Investigation of NVH Phenomena at Electric Vehicles

The vehicle development faces new challenges when utilizing electric engines. Müller-BBM VibroAkustik Systeme and Mahle Powertrain discuss different phenomena, experienced during measurement campaigns with a large amount of electric vehicles of various vendors. Additional measurement equipment and analysis is necessary, as the architecture of the powertrain has changed. This requires different measurement positions and new approaches for measuring rotational speeds.

AUTHORS

Dipl.-Ing. Jakob Putner
is Acoustic Engineer at
Mahle Powertrain GmbH in
Aschheim (Germany).

Dr.-Ing. Dejan Arsić
is Key Account Manager
at Müller-BBM VibroAkustik
Systeme GmbH in Planegg
(Germany).

PERCEIVABLE NOISES AND VIBRATIONS

Sound quality is one of the key interfaces customers evaluate with their vehicles. Therefore, acoustics play an important role in the development process of an automobile. In decades of NVH engineering, expert knowledge was built up, and a thorough understanding of Internal Combustion Engine (ICE) based powertrains has been achieved. Experienced engineers can efficiently troubleshoot NVH problems, using their knowledge of a wide range of known phenomena. New powertrain concepts, either fully electric or hybrid (combination of electric and combustion engines), come with new NVH problems and previously unknown phenomena. The entirely different setup of electric engine and gearbox and the higher rotational speeds are now creating perceivable noises and vibrations at way higher frequencies. Further, the omission of both combustion engine and exhaust system eliminates two of the most dominant sound sources. These systems were typically masking many other sounds, which are now perceivable. In the present report, we will discuss different phenomena we have experienced during measurement campaigns, with a large amount of different electric vehicles of various vendors. Besides a description of the sources themselves, transfer paths will also be addressed with a comprehensive comparison of a vehicle with a combustion engine and an electric engine. We will further address the additional demand on measurement equipment and required analysis, as the architecture of the powertrain has changed. This consequently requires different measurement positions and new approaches for measuring rotational speeds (e.g. from the inverter).

DATA ACQUISITION

The data acquisition task itself has not changed drastically, if only NVH is considered. Sound pressure, acceleration and rotational speed are still in focus, and positioning can be easily adapted. Low noise microphones should be chosen, as a wide range of phenomena is

