

Current and New Approaches for Brake Noise Evaluation and Rating

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ABSTRACT

Predominant brake noise evaluation and rating was developed many years ago and no longer fulfills the need of modern development work.

An extended description of a noisy brake event (European expert group guideline EKB 3006) and a standardized test data exchange format, allowing the comparison of different source test results (EKB 3008) are presented.

Today's noise rating systems are described and compared by selected examples.

The paper proposes an open 4 level noise rating system (EKB 3007). It starts with simple occurrence statistics, noise rating based on sound levels, situational noise rating including duration and finally based on the human perception, described by psychoacoustics.

INTRODUCTION

The classical technical development process is usually cascading down from subjective targets to objective targets. Starting from market studies, benchmark and performance improvement the objective targets are built to the design of the requirements like stopping distance. Based on the functional requirements system specifications are identified, and last but not least the entire component specifications with all the tolerances. With these tolerances from each component, the production starts with a quality control to ensure that the entire system specification will meet the performance requirements.

Not such straight forward is the NVH development process. Although subjective targets and objective targets seem on the first look clear. "There should be no noise". However, by looking in more details it is not technical clear identified what is no noise? What are the technical numbers? What are the measurables? What are the component tolerances and what are reproducible

conditions? For the brake noise evaluations in the development process three major tests exist:

1. Inertia Type Dynamometer
2. Chassis Type Dynamometer
3. Vehicle Measurements

1. Inertia Type Dynamometer - Early in the development phase there is no prototype vehicle available, the measurements can be performed on the NVH inertia dynamometer. The advantage of the inertia dynamometer is that only the corner module itself as prototype must be available and so it can be used early in the development process. Secondly, a good control of environmental conditions is possible. The disadvantages are that boundary conditions of the vehicle must be simulated and that the transfer path for airborne and structure-borne noise in the vehicle compartment is missing.

2. Chassis Type Dynamometer - The advantage of the chassis dynamometer is that the authentic boundary conditions and stiffness of the entire chassis and vehicle are present. As well the environmental conditions can be controlled. The disadvantages are the presence of the roller noise, the lack of prototypes and a high cost-intensive investment.

3. The Vehicle itself on Road Test - This is the most realistic test regarding drive and ride. The evaluation of noises can be done outside in the wheel house or inside in the vehicle compartment. The disadvantages are the usage late in the development phase, need of expensive prototypes vehicles and the fact that environmental conditions cannot be controlled.

All three brake noise evaluations have their advantage and disadvantage and it makes sense to combine all tests in the development process.

To correlate this NVH data two major points are very important:

1. Equivalent and coherent Data
2. Target Definition

Unfortunately it is not so simple as to add only 20 or 30 dB to a microphone in 50 cm distance from the brake to compare the result with the vehicle compartment. Even this is valid for one frequency, it could be wrong for other frequencies. The frequencies of noise travel in different ways. The noise travels on several structure-borne paths and several airborne paths inside the vehicle compartment to the driver's car. The air-borne path from the wheel house through the vehicle compartment to a microphone inside has to be taken into account.

Brake noise evaluation today predominantly is based on a description of a noise event defined in the early days of brake noise standardization in Europe and later documented in the SAE 2521 noise test procedure.

Brake noise rating as final step of sophisticated brake development is unchanged subjective. More and more teams agree on a change.

BASICS OF NOISE PERCEPTION AND PSYCHOACOUSTICS

PERCEPTION OF BRAKE SQUEAL - Beside physical units, phenomena of sound perception have to be considered in order to align measurement results to driver's subjective response. Squeal can basically be characterized as a *pure tone* with a single spectral component. In reality, it is often modulated or can contain harmonics, thus appearing as a *complex tone*. The relation of a squeal signal to random background noise and low frequency harmonics of the power-train effects perception in a specific way. Therefore it is not only the sound level that has to be considered to assess the annoying effect of brake squeal. Modulations, roughness and sharpness of this tonal noise induce changes of perception. The capability of brake noise to catch the attention of driver and pedestrian as well as the annoyance will change accordingly.

