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Comprehensive Automotive Active Sound Design

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ABSTRACT
In the past years Active Sound Design (ASD) has found its entrance into the automotive field as an efficient means to add some sporty sound components to vehicles with combustion engines. Nowadays, with the growing market share of hybrid and battery electric vehicles and the legal requirement to add artificial exterior sound with Acoustic Vehicle Alert Systems (AVAS), wider applications scenarios open-up. These new scenarios require new skills, processes and tools to efficiently define, generate and implement these new types of sounds. Active Sound technologies allow a stringent implementation of a Brand Sound for the Auto OEMs. This stringent implementation requires a corresponding Brand Sound approach to define this concept into various vehicle sounds. Today's applications of Active Sound Design require a flexible and comprehensive generation of different sound types for combustion and electric powertrain driven vehicles, so that the corresponding toolchain must be flexible, easy to edit, and of specific suitability for automotive applications. A major prerequisite is that the generated sounds are authentic, even though they are completely synthesized and may have a new unusual character. Several specific sound generation features are required to achieve this, and an efficient tuning to the dynamic vehicle parameters is mandatory.

1 INTRODUCTION
The Automotive market is evolving a lot in the past years, and the manufacturers are being confronted with emissions legislations forcing them to reduce the amount of CO2 emitted. Therefore, some new technologies are in place or still being developed in order to achieve these new goals.
For the internal combustion engine (ICE) driven vehicles, engine downsizing has been the most common practice to reduce the emissions. These modifications can play an important role during the vehicle development, specially to the NVH attribute.
In parallel, many manufacturers are quickly moving from ICE vehicles to hybrids or fully electric powertrain vehicles. These vehicles have low or no emissions but bring a lot of complexity to the vehicle NVH development as completely new sounds are present in these vehicles.

The manufacturers can take advantage of these changes to not only think of reducing annoying sound sources but also to add sound to their vehicles in order to overcome some of these challenges.
This paper describes how active sounds can be applied to all kinds of vehicles to enhance their interior sound quality. It also discusses the application of active sound to exterior artificial sound generation for hybrid and electric vehicles, to comply with pedestrian safety regulations.

2 ACTIVE SOUND DESIGN TECHNOLOGY FOR AUTOMOTIVE APPLICATIONS

Active sound design (ASD) is a methodology that, in addition to functional sound, generates meaningful sounds to be replayed in the vehicle (internal or external) in order to improve interior sound quality (internal) and to ensure pedestrians' safety (external).
In ICE vehicles, due to acoustic treatments, the vehicle can become quieter and more comfortable and the downsizing of the powertrain can negatively impact the interior sound. Reducing the number of cylinders has a direct impact on the noise signature of the car. Going from an 8-cylinder engine to a 4 cylinder (or smaller) completely changes the audible driving experience and brand sound. ASD can be used in such cases to restore the original brand sound of the 8-cylinder engine by synthesizing additional engine orders and layering them on top of the natural sound of the 4-cylinder engine. ASD techniques are applied in such vehicles to overcome the bad sound signature in different driving scenarios[1]. In addition, ASD creates the opportunity to make the engine sound richer and fuller, improving the driving experience of the vehicle.
In hybrid and fully electric vehicles, it is also mandatory to emit an exterior sound at low speeds for alerting pedestrian and other "weaker" traffic participants about the presence / approaching of the vehicle, with the Acoustic Vehicle Alerting System (AVAS). The minimum noise level of the AVAS system is strictly regulated, but the actual characteristics of the sound is not. As it is heard by pedestrians and others near the vehicle (and possibly also the vehicle occupants) the AVAS sound can have a large impact on the brand sound of the vehicle. Therefore, it is very critical to design a sound with the right characteristics.
Full electric vehicles are very silent at low speeds and provide very little noise feedback to the driver. At higher speeds, noise sources such as wind noise and road noise no longer benefit from masking by the combustion engine. Here, ASD can be used to enhance interior sound to compensate for the lack of acoustic feedback and emotion to the passengers. Secondly, new noise sources that have become apparent, can be partially masked again by enhancing the sound with ASD and at the same time provide the right driving experience. This allows the driver to have the perception of driving a sporty car just by playing the right active sound over the speaker system[2].
There are already several vehicles on the market with artificial interior sounds and also with AVAS systems in place as they are becoming mandatory in different parts of the world.

Several ASD techniques can be applied for different types of vehicles. Together they enable OEMs to take the great opportunity to design a sound that represents their brands signature for the next decades. Figure 1 illustrates the mandatory and optional ASD challenges for both exterior and interior sounds.

ASD sounds easier in theory than in practice. But what exactly should a vehicle sound like? How should the sound change for different driving scenarios and change for different vehicle speeds or loads? How to generate very creative authentic sound models that improve the driving experience without being perceived as artificial? There are many aspects to consider and many tests that need to be done.

