Vehicle Interior Noise – Combination of Sound, Vibration and Interactivity

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We humans take in the world via a variety of senses. Interaction phenomena are expected in the context of sound and vibration. In fact, the evaluation of acoustical comfort in a vehicle cannot be achieved with consideration of only the airborne noise. A passenger must be regarded as part of a vibro-acoustic system in which coupling with the vehicle occurs via contact points of the steering wheel, seat, floor panel and pedals. Within this context and quiet vehicles with low interior sound pressure levels, vibrations can become more important. The impact of combined sound and vibration stimuli on subjective evaluations has not yet been fully clarified. This article explores different test situations and their influence on measured results. Test subjects were asked to evaluate sound, or vibration, or both, with respect to their quality in different test situations. Different test settings were considered – real vehicle drive, noise and vibration reproduction in a driving simulator, and noise playback in a listening room. The tests provided information about the interaction of sound and vibration, and about the importance of other aspects such as situational awareness and interactivity.

Interior noise has become an important vehicle quality task for acoustical engineers in the automotive industry for more than 30 years. However, the goals have changed during this period. At first, acoustical engineers in the automotive industry were confronted with the task to make the interior noise of a vehicle tolerable and to reduce the SPL as much as possible. By reducing passenger cabin noise over the years, the engine sound provided less masking to other sounds. As a consequence, other sound sources could be heard. Since vehicles have continuously become quieter, the customer's sensitivity to acoustical comfort has increased. On the one hand, certain noise sources have become more perceptible due to reduced overall sound pressure levels. Human hearing adapts to an average level and becomes more sensitive for any changes in the time and frequency domain (see Figure 1).

Consequently, engineers had to broaden their work scope and had to deal with more intricate problems. They had to eliminate specific sound contributions that were completely masked in the past. They had to focus on several sources with different properties and characteristics. And finally they have had to maintain or even emphasize specific noise properties that are judged in a positive way.

The automotive industry realized that an explicit sound design is necessary in the field of vehicle development to improve the attractiveness of the product. Overall, the sound and vibration of a vehicle was no longer considered as only disturbing, which has to be reduced as much as possible, but drivers and vehicle manufacturers have noticed that an appropriate sound is useful for driving, produces driving pleasure and enhances the attractiveness and quality perception of the product.

Interaction of Senses

Because of permanent interaction effects between different parallel senses (tactile, auditory, olfactory, visual, gustatory), single-sense perception processes are internally combined into overall perception. Often, it is difficult to separate one activated sense from another without involving total perception. This phenomenon plays an important role in the context of vehicle interior noise, where visual, inertial, and vibrational inputs are presented. "We unconsciously utilize all sensory information to evaluate sounds."[1]

Based on a paper presented at Noise-Con 08, institute of Noise Control Engineering, Dearborn, MI, July 2008.

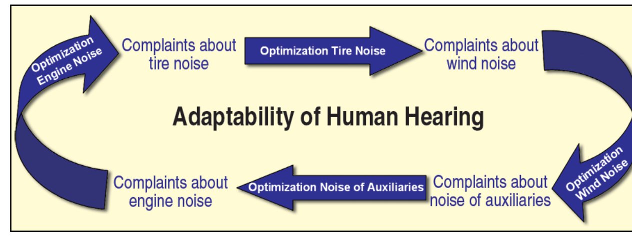

Figure 1. Adaptability of human hearing – permanent new challenges for acoustic engineers.

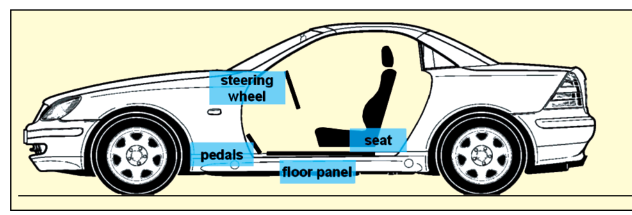

Figure 2. Main contact points of vehicle drivers.

So in the context of noise and vibration, interaction phenomena must be expected.

