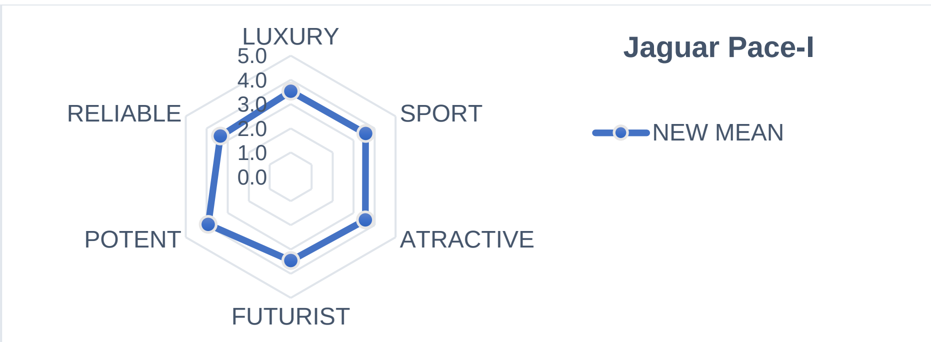

Figure 23: Spider chart for Jaguar Pace-I sound sample 1

Jaguar Pace-I sound 2																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	4	2	3	2	4	3	2	4	1	2	4	2	3	3	2	2	2	3	1	1	2	2	2	1	2	3	0.941	1.443	3.326	**2.52**
SPORT	3	4	4	3	5	3	4	4	5	3	5	4	3	3	2	2	3	4	0	1	3	5	3	3	5	5	1.270	2.153	4.693	**3.76**
ATRACTIVE	3	4	1	3	4	3	3	2	4	2	4	1	2	3	2	2	3	4	2	2	3	5	2	2	3	4	1.021	1.787	3.828	**3.18**
FUTURIST	4	3	4	3	5	4	5	3	3	4	2	5	2	4	2	3	3	4	3	2	3	3	3	4	4	5	0.948	2.514	4.409	**3.44**
POTENT	4	4	4	3	5	3	5	4	5	4	5	5	3	4	2	5	3	5	1	2	4	5	3	2	5	5	1.190	2.656	5.036	**3.81**
RELIABLE	3	4	2	3	4	3	4	3	1	2	3	2	4	3	2	3	3	3	0	2	3	1	2	1	2	5	1.134	1.481	3.749	**2.71**

Table 11: Jury test results for Jaguar Pace-I (Sound sample 2)

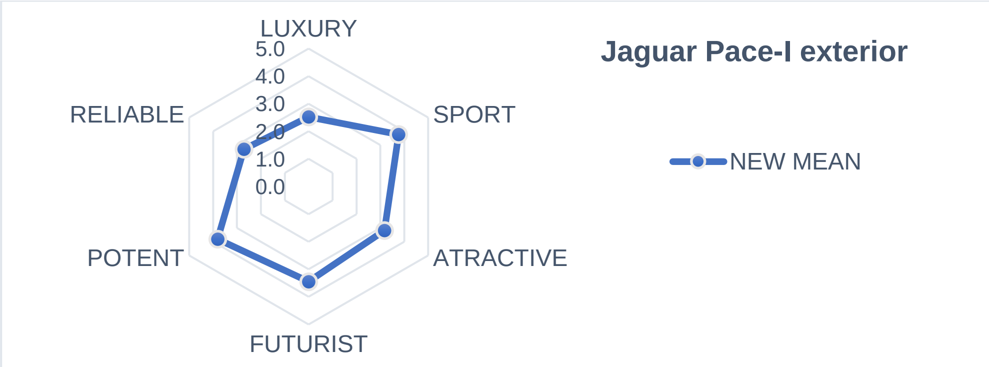

Figure 24: Spider chart for Jaguar Pace-I sound sample 2

<u>Hyundai IONIQ results:</u>

Hyundai IONIQ																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	5	4	4	5	5	2	4	1	3	2	5	0	4	3	1	2	4	3	1	1	5	4	3	1	1	0	1.674	1.134	4.481	**3.23**
SPORT	3	2	1	3	3	2	3	2	1	2	1	1	3	3	2	1	3	2	0	1	3	1	3	2	3	0	0.999	0.962	2.961	**1.50**
ATRACTIVE	5	4	3	2	3	2	4	0	1	2	1	2	3	3	1	3	2	2	2	1	4	2	2	1	2	2	1.151	1.118	3.420	**2.31**
FUTURIST	5	5	2	4	4	4	4	3	1	4	4	2	5	4	2	5	4	3	2	1	5	5	3	1	4	2	1.359	2.026	4.743	**3.75**
POTENT	3	2	2	3	3	3	2	2	2	3	2	2	2	3	2	2	4	2	0	1	3	2	2	1	3	0	0.925	1.229	3.079	**2.38**
RELIABLE	4	4	2	3	4	3	2	1	5	2	3	4	3	1	2	3	4	2	1	1	3	4	2	1	2	0	1.272	1.266	3.811	**2.46**

Table 12: Jury test results for Hyundai IONIQ

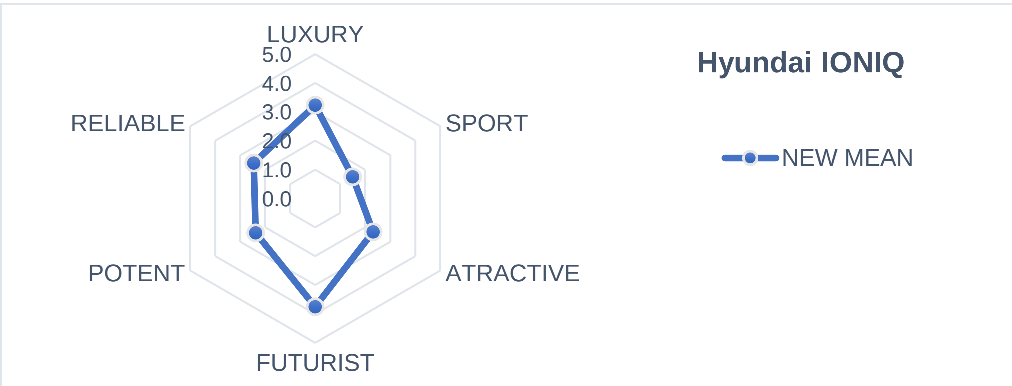

Figure 25: Spider chart for Hyundai IONIQ

Mustang Mach E results:

Mustang Mach E																														
	JURORS NUMBER																													
Rating Aspect	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***STAND. DEV.***	***INF. LIM.***	***SUP. LIM.***	***NEW MEAN***
LUXURY	3	0	1	3	2	3	4	1	4	2	1	1	3	4	0	2	2	1	2	2	0	1	3	0	0	5	1.440	0.483	3.363	**1.94**
SPORT	4	0	4	2	3	2	3	4	3	2	3	1	2	2	0	5	3	1	3	3	1	3	5	3	3	5	1.379	1.313	4.071	**2.89**
ATRACTIVE	4	1	2	2	3	2	2	2	4	2	4	2	1	2	0	3	3	0	2	1	0	2	5	0	1	0	1.383	0.540	3.306	**1.94**
FUTURIST	5	1	4	4	5	3	3	2	1	5	2	2	2	4	1	0	5	1	1	1	3	4	4	1	3	0	1.629	0.948	4.206	**2.35**
POTENT	4	1	3	2	3	2	3	3	5	3	4	2	4	4	2	2	3	1	3	3	3	3	5	1	2	3	1.084	1.762	3.930	**2.65**
RELIABLE	4	3	4	4	3	2	2	3	5	2	2	4	3	3	1	3	2	3	3	0	3	3	3	1	0	4	1.225	1.467	3.918	**2.69**

Table 13: Jury test results for Mustang Mach E

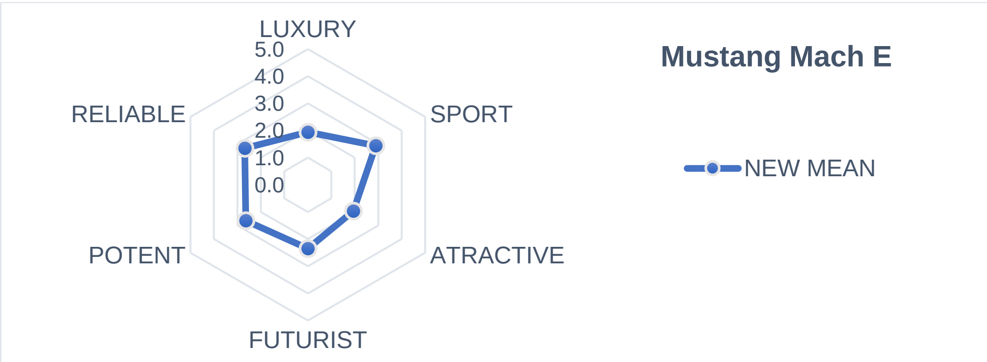

Figure 26: Spider chart for Mustang Mach E

Porsche Taycan results:

Porsche Taycan																														
	JURORS NUMBER																													
Rating Aspect	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***STAND. DEV.***	***INF. LIM.***	***SUP. LIM.***	***NEW MEAN***
LUXURY	4	1	1	3	2	2	2	2	1	2	2	0	2	2	2	2	2	3	0	1	1	1	3	1	1	2	0.919	0.812	2.650	**1.60**
SPORT	5	5	3	5	4	4	4	4	5	2	3	0	3	2	3	2	2	3	0	3	5	5	4	1	4	5	1.517	1.791	4.825	**3.13**
ATRACTIVE	4	4	2	5	3	3	3	2	4	2	2	0	2	2	3	3	3	3	0	2	4	5	2	2	3	0	1.329	1.286	3.944	**2.47**
FUTURIST	4	3	4	5	3	4	4	4	3	5	3	2	1	3	3	3	3	1	0	1	5	1	2	4	3	2	1.354	1.569	4.277	**3.17**
POTENT	5	5	2	5	4	4	5	5	5	5	3	1	3	4	3	3	3	3	5	3	4	5	4	3	4	5	1.107	2.777	4.992	**3.43**
RELIABLE	3	4	4	2	1	4	3	1	1	3	4	0	2	3	3	1	2	3	2	3	4	2	3	3	2	2	1.105	1.395	3.605	**2.60**

Table 14: Jury test results for Porsche Taycan

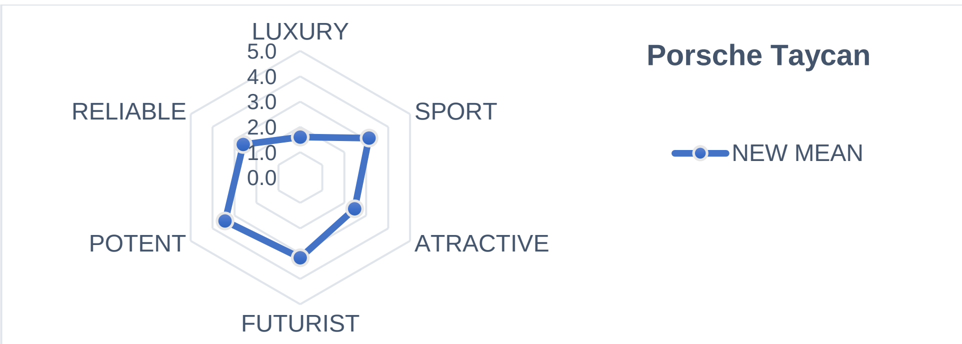

Figure 27: Spider chart for Porsche Taycan

Skoda Enyaq Iv results:

Skoda Enyaq iV																														
	JURORS NUMBER																													
Rating Aspect	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*STAND. DEV.*	*INF. LIM.*	*SUP. LIM.*	*NEW MEAN*
LUXURY	5	3	4	5	4	4	3	2	1	2	3	1	2	3	0	2	2	2	2	1	1	3	2	2	1	0	1.350	0.958	3.657	**2.00**
SPORT	3	1	2	3	4	4	3	3	3	2	4	1	1	3	0	1	2	2	0	3	1	4	3	2	4	3	1.235	1.149	3.620	**2.64**
ATRACTIVE	3	2	3	3	3	4	2	2	2	2	2	1	1	3	0	1	2	1	1	1	1	4	2	1	2	3	1.020	0.980	3.020	**1.91**
FUTURIST	5	3	5	5	5	5	4	4	3	5	4	4	1	4	0	5	3	1	3	2	4	3	2	3	4	5	1.421	2.118	4.959	**3.54**
POTENT	4	2	3	3	5	5	3	4	3	5	1	2	3	4	1	4	2	1	2	2	3	3	2	2	4	3	1.197	1.726	4.121	**2.90**
RELIABLE	3	2	4	3	4	4	2	3	3	3	3	2	2	3	1	2	2	2	3	3	3	4	2	1	1	1	0.948	1.591	3.486	**2.56**

Table 15: Jury test results for Skoda Enyaq iV

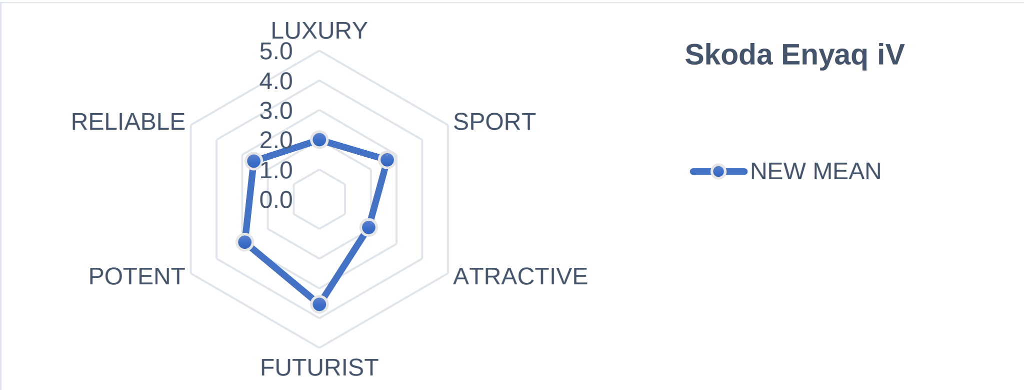

Figure 28: Spider chart for Skoda Enyaq iV

4.1.1. Top ranking results

From the results shown above, it could be seen that the best scores for the categories are distributed specifically between Jaguar, BMW, Nissan, and KIA as shown in the table below.

BEST RANKING SCORE	*MEAN*	*EV MODEL*
LUXURY	3.53	Jaguar PACE I-interior
SPORT	4.71	BMW i4E
ATRACTIVE	4.35	Nissan Leaf Canto
FUTURIST	4	KIA EV sound1
POTENT	4.72	BMW i4E

Table 16: Best ranking scores from Jury test results

To interpret how these sounds are perceived as more characteristic of one aspect than another, correlations are made in the section below.

4.2. Correlations

In the analysis of the Jury test results and the sound samples respectively, it was observed that grouping sound samples with similar tendencies towards certain aspects was possible. For each group of sounds with similar affinities, the sounds samples were analyzed based on the metrics mentioned above to recognize why the jurors rated these sounds similarly. In order to visualize and to interpret more clearly the behavior shown in the charts, it was decided to establish three groups of distinguishable correlations.

4.2.1. Even distribution tendency

The first distinguishable group was consisted by three vehicle brands, KIA, Jaguar and BMW, that presented spider charts with similar perception behavior. These are four sounds samples that have been shown to be perceived by jurors as sounds with all the characteristic aspects for which they were being tested with a considerable rating. Figure 29 shows a spider chart with the results taken from the Jury test corresponding to ranking of the four sound samples.

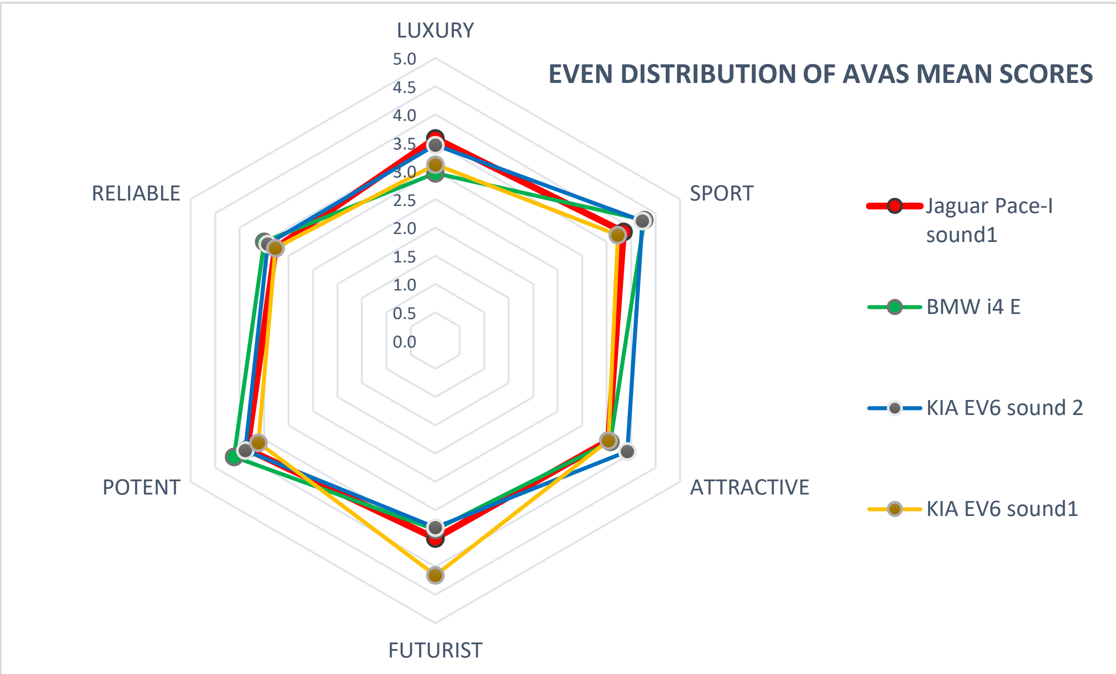

Figure 29: Spider chart for ranking with even distribution behavior.

It can be seen that there is no particular characteristic with a higher trend in this case, rather the rates are normalized around the same score. This can be interpreted as if the corresponding sound samples were perceived by the jurors as common vehicle sound, similar to the ones for ICE. To understand the reason for these results the sound analysis in the mentioned metrics is needed.