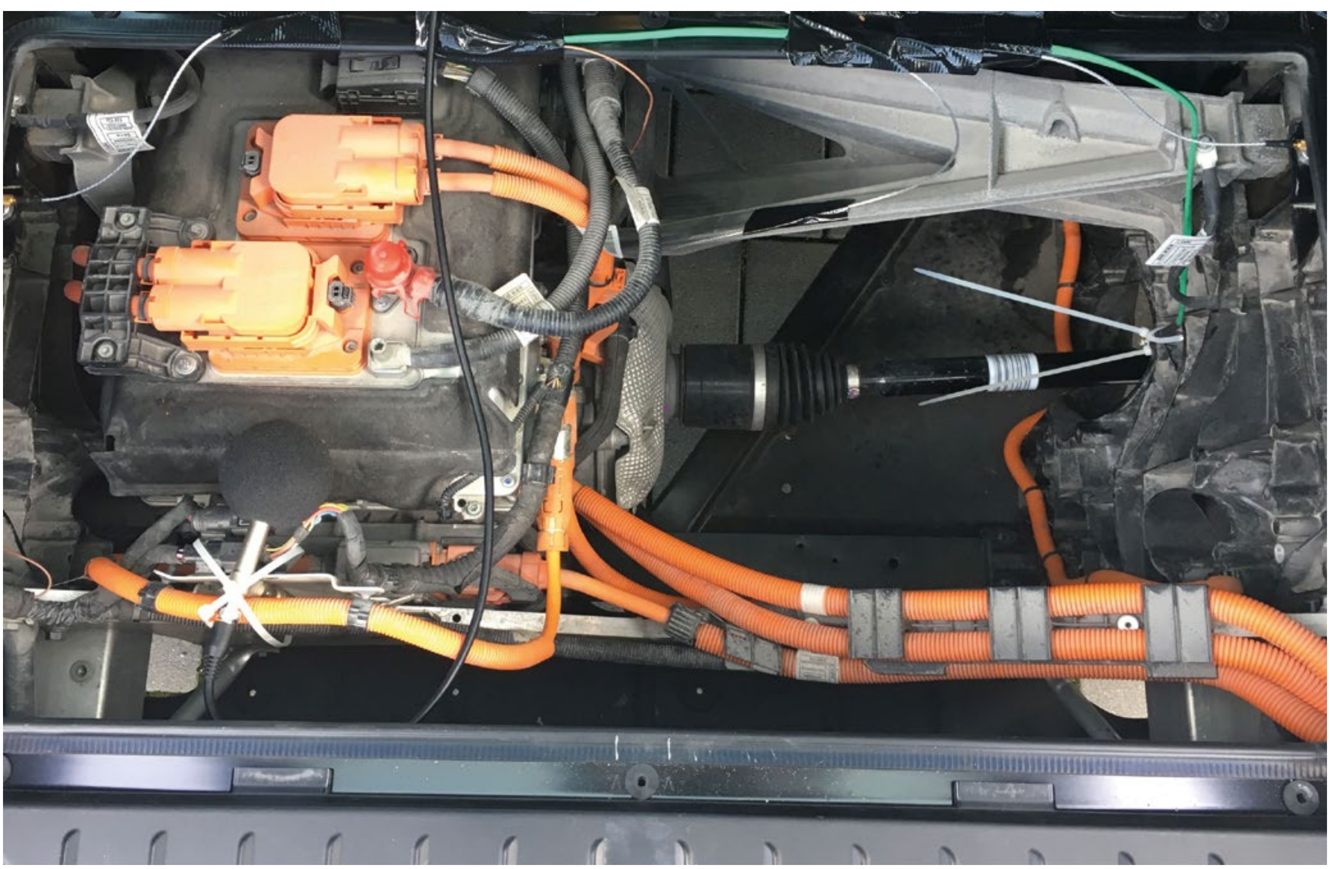

FIGURE 1 Both engine and gear box are combined as a drive unit, with almost no chance to acquire rotational speed (© Müller-BBM)

rather near the noise floor. In addition, it is advisable to measure high voltages with a high sampling frequency, to investigate noises created by the power electronics. As **FIGURE 1** illustrates, the electric engine and gear box can be considered a rather compact drive unit. There is almost no possibility to get access to rotating parts, which frequently are the cause of disturbing noises and vibrations. To manage this problem a wide range of approaches have been evaluated; beginning with accessing the CAN bus interface, which is simply too slow for fast rpm changes. Subsequently, orders cannot be analyzed in a sufficient way. As gears are still utilized, inductive rpm sensors are a good possibility to compute the rpm based on the passing gear, in case the sensor is applicable. To circumvent these problems, it seems reasonable to acquire the inverter signals, changing direct current to altering current. With the measured angular position of the individual rotors and the known phase shift, it is now possible to determine the rotational speed of the electric engine.

Nevertheless, traditional optical transducers are still used; especially with hybrid vehicles, where it is often easier to access rotating parts. These are usually the baseline for more complex rotational analysis, such as torsional vibration. With more complex operational states of the powertrain, some phenomena, which have been neglected up to now, must be addressed now. Start and stop procedures of the engine, which are not very smooth, can create faulty rpm signals. This results in either no signal at all, or rpm values that are much too high. Hence, it is important to take special care of the signal and avoid these errors at any cost. Further, it seems sensible to use incremental encoders indicating the direction of the rotation.