Multi-modal effects have to be explored to comprehend sound perception in the presence of different sensory stimuli and to optimize vehicle sound as best as possible to accommodate further influences on sound perception and evaluation. Several studies have already pointed out the necessity of considering both noise and vibration in the context of sound quality and acoustical comfort.[2]

A passenger must be regarded as a part of a vibro-acoustic system coupled via contact points in the vehicle – steering wheel, seat, floor panel and pedals. It is a coupled system – person and machine (see Figure 2). Vibrations become increasingly important in quiet vehicles with low interior sound pressure levels.

A balanced configuration of the vibration level in a vehicle has to be determined considering comfort as well as information content. Further research in the field of human perception of combined stimuli is necessary. That is not only important for product quality, but also in the context of occupational health and safety and environmental impact assessment. It is known from studies of reactions to whole-body and hand-arm transmitted vibrations that certain vibration magnitudes and frequency components increase health risks. The organs and extremities of humans have certain resonances that could be excited via contact points within a vehicle. However, "human responses to vibrations are varied and differ greatly over time and from one person to the other. Therefore a vibration limit is meaningless without the specification of relevant criteria . . . It is difficult or impossible to summarize all effects to define a standard with limits and standard values for all conditions and for the whole frequency and level range."[3]

Study of Intermodal Aspects

The results of diverse studies showed interaction effects. Vibrations have both positive and negative effects on sound perception. Partly, it was observed that vibrations can lower the annoyance caused by noise.[4] This effect is very interesting for automotive sound and vibration design.

Some studies found no evidence of interaction between sound and vibration. For example, Amman *et al*. assumed that there is no significant interaction of sound and vibration and concluded "setting sound and vibration targets for vehicle programs that are independent of one another seems to be a reasonable approach . . .

This simplifies the target-setting process significantly, since sound targets do not have to be a function of vibration levels and vice-versa."[5] Amman *et al*. examined the assessment of transient NVH events that occur when vehicle tires impact with a discontinuity in the road (impact harshness); they also examined the perceptual relationship of steady-state noise and vibrations experienced when driving over a coarse road.

To what extent the conclusions of Amman *et al*. can be transferred to all NVH-issues is questionable. Several publications report interaction effects in the field of sound and vibration. Hashimoto stated that the addition of seat and floor vibrations to vehicle interior noise increase the perception of power, unpleasantness and booming.[6] This issue is also intensively studied in other contexts, such as helicopters and aircraft.[7] Table 1 displays a selection of known concepts and theories of sound and vibration interaction

Table 1. Concepts and theories of noise and vibration effects (partially overlapping).

Additive Interaction	Vibrations increase noise evaluations
Subtractive Interaction	Vibrations decrease noise evaluations
Cognitive Capacity Theory	Noise and vibration act as cognitive load; in case of high cognitive load, difficult to assess different senses separately
Mismatch Theory	Humans mainly focus on single stressor (difference between stressors becomes more salient)
Contrast Theory	Stimuli divert attention (or mask) effect of other stimuli
Dominating Theory	One stimulus attracts more attention than the stimulus and dominates evaluation
Masking Theory	Loud noise raises vibration thresholds and vice versa
No Interaction Effects	Assessment of combined stimulus (effect) is equal to sum of individual stimuli (effects)

Table 2. Advantages and disadvantages of driving simulator for NVH.

Test Surroundings	*Seat in laboratory (artificial surrounding)* – Exact control of noise and vibration stimuli. Conflict: artificiality of situation. *Realistic test surrounding (simulator)* – Test person perceives stimuli in real vehicle sitting on original seat, seeing typical controls and instruments, orienting in usual automotive spatial geometry. *Stationary version* – Control of noise and vibration stimuli. Conflicts: artificiality of situation, limited driving feeling. *Mobile version* – Most realistic test surrounding. Conflicts: Limited comparability of occurred stimuli and assessments, respectively.
Contact Points	Test person experiences vibrations via seat and/or floor panel and steering wheel. Conflicts: Excitations are often realized only in one or two degrees of freedom over limited frequency range.
Interactivity	Simulation systems reproduce noise and vibration depending on test person's actions. Conflicts: limited comparability of occurred stimuli and assessments, respectively.
Room Acoustics	Human hearing automatically adapts to current location with its acoustic properties; in case of a mismatch between noise and acoustic room properties, test persons are often confused and irritated.

Figure 3. Stationary driving simulator, interior of SoundCar (left); exterior view (right).