PSYCHOACOUSTIC APPROACHES - Methods of psychoacoustics have been developed to quantitatively evaluate the influence of specific sound parameters on sensation which occurs in human mind. Therefore two different sides of perception have to be considered:

Firstly, within the field of physics, sound waves are generated due to vibration of brake components. Those waves are propagating through air as air-borne waves and through mechanical structures as structure-borne waves. With view on the driver, the final pathway to the ear is an air-borne one. Sound waves reaching the ear are therein transformed to mechanical vibration, hydro-acoustical waves and finally to neuronal signals, which are the fundament of data processing of the brain. Up to the inner ear, physical phenomena define sound transmission.

Secondly, within the field of neuronal processes, sensations occur in consciousness which can neither be measured directly, nor exactly be described by the perceiving subject. In contrast to the field of physics, which can directly be accessed in a mathematical manner, the field of subjective phenomena needs specific methodology. It is most important for brake noise assessment to refer to the subjective quality of sensation, while this – and not physics directly – defines the customer's assessment. Psychoacoustics describes quantitative relations between sound features (like sound pressure, modulation, harmonic spectrum) and quality of sensation (perceived intensity, roughness, timbre).

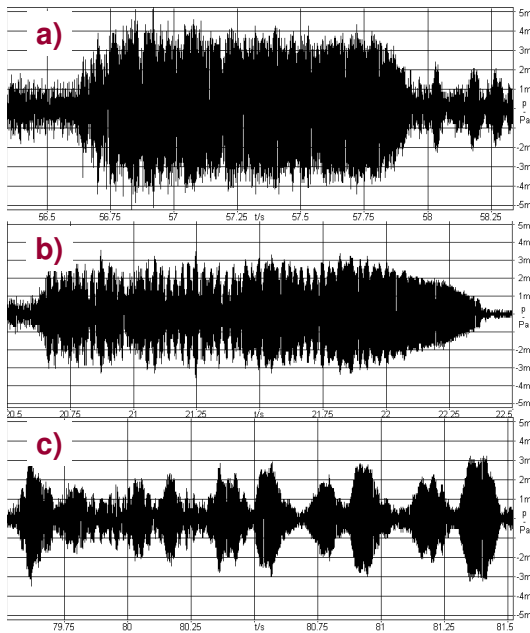


Figure 1: Three plots of drum brake squeal at 1.2 kHz showing different perceived quality due to different temporal behavior: a) relatively constant, b) modulated, c) intermitted/repeated

The frequency-dependent sensitivity of the ear is usually included into assessment by application of a weighting factor that varies with frequency, e.g. the A-weighting. This weighting factor was derived from psychoacoustic tests with a high number of test persons (sic!). It was derived with respect to sinusoidal tones and therefore it fairly applies to tonal brake noise. Use of loudness in [sone] instead of A-weighted levels [dB(A)], however, is more appropriate, especially in case of broad-band noise. In contrary to the sound level in [dB] the A-weighting sound level [dB(A)] is not a pure physical value, but it contains a simple estimation of the effect of a measured sound on subjective sensation. Changes of annoyance of squeal noise due to further parameters can be described by following parameters:

physical feature	subjective feature
fundamental frequency	pitch
modulation	roughness
fluctuation	temporal and/or pitch change
repetition	rhythm
harmonic content	timbre, sharpness
non-linear distortion	distorted sound: timbre & roughness
spatial distribution of sources	spatial hearing

The listed physical parameters lead to modified annoyance of brake squeal even if the sound pressure is kept constant (Figure 1). Further parameters can be

taken into account. The psychoacoustic parameter *pitch strength* describes the sensation of pitch. It has been defined to be 100% for a pure tone (Zwicker and Fastl [1], Haverkamp [2]). Very low or very short signals completely lose the tonal quality (Truax [3]) and have to be excluded from assessment.