INTERIOR NOISE

As mentioned earlier, the whole vehicle development faces entirely new challenges when utilizing electric engines. While the combustion engine has been masking a wide range of different noises, these are now perceivable and need to be addressed. This seems rather reasonable and requires more care designing the other sound sources. Nevertheless, it seems more complex to cope with unexpected phenomena appearing with the use of an electric engine. Power electronics are known to create noises, the battery needs cooling, and various control elements are suddenly perceivable.

As the ICE is usually considered as a source with rather low frequencies, up to 3000 Hz, way higher frequencies are observable with electric engines. This can be seen in **FIGURE 2**, where a hybrid vehicle has been investigated. The electric engine has a low overall level and is rather uneventful. The dominant orders are rather high and a few high frequency lines are observable. As soon as the combustion engine begins running, the overall levels rise drastically. This is especially true for low frequencies, where the dominant orders can typically be observed.

These high frequencies now have an impact on the entire component design and the test procedure itself. To achieve a distinctive and pleasant interior noise, damping materials are selected with respect to the dominant frequency range of the sound. Hence, low frequencies have been in focus for intensity measurements, reverberation time, and damping. Whilst it seems obvious that different materials must be selected, the measurement procedures have to be adjusted, as it is now important to excite these materials with sufficient energy in high frequencies and allow for reproducible measurements.

Order analysis is one of the standard tasks in vehicle acoustics, as usually there is a correlation between the frequency of the perceived sound, and the rpm of the rotating part. This is the same for combustion engines and electric ones. Due to the high rotational speed of the electric engine, the frequencies of the dominant orders are higher than before. However, a few differences can be observed when investigating a classical spectrum as shown in **FIGURE 3**, where an accelerometer has been mounted close to the electric engine. In contrast to the combustion engine, an additional order fan is visible at higher frequencies, both into negative and positive direction. The cause of these additional frequencies is usually the pulse width modulated signal, used to control the rotational speed of the engine, where the frequencies of the orders correlate with the engine control signal. Therefore, the mechanical properties of the engine are influenced by two factors: the rotation of the engine and by the PWM signal. The task is now to distinguish between the frequencies induced by the engine control signal and the orders themselves, and to interpret the crossings of the frequency lines and the orders, as the values might be higher than expected if a single order is considered.

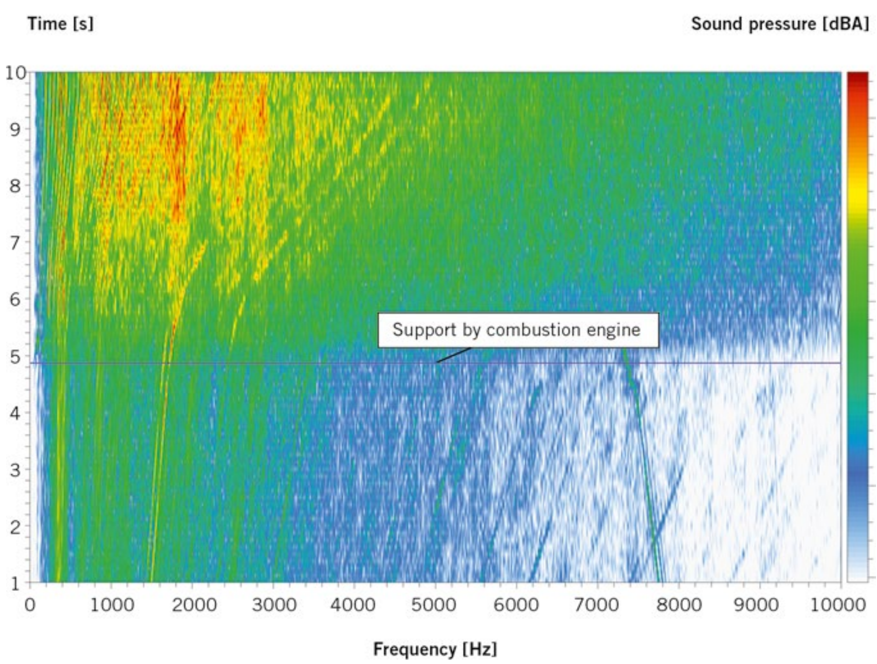

FIGURE 2 Comparison of interior noise in an ICE-based vehicle and an electric vehicle (© Müller-BBM)