Figure 4. Mobile driving simulator equipped with 3D sound simulation system (H3S) and test person (left); experimental leader (right).

phenomena. The list shows widespread concepts that are partly overlapping; but the list is not exhaustive.

Until now, no general concept is broadly acknowledged. Presumably, occurrence of the noted effects varies with context, with "ratio" of sound and vibration or from individual to individual. The current knowledge is insufficient to provide a complete explanation about the interactions between these sensory dimensions; in particular when evaluating acoustical comfort criteria.

Driving Simulators

Combined playback of sound and vibration in real passenger cabins is possible by means of driving simulators. Table 2 displays the importance of driving simulators with respect to acoustical comfort and sound quality investigations in the field of automobiles.

The SoundCar is a listening environment that consists of a real vehicle cabin with authentic control instruments equipped with a simulation system of acoustical and vibrational feedback (see Figure 3). The sound simulation system (H3S) provides an interactive simulation of a current driving situation, which depends on the driver's actions and vehicle controls. The simulation hardware is mounted in the engine compartment. An additional subwoofer, located in the trunk, generates low-frequency sound below 150 Hz. The vibrations in the low-frequency range are particularly important with respect to the subjective assessment of acoustical comfort.[8] Seat excitation is provided by an electrodynamic shaker in the Z direction. Excitation of the steering wheel takes place in the direction of rotation by direct control of the steering shaft.

Reproduction of sound at the ear is based on recordings made during tests of engine noise on a four-wheel chassis dynamometer and coast-down measurements for determining wind and tire noise. The application of binaural technology guarantees realistic reproduction of the complete spatial hearing sensation. Headphones provide localization reproduction accuracy. The sound simulation system can be used in stationary driving simulators as well as in mobile driving simulators (see Figure 4).

Vibrations cannot be controlled in the mobile simulator and depend on the actual vehicle used and the sound simulation system installed. The advantage of a mobile sound simulation is that perfect driving dynamics and an authentic vibrational setting are given by using a real vehicle. In contrast, a stationary sound simulation

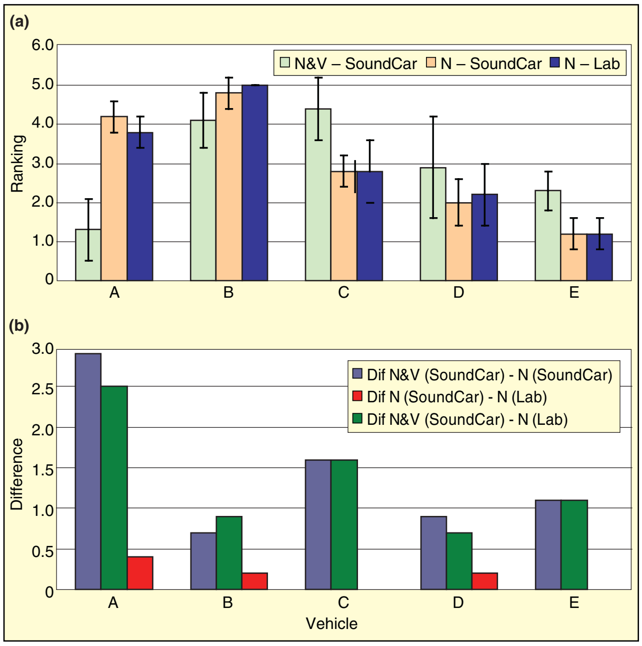

Figure 5. Rankings of five vehicles in operating mode "50 km/h in third gear" with evaluation criterion "appropriate noise to slow driving;" top: ranks (mean); bottom: differences in rankings between the settings.

