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Sound design of electric vehicles - Challenges and risks

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ABSTRACT

Sound quality depends on cognitively processed features referenced to an assigned set of expectations. It describes the perception of suitability and desirability of a sound attached to a certain product. However, since experiences of electric vehicle technology and established expectations rarely exist, several questions remain unanswered. What are the references customers use to evaluate sound quality of electric vehicles? How to meet customers' needs without established targets? Is it possible to simply set sound quality standards, where customers will increasingly adapt to?

Experiments and interviews are needed to answer reliably these questions. It is evident that successful sound design of electric vehicles depends on several aspects. Besides customer preferences, technology image, strategies of car manufacturers, economic and ecological factors, the social discussion of electric vehicle technology will contribute to the acceptance or rejection of sound design concepts. In fact, expectations are socially shaped and the impact of public discourse on expectations must be considered.

The paper will present results gained in test drives, where subjects drove electric vehicles and commented different sound concepts. Moreover, the experimental results will be discussed from a broader contextual perspective.

Keywords: sound quality, psychoacoustics I-INCE Classification of Subjects Number(s): 13.2, 63.7

1. INTRODUCTION

The electric vehicle technology breaks new ground for automotive development and for acoustical design in particular. It permits generally for thinking in new directions of sound design regarding interior and exterior vehicle noise. However, the acoustical requirements for electric vehicles are not clear in detail and the discussion about acoustical needs in order to fulfil customer demands still polarizes. The lively discussion ranges from concepts of providing extremely quiet cars to electric cars with playback of fully synthesized "modern" sounds.

With respect to vehicle exterior noise, there general hope is raised for quieter road traffic and less noise polluted cities. At least, under certain conditions a road traffic noise reduction is possible to a certain degree. However, at the same time politicians and blind unions call for a better audibility of electric vehicles and propose warning and alerting signals for increased pedestrian safety. It is still open, whether solutions of simply playing back some additional sounds will significantly ban the risk of collisions between pedestrians/bicyclists and vehicles in general. However, politicians take already first legal actions and measures.[1]

Regarding the interior noise of electric vehicles, the development and conceptual orientation of sound design is not settled so far. On the one hand the sound character of the electric motor could be kept and refined [2], or on the other hand there are ideas for synthetic sound playback of sporty vehicle interior noises [3]. However, there is no established knowledge about customer preferences, demands and needs. Although several customer surveys are carried out [e.g. 4], the outcomes are rather vague. Customers are usually without experience with electric vehicles so far and therefore they cannot rely on an established set of expectations to express reliably their wishes and needs. This means that they must hypothetically construct experiences to specify what is needed and what is unnecessary. Thus, it is of great relevance to determine how customers respond to new vehicle sounds and how they create new frames of reference for (sound) quality assessment in electric vehicles. This goes beyond to simply ask what they think, in case they would drive an electric vehicle, an appropriate interior sound

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is. In case of hybrid vehicles, noise and vibration aspects in the complex interplay between combustion engine and electric motor have to be considered, since certain phenomena are "unfamiliar to most drivers and often judged as disturbing"[5].

In order to investigate the perception and assessment of different sound proposals in the original context, a pilot study was carried out. [6] This should provide data about customer reactions to different sound design concepts while driving a series-production electric vehicle.

2. CASE STUDY ABOUT THE ACCEPTANCE OF SYNTHETIC SOUNDS IN AN ELECTRIC VEHICLE

2.1 Generation of Synthetic Sounds for Case Study

In order to create synthetic sounds depending on the driving condition of an electric vehicle in real-time, a sound synthesis tool was developed. This sound synthesis tool allows for developing sounds by means of several synthesizers providing harmonics at certain intervals, Shepard tones, noise, modulation or roughness. Figure 1 shows the sound synthesis interface used for the development of synthetic sounds. According to Küppers synthesizer programming is superior to any sample based algorithm and by means of several oscillators many possibilities exist to create complex spectral sounds [7].

