

Consistent Active Sound Generation Concept for Hybrid vehicles

Bodden, Markus¹
neosonic
Ursulastr. 21, D-45131 Essen, Germany

Belschner, Torsten²
neosonic
Markgrafenstraße 13, D-79115 Freiburg, Germany

ABSTRACT

Hybrid vehicles represent the most complex scenario for the interior vehicle sound composition, but seem to be rather unattended compared to the effort spent to optimize interior sounds of standard ICE vehicles. This scenario is further complicated by the legal requirement to equip HEV/PHEVs with a pedestrian warning system (AVAS). The driver faces inhomogeneous sound compositions of pure electric or combustions drive sounds, different combinations of both, plus with or without portions of the AVAS-sound audible in the interior. This leads to an inconsistent representation of the vehicle and puts strong pressure on standard NVH performance, which has to aim at reducing all different audible sound contributions to a minimum, resulting in high costs and increased weight. Active Sound Generation methods offer an elegant and cost-saving solution to overcome this problem, since they allow to implement a stringent sound concept. The different driving modes have to be presented in such a manner that they can still be recognized by the driver, but at the same time transitions have to be harmonized and the overall sound impression has to be homogenous and has to represent a unique vehicle.

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1. INTRODUCTION

Legislation forces automotive industries to reduce their vehicle fleet fuel consumption worldwide. An important means to achieve this aim is the electrification of the vehicle fleet. A part of that process will be achieved by an increasing number of Battery Electric Vehicles (BEV) and Hydrogen Fuel Cell Vehicles (FCV), but the tough targets will only be achieved with an increasing number of Hybrid or Plug-In Hybrid Electric Vehicles (HEV or PHEV). Research institutes estimate an increase of the share of hybrid vehicles on worldwide produced vehicles to 25% until 2023 [1].

¹ db@neosonic.eu

² tb@neosonic.eu

These vehicles establish a hybrid situation not only from the powertrain point of view, but also from the acoustic point of view. The electric powertrain and the combustion powertrain have completely different sound characters, and the different ways in which these different types of propulsions are combined create new and inconsistent sound scenarios. In order to combine the combustion and the electric engine in an efficient manner, different OEMs use various constellations of both engine types working together.

As a result, customers are confronted with unusual and variable acoustic scenarios. In order to achieve a targeted high Sound Quality this leads to very high passive NVH requirements following a conventional engineering approach, resulting in both, increased weight and costs.

In addition to these powertrain driven constraints regulations for pedestrian safety impose another acoustic burden on hybrid vehicles. Since hybrids belong to the group of silent vehicles, they will have to be equipped with an exterior pedestrian warning system, AVAS. These systems emit a generated sound in the speed range up to at least 30 (US) or 20 kph (all other main regions). The emitted sound has to meet specific legal requirements, basically consisting of minimal overall levels and third octave band levels (for details see e.g. [2]).

Depending on the NVH performance and the driving scenario (e.g., in car park, window open) the passengers will hear part of the AVAS sound in the interior, but only in the driving conditions where it is active. This additional AVAS sound might thus overlay another non-stringent sound component to the overall sound scenario and results in even tighter passive NVH requirements.

On the other hand, the AVAS sound opens a new opportunity to overcome the hybrid vehicle sound issues – the usage of Active Sound Design. While active sound generation methods are well established and commonly used nowadays by basically all major OEMs to support the sportiness of combustion engines, they are only rarely used for hybrid or electric vehicles. But, the AVAS topic forces OEMs to work on Active Sound Design for these vehicles, and they have to generate sounds which are different from combustion sounds and represent the electric way of driving. The logical evolution of this task is the aligned generation of interior and exterior sounds, which is discussed in [3] and extended here to the specific requirements of hybrid vehicles.

2. SOUND SCENARIOS OF HYBRID VEHICLES

Figure 1 illustrates the dominant dynamic sound contributions that compose the hybrid vehicle interior sound.

In hybrid vehicles the combustion and the electric powertrains can work in very different combinations, resulting in a variety of different sound scenarios.

The first important influencing factor of the resulting sound character is the architecture of the transmission system. Main systems are:

- *CVT transmission.* The continuous variable transmission seamlessly goes through a range of gear ratios, and basically is used to operate the combustion engine in the most efficient working condition. As a result, the fixed relation between rpm and gear/vehicle speed is broken. The acoustic result is unusual – rpm does not follow speed in a stringent manner and might follow an arbitrary course for the driver. The sound is thus somehow decoupled from the driving condition.
- *Electric motors integrated into Direct Shift Gearbox.* The combustion engine behaviour is like for a traditional combustion car, rpm and thus pitch follow speed for the selected gear.