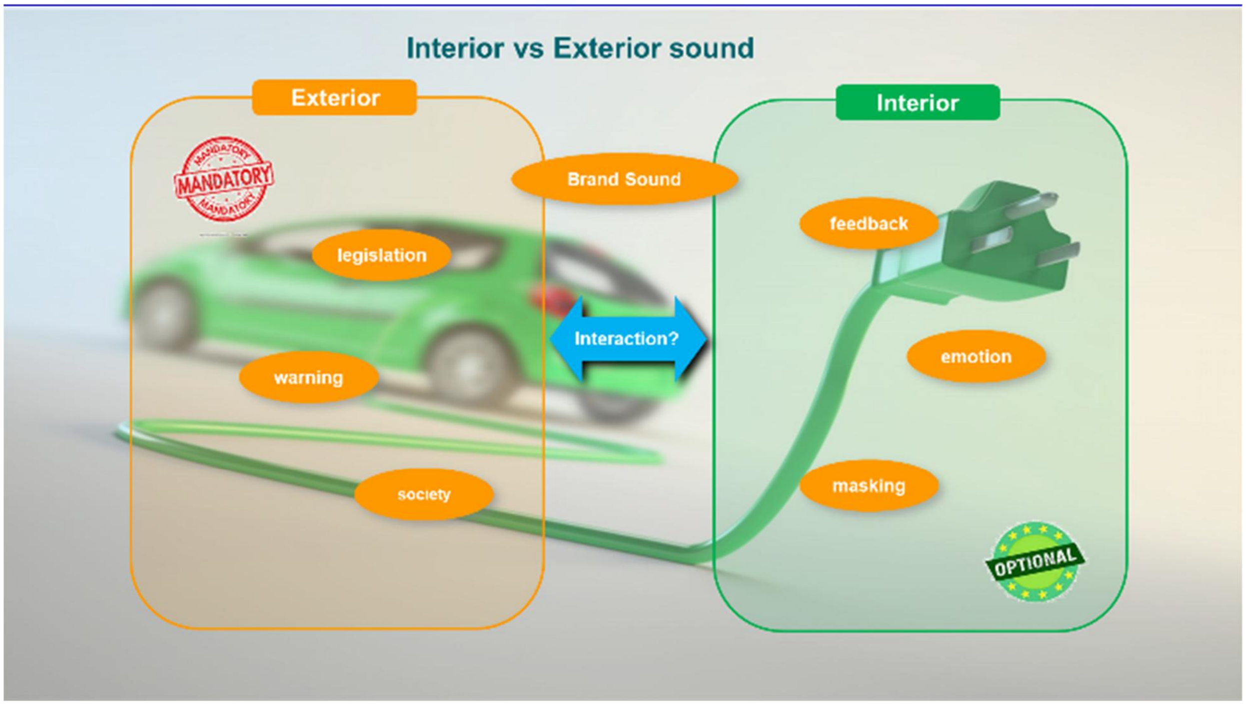

Figure 1: *Interior vs Exterior vehicle sound*

3 CREATING A CONSISTENT SOUND SCENARIO WITH ACTIVE SOUND DESIGN

When dealing with vehicle sounds, one needs not only to manage the sound of individual components, but also to ensure that the resulting sound is pleasant when all the components are interacting with each other at once.

There are several contributors to the interior vehicle sound. When we consider all sound sources in the vehicle, there are big changes from ICE driven vehicles to EV vehicles. In the Figure 2(a) one can see that for ICE, engine noise dominates in low speeds while road noise becomes more important when speed increases until the moment where wind noise is the dominating noise.

Figure 2(b) shows that new noise sources, before masked by the ICE noise are now audible in electric vehicles. At higher speeds road noise and the wind noise become much more important and the biggest noise contributors. All the other auxiliary systems and components like the HVAC system or battery cooling systems are also audible inside the vehicle[3].