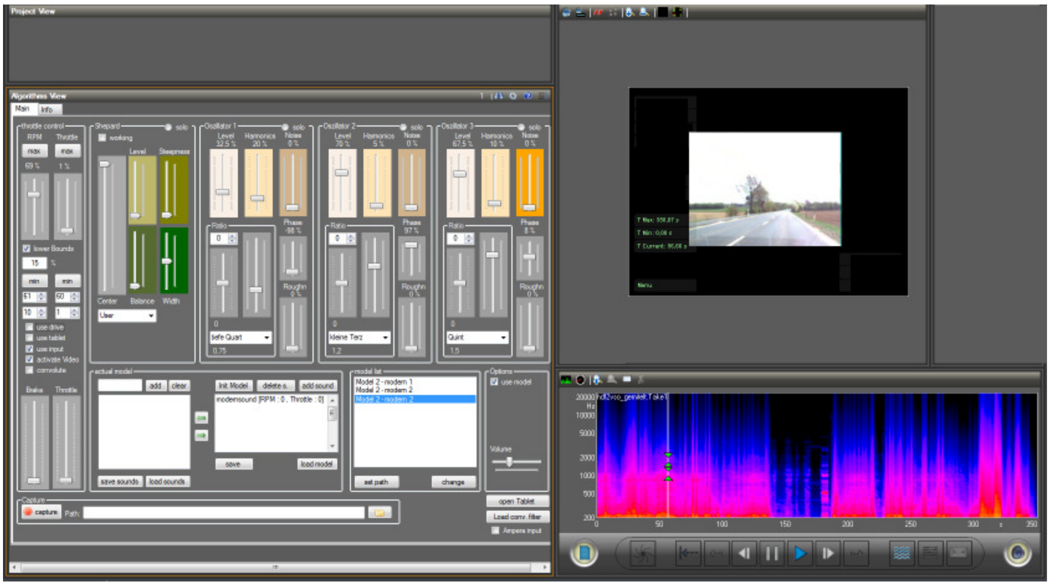

Figure 1 – Sound synthesis tool for development of sounds

On the basis of different developed sounds distributed over the entire vehicle map (speed and load map ranging from zero to maximum) for all driving conditions, respective sounds can be provided. This means that specific sounds are developed for certain driving conditions covering the whole operating map. Between these sounds the respective sound is virtually created by interpolation. The final degree of detail of sound synthesis is up to the sound designer developing a certain sound character and it is not limited by the synthesis tool. Moreover, to emphasize additionally rapid load changes, a loudness adaption function was implemented. In case of a rapid positive load change, a strong loudness increase of the synthetic sound occurs additionally. After the load change the loudness of the synthetic sound decreases with an adjustable decay. This feature provides, if desired, a stronger impression of load feedback, on top of the possibly designed loudness increase with increasing speed and load of the respective synthetic sounds in the operating map. Frequently, the use of Shepard tones is proposed [7], which was discovered by Shepard in 1964. [8] Shepard tones have the advantage that they can create an auditory impression of continually increasing or decreasing frequency, although the spectral content remained constant. This allows for creating an impression of a sound permanently moving upwards (or downwards) without the need for changing significantly the spectrum of the sound. This avoids the occurrence of disturbing and unpleasant high frequency content.

2.2 Developed Sound Concepts

In order to collect data with respect to the acceptance of synthetic driving noises in electric vehicles, three sound concepts were developed based on the developed sound synthesis tool. The different sound concepts exemplarily cover conceivable sound design approaches. The developed sound concepts were (1) a sound resembling a combustion engine, (2) a modern, rather unconventional sound, and (3) an inconspicuous, modest sound. In order to compare the reactions to these sound concepts with the reactions evoked by the original sound the fourth sound under investigation was the original vehicle sound of the electric vehicle. Table 1 summarized some differences between the sound concepts under scrutiny. Moreover, figure 2 displays the design of the different sound concepts regarding loudness with respect to different driving conditions. It is clear that the total loudness due to adding synthetic sound to the original sound must increase in the sound concepts 1, 2 and 3 compared to 4. However, the amount of loudness increase was designed in order to investigate certain sound design possibilities and their acceptance level.

Table 1 – General properties of sound concepts applied in the pilot study

Concept	General Character	Idle noise	Roughness	intervals (relative to fundamental frequency)
Sound concept 1	like combustion engine	yes	yes	lower octave, quint, tonic
Sound concept 2	modern	no	no	lower quart, minor third, quint
Sound concept 3	inconspicuous	yes	no	tonic, quint, higher octave

Sound concept 1 used the main engine orders of an eight-cylinder combustion engine. In case of sound concept 3 engine orders were chosen with higher frequencies causing a different sound character. Sound concept 2 was realized by using the lower quart, minor third and quint in relation to the fundamental frequency, which is related to vehicle speed.

In addition, the synthetic sounds possess an adaption of the loudness according to load and load changes. This means that in case of rapid load changes, a stronger loudness increase of the synthetic sound occurs. This loudness adaption was implemented with different intensity for the three synthetic sound concepts. Furthermore, in case of sound concept 1 amplitude modulation was applied to create additionally a perception of roughness.

The synthesis also included a function to generate additional noise to reduce the perceived artificiality of any synthesized sound. This was performed for all three sound concepts; however, the degree of adding random noise to the synthesis sound was varied over the different concepts in order to detect potential influences of this measure on the perceived naturalness of synthesis.