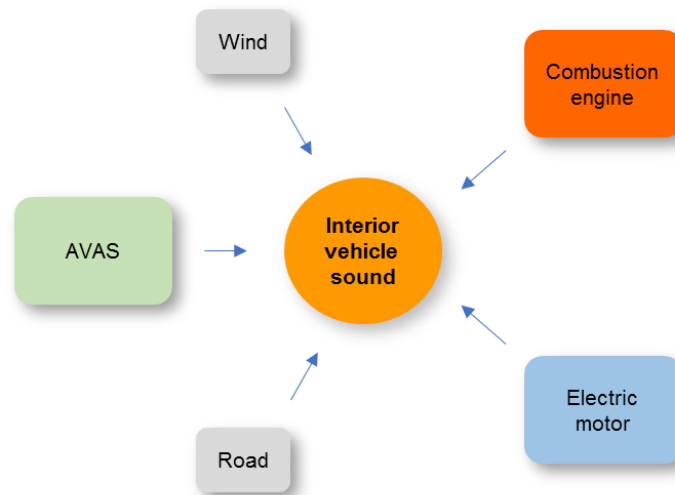


Figure 1: Composition of hybrid vehicle interior sound. Two engine type sounds with completely different character contribute, and the mandatory exterior AVAS sound is partly transmitted to the interior.

Apart of the transmission system the electric and combustion engines are combined in different and multiple ways, and this has a direct impact on the sound that is generated. Some of these conditions are directly linked to the actual vehicle dynamics, others not.

The following conditions have to be considered:

- *Pure EV mode.* Only the electric motors are used to drive the vehicle. The driver mainly hears road and wind noise, plus usually high frequency tones of the electric system.
- *Pure combustion mode.* Only the combustion engine drives the vehicle, and the driver hears – depending on the transmission system – either the conventional combustion sound or the somehow decoupled sound caused by the CVT transmission system.
- *EV mode supporting combustion mode.* The electric motor supports the combustion engine, so both work at the same time. The acoustic result is the overlay of both generic sounds. But, the acoustic contribution of each motor is different compared to single motor mode since the motors have to provide a different load than in single mode. Although the vehicle is more responsive in that mode, the sound thus usually does not transmit this information.
- *Combustion engine charging the battery or warming the cooling circuit* for the heating system, so not supporting drive. Some hybrid vehicles include a mode where the combustion engine only charges the battery, but is not used to support driving. In addition, hybrid vehicles which do not have an electric heater have to use the combustion engine cooling circuit for heating, so the temperature of the cooling liquid has to be high enough to allow heating, and the combustion engine will run just to warm the engine, but not to support driving. In these cases the sound generated by the combustion engine has no relation to the dynamic driving condition.

In addition to that, the vehicle speed creates an additional relevant parameter:

- at speeds where the AVAS system is emitting sounds parts of these sounds are usually audible in the interior
 - US: standstill to at least 30 kph, plus reverse

- EU, CN, Japan: 1 to at least 20 kph (no sound in standstill required), plus reverse
- At speeds where AVAS is not emitting sounds the interior contribution is not present.

The transition between AVAS on and off may be abrupt or smooth, depending on the ability of the AVAS system and the sound tuning of the OEM.

This combination of influencing parameters leads to an acoustic scenario that is neither stringent nor consistent. Combustion and electric motor generated sounds occur in single and mixed modes, sometimes decoupled from the actual driving condition, and sometimes mixed with an additional AVAS contribution. This is a huge contrast to combustion vehicles, which are highly treated to offer a refined and consistent sound.

Active Sound Design methods offer the most efficient and most economical solution to change this situation for hybrid vehicles. Nevertheless, in order to tackle all the different conditions listed above comprehensive methods and a stringent concept have to be used (e.g., see [4], [5] and [6])

3. HEV SOUND CONCEPT

The different sound components of hybrid vehicles interior sound have different origins and thus different basic sound characters:

- **Combustion based sounds** usually are low frequency centred, consisting of a combination of lower engine orders. Under load condition, a significant roughness contribution can be observed. The character strongly depends on the number of cylinders defining the main order.
- **Electric motor-based sounds** usually contain much higher frequency tonal components and usually no roughness.
- **AVAS sounds** are designed by the OEMs and have to fulfil legal requirements. Depending on the AVAS device capabilities the range can be broad from rather simple to quite complex sounds. Due to loudspeaker limitations and legal requirements the frequency range is between 200 Hz and 5 kHz.

