The Change of Vehicle Drive Concepts and their Vibro-Acoustical Implications

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Abstract

The sound quality of vehicles is important in gaining market advantage. It contributes greatly to the perceived overall quality of a vehicle and therefore must be deliberately optimized.
This is a very hard task, since today the development cycles in the automotive industry are constantly reduced and new drive concepts, reduction of emission and fuel consumption, which lead to vehicle weight reductions through material changes, tightened ecological specifications, increase of vehicle classes and increasing diversification, the introduction of alternative powertrains and engine concepts challenge the vibro-acoustical engineering. Thus, the general aim - to create a pleasant, harmonious passenger cabin sound - can only be achieved with new approaches, concepts and technologies which cope with the increasing complexity of NVH-problems and vibro-acoustical conflicts.
Alternative drives come or will come into the market in the near future. Since these alternative drives will gain in importance, it is imperative to look into acoustical problems and conflicts right from the beginning. Moreover, as a new objective the adequate vehicle sound tailored to suit the auditory expectations and needs of the customer must be found. This requires virtual engineering coupled with subjective testing in order to find target sounds.
Here, it is very important to have already reliable information about sound issues available in early design phases to guarantee the development of the intended sound and quality and to achieve high quality standards in general. Simulation techniques find their permanent use in vehicle engineering for the virtual construction and testing of subsystems or the whole car in almost all development phases.
The paper will discuss future prospects and developments in the field of automotive acoustics and will present selected applications to underline the need for new approaches and concepts.

1. Introduction

The consideration and optimization of NVH quality of vehicles is already a major task for acoustic engineers for more than 30 years. In the beginning, the engineers' major task was to make the vehicle interior noise acceptable or at least less annoying. These days it was sufficient to concentrate on the simple reduction of overall sound pressure level in the passenger cabin. The silencing of combustion engine was the prime mission. With the stepwise engine noise reduction further noise sources were no longer masked and were suddenly heard by the drivers. Consequently, the acoustic engineers had to broaden their work scope and had to deal with other sources and with more intricate problems

respectively. The identification and elimination of disturbing noise focusing on several noise sources was a new, more challenging task and in this context the simple interpretation of simple dB(A) values turned out to be completely inadequate. Engineers had to analyze the sound and vibrations of the vehicle with respect to spectral content, temporal or tonal patterns and psychoacoustic properties. It turned out that further sound quality relevant parameters have to be found and applied in order to assess adequately the present sound and vibrations and to derive detailed targets.
As a result of the successful sound and vibration optimization over the last decades the vehicles today are often much quieter than several years ago and even very "quiet" sources and quiet disturbing noises, such as squeak and rattle, can be heard. Interestingly, even these quiet disturbing noises frequently pose problems and cause customer complaints. Finally, it must be stated that the annoyance level of a certain sound source within a vehicle cabin is only related to its sound pressure level in a very limited way. But rather its psychoacoustic properties, its time of occurrence, its unexpectedness determines the subjectively assigned level of disturbance and annoyance to the sound source. Therefore, besides the vibro-acoustical measurements the performance of listening tests, interviews with customers and sound evaluations by acoustic experts were and still are indispensable.

In the last years the general work scope of acoustic engineers in the automotive industry has even more broadened. The active sound design, the deliberately control and the intentional development of the sound and vibration was and is necessary to reflect adequately customer wishes. The previous reactive procedure, carried out after first prototypes are available (troubleshooting) is still important, but it is not sufficient anymore to meet all customers' demands and to maintain a competitive advantage. Even at early stages of vehicle development NVH engineers must intentionally design sounds and develop target sounds, but rather work only on "symptoms" and problems. Again, the reduction of sound pressure levels or even the compliance with certain sound pressure level limits does not automatically lead to the product's target sound or to satisfied customers. It is clear that customers do not assess a vehicle on the basis of considered sound pressure level limits, but rather they use their emotional feelings during the drive and on the basis of these sensations/emotions they find their expectations more ore less fulfilled. The vehicle sound must be deliberately designed, which means that certain noise aspects have to be emphasized while other noise properties and features have to be reduced or eliminated. This sound engineering must always reflect the type and general performance of the vehicle, the brand image of the car company, the preferences of the potential customers and the target group.
In order to fulfill these requirements the development and application of simulation techniques is inevitable. Simulation techniques (capable of predicting NVH behavior of the vehicle at early design phases), transfer path analyses (projecting and assessing contributions of individual noise paths) and driving simulators (which provide authentic vehicle scenarios) are essential tools for predicting and optimizing the products' sound quality at early stages of development. The use of such tools will be more and more inevitable in the future, since the development cycles in the automotive industry are constantly reduced to meet the customers' demands and to react quickly to market needs. Here, the simulation of modifications and their effect is very important and so possible improvements can be assessed in advance.
Finally, new constraints and general concepts are emerging in the automotive field, which requires a completely rethinking. New engine concepts, tightened ecological

specifications, extension, increasing diversification, etc. challenge the acoustic engineers trying to develop a pleasant, harmonious passenger cabin sound.
In particular, with respect to alternative power trains and engine concepts, complete new problems and questions arise. The alternative drives will gain in importance in the near future and they will change the general perception and assessment of vehicle noise. For example, the German government estimates that 2020 one million electric cars will be on German roads, which would make up a 2% share of all passenger cars [1]. To achieve this ambitious goal, the government provides a financing of half a billion Euros. "There is no doubt that electric motors will eventually replace combustion engines, the question remains how long it will take for EVs to reach mass production […]" [2]. Therefore, the acoustic engineers must face the new challenges quickly in order to provide the right, in line with the market solutions. What are the preferred sounds in the future? Is the consideration of authenticity of the sound necessary? How should a vehicle exterior sound be composed? How is pedestrian safety guaranteed? How could possible "warning signals" sound? For a successful clarification of these issues advanced tools and methods have to be applied.