In general, shaping of the outer ear enables identification of the direction of the sound source. For narrow band noises and pure tones like squeal, however, spatial hearing is limited. While front-back reversal is enabled, the perceived direction of the source often appears mirrored, i.e. front direction is mistaken with rear direction (Blauert [4]). In case of brake squeal assessment this phenomenon can cause wrong identification of the sound exciting corner/axle.

Psychoacoustic investigations regarding vehicle noise with various tonal components by Bodden and Heinrichs [5] confirm that annoyance increases at high frequencies. A certain difference between thresholds for detection and for acceptance occurs, depending on the frequency. It ranges at approx. 6 dB (low frequency) and 3 dB (high frequency) for one tonal component. Perception, however, is influenced in an ambiguous manner if more than one tonal component occurs. High frequency tones cause an uncomfortable feeling if they exceed the spectral domain of fundamental frequencies of speech and music. Above 4-5 kHz the ability to discriminate changes in the frequency of pure tones diminishes and the sense of musical pitch disappears (Moore [6]).

ADVANCED ASSESSMENT OF HUMAN PERCEPTION

PSYCHOLOGICAL ACOUSTICS - Psychoacoustical approaches are exclusively dealing with the contribution of single physical features to single qualia (quality parameters) of sensation. Main processes of perception are excluded. Psychology of perception – in this case: psychology of audition – needs to address those processes:

- grouping of single qualia
- relations to a given context
- integration of experience data stored in memory
- identification of sound sources (e.g. “a bird”)
- decoding of symbolic content / meaning

While listed processes show main influence on the assessment of noise, e.g. the grade of annoyance or of functional plausibility, psychological methods need to be applied to provide the full picture of parameters influencing human perception. Psychological acoustics is therefore different to psychoacoustics, but both complement one another.

PERCEPTUAL OBJECTS - Physical objects from the human environment are not as such represented in the perceptual system, but by means of simplified models. Those models connect basic features with

channels (roughness, intensity, color, pitch, etc.) to each other, thus shaping perceptual objects. A perceived sound is shaping a sound object, which tends to couple with perceptual objects of other senses (e.g. squeak $\leftrightarrow$ vision of vehicle brake). The various features integrated into those objects, however, are not of physical nature - although the nature of stimuli is physical. Instead a specific subjective representation is generated as a cumulation of subjective features (qualia). The impression of color is a typical subjective quality: it does not exist in the physical environment, where optical qualities of light are defined by spectra and temporal behavior. The same applies to sound sensation: it is not needed to optimize physical behavior of sound sources as such, but to design subjective qualities of sound.

SOURCE IDENTIFICATION AND FUNCTIONAL PLAUSIBILITY - The identification of sound sources and the meaning of sound are important facts which strongly influence perception. A brake noise may not be annoying, but the assessment drastically changes if the driver interprets it as a danger signal. Beside elementary features, the annoyance of brake squeal is given by various cognitive parameters, like associations, symbolic content and multi-sensual correlations. Typically, a pure tone of high frequency is associated with a babies crying or alarm signals of animals. Those signals claim a fast response of the perceiving system, which in nature would lead to a status of alert or a shortening reaction of the individual. The associations therefore cause further focus of the driver's attention on brake squeal, and his concentration on driving operations is partly reduced. This reaction is amplified on a symbolic level, where brake squeal refers to artificial alarm signals like the tone of a siren. A brake squeal can indicate a specific friction condition within the normal range of brake operation, but it can also show a condition of damage with metal seems to be grinding on the disc. In both cases – with exactly the same noise – the assessment differs widely. Therefore a noise assessing index must include information about the easiness of source identification and/or similarity to sound which indicate damage or danger. A feasible way to include this analysis consists of comparison with characteristic signal features provided by an expert system. The same applies to a semantic analysis (of meaning).