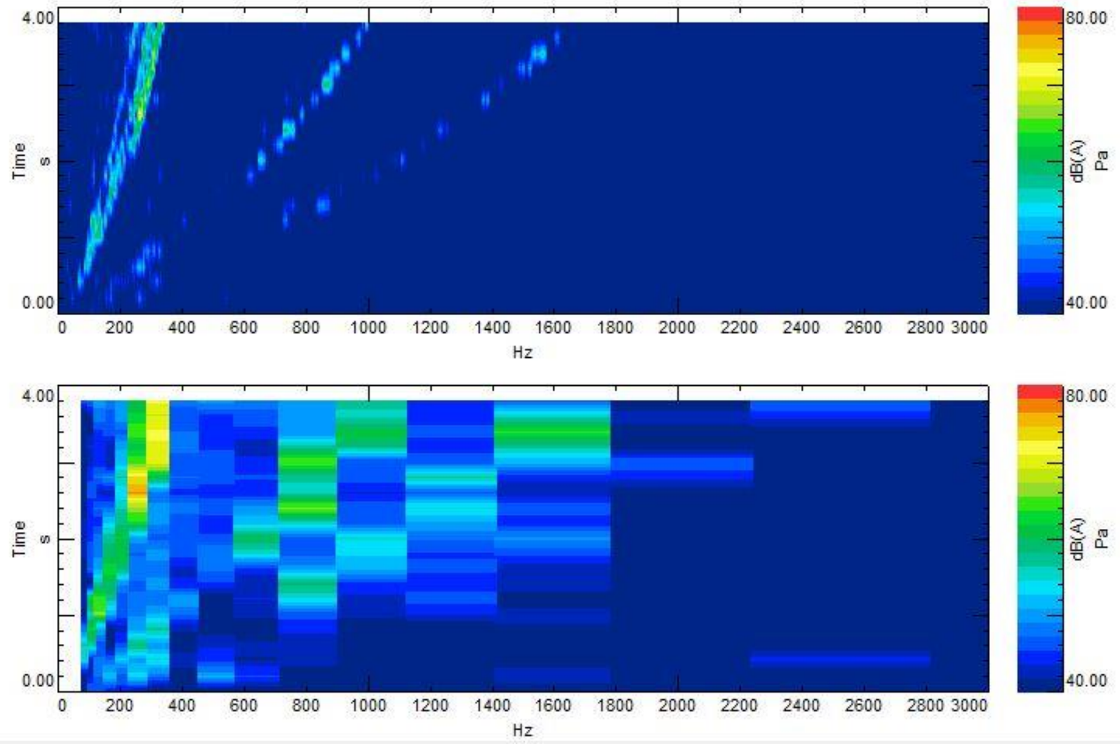

Figure 30: KIA (sound sample1) harmonics and noise colormap

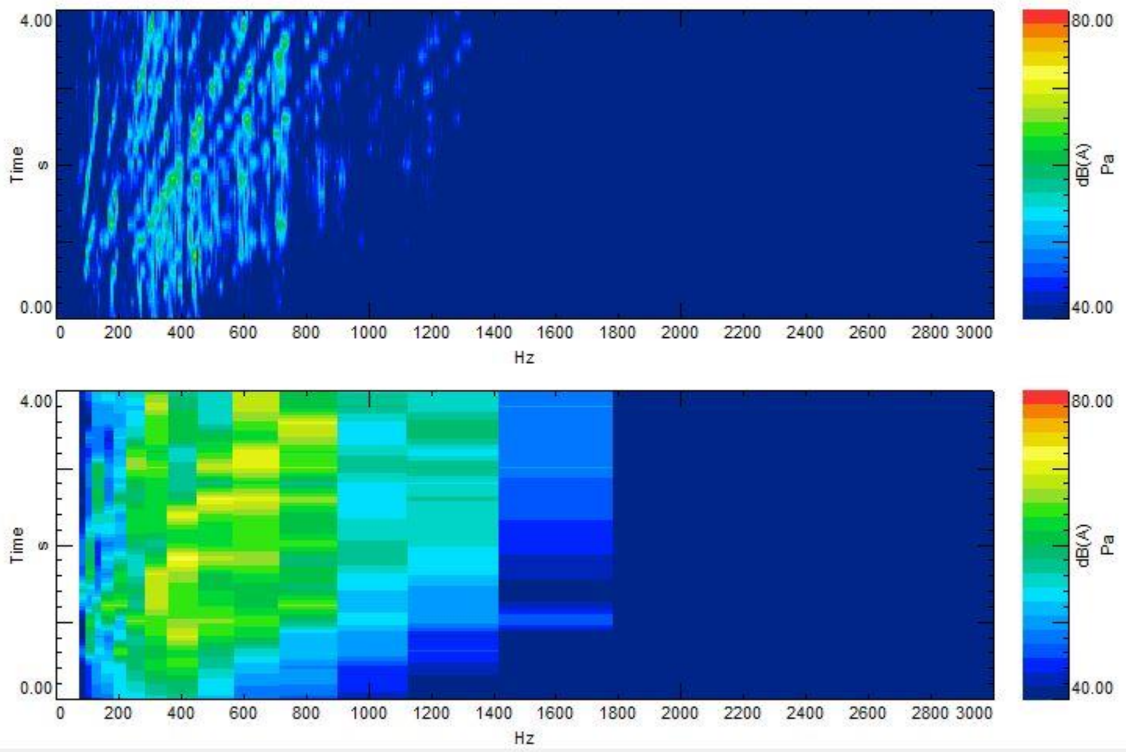

Figure 31: KIA (sound sample 2) harmonics and noise colormap

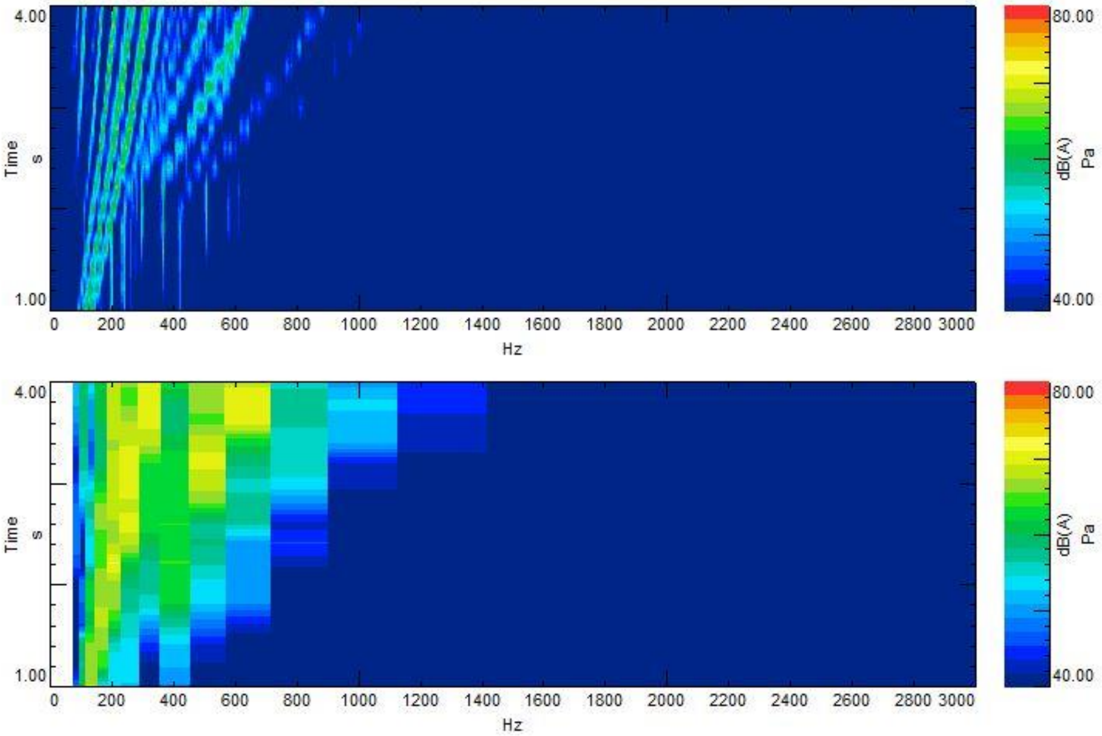

Figure 32: Jaguar Pace-I (sound sample1) harmonics and noise colormap

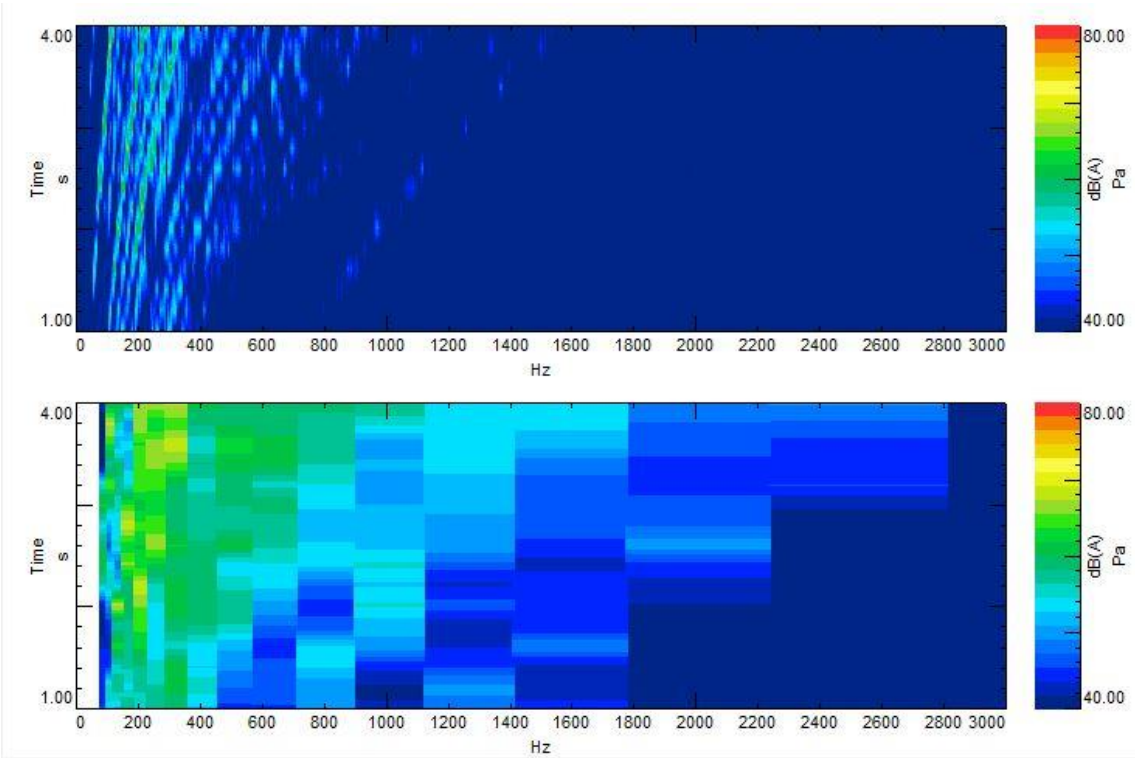

Figure 33: BMW i4E harmonics and noise colormap

From the first graph of figures 30, 31, 32 and 33, it is deduced that these sounds are created with harmonics at low frequencies which are considered as the more familiar frequencies as they are close to the common vehicles' ones. The one-third octave band

content for all four AVAS sounds cover a range from 50Hz to 1200Hz approximately, meeting the regulation requirements more than once. The sound modulations at these frequencies are shown at a sound pressure that goes from 40dB to 80dB, where a level of 60dB predominates for most of the modulations. These low frequencies content can also be seen in the figure 34 which indicates the sharpness of these sounds and how similar they are in hertz content.

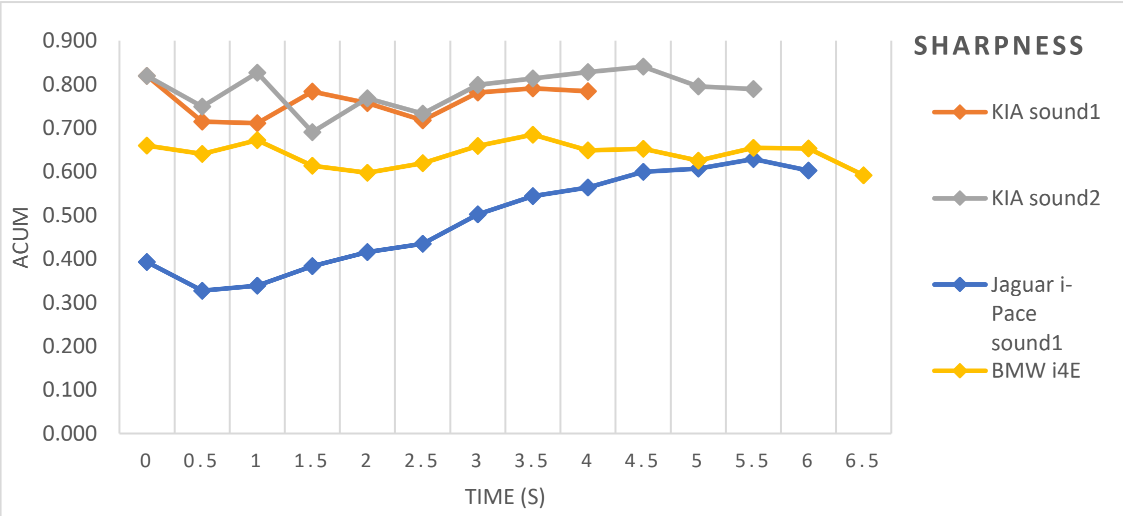

Figure 34: Sharpness graph of first correlated group

The low frequency content of these sounds is also evidenced by the low register of acoustics in the sharpness of these sounds. Even though the KIA and BMW sharpness are more similar in way they are distributed along the time of sound reproduction, Jaguar's sound imitates more this tendency from second 3 approximately. This gives a sharpness range that goes from 0.3 to 0.8 acum for the first group of AVAS sounds.

From the second graph of figures 30 to 33, the background noise is also illustrated which indicates that between all the orders found at low frequencies in the sounds there are modulations in the background that accompany the sound to intensify its perceptual effect. Noise is also introduced in the sound in a controlled amount so that the sound is designed with more texture or depth. This can be seen in the graph as the areas of light blue and light green. Adding noise-based envelopes, sound designers can make percussive elements or sudden sound events stand out more prominently and create a sense of sharpness or presence. In that sense, the noise content is important as it can be shaped using synthesis techniques, filtering, modulation, and other processing methods, to generate a wide range of sound effects or futuristic soundscapes.

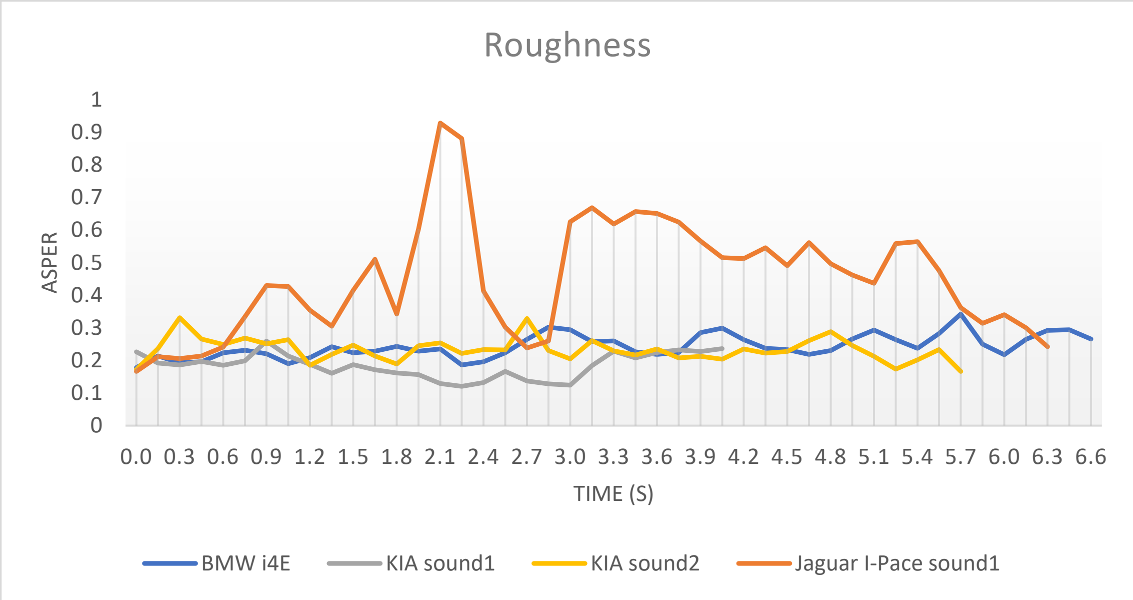

Figure 35: Roughness graph of first correlated group

Figure 35 indicates that sounds for these models goes fluctuating along the time they are reproduced while the vehicle is accelerating. These fluctuations happen rapidly as the frequencies and amplitudes changes in each AVAS sound respectively, and this will also depend on whether the vehicle is being accelerated steadily or if there are variations in speed. Both KIA models and BMW´s fluctuates moderately similar, meanwhile the Jaguar´s model presented a mismatched shape. It was deduced that this uneven result could be due to the quality of the audio recorded for this specific vehicle or the amount of background noise that may have affected the analysis. However, based on the other three models it is observed that the fluctuations presented are not too marked and that the complete evolution lines show a somewhat constant trend horizontally. This results in no specific sound aspect being defined as such for the judges scoring these models.