2. New Power Trains

Several versions of new engine concepts and alternative drives will come into the market in the near future, such as micro-hybrids, mild hybrids, full (parallel or 'power-split') hybrids, plug-in hybrids, extended-range electric vehicles, battery-electric vehicles or fuel cell vehicles. Presumably these concepts will be applied to several kinds of vehicles, such as passenger cars, motor-cycles, buses, small transporters, heavy vehicles, etc. Electric cars seem to be adequate for special needs and applications (second car, city cars used only for short distances, local public transportation), but appear still insufficient to fulfil all costumer needs. However, alternative drives will gain in importance, and therefore it is imperative to look into acoustical problems and to create appropriate vehicle interior and exterior sounds.

2.1 Noise and Vibration Problems of a Hybrid-Electric Power Train

A major priority for a complex hybrid system development is to achieve an optimized energy and operation management. Besides these aspects another important objective is to design, develop and implement solutions to meet the specific NVH-requirements [3], because it was frequently observed that noise and vibration problems often occur in hybrid vehicles equipped with an electric and an internal combustion engine.
In particular, the operating noises of the electric drive as well as the operating behavior of the combustion engine, for example a sudden start or shut off, are not familiar to most drivers and noise patterns and perceivable vibrations could provoke complaints. Here, smooth transitions must be realized. For example, the vibro-acoustical properties of a hybrid vehicle prototype were examined [4]. Figure 1 shows the measurement of a run-up from 0 to 50 km/h, which was measured on a four-wheel chassis dynamometer. It can be clearly seen in the diagram that the electric drive operates at first and during acceleration the combustion engine begins to operate. In the figure it is observable that an annoying noise around 7 kHz occurs which is caused by the power inverter. Moreover, at 7.5 s the combustion engine starter noise can be perceived. At 11 s an increase of the engine

roughness in the range of 300 to 500 Hz is observed due to the load taken over by the combustion engine. Before, the whine noise (500 - 2000 Hz) of the electric motor can clearly be heard.

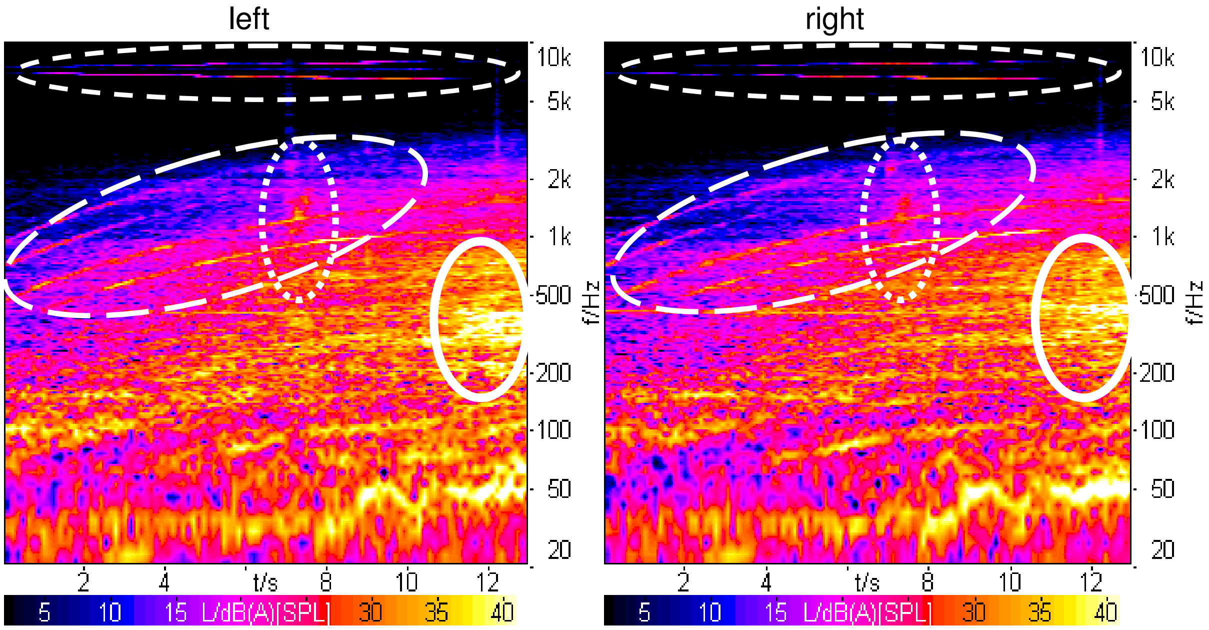

Figure 1: Binaural interior noise spectrogram of run-up 0-50 km/h showing whine noise, inverter noise, engine start at 7.5 s and roughness increase at 11 s; FFT vs. time

In order to cope with the task of sound quality improvement and avoidance of perceivable unintentional sound events, binaural transfer path analyses and synthesis must be performed. This allows for the identification of the most efficient measures for a systematic, efficient improvement of the interior vehicle sound quality.
The binaural transfer path analysis (BTPA) and synthesis techniques (BTPS) have been developed to determine the contributions of single transfer paths and predicting the vehicle overall interior sound with respect to relevant receiver positions. The BTPA does not only allow for predicting order levels and spectra, but also for the binaural auralization of various driving conditions. This binaural transfer path analysis and synthesis techniques in theory and practise are well described in [5-9].