Idle sounds were introduced in sound concept 1 and in sound concept 3 with lower amplitude. Sound concept 2 did not possess any idle noise.

Figure 2 shows the loudness differences of the sound concepts under scrutiny for different driving conditions. It is clear that the lowest loudness occur in the test scenario “original sound only”. At constant speed, sound concept 3 is also relatively quiet, but has a considerable loudness increase for tip-in situations. Sound concept 1 and 2 are more prominent in terms of loudness (see figure 2) and temporal and spectral patterns (see figure 3). Figure 4 illustrates the influence of loudness adaption level in case of load changes on perceivable patterns by means of the Relative Approach analysis, which identifies changes in the short time spectrum in the frequency and time domain. [9] It can be seen that in case of a tip-in within the “original sound only scenario” no prominent patterns occur, where in case of a load change in the sound concept 3 noise patterns occur suddenly. In case of sound concept 1 this phenomenon occurs as well, but in general the amount of noise patterns is generally higher compared to sound concept 3. Sound concept 2 has also a lot of noise patterns in the frequency domain, but the load change is not indicated by a considerable increase of patterns.

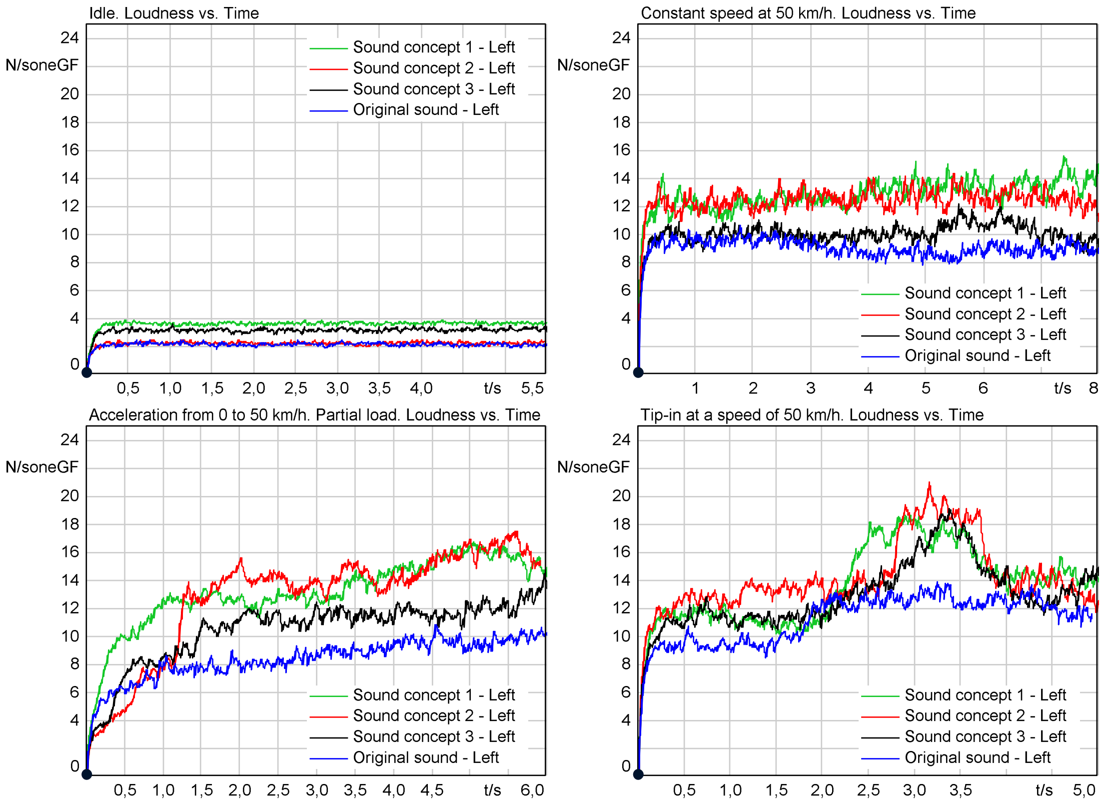

Figure 2 – Loudness over time of different sound concepts and driving conditions according to the DIN 45631/A1. Top left to bottom right: Idle, constant speed at 50km/h, acceleration from 0 to 50 km/h with partial load, tip-in at a speed of 50 km/h (only left channel shown).