4.2.2. Potent and Sport tendency

The second group of AVAS sounds that were differentiated is formed by Jaguar Pace-I (sound 2), Audi E-tron GT and Porsche Taycan. These EV models were perceived as more potent and sport vehicles based on their acceleration sounds. It is an SUV with a sportier physical appearance and two well-known sports cars that undoubtedly mark an aspect of sportiness and power. The figure shows how the spider charts of these three cases show a very central ranking in the aspects of luxury, reliability and attractiveness. However, the aspects of powerful and sporty stand out and there is also a small difference in the futuristic aspect.

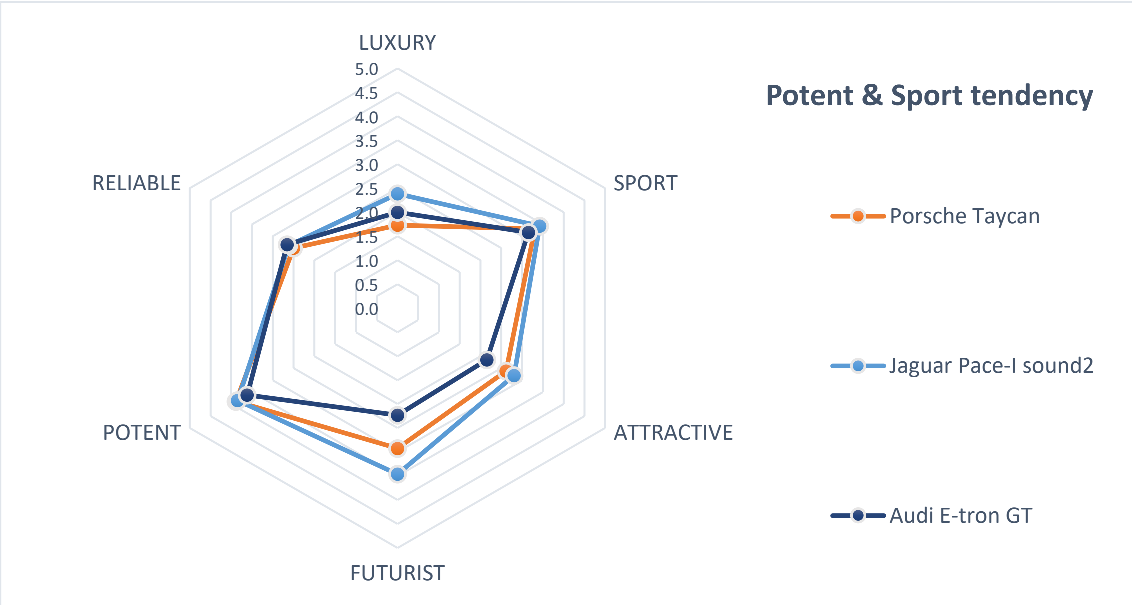

Figure 36: Spider chart for ranking with 'potent and sport' tendency.

Similarly, the analysis of these three sound samples allows the better understanding of this tendency in perception by the jurors when the tests were being completed. The first graph of figures 37, 38, and 39 shown below demonstrates that for this case, orders with high frequencies have been introduced in the one-third octave band content. The lines that are distinguishable from the colormap for this group of AVAS show a much higher growth trend than those of the previous group. In other words, if we take as an example the case of the Porsche Taycan, we can see that there is an order that goes from the frequency of 1200Hz in growth up to 2600Hz approximately. This tendency that covers a much greater range of frequencies makes the sound generate that sensation of sportiness and power. The sound produces an effect of greater acceleration that is attributed to a more powerful car.

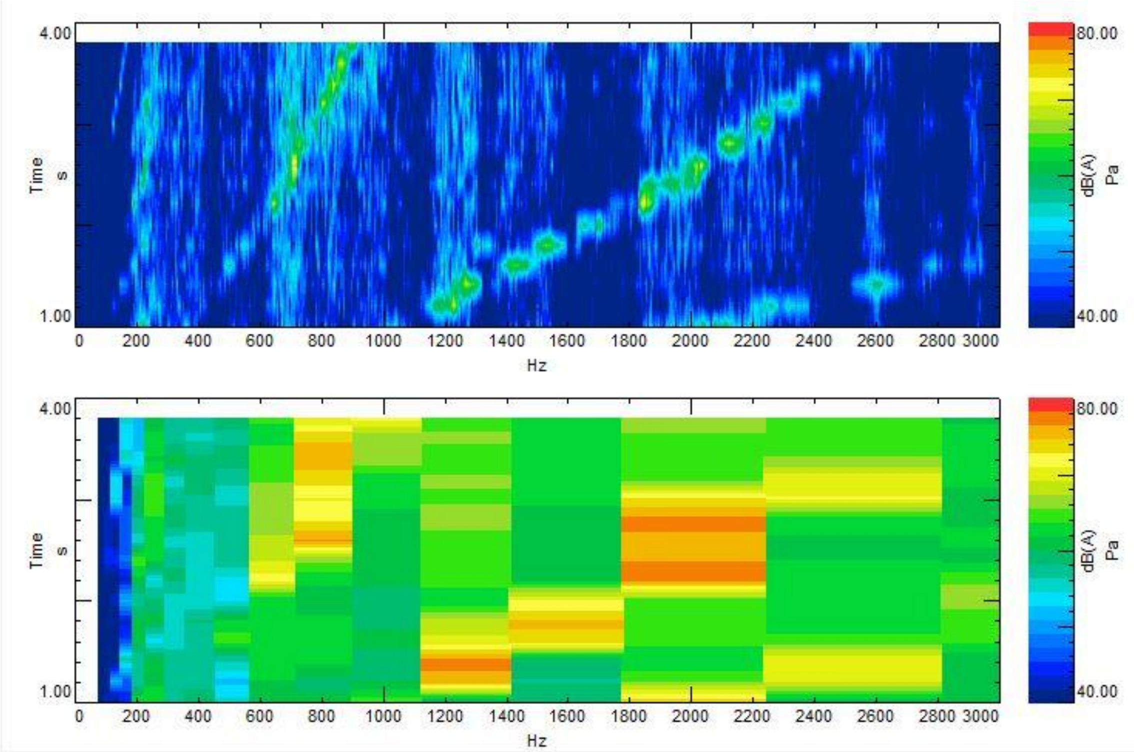

Figure 37: Porsche Taycan harmonics and noise colormap

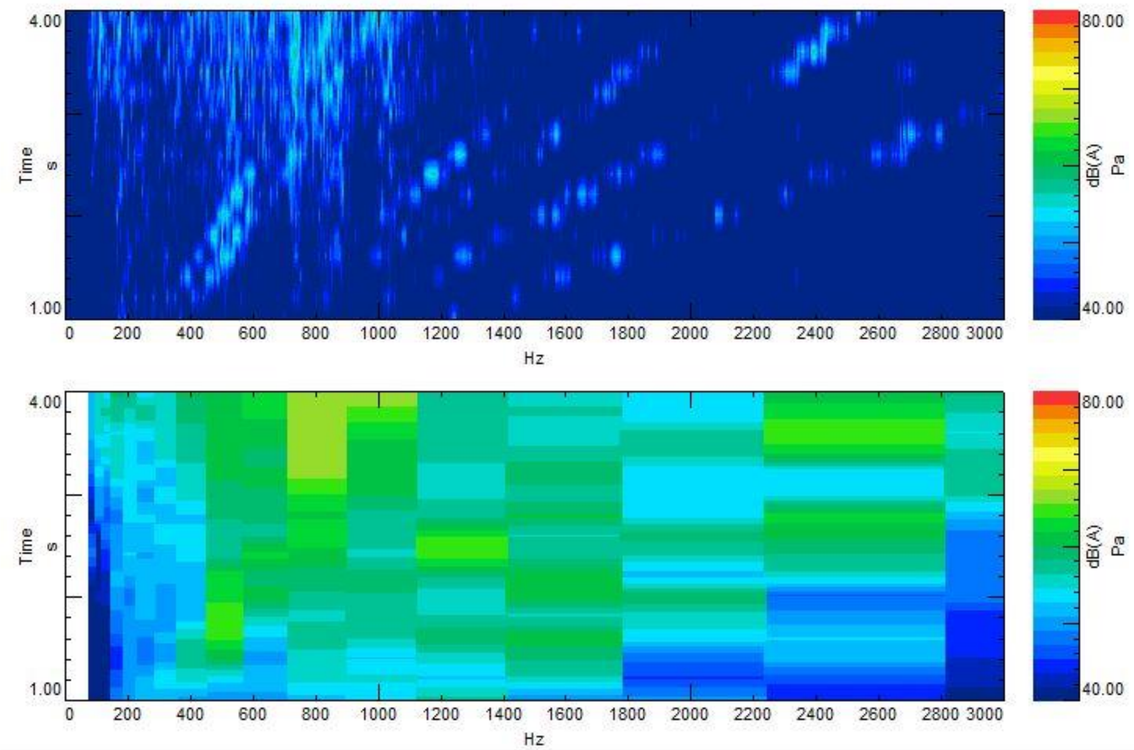

Figure 38: Jaguar I-Pace (sound2) harmonics and noise colormap

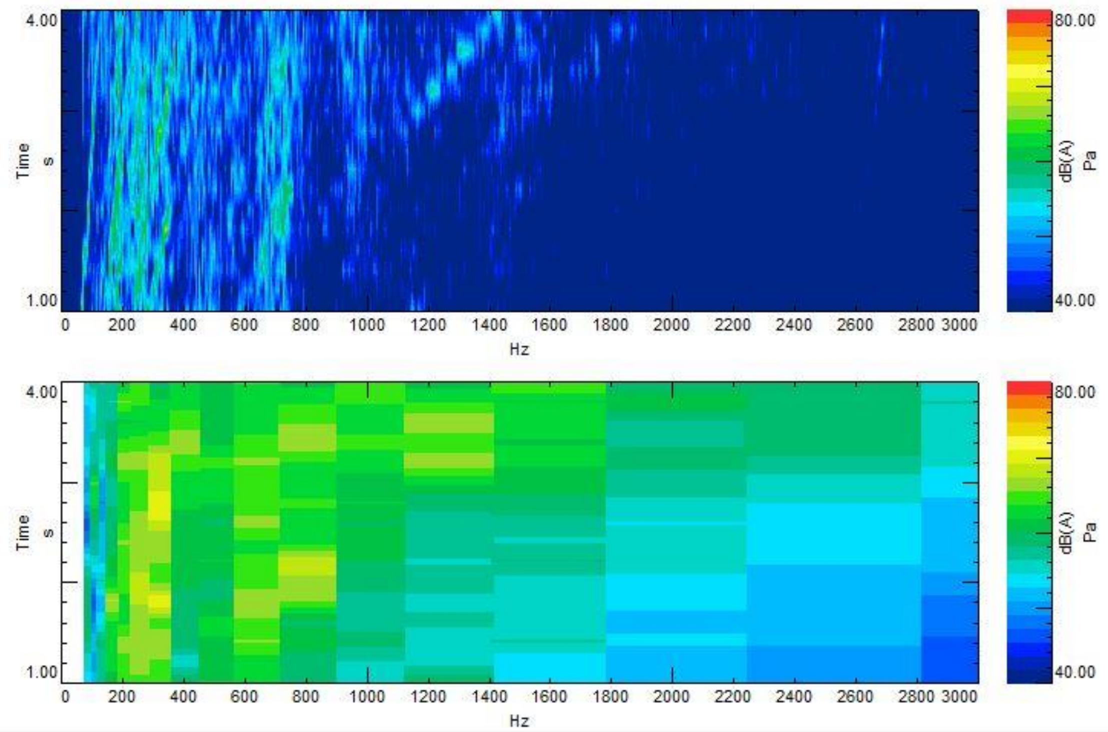

Figure 39: Audi E-tron GT harmonics and noise colormap

The sharpness analysis for these sounds shown in figure 40 illustrates the higher frequencies content and a very similar behavior along the time the sound is being played. The range from around 0.80 to 1.60 acum is covered for the sharpness of this correlated group. An almost straight tendency is evidenced in this case for all three sound sharpness that produces the similar effect perceived by the jurors. In the same way, the sound pressure is detected from 40dB to 80dB where 50-60dB encompasses the majority of modulations.