The synthesized interior noise and vibration of the investigated hybrid vehicle are compared to the recording for validation. In figure 2 it can be seen that all relevant, typical patterns, which were measured, are also included in the synthesis results. Be aware that parasitic noises like tire noise or roller noise are not considered by the model. In a next, important step the overall sound must be split into main contributions, and then have to be split into single noise path contributions. This is necessary to detect cause for and the transfer of disturbing noises to the driver's ear. The disturbing noise patterns can be identified and assigned to certain transfer paths and respective sources or components. Figure 3 displays that the whine orders, caused by magnetic forces of the electric motor, are transferred not only as structure borne noise, but are also radiated directly from the motor and inverter. This fact directly drives requirements for sound quality optimization.

Further noise patterns are the inverter switching noise (airborne) and low frequency booming of the electric motor (structure borne).

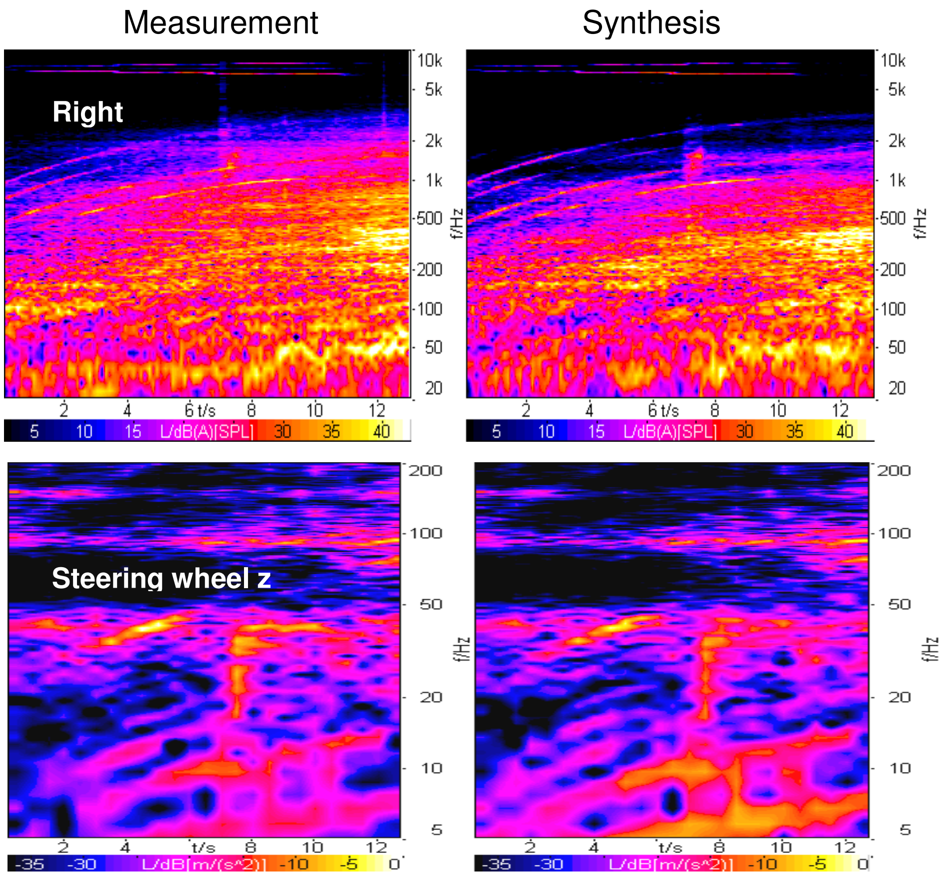

Figure 2: Comparison of recorded and synthesized interior noise and vibration. Top: interior noise (only right channel shown), bottom: steering wheel vibration (vertical direction)