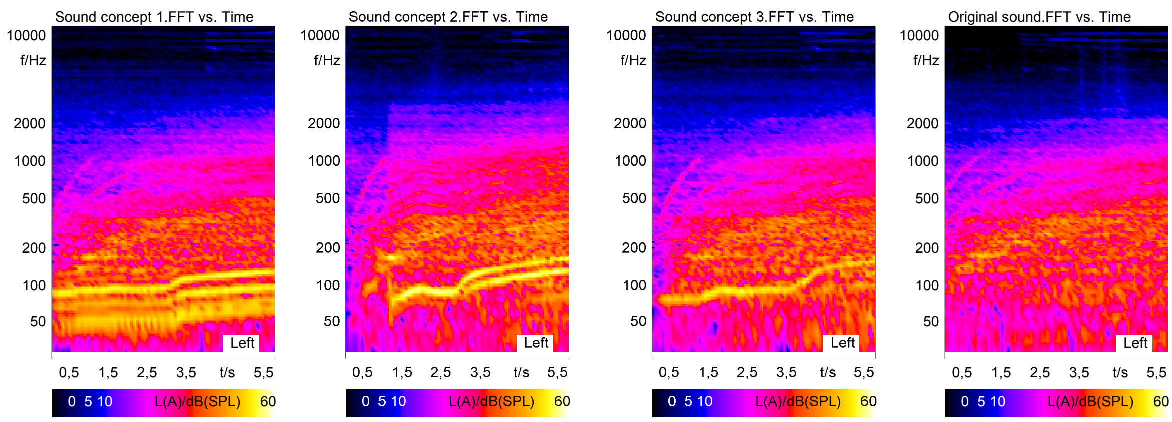

Figure 3 – FFT (A-weighted) vs. time of different sound concepts for the driving condition “acceleration from 0 to 50 km/h with partial load”

In summary, the sound concepts vary in spectral content and sound character, total loudness, modulation, loudness adaption level in case rapid load changes, existence of idle sound, level of variation of sound and their specific magnitude-load-speed relationship. Since several parameters are changing at the same time, in-situ judgments cannot be directly assigned to certain properties included in the sound concepts. The pilot study was designed as an explorative study to identify aspects relevant to the perception and assessment of sounds while driving an electric vehicle, rather than determining the target sound for the test vehicle. However, by means of the analysis of free comments given by the test subjects while driving and of interview data collected after the test drive, conclusions can partially be drawn with respect to the acceptance of specific synthesis sound measures and actions. Thus, the verbal data was subject to an extensive text analysis based on a qualitative content analysis. [10]

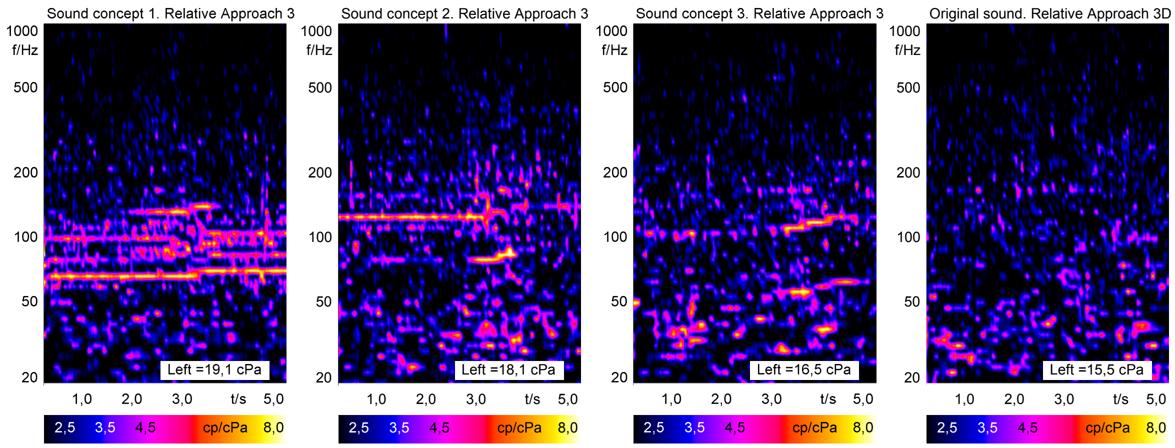

Figure 4 – Relative Approach Analysis vs. time of different sound concepts for the driving condition "tip-in at a speed of 50 km/h" (only left channel shown). The tip-in event occurred at about 3 s.

2.3 Explorative Study in Realistic Test Environment

2.3.1 Procedure

In general, laboratory experiments use artificial test situations in order to control confounding variables. Thus, subjects need a high level of abstraction to transfer associatively the experienced test situation to more realistic contexts. In every-day life, any evaluation of stimuli is embedded in a complex realistic situation. To overcome the drawback of laboratory experiments, tests can be carried out in more realistic contexts ensuring high ecological validity of test results.