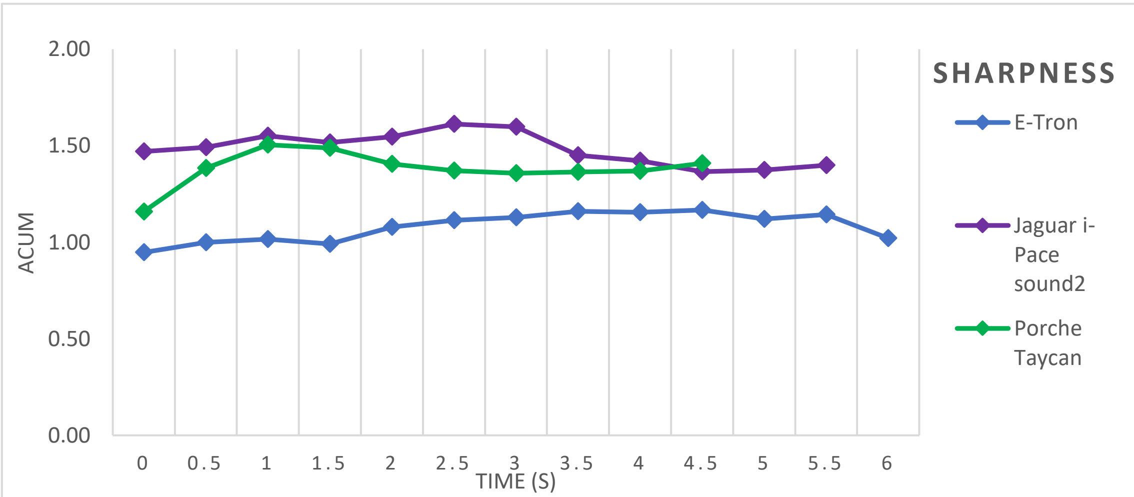

Figure 40: Sharpness graph for second correlated group

In addition to the similarities found in the growth trend of the orders, the second graph of Figures 37, 38 and 39 show the background noise that has been used for each case of AVAS that generates a so-called filler to the main sound that is more distinguishable. This makes the sound heard when the car is passing not too dull and generates a greater impression of presence. The separation between the detected orders and the modulations in between them is also an important factor in grouping these sounds together to provide the same effect to the listener's ear. At the same time, it should be mentioned that Figure 36 shows a difference in the futuristic aspect for the three models. This could be explained by the difference in background noise that is found for each sound sample. In the Audi case, its graph shows a greater presence of background noise at low frequencies (greener area) which makes that the sound is not perceived as futuristic as the rest. Meanwhile, for the Jaguar case it is possible to distinguish background noise presence at both low and high frequencies which interaction creates that perception of futuristic sound. For Porsche, its registration shows background noise along all the frequencies in the graph which gives the reason to rank it in between both sound samples.

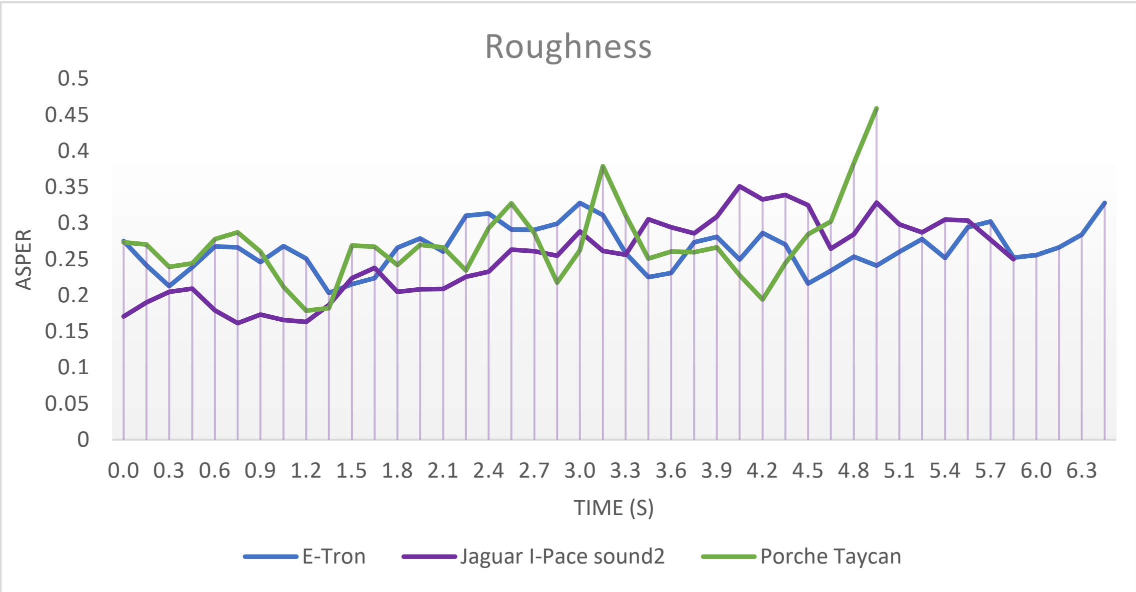

Figure 41: Roughness graph for second correlated group

Finally, the roughness analysis as shown in figure 41 gives reason to the ‘potent and sport’ emphasis resulted in this group. Although it can be observed that the roughness lines fluctuate as time progresses, it is possible to distinguish some increases at the end of the course for the Taycan and the E-tron. The high roughness content in the sound is attributed to a greater sense of sportiness in the vehicle. The results of this analysis could be affected by the quality of the sound samples used for the test; however, the behavior of their roughness is very similar. Porsche Taycan starts its roughness at 0.27 asper and fluctuates until it reaches 0.46 aspers. Jaguar Pace-I goes from 0.17 asper, and it also fluctuates having its highest peak at 0.35 asper. Finally, Audi E-tron covers a range of asper that goes from 0.21 to 0.32.

4.2.3. Singular tendencies

In contrast to the models previously analyzed for the last four cases of AVAS sounds it was not possible to establish a correlation between them due to different behavior in the ranking results. However, every sound presented special characteristics that mark their own tendency in the sound model that are detailed below. This group of sounds corresponds to the generated by Hyundai, Fiat, Nissan, and Mustang.

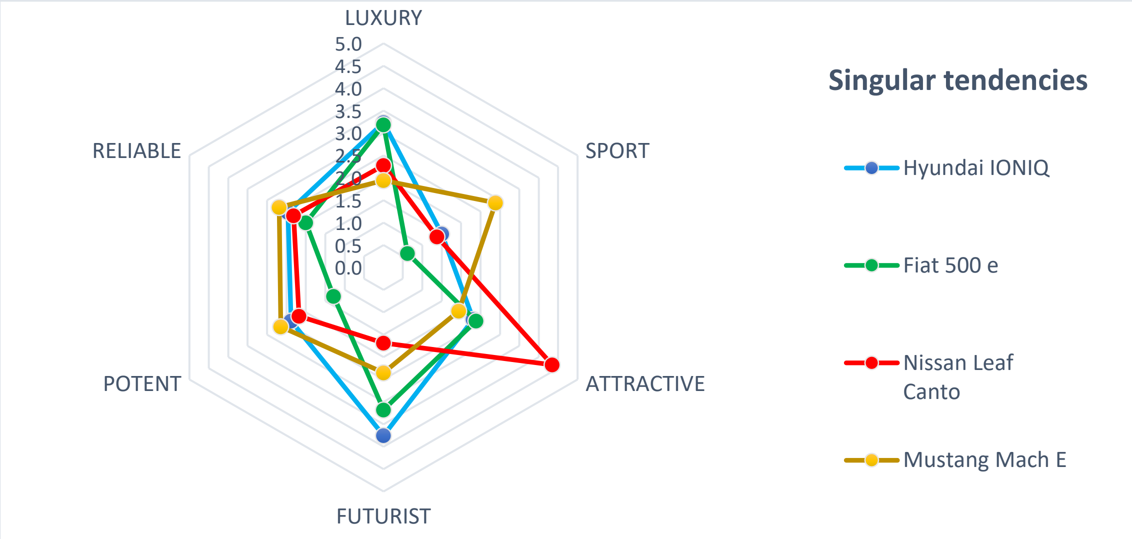

Figure 42: Spider chart for group with singular tendencies

Figure 42 shows the spider chart for the four models together and it is clear that none of them shares a tendency in results. Nissan Leaf Canto has its higher rate at the 'attractive' aspect, meanwhile Mustang Mach-E has its peak at 'sport' characteristic. Fiat 500e shows very weak results at 'sport and potent' perceptions and a similar normal distribution for the rest of aspects. Hyundai IONIQ presents a greater impact in 'futurist and luxury' aspects and has a medium rate in the remaining factor. In that way, each model has its own singularity that varies depending on how the sound has been designed and is perceived by the jurors. For this group of vehicles, it has been applied the extra metric mentioned in previous sections called prominence ratio to appreciate in a more detailed way the characteristics that creates a different perception for each of them.

<u>Hyundai IONIQ</u>: Based on Figure 43, the AVAS sound for this particular case consists of well-defined orders at low frequencies, being in the range of 200Hz to 1200Hz. This is evidenced by the first and the third graph clearly. The almost straight lines formed at low frequencies demonstrate that there is no modulation in the acceleration sound. At the same time, this is combined with the noise background depicted by the second graph which shows that the sound has been designed to be more luxury and futuristic as panning noise elements covers all background simulating motion, spatializing sounds, and creating dynamic transitions.

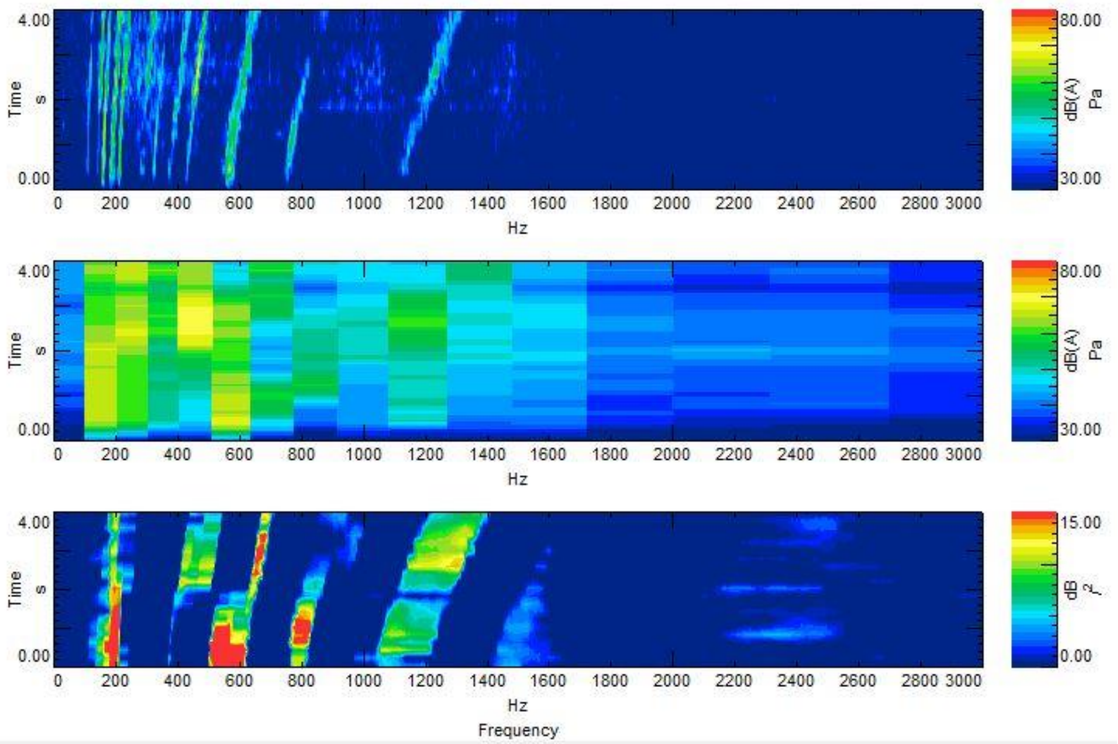

Figure 43: Hyundai IONIQ harmonic content, noise and prominence ratio

Mustang Mach-E: In this case, the first graph of Figure 44 illustrates the harmonic content which is located principally at low frequencies and at mid-range frequencies. This shows that there are several modulations between the prominent orders. The third graph corresponding to the prominence ratio illustrates, in this special case, a much clearer vision of what this metric is intended to represent. Although there is a higher register of harmonics and modulations in the first graph, this third graph indicates that there are only two prominent orders, one at approximately 160 Hz and the other at 1200Hz.These two orders indicates the more distinguishable frequencies in the sound according to the background level and the sidebands of the same harmonics. The order in the central frequency band is the one that creates a bigger effect of 'sport' sound in this vehicle. Nevertheless, the background noise that has been used for this model as shown in the second graph helps to generate that outstanding character before the rest of the qualified aspects.