A concept to create a stringent and consistent sound character for hybrid vehicles has to consider these differences. The task is significantly more complex than for combustion or pure BEV/FCV.

The concept basically uses a combination of different available Active Sound Design algorithms. Since the three above discussed sound characters have to be considered, the incorporated active sound generation algorithms should allow to modify these sounds and thus reproduce the corresponding characters.

The corresponding singular methods are available, but have to be used in a different context and centrally controlled and aligned:

- **Order based sound generation methods** can be used to support combustion-based sounds – these algorithms are well established. Nevertheless, if these algorithms should be used to create sounds that are similar to combustion engine sounds in cases where the combustion engine is not active, the algorithm has to be more elaborated than standard combustion engine support algorithms. In these cases the number of generated orders has to be higher and other specific sound features have to be generated to produce more realistic and authentic sounds.
- **Complex sound generation methods** which are usually applied to pure BEV/FCVs have to be used to create a broader range of sound characters apart

from the strict order-based synthesis. Different sound generation methods can be applied here, allowing combinations of tonal based and broadband based sounds.

- It is inherently clear that the AVAS system implements an Active Sound Design, and it is obvious that the overall sound scenario can be optimized if the central Active Sound Design either also generates the AVAS sound or at least uses the same sound generation algorithm as the AVAS system.
- A central process controls which sound generation method is used in which driving condition and aligns them.
- For interior sound reproduction the system uses the audio system of the vehicle.
- For exterior AVAS reproduction either attached external loudspeakers are used, or stand-alone AVAS boxes with aligned sound generation algorithms.

The scheme for aligned sound generation is shown in figure 2.