CONTRIBUTION ANALYSIS AT THE DRIVER EAR

To better understand the sound generation of the main sources, a hybrid vehicle has been investigated on a dyno, by applying the well-established Operational Transfer Path Analysis (OTPA) [1], which is a standard method in NVH development. The OTPA aims to rank the contributions of individual sources to the overall observed signal. This way it is possible to investigate the sources individually, without disassembling the vehicle, and by only using operational measurements. For a comprehensive analysis of the noise at the driver ear, vehicles are equipped with microphones at the combustion and electric engines, tires, exhaust and intake. Accelerometers have been placed on engine mounts, gearbox mount, exhaust system, electric engine and the frame itself. Driving speed and rotational speed have also been recorded. **FIGURE 4** illustrates the results of the contribution analysis at the driver ear. As expected, the overall sound pressure level at the driver ear is lower for the electric engine. Comparing the individual sources, it becomes clear that the ranking of the structure borne contributions remains the same, even though lower contributions can be observed. The reason is rather obvious, as the chassis is still the same. Considering airborne noise, the tires are the dominant source for the electric vehicle, as exhaust and ICE are not in use. It should be noted that all possible sound sources have been measured in hybrid and electric mode, although e.g. the exhaust system is not being used in electric mode. Therefore, contributions have been calculated which are result of crosstalk. The ranking itself is still correct. Nevertheless, it should be mentioned that the results cannot be generalized. Depending on the quality of the gear box, some high frequency whining has been experienced with some vehicles.

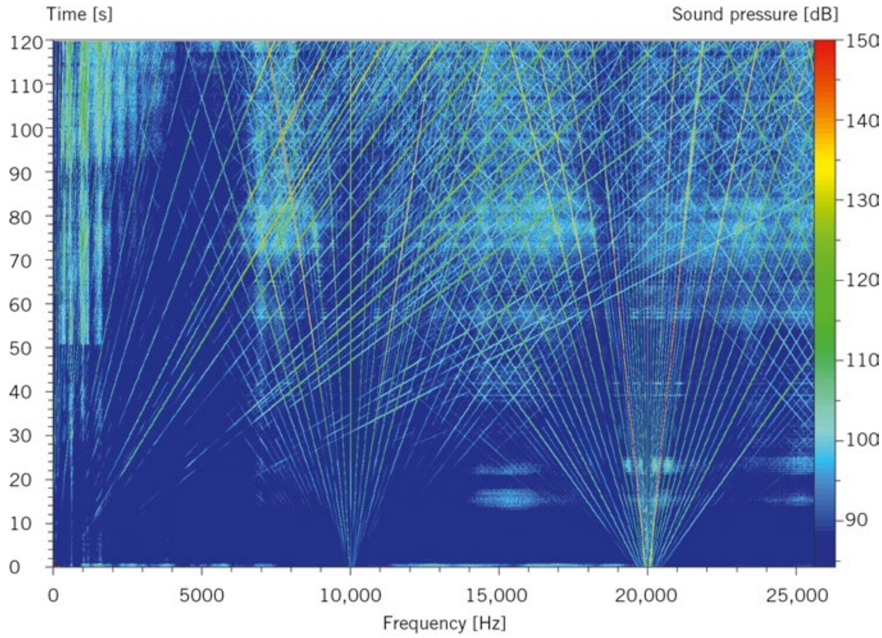

FIGURE 3 Order analysis including hybrid orders (© Müller-BBM)

EXTERIOR NOISE

Besides the previously discussed interior noise, exterior noise is also an important issue [2]. On the one hand, side sound designers try to create a distinctive unique sound for each brand and model. On the other hand, regulations are rather strict when it comes to maximum levels while performing predefined maneuvers. This is different for electric vehicles, which are rather quiet and supposedly a threat for pedestrians and bicyclists.