This principle is used by the Explorative Vehicle Evaluation method (EVE) [11], where a test subject creates stimuli for judgment by itself in most realistic context and can even use its own vocabulary to judge the vehicle and its acoustics. These conditions increase the perceived naturalness of the test situation and a most significant set of information for sound design is gained. It is evident that the differing impact of confounding variables, the individual vocabulary and complex interplay of senses must be critically discussed in detail with respect to the generality level of results. However, the method EVE aims to explore the perception and assessment process in close to reality contexts, to detect relevant variables and to "explain" variance by illuminating the individual assessment strategies. It does not aim to develop dose and response relationships in mathematical terms. The EVE method was adapted by Sellerbeck to automotive sound development processes. [12]

2.3.2 Data Collection

The different sound concepts, described in chapter 2.2, were implemented and assessed by test subjects in a compact class series-production electric vehicle (Opel Ampera).

The test procedure, data acquisition and questioning of subjects were performed according to the method described in chapter 2.3.1.

The test subjects drove 20 to 25 minutes the electric vehicle on a defined test route in the area around Aachen, Germany. The test route was chosen to provoke as much as possible relevant driving situation (including city and highway driving with various speed limits). Figure 5 illustrates that all relevant speed ranges were well covered. Since electric vehicles are considered to be mainly applied in urban context, lower speed ranges had a greater share in the test route, which is confirmed by the statistical analysis of the speed data. During a test drive only one sound concept was presented in order to promote the impression of an every-day drive.

In total, ten subjects (six male, four female) took part in the case study with different background concerning experiences with electric vehicles and NVH background knowledge. Five subjects evaluated all sound concepts. To avoid any memory effects, a waiting period of several working days was between test drives. Thus, test subjects could not recall all acoustic details and were gradually reset. Several test subjects explained after the test drive that they could not directly compare their recent experiences with the previous experiences due to the long time between the test performances. The subjects compared the different test drive experiences more in general. (E.g. The first sound was better than the second test drive sound.)

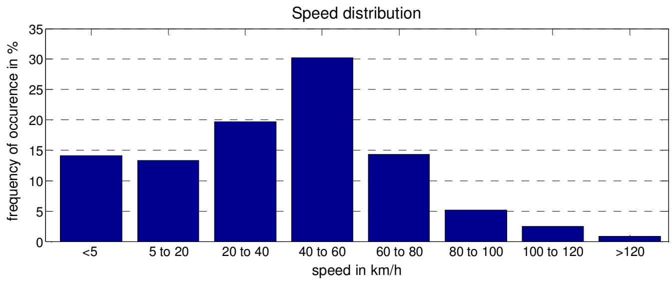

Figure 5 – Speed distribution based on 29 test drives.

In total 29 test drives were performed providing approximately 15 h test drive data for subsequent analysis. During the test drives the subjects were requested to express spontaneously their associations, emotions, feelings and thoughts with respect to the vehicle, its general comfort and its acoustics in their every-day life language. For each test drive vehicle interior noise, comments, vehicle speed and throttle position were recorded as exemplarily shown in figure 6.

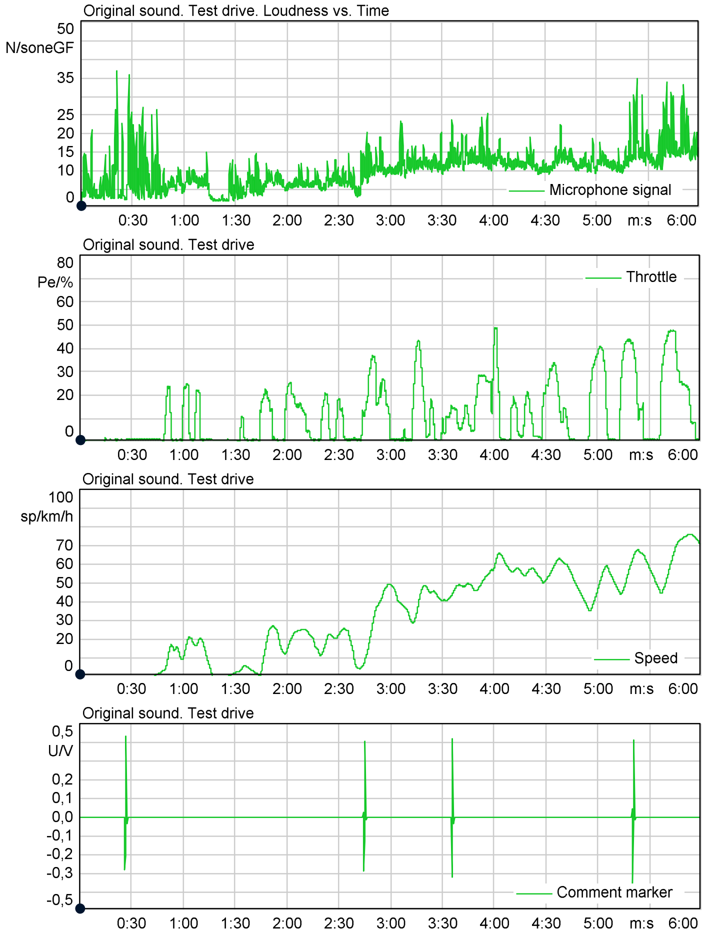

Figure 6 – Example of test drive data. From top to bottom: Recording of interior noise (including comments), throttle position (in percentage), speed (in km/h), and trigger signal indicating most relevant comments in the measurement