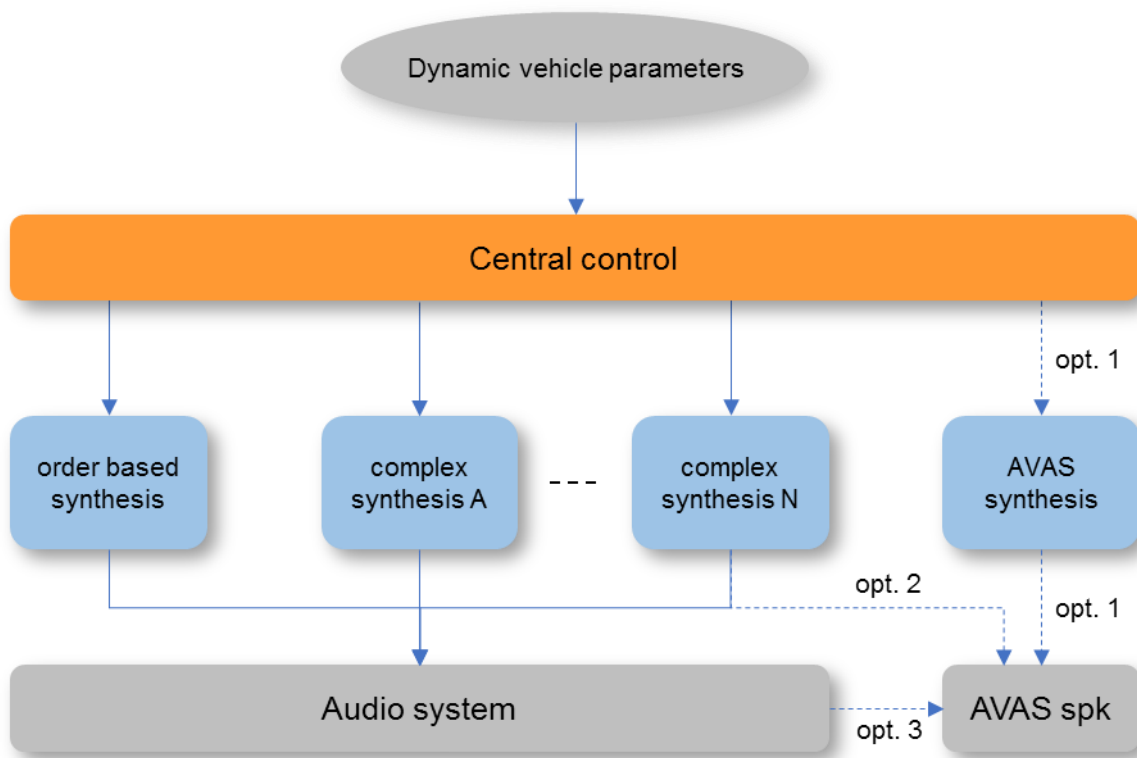


Figure 2: Concept for Active Sound Generation for hybrid vehicles. Several different sound generation algorithms can be used in parallel and are centrally controlled. The AVAS sound generation is embedded according to the vehicle implementation option from section 3.2.

The combination of the different sound generation algorithms allows to create a broad variety of different sounds. The manner how these sounds should be combined depends on the individual Hybrid Brand Sound strategy that the OEM has to establish.

3.1 Sound strategies

Since hybrid vehicle sounds contain the different characters described above, OEMs can define different strategies for the resulting Active Sound Design. Basically, two different generic strategies can be used which will be discussed in the following chapters.

3.1.1. Strategy 1 – maintain individual characters

In this approach, the respective characters of the different driving modes will be maintained. The Active Sound Design methods will be used to

- ***enhance the Sound Quality of each driving mode.*** Usually order based methods will be used to enhance the combustion sound, and complex sound generation methods to add sounds to the electric driving sound to mask or embed annoying high tonal components. But, since complex sound generation methods are available, they can also be used to enhance combustion sounds.
- ***align the transitions of driving modes.*** In order to avoid abrupt changes in the sounds, especially the transitions of the driving modes have to be treated.
- ***embed the AVAS sound.*** The low speed range has to be treated in such a manner that the AVAS sound component melts into the rest of the vehicle sound. This can best be achieved if the electric drive sound embeds the AVAS sound character in this speed range.
- ***harmonize the overall sound scenario.*** The different characters of the individual contributions have to be aligned in such a manner that there is no mismatch of the sound characters of the different contributions.

The Active Sound Design of this strategy works more in the background, aiming at aligning all the different sound components.

3.1.2. Strategy 2 – create a new overall common sound character

This approach aims at establishing a new, common and stringent sound character that is present in all driving conditions, thus giving the vehicle a new unique acoustic personality.

- A ***new acoustic identity*** is defined for the overall vehicle sound. This overall identity has to embed all the different inherent sound contributions from the vehicle to allow a unique sound representation without increasing the overall sound level too much. From a concept point of view this task is identical as for the definition of the driving sound for pure electric or fuel cell vehicles, but more demanding since the combustion engine sound has to be taken into consideration, which usually is the dominating sound source with regard to level and character.
- For each driving sound contribution the Active Sound Design adds this global identity. Depending on the character of the identity the corresponding sound generation algorithms have to be used, and usually this will be a combination of order based and complex sound generations – the sound generation systems will be active in all conditions.
- The AVAS sound is designed based on the same principles and aligned to the vehicles' identity. This requires that the AVAS sound generation capabilities are linked to the interior Active Sound Design algorithms.

In contrast to strategy one the original contribution characters might not be maintained, but might be more or less completely superimposed by a new defined character. Due to the unusual acoustic behavior of CVT transmission, this strategy is especially effective for vehicles using this transmission system. The new defined character does not refine the inherent character of the CVT sound, but allows to superimpose a new character.

Nevertheless, the differentiation between the different driving modes can be expressed, so the driver can still get the feedback about the current driving condition. The decision which of the various modes should give a distinct feedback to the driver can be

made by the OEM, but he can also define that this information should be completely hidden. As the other extreme each driving mode can be assigned with a specific sub-character, so that the differentiation is intuitive for the driver. In this way associations can be linked to each mode, for example extreme sportiness feedback for combined combustion and electric drive, or positive “green” feedback for recuperation.

A corresponding approach, which was originally developed for the sound generation for electric vehicles [3], can be adapted to this more comprehensive hybrid vehicle strategy and is depicted in figure 3.