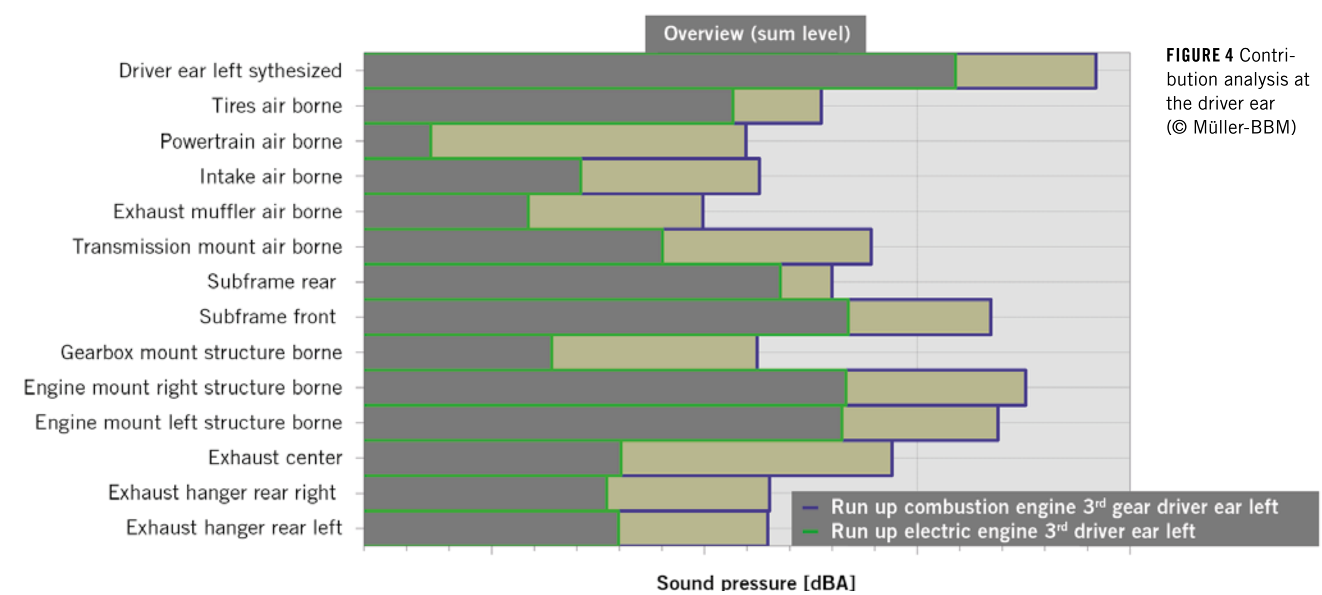

FIGURE 4 Contribution analysis at the driver ear (© Müller-BBM)