In addition, the experimenter took notes about test drive related aspects, relevant comments, which could be addressed in the postexperimental interview, and used a trigger to mark relevant comments in the data stream of the recording. This allows for a quick identification of comments relevant for categorization and further analysis.

After the test drive a semi-structured interview took place in the car and the subjects could explain their thoughts and feelings in detail, they answered some questions raised by the experimenter regarding their in-situ judgments and comments, they evaluated the perceived overall quality and sound quality. The possibility to explain in-situ judgments have two advantages: (a) the subjects can add detailed descriptions to the comments, which they have been provided while driving, and (b) the experimenter can collect further information to understand the given comments more in detail (communicative validity). In addition to the collection of subsequent explanations and reflections provided by the test subjects with respect to the comments given during the test drive, a guideline interview was performed, where additional background information was collected. Afterwards, all relevant statements were identified and categorized. Furthermore, the comments were classified with respect to their connotation as positive, neutral or negative and whether the comments refer to synthetic sound or to the original sound of the vehicle. This procedure allows studying the link between driving conditions, provided sounds and specific customer reactions in realistic context. Moreover, general strategies and assessment behavior underlying the distinct evaluations can be studied in detail.

2.3.3 Results – Reactions to Sound Concepts

Quantitative Analysis

Figure 7 displays the frequency of occurrence of driving situations based on all 29 test drives in terms of a color map and the comments given by test subjects while driving. The small rectangles show the respective driving conditions, where the comments were given as well as the general connotation of the comments as positive, neutral or negative indicated by color. It has to be mentioned that repeated comments by a test subject, who replicates comments (e.g. there it is again), were not considered in the further analysis and are not shown in figure 7. This avoids that a test subject gains in importance due to repeated comments increasing the total number of judgments. Of course, the number of comments provided by the subjects varied, but astonishingly the total number of comments was similar over the test subjects and ranges normally between 15 and 20.

Although only a small sample size could be considered, meaningful information about the relevance of certain driving conditions for sound design optimization and the suitability of certain sound concepts are gained.

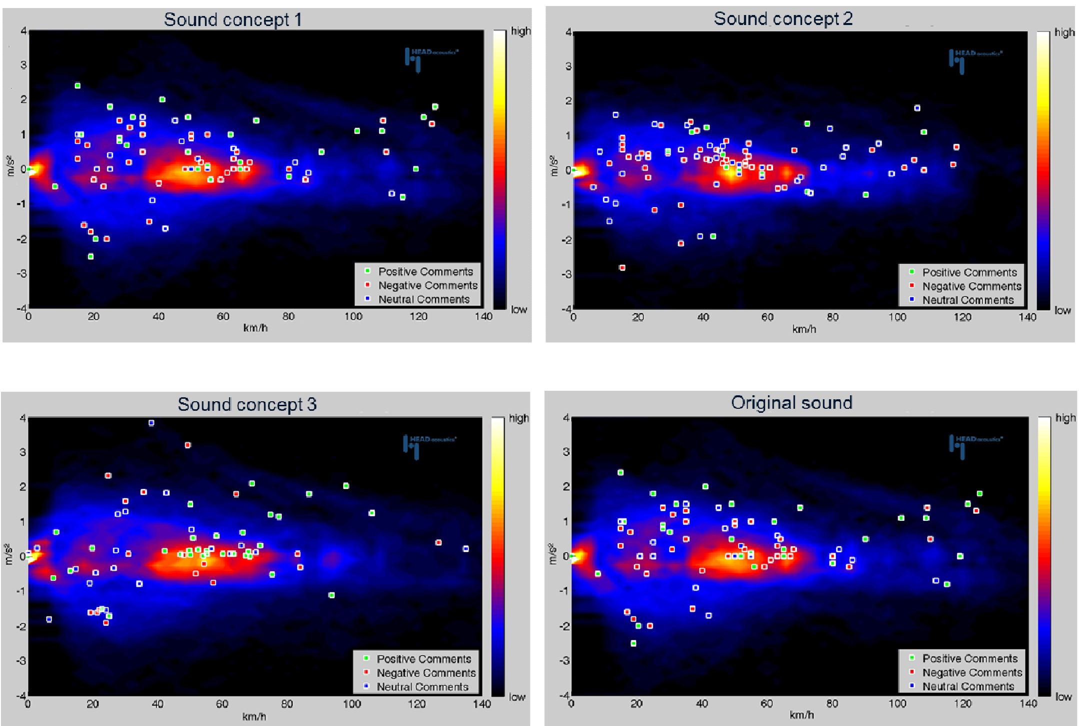

Figure 7 – Distribution of comments (classified as positive, negative or neutral) referring to the different sound concepts over speed and acceleration

Based on the simple distribution of comments, their number and connotation, first conclusions can be already drawn: All sound concepts provoke positive as well as negative comments. This means that all concepts cannot be considered as target sound concept leading to utmost customer satisfaction.