The correlation of single parameters perceived to expectations to a correct technical function also influences the effect of sound on the driver. If the perceived noise is in line with an expected activity, annoyance is low. In contrary, the sound can gain positive rating. This correlation is higher for a squeal that occurs during a sharp stop brake than to a slight low-pressure application. Thus, the plausibility of noise occurrence is coupled to functional assumptions and knowledge. Plausibility is at minimum in case a brake squeal occurs in off-brake condition, without any action

by the driver. Moreover, the whole temporal behavior of a noise event is crucial for functional plausibility. Perception of a signal with limited duration is influenced by three temporal phases: *onset transient phase* (attack transient), *stationary phase* (body) and *decay phase* (Schafer [7]). The rise time of the transient phase is measured until a magnitude of -3dB regarding the stationary signal is reached (Luce & Clark, 1965, cited by Meyer [8]). The rise time of a high frequency squeal is short and can often not be segregated by human hearing. In fact, however, it is a smooth fade-in – otherwise a sharp "click"-noise would be audible. On the other hand, a mid-frequency moan noise is characterized by its ominous smooth fade-in of long duration. While functional plausibility is based on specific sound features (e. g. rise time), a classification based on those parameters is needed. Specific weight factors must also be used to include plausibility into the noise index.

COGNITIVE GROUPING - The human perceptual system is enabled to connect single events as one phenomenon via analysis of specific signal attributes, like pitch, rhythm and parameters of sound quality. Therefore, during perception a set of single physical events can be grouped to one sensation. In example, repeated pattern of similar squeals with equal duration, separated by pauses of constant length, will be perceived as one single, intermitted process. A system for noise evaluation must be capable to apply rules of pattern recognition and to decide whether this event shall be grouped or not. Evaluators who are aware of the technical system additionally use their knowledge to intuitively make up a functional hypothesis of the process behind, e.g. rotation of a disc with specific lateral run-out causing periodical chirps. Those hypotheses help to define a pattern which can serve as a "schema" (Bregman [9]) and supports the grouping. Before calculating a noise index, subjective grouping of sounds has to be estimated by the measurement system. The evaluated parameters shall represent the likely perception instead of the physical phenomena which are measured. Those parameters shall be included into an advanced noise index after application of corrective algorithms which simulate perceptual grouping.

REFERENCES TO MULTI-SENSORY ENVIRONMENT - Perception of brake noise – like perception of any sound – is influenced by the context in which sensations occur. Usually, the context is a set of sensory data of various senses. Thus sound sensations are always embedded into a multi-sensual context. Brake engineers may disagree that the kind of vehicle, the comfort of seating, the view upon the instrument panel, pedal vibration and others influence the sensation of sound. During every day's perception without focus on specific sounds, however, this exactly happens. A squeal with same sound properties is assessed differently if perceived inside an old truck or a modern comfortable limousine.

CROSS-SENSORY IMPLICATIONS OF SOUND SENSATION - The coupling of sensory features is illustrated by a comprehensive model (Figure 2).

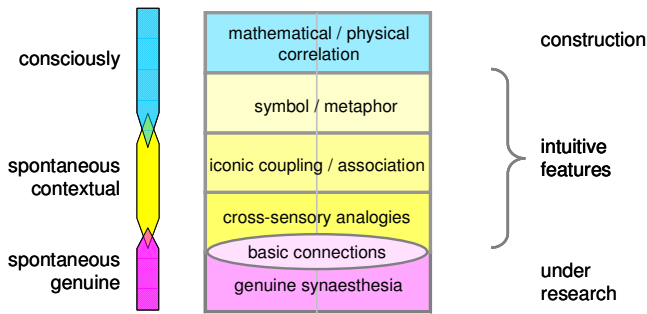


Figure 2: Overview of main perceptual strategies of cross-sensory coupling.