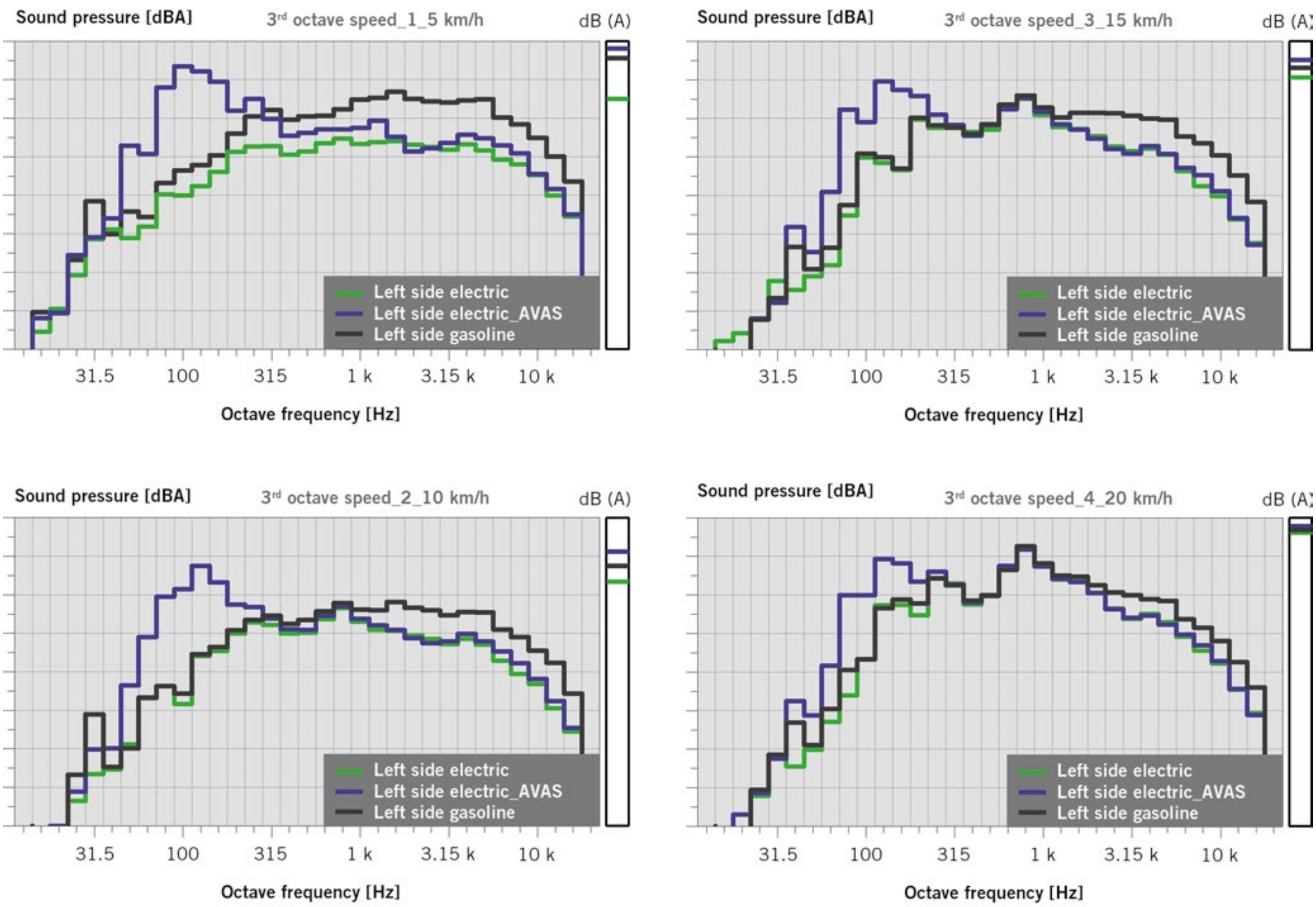

FIGURE 5 Comparison of exterior noise measurements for electric engines, combustion engines and the AVAS system (© Müller-BBM)

Therefore, a certain level must be guaranteed and accelerations should be signalized acoustically, with a so-called frequency shift. Quiet car regulations include the Acoustic Vehicle Alerting System (AVAS) [3]. Exterior noise is measured at different speeds, at three distinct positions around the vehicle, and the averaged third octaves are computed considering the background noise. The results for different speeds, namely 5, 10, 15, and 20 km/h, of a hybrid vehicle, are illustrated in **FIGURE 5**. The levels of the electric engine are much lower than the ones of the combustion engine for all the