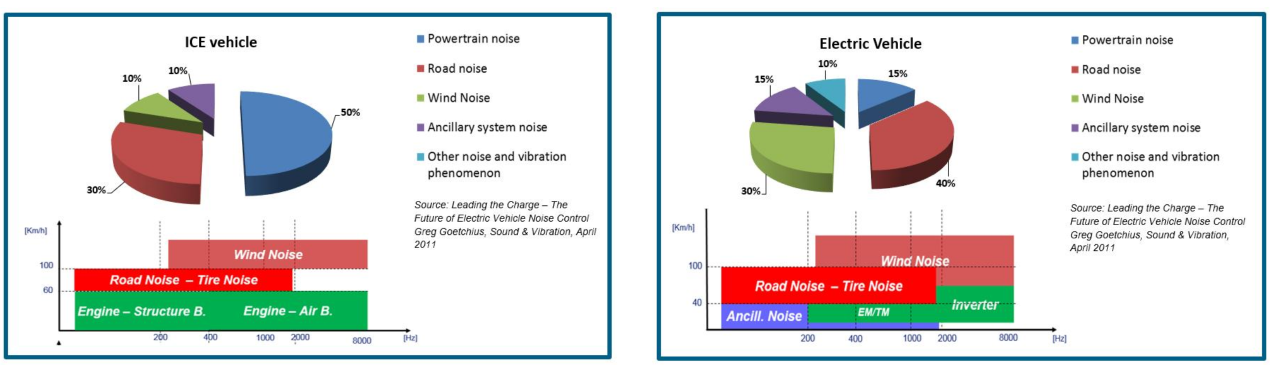

Figure 2*: (a) Main noise contributors per frequency range and speed in ICE driven vehicles. (b) Main noise contributors per frequency range and speed in electric vehicles*

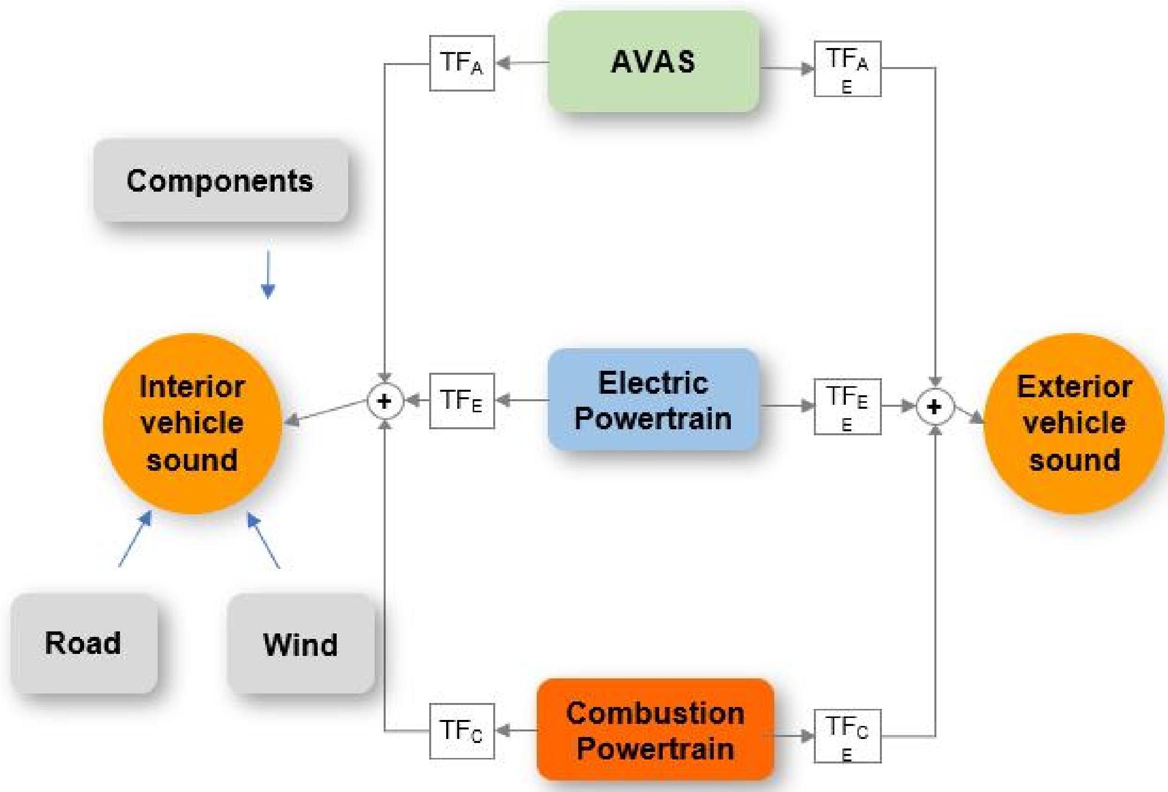

Figure 3: *Different sound contributors for ICE vehicle, hybrid and fully electric vehicle*

The exterior vehicle sound is a combination of powertrain noise (ICE or E-motor), road noise (mid-high speed), and for xEV the AVAS (low-speeds) system. This is also important as maximum (ICE) and minimum noise standards (EVs) are in place and OEMs need to comply to these in order to sell their cars in the market. Figure 3 shows a breakdown of these different internal and exterior noise sources, and the paths over which they travel to the receivers

When designing active sounds for a vehicle, all these noise sources need to be considered. The combination of these sounds with the artificially added sound is a big concern during the design. Therefore, validation in the target vehicle (or on vehicle simulators) is of extreme importance and allows final tuning of the sound.
A-OEMs traditionally have the strategy to reduce the interior sound to a minimum by optimizing sources and transfer paths. Due to this approach, the outcome usually is an increase of weight and costs with a negative economic impact and vehicle dynamics.
Active Sound Design offers an alternative opportunity. In this approach, ASD is used to create a consistent sound scenario and is capable to develop and deploy a stringent brand sound strategy.