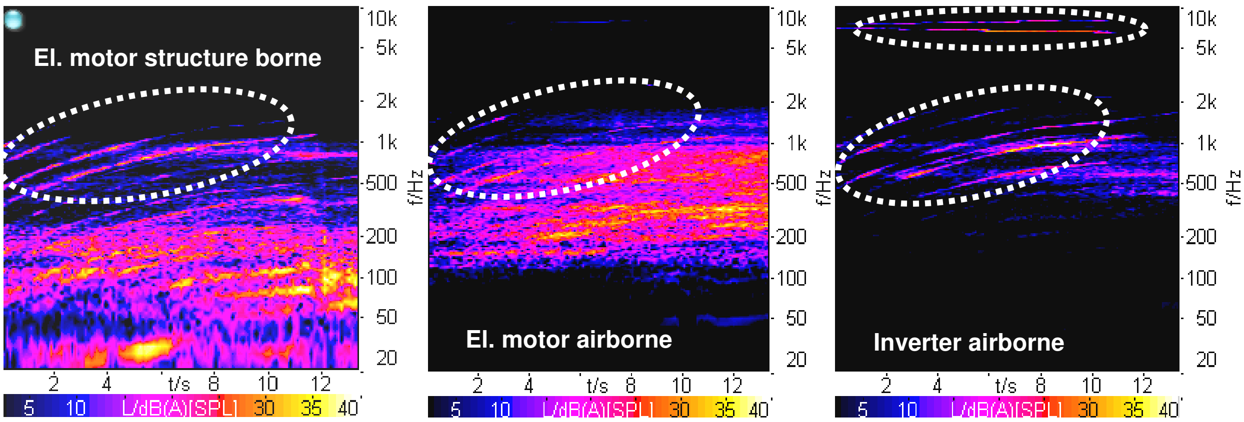

Figure 3: Interior noise contributions of electric drive components (only right channel shown)

As another example the main contributors to steering wheel vibration are shown in figure 4. The tonal pattern at 30 - 40 Hz is transferred via the electric motor mounts while the broad-band jerk at engine start comes from the left engine mount and engine roll restrictor. Vibration from the electric drive is particularly critical because electric mode is limited to lower speeds and thus noise levels are relatively low. Strong vibration is perceived very disturbing in this specific driving context.

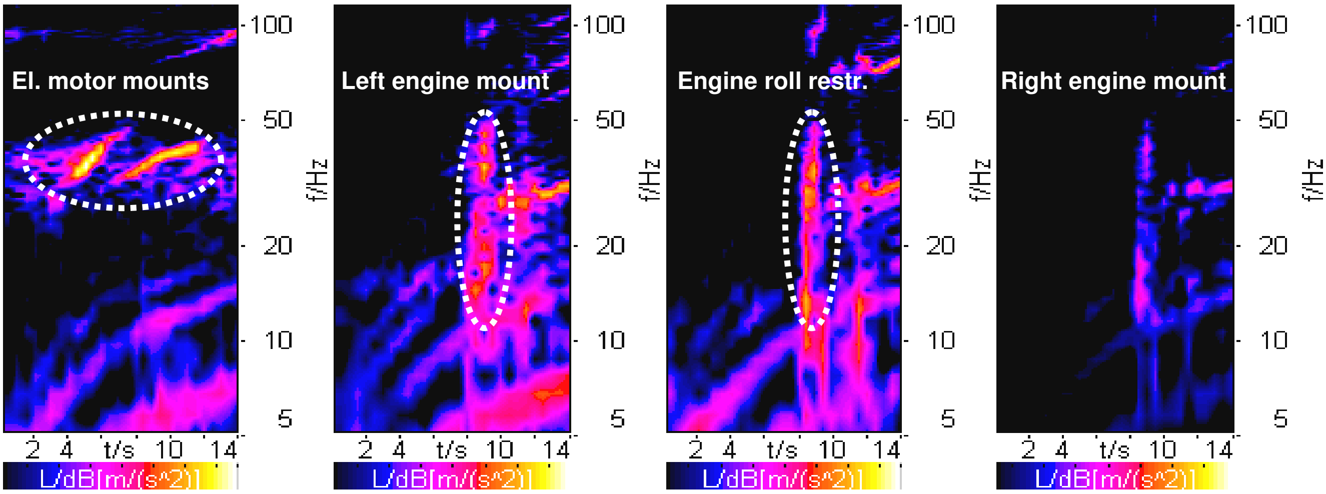

Figure 4: Contributions of steering wheel vibration (vertical direction)

The transfer path model can also be used to simulate effects due to virtual modifications and to support the development of remedies at an early development stage. In the presented investigation of a hybrid vehicle the mounts of the electric motor have been optimized in the simulation by tuning both the mount transfer functions and the stiffness of the attachment points, resulting in improved isolation in a wide frequency range. As a result the disturbing, prominent interior noise patterns during electric drive as well as steering wheel vibrations could be reduced. Figure 5 shows the result of the synthetic optimization. The respective contributions (electric motor only) before and after optimization are displayed.

In a next step effect of the remedy is simulated in the complete interior noise. As expected, an improvement of the electric motor mounts alone is not sufficient to achieve good interior sound quality. Due to further contributors of comparable level (see also noise shares in figure 3), additional airborne noise insulation of the electric motor and inverter is needed in order to reduce whine noise. Similarly, airborne noise encapsulation alone will not solve the whine noise issue. This kind of trade-off is considerably supported by the ability to listen to synthesized sounds based on different modification scenarios. Then the different modifications and the level of improvement can be evaluated using cost-benefit analyses.

Thus, the binaural listening to predicted scenarios clearly supports the assessment and thus the whole NVH design process.