In general, the playback of synthetic driving noises led to more comments compared to the test drives without any sound playback. Obviously, synthetic sounds can additionally stimulate emotions and feelings.

Cluster of comments were found in the mid-speed range with moderate acceleration and in the low speed range with positive and negative acceleration. This might be due to the selection of the test route, but reflects the most relevant driving conditions in perceptual sense for electric vehicles as well.

In the low speed range with low or negative acceleration, mainly negative comments occurred. In particular, the original sound caused a lot negative comments in these driving conditions. Most comments were provoked by sound concept 2, whereas sound concept 3 and original sound scenario achieved clearly a lower number of comments. Sound concept 3 stimulated obviously several positive comments in the mid-speed range with moderate acceleration.

Moreover, figure 8 provides further information regarding the adequacy of the different sound concepts under scrutiny. It can be seen that the ratio between positive and negative comments is different over the different sound concepts. The best ratio between positive and negative comments has sound concept 3. Moreover, sound concept 3 is the only concept, where more positive than negative in-situ comments were observed. This is a remarkable result, since the majority of test subjects explained in postexperimental interviews that they prefer an electric vehicle without any "unnecessary" sound playback. The original sound condition leads to a balanced result with respect to positive and negative comments. The sound concepts 1 and 2 provoked more negative than positive comments, which means that due to the additional sound the perceived quality of the interior sound was gradually reduced.

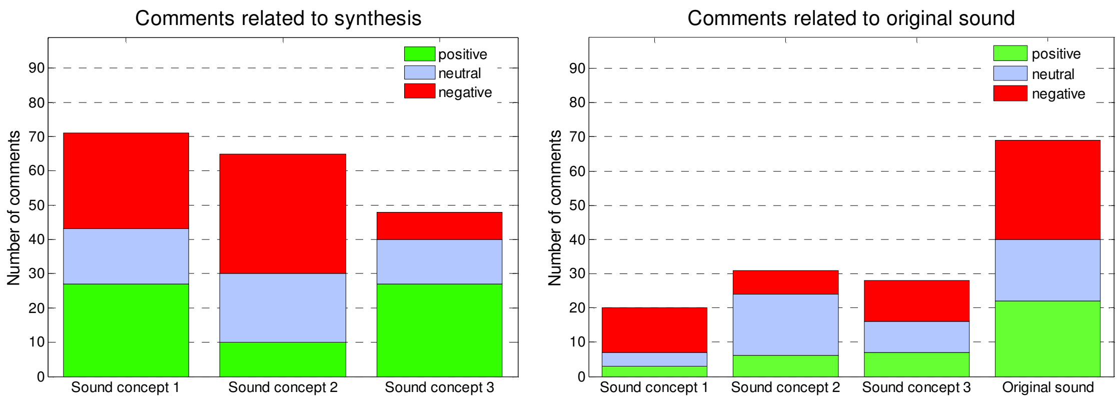

Figure 8 – Number of comments for the different sound concepts with respect to their connotation (positive, neutral, negative) and reference (synthesis, original vehicle sound). Left: Number of comments related to the synthesis; right: Number of comments related to the original sound

Qualitative Analysis

A text-analytic investigation of the comments can provide further information beyond simply interpretation of number of comments and their distribution over the driving conditions.

In general, lots of positive comments referred to the loudness adaption of the synthetic sound due to changes of the lead parameters, since it gives a good acoustic feedback. It can be concluded that a load increase should be indicated by a loudness increase of the sound synthesis, while in steady-state driving situations and in case of negative load changes a gradually decrease of loudness is preferred. Tip-in situations were frequently commented (see figure 7) and thus require specific attention with respect to sound design.

Moreover, a cluster of comments can be seen in Figure 7 for a speed within the range of 40 to 80 km/h with low acceleration. In those driving situations, subjects requested a "quiet", "gliding", "adequate" and "discreet" sound. This speed and acceleration range seems of particular perceptual importance and must be carefully considered in the sound design process.