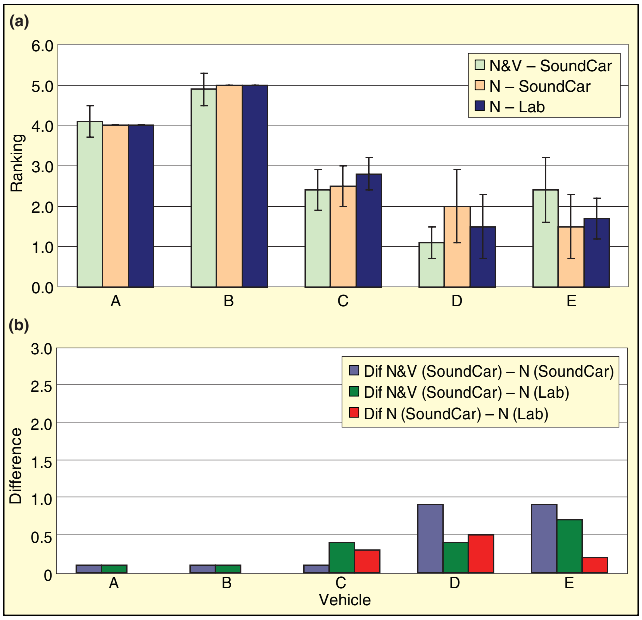

Figure 6. Rankings of five vehicles in the operating mode "3500 rpm in 2nd gear" with evaluation criterion "acoustical comfort;" top: ranks (mean); bottom: differences in rankings between the settings.

allows for the control of the vibration stimulus, but the authenticity of the driving situation is reduced. The test environment has to be selected with respect to the object of investigation,.

Investigating Noise and Vibration Effects

Case Study 1. A study was carried out to investigate the influence of vibrations on evaluations of acoustical comfort criteria using a stationary driving simulator (SoundCar). Five different vehicles (station wagons) in various operating modes were recorded. The binaural signals (the receiver position was the position of the driver) as well as the acceleration signals of the seat in the Z direction and the acceleration signals of the steering wheel in the direction of rotation were available for the listening tests. The test subjects ranked the stimuli of a specific operating mode between 1 and 5 (worst to best); equal ratings were also accepted. Three runs were carried out. In the first run, the interior noise was offered together with the corresponding vibration excitations (N&V). In a second run, only the airborne noise contributions of the five vehicles

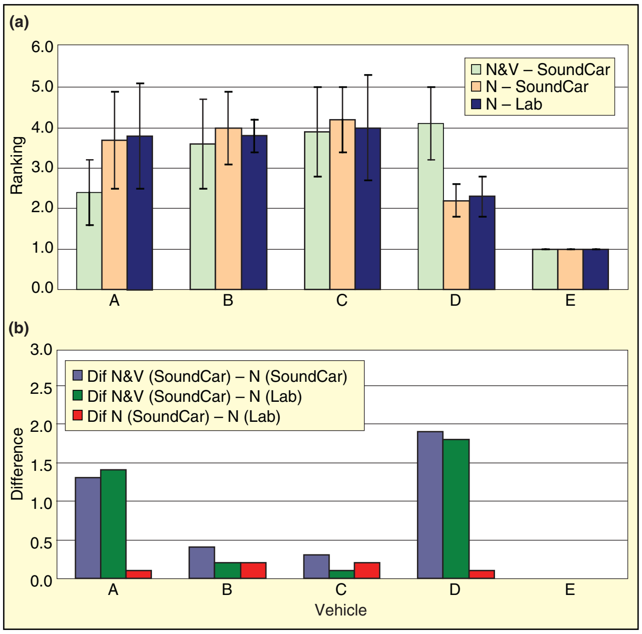

Figure 7. Rankings of five vehicles in the operating mode "starting the engine" with evaluation criterion "perceived acoustical quality;" top: ranks (mean); bottom: differences in rankings between the settings.

were presented (N-SoundCar). The stimuli were presented while the test subjects were sitting in the stationary driving simulator. In a third run, the test subjects ranked the different noise stimuli in the laboratory (N-lab). The runs took place at different days to exclude the influence of memory effects.

Figures 5a, 6a and 7a show the averaged ranks of each vehicle in different operating modes assessed in different test surroundings and conditions. The standard deviation is also depicted in the diagrams. Furthermore, Figures 5b, 6b and 7b display the differences of averaged ranks between the different test conditions. The presented noise was always identical; the vibrations were only presented in Scenario 1.

The subjective evaluations differ depending on the vibration presentation. Small evaluation differences could be observed between the test surroundings for the SoundCar and laboratory, where the stimuli – only airborne noise – were identical. Note that part of the evaluation criteria were not exclusively noise related. For example, the evaluation criterion "appropriate to slow driving" allows for the intentional consideration and integration of the vibration magnitude into the assessment. However, two conclusions can be drawn from this case study. First, the evaluation differences between noise playback within SoundCar and laboratory (red bars) show the influence of the test surrounding and context on the evaluations. The judgments were not completely equal, although the noise stimuli were identical. Second, the presence and magnitude of vibrations affect the subjective evaluation of the perceived noise.