3.1 Process and methodologies for designing active sounds

There is a step by step process to go through the design of active sounds. When developing the sound models, it's first of all important to think about which vehicle parameters should influence the generated sounds. Typical examples are vehicle or engine speed but also throttle or vehicle load. Those parameters will be the input of the sound model.

In the early stages of development, when no prototypes are available, these input parameters could come from synthetic data or by manual input methods. However, at later stages the sound models can be tested on a vehicle sound simulator or in vehicle prototypes. This stage-wise ability to craft and refine sound models is crucial. Often, a sound model created at the design table may no longer be suitable once it is evaluated in a vehicle with real vehicle-driver interaction. At the later stages of development, real-time interaction with the vehicle CAN-bus is required to access the parameters that influence the active sound. It is critical to be able to test and tune different sound models in real-time on the actual vehicle. Once the models are final, they will need to be transferred towards the production vehicles, which will require implementation on the DSP of the AVAS system or the vehicle sound systems.
How to create active sounds from the vehicle parameters? The examples in this paper used for the design of the active sounds, make use of two main different methods: Order-based synthesis and Granular synthesis.

Granular synthesis
Granular synthesis is a sound sampling method originating from music industry in the 1970's, and first described by Xenakis[4]. It is a sound synthesis method by which an original sound sample is broken down into very short time segments called grains, that are then reorganized to compose a new sound. The grains can be as short as 10ms. This work has been extended into computer-based real-time synthesis methods by Truax[5] making it more available to musicians. New sounds are composed by synthesizing grains with a certain window to ensure smooth transitions. In doing so, composers will change pitch, duration, and position of grain in the sample, thereby creating original, rich and lively sounds that will reflect more or less of their base sample.
The application of granular synthesis to automotive vehicle sound requires that these composers' parameters are now tied to vehicle dynamics parameters[6]. While the vehicle cycles through its operational condition, the granular synthesis changes the pitch of the sound in function of speed or torque.
The original sound sample used as input for the granular synthesis is the starting point of the design process. This sound usually already contains some character that supports the direction of the overall brand sound strategy. However, the final active sounds will be much more influenced by the fine tuning of the grain parameters such as grain location, duration, overlap, pitch, etc. These parameters can be mapped across various vehicle signals, and can be modified as a function of the current vehicle state. As such, granular synthesis allows to create very innovative and creative sounds that deviate from traditional order-based sounds present in classical vehicle NVH sounds.

Order-based synthesis
Order-based synthesis is a technique to synthesize a combustion engine sound based on its physical properties. Combustion based sounds usually are low frequency centered, consisting of a combination of lower engine orders[7]. Under load condition, a significant roughness contribution can be observed. The character strongly depends on the number of cylinders defining the main order. Synthesis is done by modeling engine orders in function of engine speed, where the frequency of the sound is equal to the order number multiplied by the rpm/60. See Janssens *et al*[8] for an application in vehicle sound synthesis. The phase relationships between the orders can be taken from measured data or can be randomized. For a specific engine speed, the synthesis engine will generate sine tones for each order of the specific frequency, amplitude, and phase. Modeling more engine orders will make the synthesis more natural and refined as it will be able to invoke roughness between the orders, but it also puts a higher load on the synthesis engine. This technique

has been applied for years in ICE vehicles to keep their good sound perception and to increase their interior sound quality. Order synthesis process needs to be followed by some steps to assure a final sound satisfaction. Figure 4(b) illustrates the full process applied.