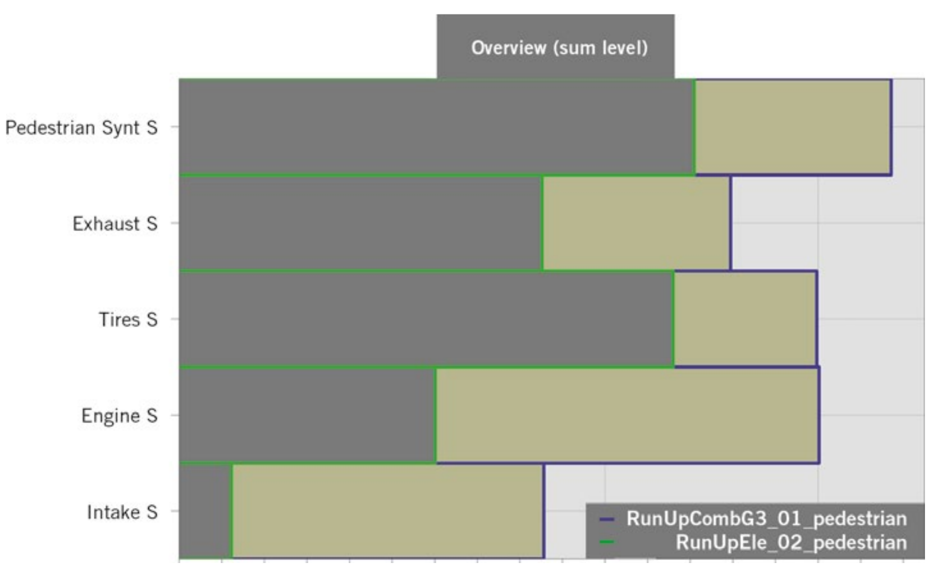

FIGURE 6 Exemplary transfer path analysis results compared for electric drive and ICE at the pedestrian position (© Müller-BBM)

velocities. At higher vehicle speeds (e.g. 20 km/h) the tire noise becomes more prominent, which is sufficient for pedestrian safety, as the vehicle finally is more perceivable. Using the AVAS implementation with a speaker inside the vehicle, an artificial sound is emitted, that might be even louder than a vehicle with a combustion engine at low speeds.

Once more the OTPA is used to investigate the sound field created by the electric and the combustion engine, in respect to the exterior noise [4]. For the experiments, microphones have been placed at the pedestrian positions (representing the response), and at the tires, engine, exhaust and intake (representing the excitation). Measurements have been conducted in electric and combined mode. The results are illustrated in **FIGURE 6**. As it can be seen the overall level at the pedestrian position is by far lower for the electric vehicle. Engine and intake can be neglected. The main contribution are now the tires, in contrast to the ICE. Again, some crosstalk can be seen in the results.

CONCLUSION

Although e-mobility presents NVH engineers with a wide range of changes, a lot of known methods can be further used. Considering the whole vehicle, measurement points and used transducers can remain the same, even though the sound field itself is rather different. While exterior noise is rather exciting due to the regulatory point of view, rotational analysis is still an exciting topic and needs to be further investigated. As already mentioned, some components now perceivable as the dominant noise of the ICE, are missing. These components are now chosen more carefully and tested more thoroughly, especially to avoid production fluctuations.

REFERENCES

[1] Noumura, K.; Yoshida, J.: Method of transfer path analysis for vehicle interior sound with no excitation experiment. In: Proceedings of the Fisita World Automotive Congress. Yokohama, Japan, 2006

[2] Finsterhölzl, H.; Caldiero, V.; Hobelsberger, J.; Baumann, W., Daiber, F.: A New Exterior Noise Testing Facility in the Development Process at BMW. In: ATZ Worldwide 108 (2006), No. 4, pp. 2-5

[3] Bock, F.; Gsell, S.; Becker, S.; Pohl, M; Arsic, D.: Auswirkungen der AVAS-Gesetzgebung auf elektrifizierte Fahrzeuge. In: Proceedings DAGA. München, 2018

[4] Putner, J; Arsic, D.: Beitragsanalyse von Fahrzeuggeräuschen mittels operationeller Transferpfadanalyse. In: Proceedings DAGA. München, 2018