Of course, the ranking method does not allow definite conclusions. The different rankings do not offer any clues with respect to the exact cause and quantitative extent of numerical differences. Nevertheless, the study shows the importance of vibrations to noise assessments and the importance of the context (realistic vs. artificial surrounding).

Case Study 2. Another experiment was conducted to study effects caused by the test environment. Evaluations of sound and vibration stimuli were given during a real test drive on the road and during driving a stationary simulator.

In the driving simulator, no moving scenery information or other visual input was provided except the test environment itself. Different operating modes of six vehicles were assessed with respect to overall quality, quality of engine noise, tire noise, wind noise, seat vibration and steering wheel vibration using a scale corresponding to school grades, ranging from excellent/very good (1) to inadequate/fail (6). Eleven test subjects took part in each test scenario; the test persons were well experienced with sound and vibration evaluation tasks. The judged driving conditions were,

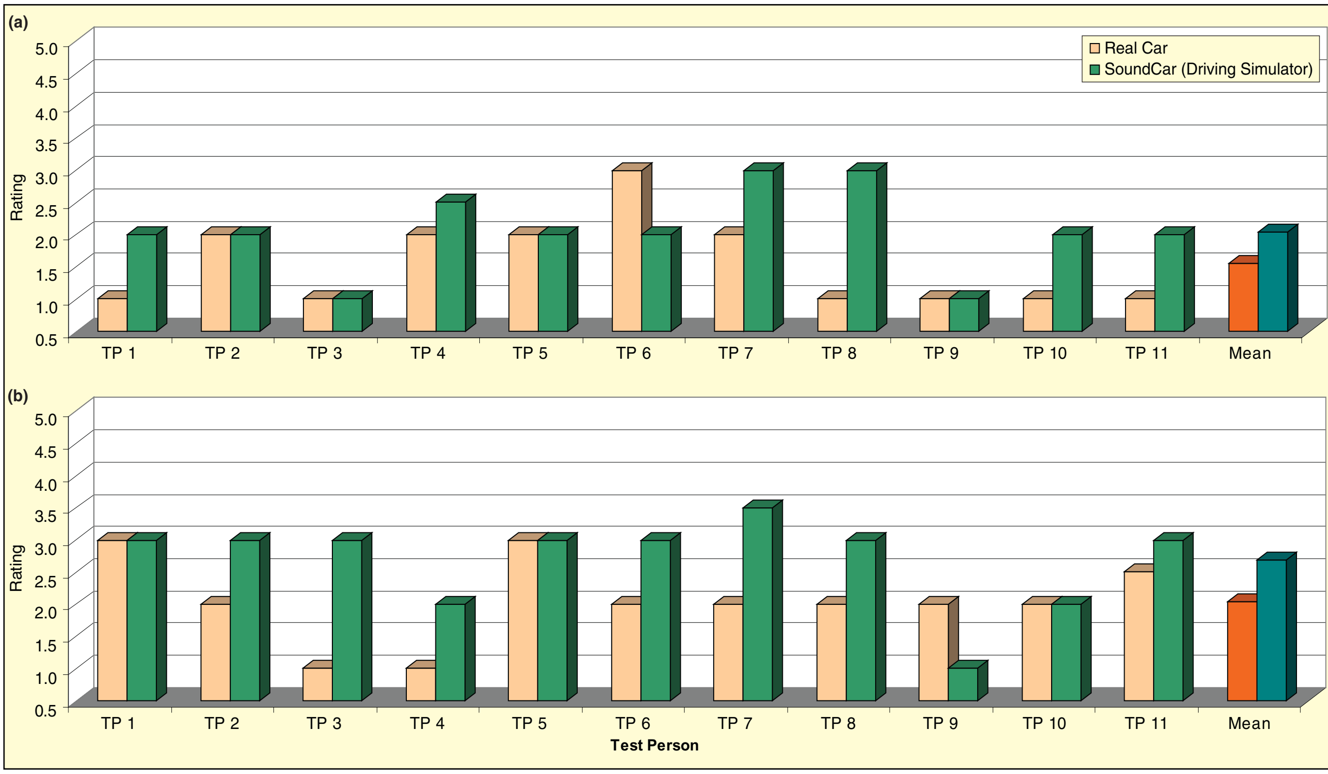

Figure 8. Comparison of ratings: one vehicle in operating mode "constant speed 100km/h (4th gear)" in the real car and played back in a driving simulator (N&V); top: engine noise quality; below: steering wheel vibration quality.