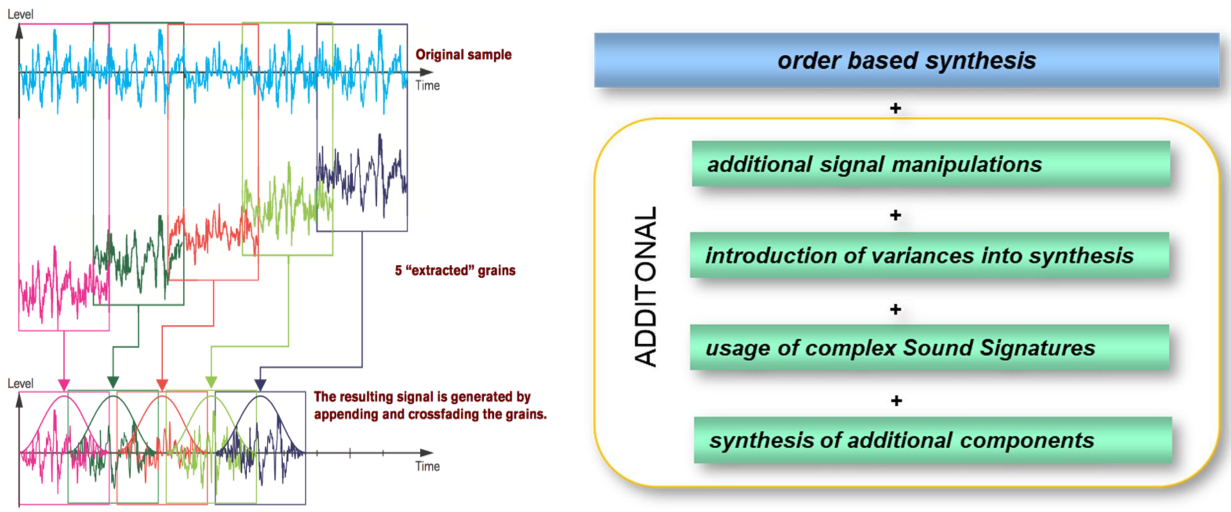

Figure 4: *(a) Granular synthesis in a nutshell – reconstructing the sounds by synthesizing small grains of an original sample. (b) Order synthesis process with additional steps*

3.2 Enhancing interior combustion engine sound with Active Sound Design

The main reason for using ASD in ICE vehicles is that the signature of downsized engines changes significantly and, in many cases, no longer represents the desired vehicle brand sounds. A 3-cylinder engine doesn't sound like a 4-cylinder engine, and certainly not like an 8-cylinder engine. Main contributors of the sound are the so-called engine orders, which are directly influenced by the number of cylinders firing per combustion cycle. The roughness of the sound increases with the load and this gives the correct impression for the driver. When the number of cylinders in the engine is reduced, this relationship between load and sound is not as evident as in engines with more cylinders.

The most used ASD technique for ICE vehicles is order-based synthesis. This technique is implemented by synthesizing artificial engine orders – the ones that are missing for that specific engine – to make it sound like a bigger or more powerful engine.

This method is extremely efficient and provides real-time sound feedback making the synthesis very straightforward. One can achieve more complex and vivid sounds with a less complex sound parameter structure. See Bodden[9] and Belschner[10].

Order synthesis also allows to do additional sound manipulations which gives the possibility of direct parametrization of more complex required perceptions. One can add noise variances into the synthesis increasing the liveliness and naturalness of the final sound.

This allows to use more complex sound signatures which contributes to a better harmonization of sound and gives the possibility to generate a powerful brand identity. Lastly, synthesizing additional cylinders addresses emotions like giving a "sport" or a "race" feeling during the driving experience.

Figure 5(a) shows the frequency spectrum maps of a vehicle that originally has a 3-cylinder engine, and by using ASD with order synthesis, converted into a 4- and 8-cylinder vehicle.

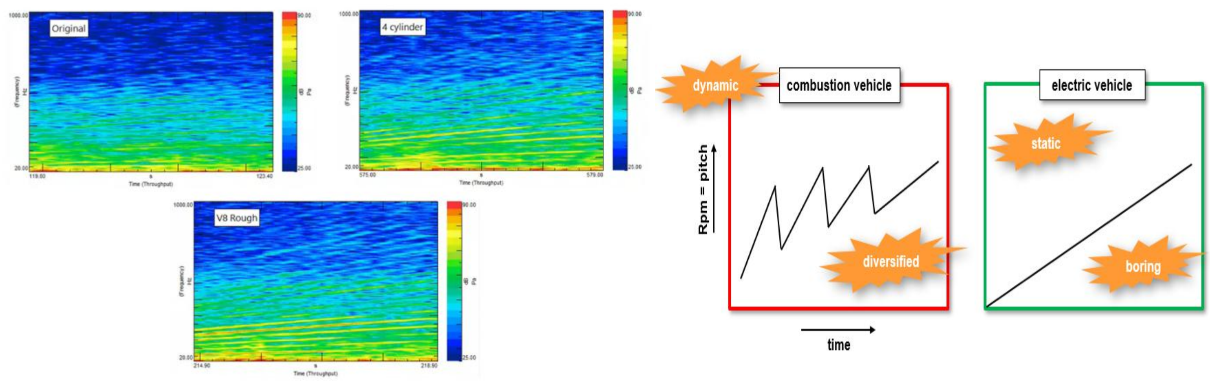

Figure 5: *(a) Order synthesis applied to a 3-cylinder vehicle, perceiving it as a 4- or 8-cylinder engine. (b) Pitch profile of ICE (left) vs EV (right) and their sound perceptions*

The order-based synthesis technique is proven to be very efficient for ICE vehicles and since engine downsizing is still a trend these systems will remain present in the market. This technique is also applied to electrified powertrains, in applications where the OEMs want their EV to sound like ICE vehicles (i.e. sportive brands moving towards electrification).
One of the key aspects of a flexible and easy-to-edit toolchain is the possibility to use both techniques (order-based and sample-based) at the same time to design a unique sound.