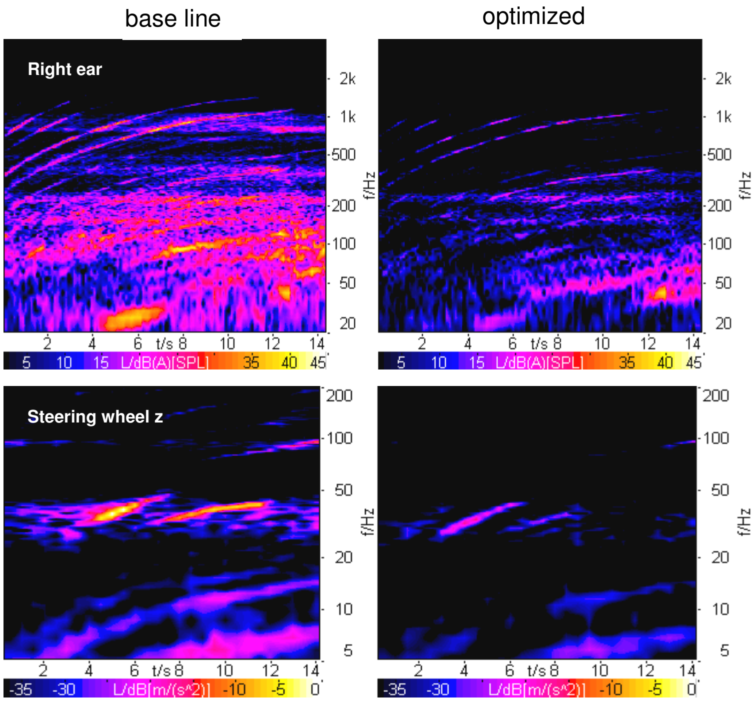

Figure 5: Contributions of electric motor to interior noise (top) and steering wheel vibration (bottom), before and after optimization

2.2 Exterior Noise of Electric Vehicles

Vehicle exterior noise of alternative drives is an important issue for sound engineering as well. The consideration of vehicle exterior noise is relevant with respect to two aspects: (a) to meet the pass-by noise regulation with respect to the allowed maximum pass-by noise sound pressure level, (b) to generate an exterior noise, which sounds appropriate and ideally conveys an impression of product high quality. Therefore, it is necessary to consider exterior noise issues already in the development phase in order to create the intended exterior sound. Although the sound pressure levels of electric cars are below the conventional cars equipped with combustion engines in general (see figure 6 and 7), annoying and displeasing noise patterns can occur.

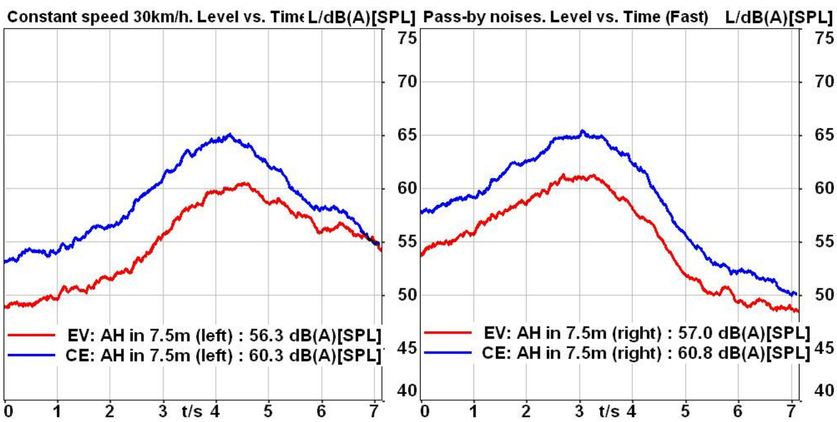

Figure 6: Comparison of the pass-by noise of an electric vehicle (EV) and a vehicle equipped with combustion engine (CE) for the driving situation “constant speed with 30 km/h” (left and right channel shown); Level vs. time

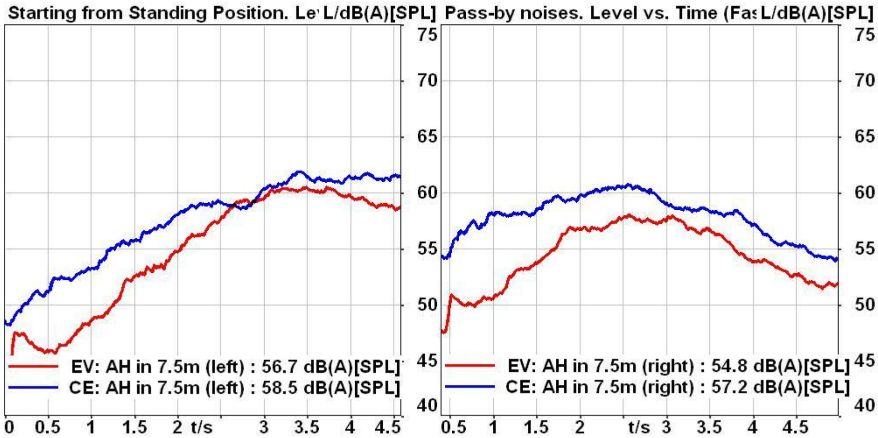

Figure 7: Comparison of the pass-by noise of an electric vehicle (EV) and a vehicle equipped with combustion engine (CE) for the driving situation “starting from a standing position” (left and right channel shown); Level vs. time

Figure 8 displays orders due to the operating noises of the electric drive and the power inverter, which run in opposite directions. This behaviour leads to a permanent change of the modulation frequency in the frequency range around 5 kHz. This is often assessed as unpleasant and obtrusive. The observed phenomenon - the run of tonal components in opposite directions - is untypical for vehicles equipped with combustion engines and attracts attention in spite of the relative low sound pressure levels of the tonal components.