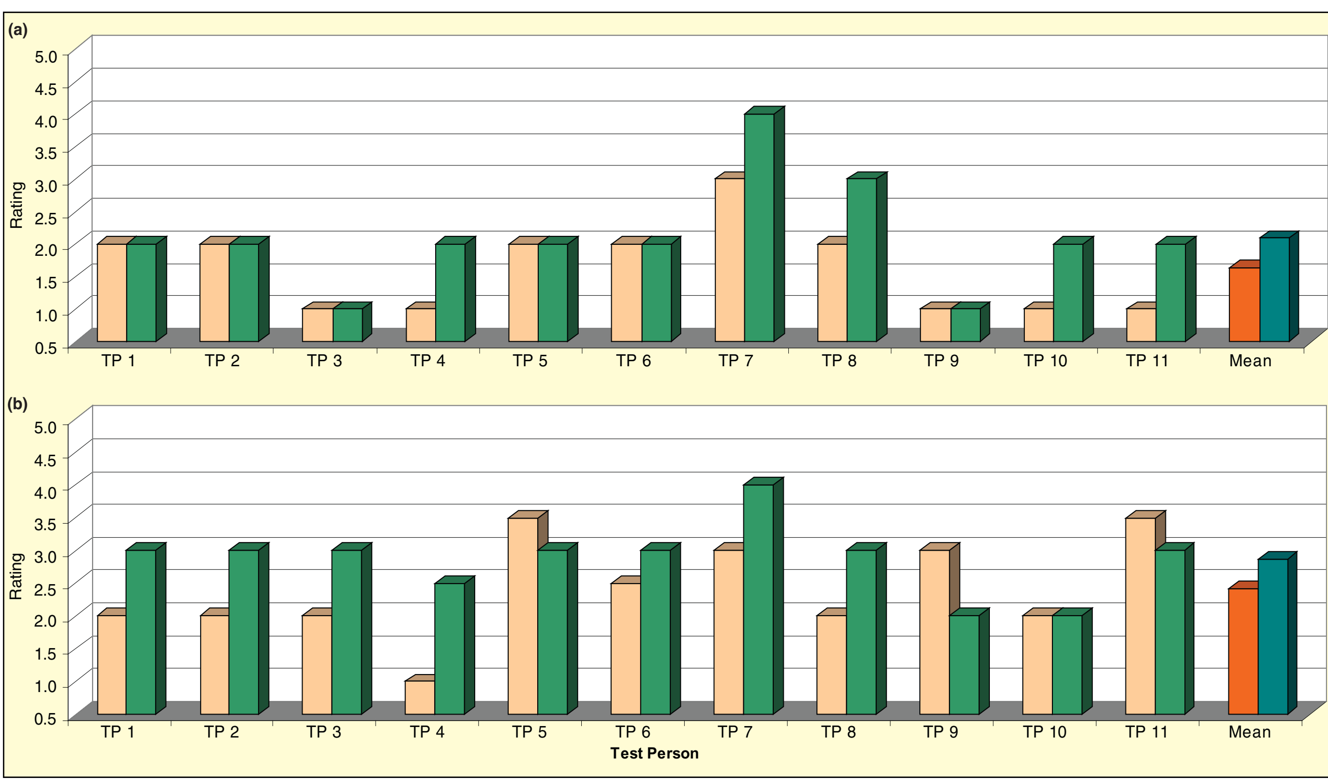

Figure 9. Comparison of ratings: one vehicle in operating mode "constant speed 130km/h (5th gear)" in the real car and played back in a driving simulator (N&V); top: engine noise quality; below: steering wheel vibration quality.

among others, 4th gear at a constant speed of 100 km/h and 130 km/h. Some results of the evaluations given in a real car compared with evaluations made in the stationary driving simulator are shown in Figures 8 and 9.