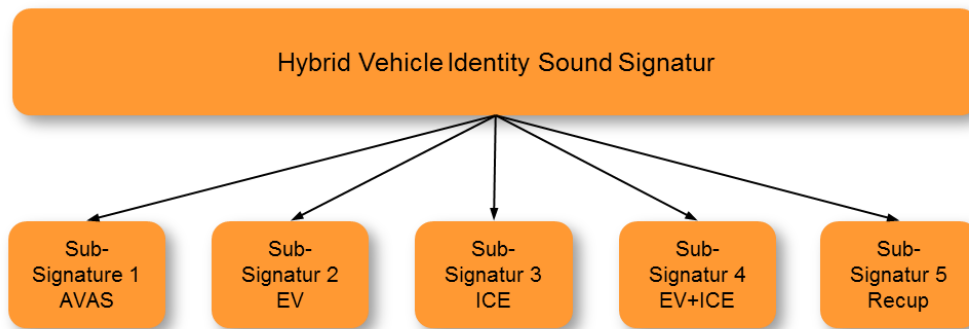


Figure 3: Sound Signature approach from [3] extended to the hybrid vehicle concept. The Hybrid Vehicle Identity Sound Signature defines the overall character of the hybrid vehicle sound, the sub-signatures define the character of the different driving modes and AVAS.

3.2. Vehicle implementation

From a technological point of view the integration of the concept into the vehicles is similar or identical to the implementation of the currently used Active Sound Design methods which are already in various series applications, e.g., for combustion engine sound enhancement or electric vehicle interior sound generation. Since for most applications different sound generation algorithms have to run in parallel, sufficient processing resources with regard to MIPS and storage memory have to be available.

In contrast to pure interior Active Sound Design, where the interior audio system is used, the exterior AVAS sound has to be considered in that concept, too. There are three different options which are depicted in Figure 4.

In option 1 the sound for exterior and interior are generated on two different devices which operate completely independent. The exterior sound is generated and played back by AVAS box(es), the interior sound is generated and played back by the interior audio system (Head-Unit or external DSP amplifier). In order to achieve a consistent and aligned sound, both sound generation devices should run aligned sound generation algorithms, which are ideally configured by a single editor.

In option 2 a separate hardware device is used to generate both, exterior and interior sound at the same time. For the exterior sound reproduction just an external speaker box is required, and for the interior sound playback an input interface to the vehicle audio system. This option has the advantage that the alignment of interior and exterior sound generation is guaranteed, and that no further processing algorithms have to be implemented on the vehicle audio system despite the input interface and the sound mixing, so no further resources have to be made available by these systems.

Option 3 uses the audio system resources to perform the generation of exterior and

interior sound, so completely integrates the processing into the Head-unit or an external DSP amplifier. As in option 2 it only requires an external loudspeaker box for the AVAS sound reproduction. It offers the same advantage of aligned exterior and interior sound generation, but requires sufficient resources made available while it saves expenses for an additional separate hardware box.