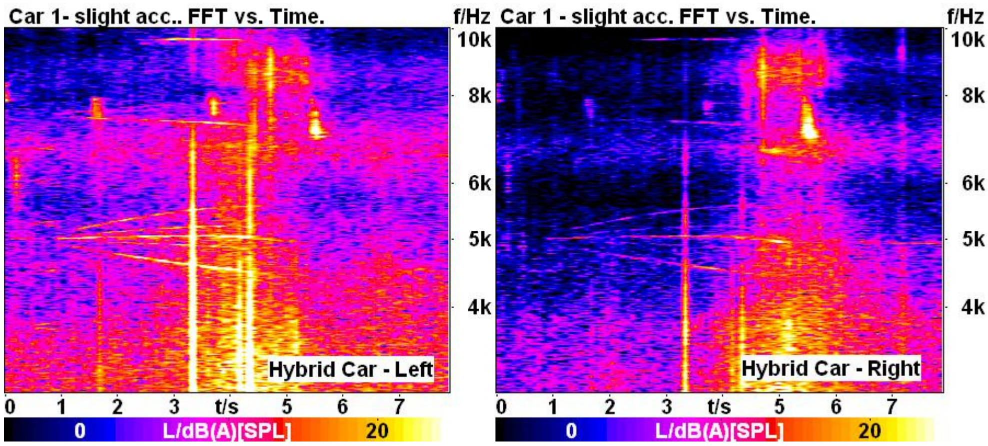

Figure 8: Pass-by of a passenger car with slight acceleration: Medium class car with hybrid drive (only in electric mode); FFT vs. time (3 kHz to 10 kHz)

Figure 9 illustrates even the stability of specific noise patterns with increasing distance. The power inverter noise around 6 kHz of the investigated hybrid car, which was driven only in e-mode, remains relatively constant and is still prominent and recognizable in greater distance. This means with respect to sound optimization of vehicle exterior noise that the reduction of the sound pressure level alone is not sufficient, since disturbing patterns are recognizable almost independent from their absolute level.

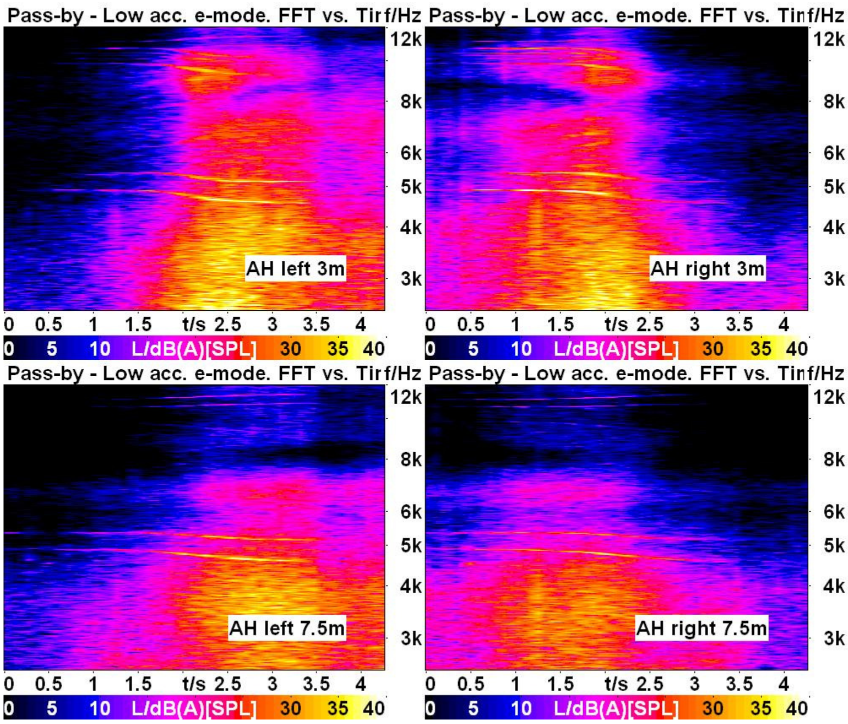

Figure 9: Pass-by noise (low acc. in e-mode) measured in different distances to the vehicle; FFT vs. time; top: 3 m distance, bottom: 7.5 m distance

Another application of electric motors lies in the context of scooters and motorbikes. Here, a considerable traffic noise reduction potential is given. As Figure 10 illustrates sound pressure level differences up to 20 dB can be found between conventional scooters (blue) and electric scooters (red, purple).