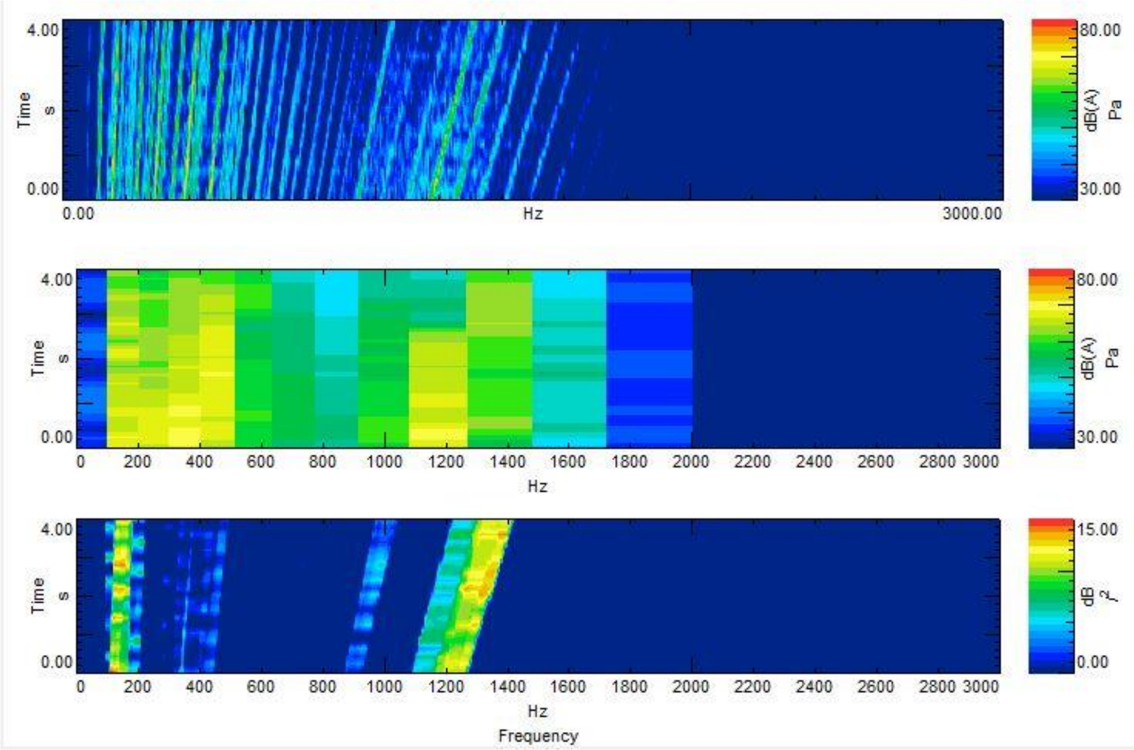

Figure 44: Mustang Mach-E harmònic content, noise and prominence ratio

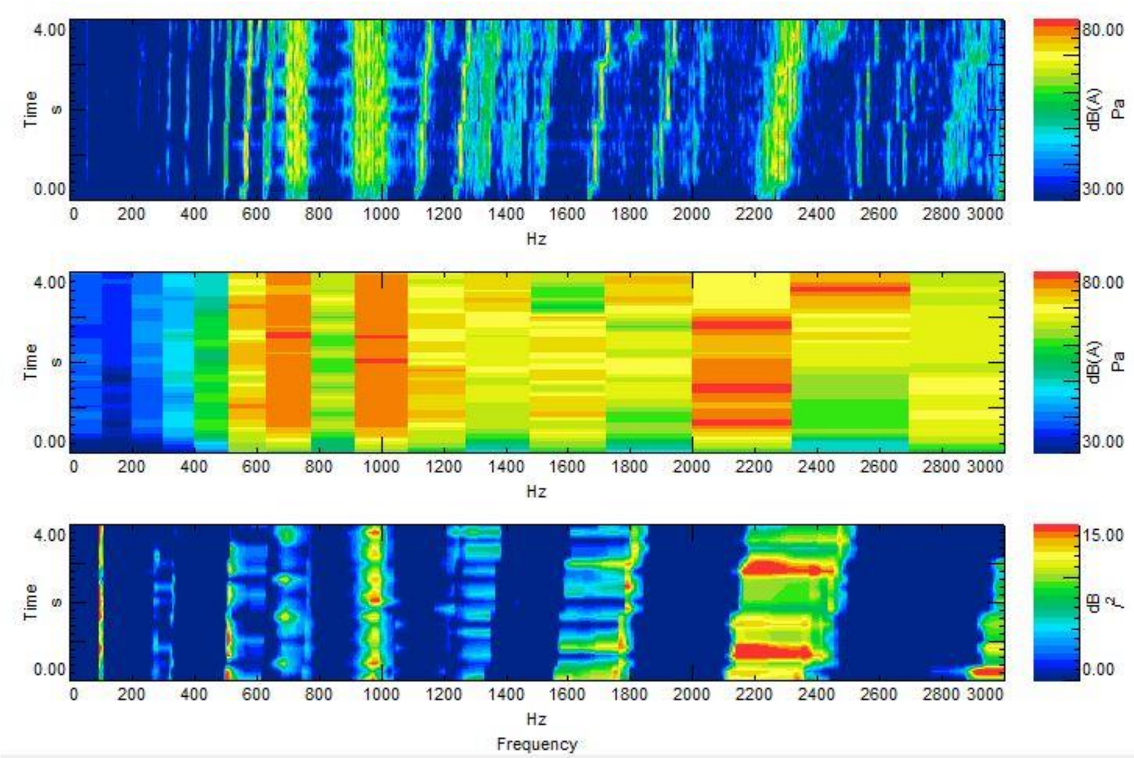

Figure 45: Nissan Leaf Canto harmonic content, noise and prominence ratio

Nissan Leaf Canto: As it is shown in Figure 44, the AVAS sound for this vehicle presents audible orders from low to high frequencies but with more prominence at higher frequencies. It is also found that every audible order is modulated by its own sideband orders that add an element of novelty and uniqueness to the AVAS sound, catching the attention of pedestrians and increasing their awareness of the electric vehicle. When the AVAS sound differs from the background noise or other sounds in the environment, it stands out and grabs attention. In this case, the incorporation of interesting and unexpected modulations, the AVAS sound can pique curiosity and create a memorable impression. As it is seen that this sound is full of harmonics well distributed and harmonically rich modulations, the AVAS is perceived as more tolerable, aesthetically pleasing, and attractive. This is an important aspect to ensure a greater acceptance in jurors and pedestrians in general.

Fiat 500e: For the last sound model, analysis results have presented a particular behavior due to the way it has been designed. It is a sound that involves a difficult interpretation as the main feature of it is that when the vehicle reaches a certain speed at a preferable constant acceleration, a song is played together with the motion sound of the vehicle. This has been designed as a model of brand identity for Fiat, its iconic vehicle model and its manufacturing country, Italy.

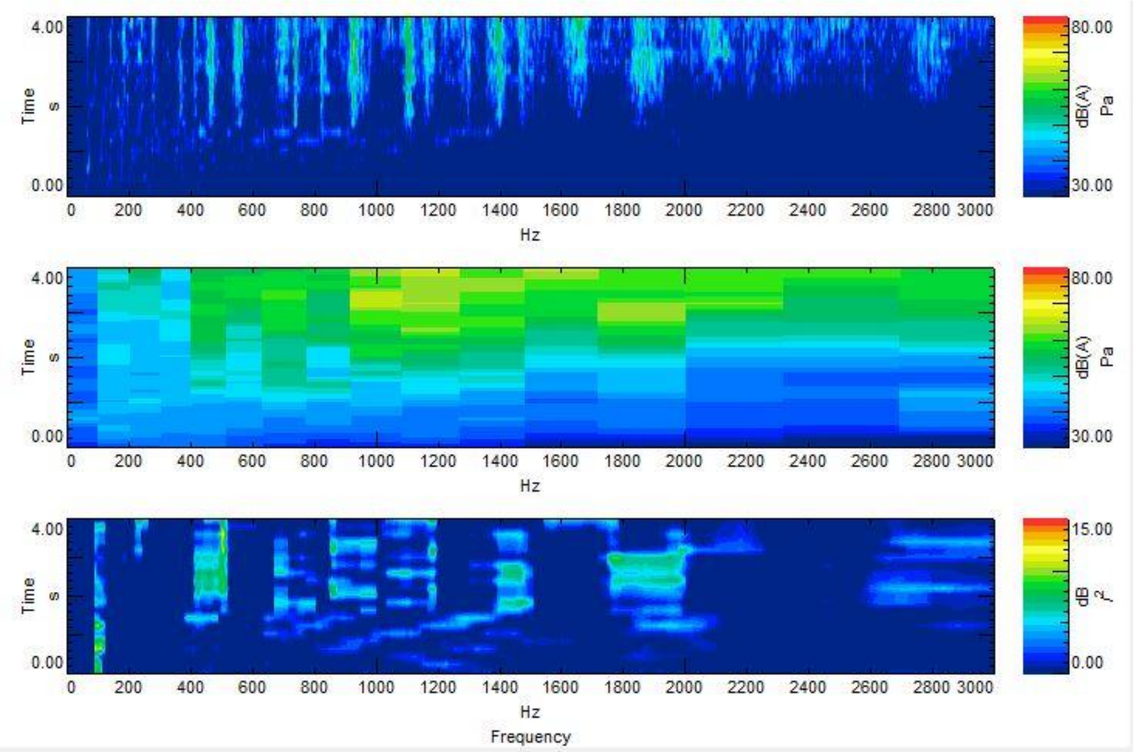

Figure 46: Fiat 500e harmonic content, noise and prominence ratio

Thus, based on the first graph from Figure 46 it is possible to observed that there are order harmonics at different frequencies along all the range of octave bands, with a better definition of them in the low frequencies zone. This simulates a combination of the results seen in the Nissan and Hyundai case. In the same way, the third graph showing the prominence orders has clearer results at low frequencies and the stripes become blurred and shifted at higher frequencies. This can be explained by the fact that at the end of the AVAS sound the mentioned song is audible and it changes all the perception characteristics due to human psychology is more stimulated when musical patterns or melodic sequences are present. The use of musical elements can make the AVAS sound more engaging and enjoyable for pedestrians, potentially reducing any negative associations with traditional alarm or warning sounds. This sound model is undoubtedly the most peculiar of all for incorporating melodious tones that resemble a song and remove from its structure a purely vehicular concept, but at the same time this has resulted that, according to the results of the Jury test, its strengths are the aspects of luxurious, futurist and attractive.