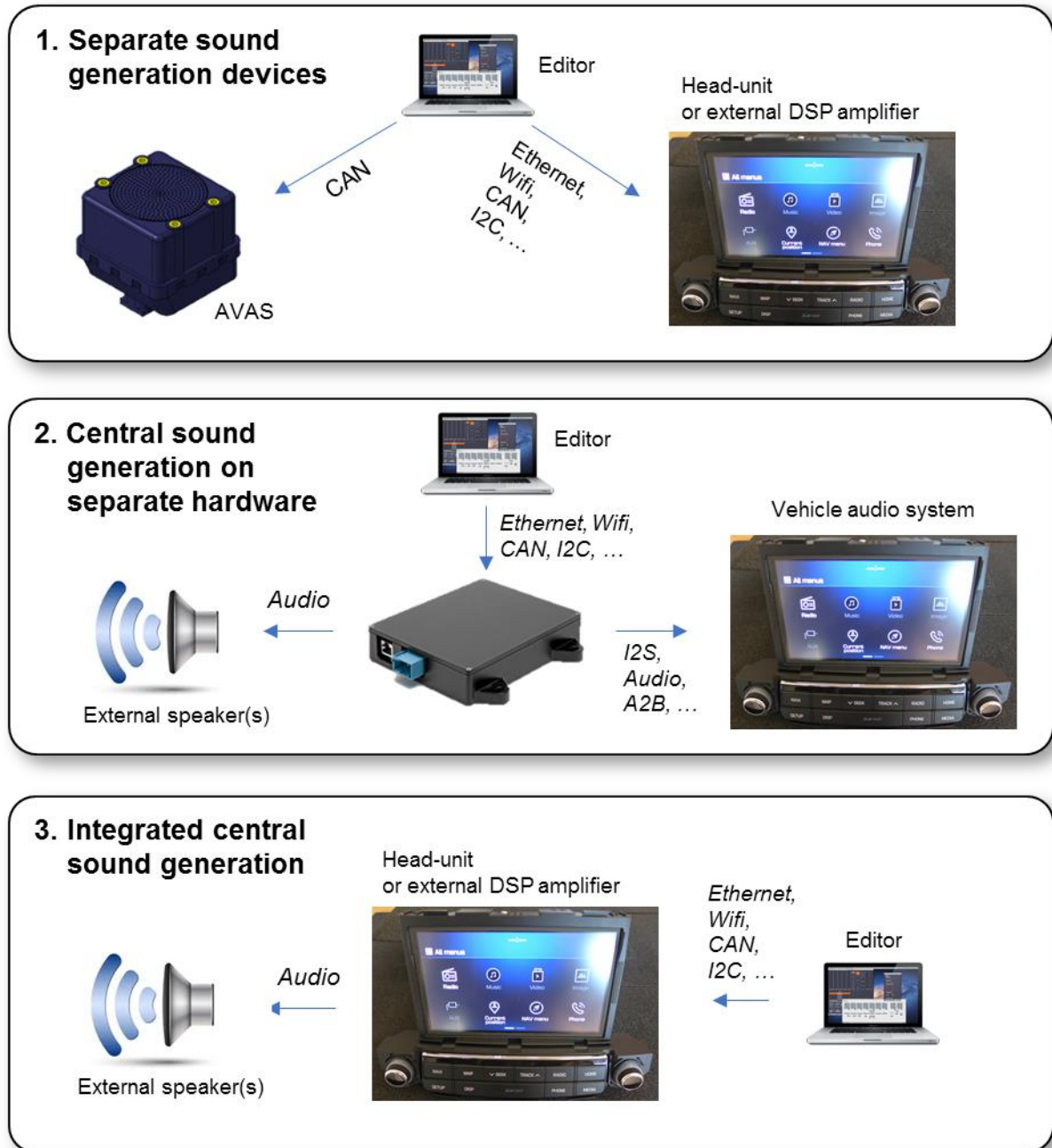


Figure 4: Different possibilities for vehicle integration. Top: separate sound generation devices exterior and interior, both controlled by a unique editor. Middle: separate hardware for central sound generation exterior and interior; Bottom: central sound generation exterior and interior fully integrated into the audio system.

4 SUMMARY

Compared to combustion or electric vehicles, hybrid vehicles represent an even more complex challenge with regard to acoustics. The combustion and electric engine can work in a variety of different operational modes, either alone or together, and create an inconsistent sound scenario. Conventional NVH methods can only optimize the acoustics up to a certain limit with negative impact on cost, weight and efficiency, and fail to implement a unique consistent character.

To overcome this, Active Sound Design methods can be used to generate sounds aligned to each of the different operation modes. They allow to align and harmonize the different sounds, and can create a unique and consistent personal sound identity.

The application allows the OEM to define and follow different strategies, by either closely maintaining the different characters of the operational modes, or by creating a single unique new character.

Implementation in mass production vehicles is available in form of sophisticated different active sound generation algorithms implemented on dedicated hardware, DSP-amplifiers or directly on head-units.

5. REFERENCES

1. Statista, URL <https://de.statista.com/statistik/daten/studie/875099/umfrage/anteil-von-hybridfahrzeugen-an-globaler-automobilproduktion/>
2. 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).
3. Bodden M.; Belschner, T.: *„Kombinierte Gestaltung von Außen- und Innengeräuschen für Fahrzeuge mit Elektroantrieb“*, DAGA 2018, München (2018).
4. Bodden, M.; Belschner, T.: *“Comprehensive Active Sound Design. Part 1: electric and combustion vehicles”*. Proceedings of the Internoise 2014, Melbourne, Australia (2014)
5. Belschner, T.; Bodden, M.: *“Comprehensive Active Sound Design. Part 2: operational sounds and Brand Sound”*. Proceedings of the Internoise 2014, Melbourne, Australia (2014)
6. Bodden, M.; Belschner, T.: *“Principles of Active Sound Design for electric vehicles”*. Proceedings of the Internoise 2016, Hamburg, Germany, 1693-1697 (2016)