3.3 Sample-based sound design applied to electrified powertrains

Hybrid and electric vehicles' novel and unique acoustic signatures require more advanced techniques to make them sound pleasant, and if desired, to mimic the sound and emotion of a traditional ICE vehicle. One key difference between traditional ICE powertrains and their electric counterparts is the transmission. Electric powertrains have a single gear, and their motor's rotational speeds have a linear relation to vehicle speed. This behavior can cause the driver to describe the experience as "static" and "boring" when compared to the RPM rise and fall of a traditional engine and transmission shifting gears (Figure 5(b)). This is one of the main motivations to use ASD in hybrids and EVs: restore this emotional response to driving the vehicle.

Granular synthesis is a sample-based technique generating rich and dense sounds from very short and simple samples. Every variation in the selection of the grain creates very different sensations, which makes this technique very advanced, and rich with possibilities. It can be used to design both exterior AVAS sounds as well as interior sounds. See further details in Bodden[7]. In complicated scenarios, as in the transitions from ICE to electric motor in hybrids vehicles, it can overcome acoustic issues by adding sounds based on vehicle parameters.
Granular synthesis can also be applied in parallel with other synthesis methods. In Simcenter Testlab Sound Designer, granular synthesis is applied in multiple layers, meaning that the final sound to the driver and occupants is a combination of three layers: Base layer, Torque Layer, and Shepard Layer.
As described in Figure 6, each layer is responsible for providing a group of perceptions to the final sound. The definition of each layer and how they are combined and mixed is an essential part of the design phase for achieving a high-quality sound. For hybrid vehicles, this scenario can be even more complex as the design is a combination of order-based synthesis (ICE engine) and sample-based synthesis (EV mode) used in parallel.

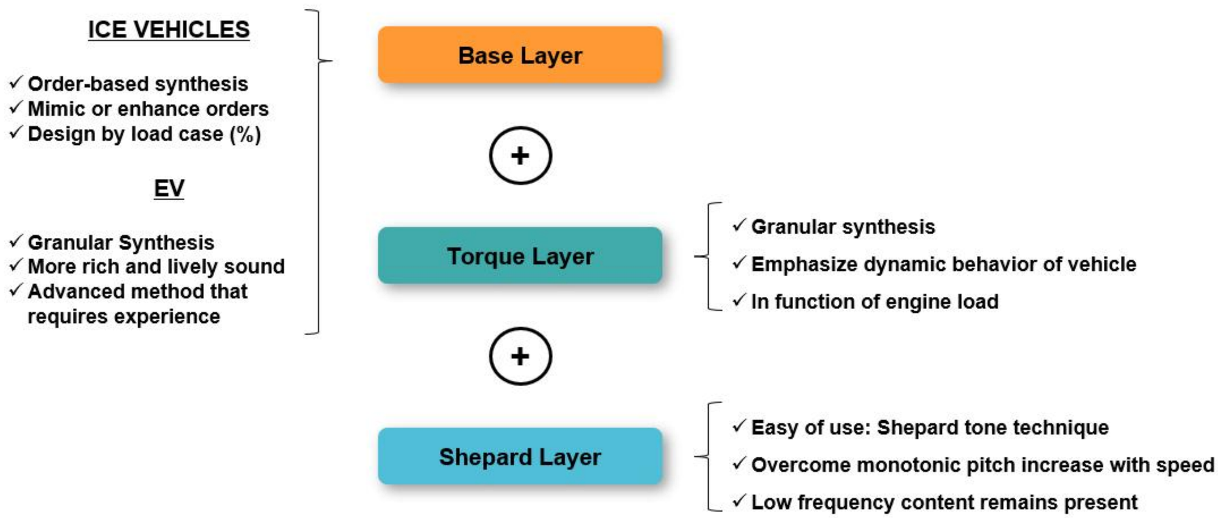

Figure 6: *Three layers used for sound design and their main functions*

The Base layer is responsible for the main overall character of the sound design. It is the foundation onto which the other layers are added under specific driving situations. The Torque layer is mixed on top of the Base layer when the driver demands more output from the vehicle, usually based on accelerator pedal position. This layer traditionally changes the character of the sound to provide the impression of power, to replace the traditional feedback of a revving IC engine. The final layer, the Shepard Layer, is used to overcome monotonic pitch increase with increasing vehicle speed. This layer uses the known "shepard tone" technique to ensure some low-frequency content in the sound remains in the augmented sound, even at higher speeds.
Once the individual synthesis layers have been defined and mapped to the appropriate vehicle parameters, the next step is to enter a final phase of integration and tuning. Normally this is done directly in the vehicle, as the sound design needs to be validated and tuned when acting together with the other interior sounds like road noise, wind noise and auxiliary sounds.
When this multi-layer synthesis approach is applied in a fully electric vehicle, it produces results such as shown in Figure 7. The figure shows a vehicle speed runup 0-70km/h followed by a rundown. The interior sound was enhanced with order-based synthesis as well granular synthesis, and the Shepard Layer as compliment. The completeness of the Testlab Sound Designer toolchain makes it possible to bring the active sound design to a high level and make an EV vehicle sound completely different.