5. AVAS Model Proposal

Based on the references obtained from the AVAS already used in the current market and from the experiences perceived by the testers during the conducted Jury test, the idea of designing an AVAS concept that would serve as an extra section to the main aim of the project was proposed. This, in turn, would serve to encompass the part of the sound reception with the creation of the same and thus have a broader view of everything involved in this feature of the vehicle.

As initial step for the AVAS proposal it is necessary to have selected the model car for which the sound would be designed. As it is mentioned in the section 2.1. the regulation that controls the AVAS implementation in EVs has been applied since 2019 for which electric vehicles that were in the market years before could avoid this. Considering this, it was decided to choose one of the best-selling and most popular electric cars around the world in 2018 after its launch, the Tesla Model 3.

Figure 47: Tesla Model 3 (2018). Taken from: https://www.km77.com/coches/tesla/model-3/2018/sedan/informacion

- Vehicle type: Sedan
- Year: 2018
- Max velocity: 245km/h
- Max power: 351CV / 390kW
- Autonomy: 602km [34]

The Tesla Model 3 has been for many years in the vehicle market leading the sales list and being recognized for its innovation, advanced engineering, and futuristic projection. For that reason, when designing a sound that will be used by this EV it has to involve some aspects to align with the car concept. These aspects include a projection of elegance with tones of sportiness and subtlety, as the Model 3 has been considered as a family car but without being out of the sporty. This can be translated in terms of previously mentioned sound characteristics to a sound that has prominence in the category of ***luxurious*** and ***futuristic*** without neglecting the ***sporting*** aspect. It should also take into account the commitment of the Tesla brand with the environment so the sound should not be so invasive and should be coupled to the range of existing sounds in the environment without being unnoticed by pedestrians. This is related to the sound characteristic of reliability when designing the AVAS sound that must be detailed and at the same time meeting all the requirements from the regulation.

It is important to mention that the design of the AVAS model in this case is limited to production of the sound only and it could be considered as a didactic sample of the acoustical engineering involved in this. The regulation n°138 [5a] is used as the frequency's references needed for the design. However, requirements involving compliance with certain sound pressure decibel levels are left out of consideration. This is because it is assumed that it will depend on the type of reproducing speakers used in the vehicle and the correct equalization of the sound in the sound system.

5.1. Sound Design

The creation and design of the sound intended to be an interesting and possible valid proposal for the Tesla Model3 was done with the guidance of a proper acoustic engineer. This made it possible to transform the ideas that were spoken out into sound and melodies that could match together in a better way to finally obtain a good result in the AVAS model. During three weeks of meetings in a recording studio the desired sound was detailed and edited every time. After the cooperative work all, the tones were got to be in harmonic composition and how it was done is briefly described below.

The software used for the sound design was Ableton, which is a professional tool for composing, recording, mixing, and mastering. The first step was to determine a pure tone that would work as the origin of the sound to further modulate it. In this case, a standard piano tone at 414Hz was established as the origin and then its timbre was changed to a more electronic sound that could better simulate the sounds related to an electric engine. In the same way, sounds and tones were added individually created by a synthesizer that together would form the AVAS composition. The synthesizer is an electronic musical instrument that generates sounds that can be altered until a desired timbre, tone or frequency is found. Every added sound was modified by filters, envelopes and low-frequency oscillators to generate a congruent auditory atmosphere, adding also effects to the sound surrounding sound. Combining different synthesizer sounds makes it possible to create a more striking and complex sound. This process is called layering and it was used with the synth pads selected for the project, which are sustained tones that intend to enliven sound [42].

Layer 1: Grand Pad

In figure 48, the filter that was used for the main sound is shown. Here, it can be seen that at low frequencies, 500Hz and 1kHz approximately, the audio filter boosts the synth sound that amplify the treble effect and reducing the low frequency content. On the other hand, at high frequencies, 5kHz approx., the audio filter cut these ranges attenuating the audio to decrease the high frequency content and increasing the bass effect. This Pad called Grand is the one that could be consider as the base of the final sound as it is the prominent sound that is heart at the background and gives the instantaneous idea that it is an electric vehicle.

Figure 48: Audio filter used in AVAS design.

Figures 49, 50 and 51 correspondes to the set of features that were established for this main sound in the final concept. They show different aspects such as pulse rate and amount that refers to the frequency and intensity of the pulsations within the sound in figure 49. In figure 50, highlights time of attack, decay, and peak that refers to the the aggressiveness with which the sound frequency changes when the vehicle accelerates. Figure 51, demonstrates the reverberation feature of the sound which simulates the reflection of sound waves within an acoustic space, adding depth, dimension, and realism to audio.

Figure 49: Pad features for the Grand sound.

Figure 50: Operator features for the Gran sound.

Figure 51: Reverb feature for the Grand sound

Layer 2: Hot Wobble

The second remarkable layer is the corresponding to the wobble sound which aggregates the futuristic or spatial effect. As well as the previous sound, it was obtain modulating a synthesizer sound which is shown in figure 52 with a low frequency oscillator. This controls the parameters of the sound such as the filter cutoff frequency or oscillator pitch. This modulation imparts the characteristic wobbling movement to the sound.

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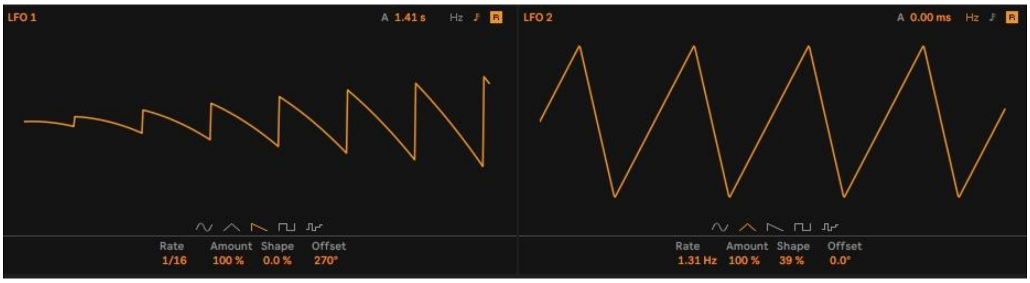

Figure 52: Low frequency oscillators for Wobble sound

Layer 3: Riser – White noise

The third layer worth mentioning is the riser effect with is created to excite the listener as it indicates the vehicle acceleration. This effect makes the sound increase gradually in intensity from a low state to give the sense of motion. In figure 53 it can be seen the configuration set for the riser which involves the modulation of the pitch and filter cutoff frequency. The steady rise of the pitch creates the upwards motion sensation and the filter reveals gradually more frequency content from the sound.

Figure 53: Riser feature configuration

Figure 54: Echo effect for the raiser feature

To create a complex and evolving riser effect it was also added white noise to the set of sounds which texturizers the audio. The configuration of the white noise can be seen in figure 54, where the most remarkable aspects are the low frequency oscillator, the frequency filter and the decay of the echo effect added to it.

Layer 4: Matrix V12 Synth

Finally, a fourth noticeable layer was added which is the one that highlights the bass of the final sound. This effect generates a great impression on the driver when driving because it makes the vehicle appear powerful. In the pedestrian it also attracts the attention when the vehicle is approaching because it marks presence and makes it noticeable as a big engine car. The set of configurations for this layer is shown in figure 55.

Figure 55: Configuration of the synth for the motor bass effect

With all the layers described above and the effects added to the sounds, it was possible to create a sound that generated a luxurious, futuristic, and sporty impression, which was desired from the beginning.

5.2. Sound Analysis

In the same way in which the Jury test sounds were analyzed, the sound created by own authorship was analyzed to verify that the results are consistent with what has been previously mentioned in the design and with the current AVAS references. the figures presented below are intended to show how the sound is structured in terms of harmonic content, 1/3 octave bands and prominence levels.

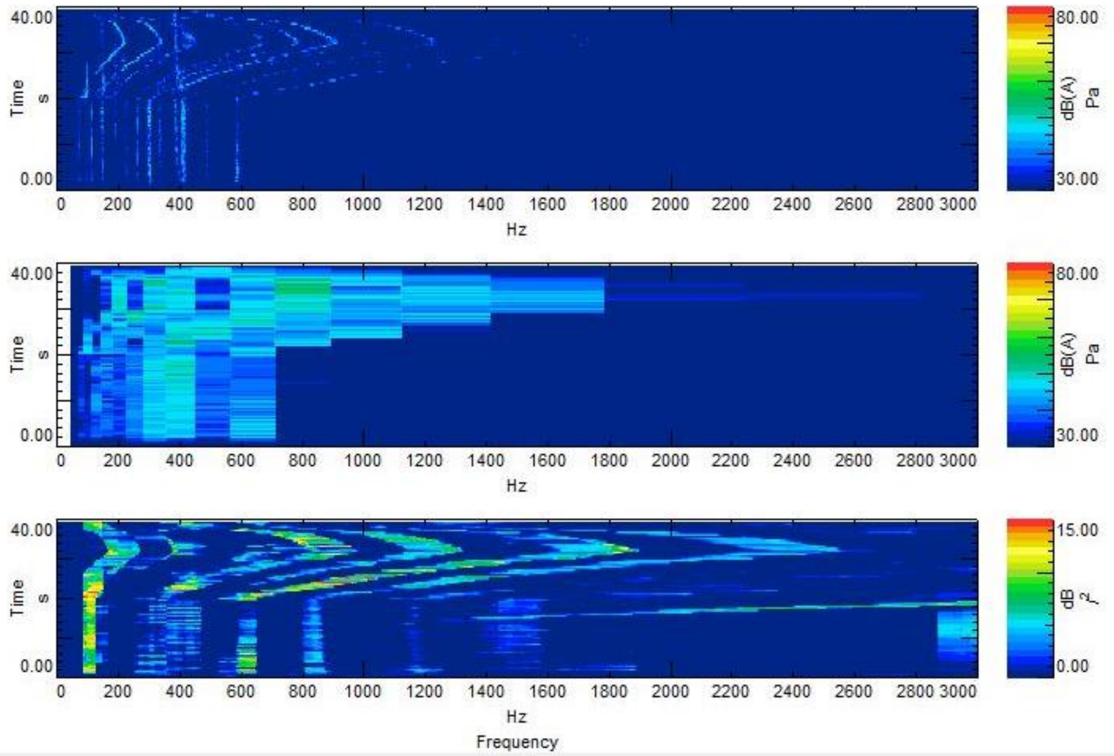

Figure 56: Sound analysis in the common dB dynamics: Harmonic content, 1/3 octave bands, prominence ratio