First of all, the tests have shown that good correlation exists between NVH evaluations made during test drives in a real vehicle and evaluations made in a driving simulator of reproduced sounds and vibrations. Small differences could be observed concerning the evaluations of the engine noise quality in the real car and in the simulator and considering the evaluations of steering wheel vibrations. The given evaluations varied in 0.5, 1 up to 2 grades.

The ratings in the real car differ partially from the driving simulator assessments. Presumably, the driving task in reality has attracted more attention, and the inadequacy of the stimuli was perceived as less apparent. However, this effect cannot be generalized, because of the small test group. It can only be concluded that evaluations of noise and vibration are context dependent and are influenced by the respective test environment.

Interactivity and Exploratory Methods

Listening tests are usually carried out to collect data about subjective evaluations of predefined stimuli. For reproducibility and analysis reasons, the tests are often completely standardized and conducted in a controlled test surrounding. Such test conditions should allow for the provable statistical correlation between subjective ratings and objective parameters. However, the stimuli representation taken out of typical context (pressing complex sensations into given scales) leads to biased results that often cannot be confirmed. Aspects such as context, ambiance, interactivity, or occurrence of several sensory inputs (combined stimuli) moderate the perception and evaluation of (noise) stimuli.

The evaluation of vehicle noise also depends on several aspects. The evaluation of vehicle interior noise quality is based on the resulting vibro-acoustic exposure. Therefore, it seems imperative that we have the application of new types of listening tests regarding reality-relevant aspects, such as the EVE method (Explorative Vehicle Evaluation).[9]

The EVE method considers the context, where evaluations of vehicle sounds are usually carried out, the interactivity, which occurs between the driver and the vehicle in common driving situations, and the spontaneity of evaluations in real drive. The process of evaluating vehicle sounds is relocated to a driving vehicle (mobile driving simulator). An advantage is that the test person creates his own stimuli, acts on his own initiative to evaluate the heard sounds and can explain his/her feelings and judgments freely and not be confined to giving forced answers to predefined quantities and scales.

The analysis of the comments and the stimuli are done with a qualitative analysis technique (Grounded Theory) as well as with triangulation methods. Apart from verbal evaluations, the binaural signal, speed, gear, RPM information as well as seat vibrations are recorded. The analyses of previous EVE studies showed that few noise evaluations given by naive test persons were subconsciously induced by vibrations.

The technique gives insights into the perception and evaluation of vehicle sounds. The purpose behind the analysis is to group similar events, sensations, and reactions under a common heading or classification as well as to discover inter-subjective evaluation patterns. Based on the results, information concerning the character and features of a preferred vehicle sound is derived. Based on the tests, a vehicle sound is developed considering the different remarks, customer preferences and acoustical analyses results. The target sound must be also matched with the vibration conditions of the investigated vehicle. Moreover, disturbing vibration components have to be identified to avoid negative acoustical comfort evaluations mainly caused by vehicle vibrations.

Conclusions

Sound and vibration must not only be considered as disturbing elements regarding NVH comfort, they could also be used to develop an acoustical and vibration environment that positively influences a customer's contentment. The creation of sounds that result in an impression of high product quality helps manufacturers stand out against competitors and meet increased requirements. Sound quality studies considering both sound and vibration require multidimensional approaches. Overall, further research is needed in the field of human perception of combined stimuli. The existing literature and presented studies show the complexity of interaction effects caused by sound and vibration in vehicles. Some studies even show no (or little) evidence for interaction effects. This means that the assessment of the combined stimuli is almost equal to the sum of individual stimuli assessments. This contradiction can only be solved with the help of further research.

The use of a driving simulator, whether stationary or mobile, provides an opportunity to control the stimuli and at the same time create an interactive experience of the whole vehicle, including its sound, vibration, haptic and visual information.[10] Simulators allow a focused investigation of multisensory effects under authentic test conditions, permitting the investigation of interaction effects and leading to development of methods that take into account comfort-oriented NVH engineering, including cross-modal perception phenomena.

The topic of combined stimuli is not only of importance to the field of product quality optimization, but it is also meaningful within the context of occupational health and safety as well as environmental impact research.

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