3.4 Exterior warning sounds to comply with legal requirements

All electric and hybrid vehicles in the market will need to comply with pass-by noise standards. These regulations describe minimum noise level for warning sound in low-speeds (< 30 km/h) and standstill conditions to warn pedestrians that a vehicle is nearby, or approaching. This is necessary because of the very low noise emissions intrinsic to these vehicles. The main tests are UN ECE Regulation 138 for Europe and other ECE regions[11], and FMVSS 141 for the US[12]. During these tests, the AVAS needs to be operational.
Before implementing the AVAS sound in the vehicle the OEMs need to develop this sound and ASD is commonly used. Granular synthesis is an advanced method and it's normally selected to develop these sounds[6]. Figure 8(a) shows the different steps of the process.

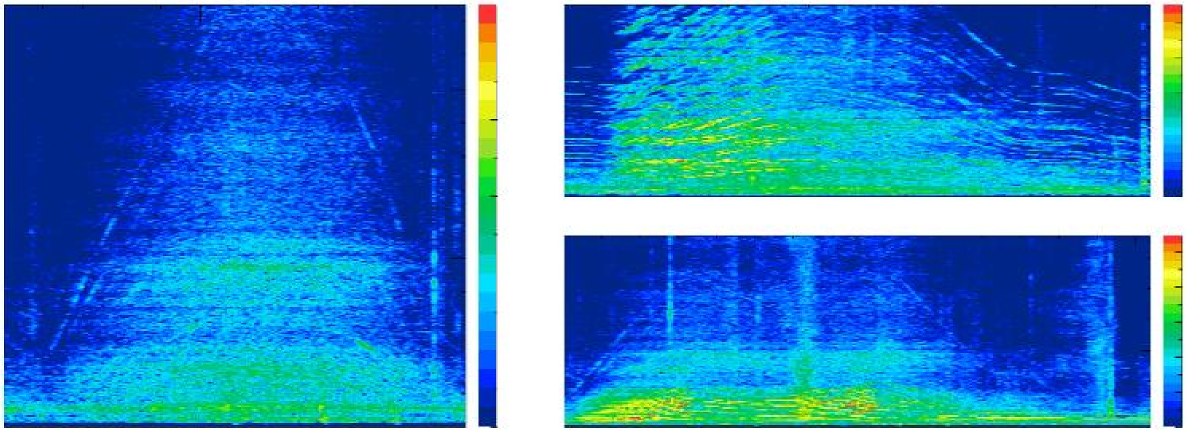

Figure 7: *Active Sound Design example in a fully electric vehicle. Frequency-map of the original sound (left), granular synthesis (right-top) and order synthesis (right-bottom)*

The AVAS sound is also typically acting in parallel with other sounds on the exterior of the vehicle and may also be perceived by occupants inside the vehicle. The integration step of physically mounting a loudspeaker behind the front bumper requires taking the transfer functions from the speaker to the side of the road into account. Also, the sound quality inside the vehicle is investigated and lastly the legal evaluation (based in local regulations) is considered. Therefore, AVAS sound design and implementation requires a flexible set of tools allowing both the design and the full in-vehicle validation and tuning process.
The process of validation of the designed AVAS sound against different regulations (region dependent) in the tool is illustrated in Figure 8(b). Differently from standard pass-by noise regulations, AVAS regulations check the frequency content of the warning sound.
Unlike ASD for augmentation of the interior sound of the vehicle, AVAS is not optional to the manufacturers, which increases its importance. Also, as the AVAS sound will be heard outside the vehicle by pedestrians and passers-by, the chosen AVAS sound for a given vehicle is literally broadcasting the vehicle brand image to others constantly. This represents a big opportunity for OEMs to craft the image and brand values they want people to have for a certain vehicle brand.