Sound concept 1 achieved several negative comments in the low speed range with low or medium acceleration. The diverse comments referred to a “relative loud”, “obtrusive” and salient acoustic feedback, which did not fit to the respective driving situation at all. Although, it was frequently stated that sound character of concept 1 is acceptable and pleasant, the sound was perceived as “inappropriate”, “too low frequent” and “not suitable” for distinct driving situations. A subject explained that the sound reminds of a combustion engine and concluded “I feel deceived”. First of all, these comments make clear that the adequacy check of a developed sound has to be determined within the original context. Moreover, it strikes that the ratio of positive, neutral and negative comments of sound concept 1 is similar to the original sound situation. This allows for drawing two conclusions: (a) the original vehicle sound has some sound quality deficits leading to several negative comments and (b) the introduced sound concept 1 produces less negative comments related to the original sound of the vehicle due to masking, but provoke at the same time negative comments related to the presented synthetic sound.

Sound concept 2 (modern sound) received the lowest relative number of positive comments. Figure 6 shows that this sound concept provokes mostly comments in driving situations with low acceleration. The subject stated that the sound was “uniform”, “monotonous” and “artificial”. According to several subjects the sound was present even in situations, where an acoustical feedback is not required (cruising). The “omnipresence of sound” with a relative constant sound character was clearly rejected, since the sound becomes “exhausting” and “tedious” after a certain time.

Sound concept 3 was perceived as “inconspicuous” leading to the best assessment of sound (see distribution and connotation of comments in figure 7 and 8). The sound was described as “pleasant” and “suitable”, “something between car and tram-way”. Few subjects even did not recognize the presence of additional interior sound, but gave more positive comments than in the original sound only test condition.

In the original sound test condition several negative comments were collected, like “howling”, “whistling” or “annoying tones”. It is obvious that the original vehicle sound has some sound quality deficits, which can be more or less masked by synthetic sounds. According to figure 8, the number of negative comments referring to sound quality deficits or disturbing noises within the original sound increases considerably in the original sound only condition. This illustrates the possibility to avoid the perception of unwanted noises by energetically or attention-attracting masking. However, in general the lowest number of comments was provoked in this scenario, which speaks for a relative coherent and not attention attracting sound of the electric vehicle.

The high number of negative comments in the synthesis sound scenarios shows the high sensitivity of customers regarding perceived (sound) quality. Adding synthetic sound, which does not match the customer preferences well, will lead to a reduction of the perceived sound quality.

2.4 Conclusion

Based on a context-sensitive, explorative method the acceptance of different sound concepts in electric vehicles were investigated in detail. So far, the acceptance of new sound concepts by customers, like adding synthetic sound to the original sound of the vehicle, is still not clear. The presented case study explored the degree of acceptance of certain synthetic sounds experienced in a real electric car while driving. While offering synthetic driving noises in the interior of an electric vehicle have led to more comments, it did not necessarily foster positive evaluations or perceptions of the car and its acoustics. [6]

In general, the presented study has shown that target conflicts occur and must be managed. For example, subjects expressed their preference for a quiet electric vehicle, but on the other hand demand an adequate acoustic load feedback. The study has shown that an important factor for customer acceptance is a well implemented adaption of loudness in case of load changes. An adequate load feedback in terms of sound is of utmost relevance.

Moreover, the test subjects were inclined to favor inconspicuous, modest sounds, which in turn lead to an increase of felt acoustic transparency of the vehicle, which was negatively connoted in the present study. [cf. 10]

In the case study it was observed that a relatively inconspicuous synthetic sound, sound concept

3, got the highest number of positive comments and received the lowest number of negative comments. This sound concept achieved a slightly better assessment than the original sound only condition, although even few subjects were not aware of the presence of a synthetic sound at all. It illustrates that the modest sound character is accepted leading to positive comments. But, this sound does still not fully mask disturbing noises within the original vehicle sound and still evoked some negative comments as well.[13]

Finally, it must be stated that the general acceptance of certain sound concepts is far from conclusive. The comments and assessments are rather inconsistent, although trends are already observable. This observation can be interpreted as evidence for a missing established frame of reference of the test subjects. It is evident that the expectations of the customers are not fixed and grounded, thus the frame of reference permanently changes. According to the analysis of interview data it was found that the frame of reference is based on previous experiences mainly related to vehicles equipped with combustion engines and (ambiguous) information from the media about the electric vehicles technology. Thus, the assessments vary over the test drives and from person to person leading to apparently contradictory assessments.

Further research must focus on inconspicuous sound concepts, which evoke positive emotions and feelings and at the same time is capable to mask unwanted noises caused by the electric vehicle itself. For it, different approaches of synthetic driving sounds must be subject to investigation to determine their benefit for increasing perceived quality and customer satisfaction.

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