It includes individual phenomena of genuine synesthesia as well as consciously, conceptual constructions beside three *intuitive strategies*. Additionally basic connections of sensory data of various channels are established. In example, those processes enable coupling of proprioceptive and visual data for control of eye movement, bearing of sound sources with intuitive head rotation to improve spatial hearing and many other tasks of sensory and motional coordination. Those elementary processes usually are not represented in conscious. Genuine synesthesia is a set of strictly individual processes which are evident only in a small number of persons (see [10-11]).

The main *intuitive strategies (coupling features)* are:

- cross-sensory analogies = correlations of single features/attributes,
- iconic coupling (concrete association) = identification of sources of stimuli
- symbolic connections = correlations by analysis of meaning

Each main intuitive strategy splits into a variety of mechanisms, e.g. analogies can be made up in-between basic attributes, like brightness or roughness, or can consider movement, shape, emotion and many other aspects. Further correlations can be constructed with reference to known physical properties, e.g. the frequency of color light can be related to pitch frequency of a given pure tone by means of appropriate calculations. The listed main strategies of interaction are acting in-parallel, showing mechanisms that initially are independently from each other. Although cross-sensory coupling of sensations is always happening during everyday's life, application of cross-sensory references to sound assessment is still in an initial state. In future it will provide much more sophisticated evaluation of noise effecting human being.

CORRELATION BETWEEN DIFFERENT BRAKE NOISE TEST CATEGORIES – TRANSFER FUNCTIONS

THE TRANSFER PATH TECHNOLOGY – The so called Binaural Transfer Path Analysis and Synthesis (BTPA/BTPS) was developed for assessing the binaural contribution of individual vehicle noise paths. They are powerful modeling tools, enabling engineers to explore noise transfer mechanism by distinguishing between excitation source strength and the transfer behavior of individual elements. The challenge of the BTPA/BTPS method is to break down a complex noise path system into its components. Hence, all acoustically relevant sources must be detected and taken into account in the BTPA/BTPS model [12].

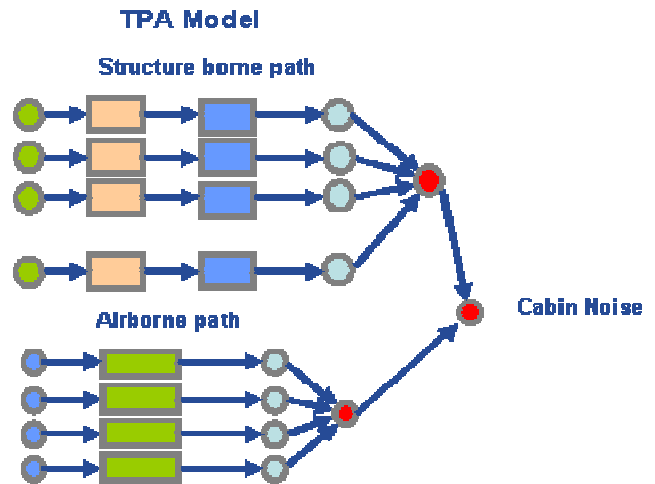


Figure 3: BTPA/BTPS model with four air-borne and structure-borne transfer path.

PRACTICAL USE OF THIS TECHNIQUE FOR BRAKES - With this transfer path method it is possible to build a simulation model based on measurements. It is understood that the requirement is a quiet brake. However, the focus is on a not audible brake. The target setting for the rated sound in a vehicle compartment can be done in an audio laboratory and it is possible to evaluate this noise with preconditions like open or closed windows. From this main noise target the target levels can be broken down through the radiated sound of the inertia dynamometer in terms of frequency dependent sound pressure level in dB in a certain distance of the microphone and the acceleration level at the anchor bracket. As well unwanted noises from inertia or chassis dynamometer can be reduced with filters, so the pure squeal of the brake only is calculated. By using this technique it is possible to get much more advantage out of the inertia and the chassis dynamometer and it is possible to use this tools for determination of target definition from inside the vehicle through the inertia dynamometer much more accurate.