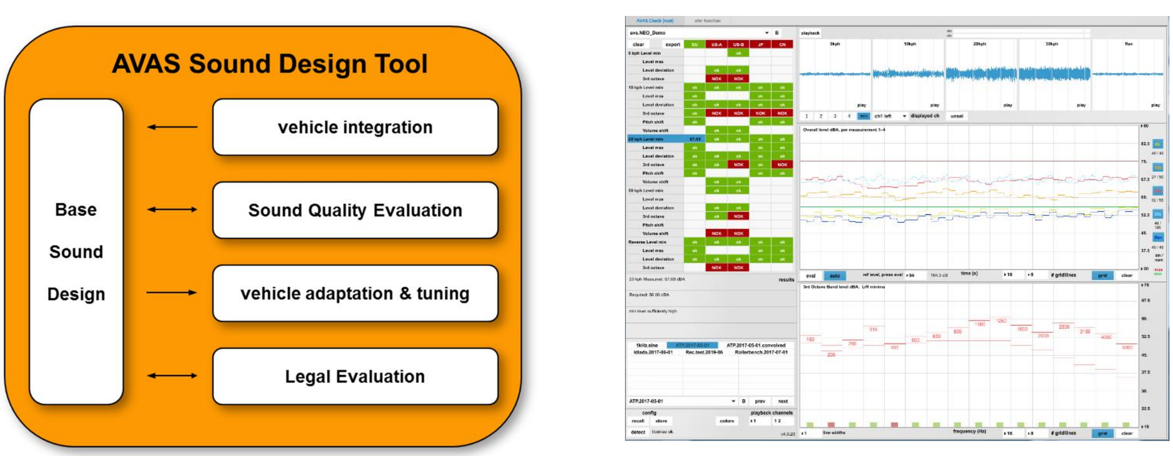

Figure 8: *(a) AVAS implementation. (b) AVAS pre-check against different regulations*

4 CONCLUSION

ASD is not new in the automotive market. However, with the electrification trend and the downsizing of ICE, it is becoming more relied upon to ensure good sound quality.
ASD techniques are normally implemented by type of vehicle powertrain like ICE, hybrids and electric vehicles. The techniques have historically been relegated to their particular application because of the nature of sounds already emitted by these vehicles. These restrictions need no longer apply.
In parallel with enhancing the interior sound of the vehicles, important legislation is in place around the world to ensure that vehicles equipped with electric powertrains emit a minimum amount of noise to ensure pedestrian safety. ASD can be used to craft these artificial exterior sounds (AVAS), and provide a unique opportunity for OEMs to establish the sound of their brand.
In order to achieve all these goals, an advanced ASD process is of extreme importance, taking into consideration the required sound perceptions and translating them to vehicle parameters like speed, torque and throttle.
A final step to make the process efficient and complete is the vehicle integration. A tuning process of the designed sound in the vehicle (or simulator) is important to take into consideration the audio system characteristics, in harmony with other sounds like road, wind and component noises.

ASD is not only making sure that any NVH annoyance will be masked with pleasant and well-controlled sounds. It is also an opportunity to all vehicle manufacturers to rethink and redesign their vehicle sound by defining the sensations that they want to provide to their customers.

5 REFERENCES

1. Bodden, M.; Belschner, T.: "Consistent Active Sound Generation Concept for Hybrid vehicles". *Proceedings of the Internoise 2019*, Madrid, Spain (2019)
2. Bodden, M.; Belschner, T.: "Principles of Active Sound Design for electric vehicles". *Proceedings of the Internoise 2016*, Hamburg, Germany, 1693-1697 (2016)
3. Goetchius G., "Leading the Charge – The Future of Electric Vehicle Noise Control", *Sound & Vibration/April 2011*.
4. Xenakis, Iannis (1971) *Formalized Music: Thought and Mathematics in Composition*. Bloomington and London: Indiana University Press
5. Truax, B. 1990 *Composing with Real-time Granular Sound' Perspectives of New Music*. USA: Hamilton Printing Company. 120-134
6. Bodden, M.; Belschner, T.: "Legal requirements and design of exterior sounds for electric vehicles". *18th Stuttgart International Symposium, Automotive and Engine Technology*, Volume 2, Springer Verlag, 2018, 111-122 (2018).
7. Bodden, M.; Belschner, T.: "Consistent Active Sound Generation Concept for Hybrid vehicles". *Proceedings of the Internoise 2019*, Madrid, Spain (2019)
8. K. Janssens, M. Adams, P. Van de Ponseele and L. Vallejos, The Integration of Experimental Models in a Real-time Virtual Car Sound Engineering Environment, *in Proceedings of the ISMA 2002 Conference*, 16-18 September, 2002, K.U.Leuven, Leuven (2002).
9. Bodden, M.; Belschner, T.: "Comprehensive Active Sound Design. Part 1: electric and combustion vehicles". *Proceedings of the Internoise 2014*, Melbourne, Australia (2014)
10. Belschner, T.; Bodden, M.: "Comprehensive Active Sound Design. Part 2: operational sounds and Brand Sound". *Proceedings of the Internoise 2014*, Melbourne, Australia (2014)
11. UN ECE Regulation 138, https://www.unece.org/trans/main/wp29/wp29regs121-140.html
12. Federal Motor Vehicle Safety Standards FMVSS 141, https://www.nhtsa.gov/document/tp-141-00-v8-draft