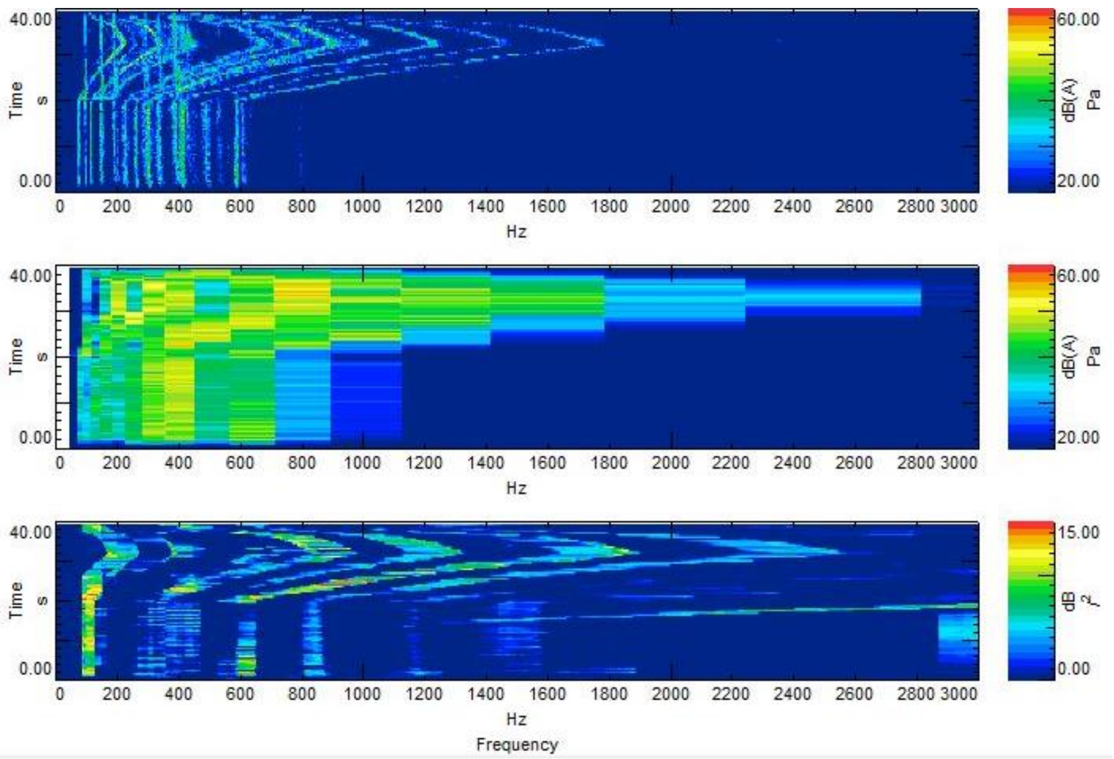

Figure 57: Sound analysis in low dB dynamics: Harmonic content, 1/3 octave bands, and prominence ratio.

Following the standards from the analysis made to the Fiat 500e, Hyundai IONIQ, Mustang Mach E, and Nissan Leaf Canto, the sound pressure levels of reference is in the range of 30 to 80dB. However, in this case as it is shown in Figure 56, the order level seems a little low for the dynamics in these dBs. This is because designing the sound in the studio with an acoustically isolated environment and professional speakers gives a different perception than that generated by the EV speakers in an open street. It can be considered that these dB levels can be modified to the appropriate levels for circulation in the vehicle's acoustic system. Nevertheless, figure 57 takes into account a shorter dB ranges from 20 to 60dB where a better appreciation of the content can be observed. The resulting sound sample for analysis has a duration of 40 seconds and is designed so that the first 20 seconds of a sound of the EV in static and the last 20 seconds of the vehicle accelerating.

In the first graph of figure 57 the harmonics content is shown. This demonstrates that the sound is rich in main harmonics modulated by the sidebands. These harmonics are in the low frequency range when the sound corresponds to the vehicle being stationary and increase to mid-range frequencies when the vehicle is supposed to be moving. The third graph of figure 57 illustrates the prominence ratio that corresponds to the principal harmonics that were designed to be modulated. It can be seen that frequencies from approximately 160 Hz to 2400 Hz are covered by these harmonics which indicates that a large part of the frequencies mentioned in the regulations about the 1/3 octave bands were occupied. At the same time, this allows to recognize that 1/3 octave bands have been exited almost by the same level of energy. This makes the increase in frequencies when the sound changes due to acceleration to be heard even, compact and with a more reliable engine appearance.

With the help of the second graph in Figure 57 it is possible to mention that the modulations in static conditions, which are at low frequency, give a more futuristic and luxurious aspect. This is because the background noise observed at low frequencies act as fillers to give an impression of a subtle but sophisticated sound. During the run-up, after 20s, the modulations progress from low to middle frequency bands increasing the sporty character while maintaining a futuristic touch. At the start of acceleration, the sound is designed with low tones that are familiar to the sounds usually heard in combustion vehicles. However, as acceleration progresses, the sound becomes sportier than the other characteristics. This was thought this way since the Tesla Model 3 gives an image of being a fast vehicle and high speeds are related to sports cars. Thus, at first impression the sound of the designed AVAS could be thought of as a normal EV at low speeds, but once it starts accelerating it makes a statement and draws attention to itself as an iconic car. In this way, it is demonstrated that aspects desired for this AVAS at the beginning of the design are achieved in the final result.

6. Economic Assessment

All the engineering work that is behind the study and creation of the AVAS of an EV involves multiple personnel and activities that represent an important budged to be considered. From the analysis of the Jury test that works as a reference for the design of a new AVAS to the final equalization of the sound to be used in the vehicle must be covered economically. To have an approximate idea of how much money is required for this project to be carried out in real life, the estimation of expenses is detailed below. It is important to mention that this is based on what has been involved in the presented project and that there could be aspects not considered due to unknowledge or inexperience in an automotive project applied in real life.

- **Total hours** used in the Project (based in academic credits) considering that every hour has a considerably fair payment: 360h x 15 €/h = **5400€**

- **Jury test**: To carry out a Jury test in a more professional way, the following expenses must be considered.

  - In the most convenient case of having 30 jurors and the test is divided into 3 groups of 10 jurors, it is needed to get 10 good quality headphones. Thus, 10 x 120€ = **1200€** [43].

  - A proper Jury test must include sounds recorded exclusively for that case in a controlled acoustic environment. For this, it is necessary to get a single microphone capable of 1/2″ precision measurement which costs **825€** [44].

  - The software to conduct the Jury test and analyze the obtained results is considered to be the LMS Test.Lab from SIEMENS. Its license for use costs approximately **1650€** [45]. *Note: the exact price was not available but there are courses at the mentioned price that allows the use of the software and its tools.*

- **Recording Studio rent**: The total of hours used for the AVAS design in the studio was approximately 36h (3h x 4 days per week x 3 weeks). Renting a studio for acoustic production reaches a price of 165€/3h [46]. This is, 165€ x 12 = **1980€**

- **Acoustic engineer**: To produce the AVAS sound it is necessary to count with an expert that controls all the acoustic topics. In that sense, contracting an acoustic engineer is required to obtain a proper sound valid to be used. For the same 36h used in the studio, an acoustic engineer earns around 20€/hour = **720€** [47].

- **Sound analysis:** In case of another software is needed to analyze how the AVAS sounds are structured, to present results about their frequencies, octave bands, sharpness, or roughness, the expenses increase. There are some software's commonly used in the automotive industry apart from the one by Siemens. For example, the software called O-Solution from Onosokki or the 'OROS' software are available in the market. Still their price depends on the required contract with the company, or the license type needed. For this case, exact price was not able to be found.

- **Homologation tests**: This expense depends on the contract that every car manufacturer has with the company responsible for the homologation tests. In Spain, the valid company for these tests is IDIADA App+ located in Tarragona.

The total of expenses for this prevision is *11775€* for which if the corresponding IVA is included (21 %) it reaches to **14247,75 euros**. Including the expenses of the homologation tests it could easily overcome the price of 20000 euros.

It can be said that being the automotive world in which millions of euros are spent on i+D for technological changes in the latest vehicle models, this price is acceptable and could even be considered an estimate that falls short. It must be considered that the innovations that are made in modern vehicles are implemented and maintained for several years, for which these costs are profitable in the final sales prices of EVs.

7. Conclusions

The scope of this work is oriented towards the study of AVAS in electric vehicles, which have been implemented to increase pedestrian safety when driving. Due to the eminent risk that the low sound levels of EVs can represent when alerting a pedestrian of their approach, automotive brands have designed several models of AVAS implemented in their vehicles. As mentioned in the initial sections, the specific objectives of the work aim to open the field of information available on these sounds and to study the effects they have had on society today. 12 different car AVAS sounds found in the current market were analyzed and put to the criterion of several jurors, who have decided how pleasant they are to their ears and what characteristics they perceive of them. With this, it was possible to know if the identity value that the brands seek to acquire with these sounds are respected or if, on the contrary, they are generating rejection in people.

26 jurors participated in the Jury test that analyzes the sound quality of these AVAS and from them results were extracted on the perspectives generated and a score was given to 6 characteristics established to be evaluated. The sound was rated in terms of luxury, sport, attractive, futurist, potent and reliable, in order to know how much of these aspects the sound is perceived. From these results it was surprising that the Jaguar PACE I was rated as the most luxurious sound, the BMW i4E as the sportiest sound, the Nissan Leaf Canto as the most attractive, the KIA EV as the most futuristic sound and again the BMW i4E as the sound that generates the greatest impression of potence.

For a better understanding of the reasons why each of these AVAS sounds generated these impressions or perspectives in the jurors, an acoustic analysis of the 12 sound samples was performed. In this, results were obtained about the number of harmonic tones that were found in the sounds, to which frequencies these tones and harmonics corresponded, how the white noise was distributed in the sound to give a greater filling effect, as well as the roughness and sharpness of the sounds, which is related to the amount of high and low frequencies. It was possible to group in 3 different sets the sounds that presented similar characteristics according to the jurors' scores. These were, Jaguar Pace I (sound sample 1), BMW i4E, KIA EV6 (sound sample 1 & 2) in a group that showed a distributed voting for the 6 characteristics mentioned. That is, each of them had a considerably high score and no specific one stood out as shown in Figure 29. The next group consisted of Porsche Taycan, Jaguar PACE I (sound sample 2) and Audi E-tron GT, which showed a greater tendency for powerful and sporty AVAS sounds. These showed higher scores in these characteristics while in the other characteristics they shared a common score at low levels. Finally, one group was found to have unique tendencies. That is, the AVAS sound of the Hyundai IONIQ, Fiat 500e, Nissan Leaf Canto, and Mustang

Mach E showed higher scores in distinct characteristics and an odd distribution in the remaining score as shown in Figure 42. Therefore, it was analyzed how the sound structure and composition of each of the sounds could be correlated so that these resulting groups were sharing scoring trends.

As the last part of the work, it was decided to involve a little more the design and acoustic production area with the proposal of an AVAS model for the Tesla Model 3. After 3 weeks of exploration of sounds and different combinations it was managed to get an interesting proposal that sought to highlight the characteristics of a futuristic, sporty and luxurious sound. This based on the image that the brand has wanted to give with its car model for years and seeking to match the recognition and prestige that this vehicle has achieved. Likewise, an acoustic analysis of the sound design was carried out to detail how it is composed and structured, in terms of frequencies, harmonics, and noise.

With this, it is possible to conclude that the objectives of the work have been covered and developed successfully. Valuable information has been obtained about the effects that the adoption of electric cars in today's world is having in terms of new sounds and impressions. Clearly, each person's perspective on different AVAS sounds varies and there are no invalid opinions. However, as in the world of fashion or consumer technology, there are brands that manage to set a trend in their models and AVAS is not exempt from this. From models with symphony-like sounds to models that simulate spacecraft or rockets, there is an option for everyone and that is something to value when purchasing an electric vehicle. The important thing in this is to comply with the regulations imposed so that the frequencies and dBs that have the sounds achieve their main objective, to safeguard the life and safety of pedestrians and people inside the vehicle.

8. Further research

The scope of the present work has involved the study of what is currently found in the electric vehicle market in terms of AVAS and social acceptance. However, as it is a topic with few years of development it needs to be further investigated to be increase positive results both in terms of pedestrian safety and consumer appreciation. This will allow to increase the motivation to opt for an electric vehicle over a hybrid or combustion one.

Among the topics to be developed is the combination of sounds that could generate a more positive impression on consumers. Knowing what sound characteristics people expect to hear from a specific vehicle and a specific segment is also of interest. Similarly, the possibility of incorporating more enveloping sounds to the AVAS that vary depending on the angle at which they are listened to could be studied, as long as they comply with the imposed regulations.

Nevertheless, it is impossible for a sound to please everyone, so developing a system in which the driver himself can design his AVAS sound from the dashboard of his car is an interesting topic. All these aspects can be investigated and developed in future work or university projects.

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