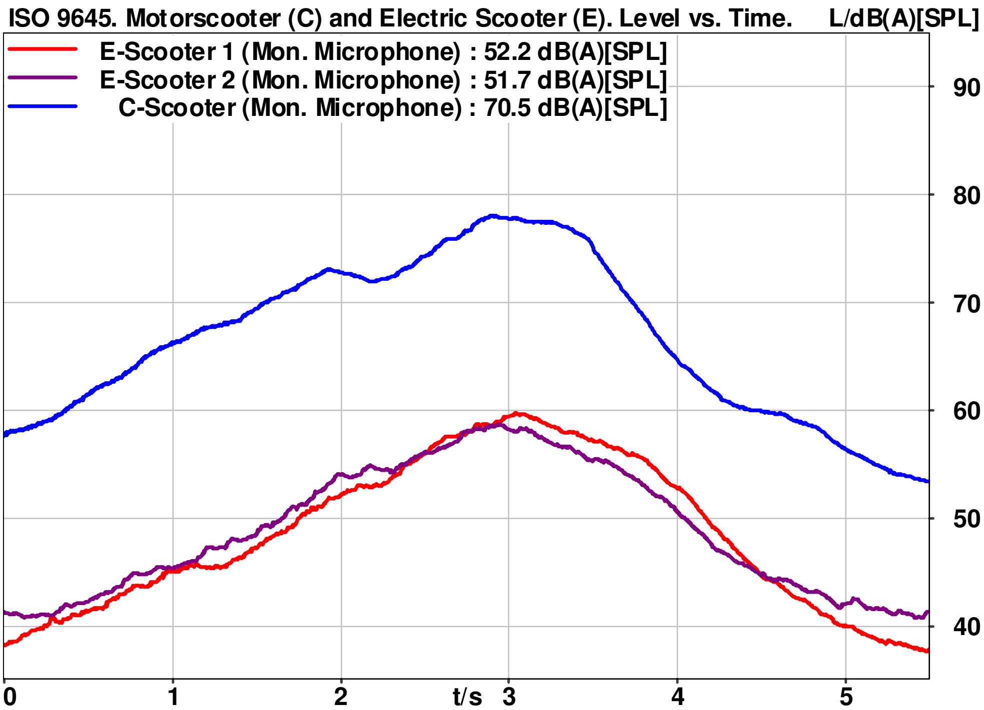

Figure 10: Pass-by noise of three scooters (two electric scooters, 1 motor scooter with combustion engine) measured in 7.5 m distance according to the ISO 9645; Level vs. time

This promising reduction of annoyance due to an electrification of scooters can be also expected for other driving situations. Figure 11 shows the loudness differences for the driving situation “starting from a standing position”, which is a very relevant driving situation, since this situation frequently occurs in the context of urban traffic. Here, the motor scooter is four times louder than the electric scooters.

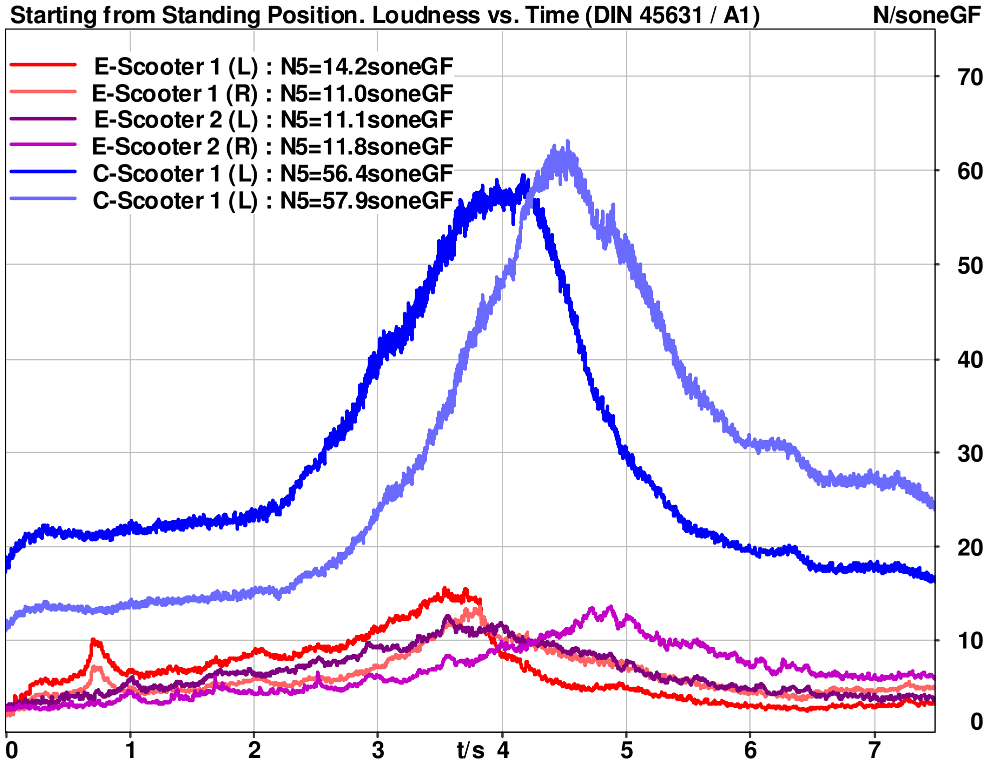

Figure 11: Pass-by noise of three scooters (two electric scooters, 1 motor scooter with combustion engine) measured in 3 m distance with an artificial head for the driving situation “starting from standing position”; Loudness vs. time analysis according to DIN 45631/A1

Furthermore, studies have shown that due to quiet electric cars the pedestrian safety can decrease [10]. In particular, blind persons seem to be at risk. In this context few countries like Japan or USA are discussing laws to guarantee a certain vehicle exterior noise level to ensure the audibility of quiet cars for visually handicapped persons. In fact, the discussion about required warning signals for an increase of pedestrian safety must also reflect quiet cars with conventional drives, since recent luxury cars equipped with combustion engines can also be very quiet with respect to driving situations with very low speed. The vehicle exterior noise for an electric driven car compared to a quiet car equipped with a combustion engine does not automatically considerably differ with respect to dB(A) or loudness. Regarding specific low speed situations, the discussion about protection of visually handicapped persons from too quiet cars must be extended to conventional cars as well [11].

2.3 Ideas for Sound Design of Electric Vehicles

A customer-oriented, client-specific target sound considers the expectations of the target customers and will achieve highest acceptance. However, with respect to electric vehicles up to now there is no extensive and proven experience available regarding sound quality and acoustical comfort. Thus, specific tests have to be carried out to determine the preferred noise characteristics and the adequate sound due to the image of the product, the expectations of the target clientele, the needed acoustical feedback, the public evaluation of alternative drive concepts in general, etc. The simple transfer of knowledge and experiences from combustion engine sound to the electric engine sound will not lead to any promising results. With respect to the object of investigation the necessary test environment has to be selected. Laboratory tests, where noise stimuli are presented and evaluated by listeners, are frequently performed to collect data with respect to target values. For reproducibility, these tests are often completely standardized and carried out in a “controlled”, in most cases artificial environment. Standardized test conditions should allow for provable statistical correlation between subjective ratings and objective parameters. However, the results are often biased because of the stimuli representation out of original context and the response limitation. Therefore, the external validity of the laboratory results is limited and they cannot be generalized, which means that the derived results cannot be confirmed under actual operating conditions within real driving scenarios. The original context, the ambiance of a real car, interactivity processes, further sensory input (haptics, visual information, vibration) can significantly modify noise assessments. All in all, the determination of vehicle target sounds requires most realistic test environments. In this field, developments in the area of „virtual reality“, adapted to special requirements of sound and vibration design, make meaningful contributions. For example, a sound simulation system (H3S) allows the examination of different sound stimuli, embedded in realistic contexts and situations. The input data for the simulation system is recorded in an aurally-accurate way and consists of run-up measurements on a roller dynamometer and coast down measurements. By means of multiple coherence the wind noise share can be separated from the tire noise. Using complex synthesis algorithms the input data is prepared and processed. Two applications of the sound simulation systems are possible. The system can be installed in a stationary driving simulator - a real vehicle cabin with authentic control instruments and equipped with the simulation of acoustical and vibrational feedback (figure 12 left). Moreover, the system can be implemented in a mobile driving simulator - a real car driving on a real track (figure 12 right). In both cases, the sound simulation system permanently provides vehicle interior noise in real-time corresponding to the use of operating controls and corresponding to the actual driving condition respectively. The single contributions – engine sound dependent on speed, load and rpm, the tire and wind noise dependent on speed - is provided to the driver’s ear in real time. The vehicle sound playback adjusted to the monitored control parameters take place via headphones. The driver can interactively produce the relevant driving situations, the aurally-accurate playback dynamically adapts to the current driving situation; the level of perceived reality is very high.

Figure 12: Stationary driving simulator with visual display (left) and driving simulator on real track (right)

The ability to both feel and hear the results of engineering via a "virtual car" (simultaneous engineering) can significantly shorten the vehicle development time. In order to use the potential of such simulation systems, innovative methods are necessary to examine vehicle noise adequately with respect to sound design and target sound development.
Using context-sensitive approaches, such as the Explorative Vehicle Evaluation method (EVE), target sound development projects can be realized [12]. The test persons are requested to drive the vehicle in their accustomed manner. During the drive the test person should report all present associations, emotions and impressions concerning the overall vehicle sound or with respect to specific noise properties. Besides the verbal evaluations, the respective noise (binaural signal), vibrations and the operating data (speed, rpm) are recorded and constitute the data pool for analysis. To verify the verbal evaluations and to collect further significant data a follow-up interview within the vehicle must be carried out, in which the test individuals can listen to the commented driving sounds again and have the opportunity to explain the evaluations in detail. After the analysis of the different data levels conclusions with respect to a modified vehicle sound can be made, which could be subsequently implemented in the mobile sound simulation system and be tested again with further test subjects.

3. Conclusions

Sound and vibration parameters must be considered as important elements regarding comfort and perceived quality. They can be important with respect to a well-balanced atmosphere causing highest customer satisfaction. In particular with respect to new engine concepts sound and vibration can provide meaningful information for acoustic orientation and handling of the vehicle. Here, complete new requirements and customer demands can emerge with respect to vehicle interior as well as exterior noise, where answers must be quickly found. Here, binaural measurement technology and a psychoacoustic understanding of sound perception are necessary with respect to sound quality tasks. To fulfill the increasing customers' demands with regard to product sound an expansion of this knowledge is still necessary.
Several approaches and tools (e.g. BTPA, BTPS, microphone arrays, sound simulation systems, driving simulators) may help acoustic engineers to solve future sound quality related tasks and to create adequate acoustic settings and „brand sounds“. All in all, sound

quality studies and target sound development - in particular in the context of new alternative drives concepts - require multi-dimensional approaches integrating new and interdisciplinary methods and procedures. There is a need for innovative, high-performance measurement technology to meet increasing requirements with respect to increasing customer expectations and shortened development cycles. To sum up, advanced psychoacoustic analysis methods and innovative measurement technologies have to be developed further to allow objective measurements that relate well to human sound perception. Only with innovative tools it is possible to survive on a competitive market, where various drive concepts will come into the market.

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