

# Automotive Sound Quality – Accessories, BSR, and Brakes

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In this third article in the series, I describe the sound quality criteria for automotive BSR (buzz, squeak and rattle), accessories, brakes and door open/close. The previous article discussed the sound quality of powertrain, wind and road noise, while the objective of this article is to provide a brief summary of objective parameters or metrics that are used for the other main subsystem/components in a vehicle. The description of the techniques used to derive either of these metrics (signal processing) or their correlation to customer perception (jury studies) is outside the scope of this article. However, an extensive list of references is provided, where these methods are described in detail.

## Engine-Powered Accessories

These are the accessories driven by the engine through a serpentine belt – alternator, power steering pump, air conditioning compressor. The sound quality attributes induced in the vehicle cabin are tonal components derived from the fundamental frequencies of the prime movers (the compressor for the HVAC system, the power steering pump for the hydraulic-assist steering system, etc.). The perceived attributes are typically classified as:

- *Moan, whine and hiss for the power steering system.* Moan is the term typically used for a tone in the low frequency range (typically 200 to 400 Hz). Whine is used for tones in the higher frequency range (up to 2 kHz), and hiss is a few narrow-band components (each one is wider than a tone but typically not broader than 100 Hz or so).
- *Moan and growl for the AC compressor.* Growl is the rough character introduced in the sound when several harmonics of the AC compressor can be heard in the cabin (Figure 1). The induced sensation is of roughness, because these harmonics are typically spaced between 40 and 60 Hz apart (depending obviously on the speed of the engine and on the number of pumping events per cycle in the compressor). Therefore, they are considered a modulation frequency which is accounted for by the psychoacoustic metric roughness. The definition for AC compressor moan is the same as for steering system moan. The generating mechanism is different, but the sensation, which depends on the frequency, bandwidth and level of the tone, is the same.
- *Whine for the alternator* (Figure 2). The definition for this type of whine is the same as for power steering whine.

The climate control system however has another sound quality attribute, which is air rush, or noise due to the blower and the ventilation ducts. This is typically broadband and induces the psychoacoustic perception of sharpness. As for the tonal components induced by these subsystems, these are approached basically following a tone-over-masking criterion, exactly like driveline sound quality (see previous article in this series, published in the April 2009 issue of S&V).

The detectability of accessory noises over masking is also the main sound quality concern in vehicles with hybrid and electric powertrains. In this case, the accessory may be driven by the electric motor or by the IC generator, and its detectability depends mainly on the level of masking, which in electric mode is extremely low. In the absence of an IC-engine signature, the noticeability of fans and pumps over road noise is a major issue and needs to be accounted for much earlier in the vehicle design cycle than for a traditionally powered vehicle. Furthermore, the acoustic signature of electric motors is rather peculiar and different from a combustion engine; if noticeable in a vehicle, it may contrast with the expectation of the driver/passengers. The plot in Figure 3 shows the spectrogram of the noise of an electric drive for a vehicle application during a sweep. The distinctive diagonal lines of decreasing frequency, noticeable in the upper portion, and

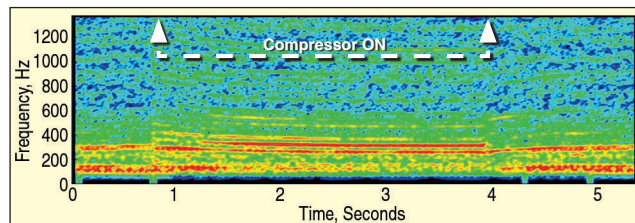


Figure 1. Example of noisy compressor (growl) inside vehicle.

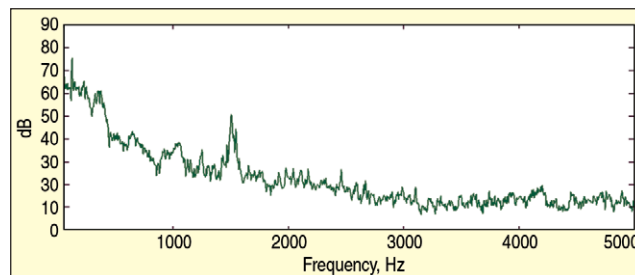


Figure 2. Example of exterior idle noise with whine (narrow-band frequency component around 1500 Hz).

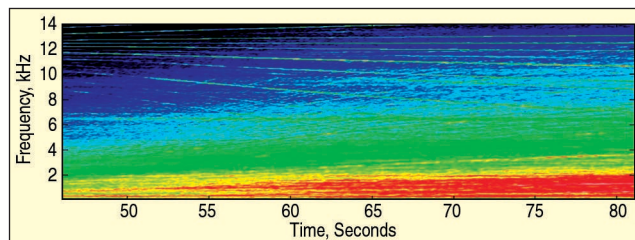


Figure 3. Electric-drive noise during sweep.

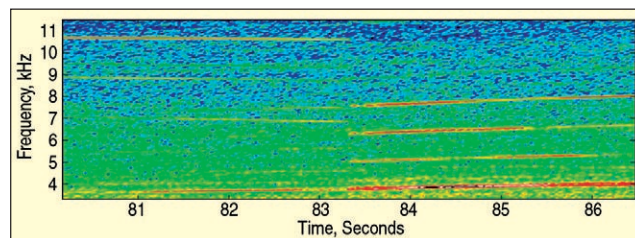


Figure 4. Electric-drive control strategy change during a sweep.

of increasing frequency in the lower portion, are typical of electric motors. Their spacing depends on the internal electrical layout of the motor and on the motor controller parameters.

In addition to the increased higher frequency content, the motor control strategy should be considered as a potential sound quality issue. The control strategy for electric motors often differs between high and low speeds due to power level considerations; therefore, as a motor is swept from low to high speeds, the motor controller often changes from low-speed control to high-speed control. This change in control strategy often results in an abrupt change in the frequency and order content that is emitted from the electric drive system. If detected, this change can be disconcerting to the driver. A change in motor control strategy can clearly be seen in Figure 4 at 83.3 seconds.

It has to be said that the decreasing higher frequencies are most likely blocked by the transmission loss of the barrier between an electric drive and vehicle compartment and would be unnoticeable to the passengers. But from a sound quality standpoint, it is

important to be aware of these differences and of the potential issues they may cause.

The sound quality metrics used for engine/motor-powered accessories are:

- Pump order slices vs. RPM (as compared to engine order slices)
- Tonality/tone-to-noise ratio/prominence ratio
- Roughness
- Delta dB(A) or loudness for off-on-off events
- Sharpness for air-rush noise

### DC Motor-Powered Mechanisms

For DC motor-powered mechanisms (seat adjusters, mirrors, pedals, sunroof, window lifters), average dB(A) is most commonly used in specifications but does not represent the SQ performance. There is nothing wrong with dB(A), which correlates well to loudness in most cases and is a good indicator of poor/good sound quality when the quality of the sound is judged only as a function of the amplitude of the sound. In general, however, we object to more attributes than just the amplitude of the sound; think of tones, modulation or beating, roughness, etc. In these cases, using only dB(A) is inappropriate, because there are more dimensions to the sound than just loudness.

As a consultant, I started working on these mechanisms in the early '90s; back then the only specification available to a supplier of mechanisms was based on average dB(A). This generated a lot of confusion. As an example, Figure 5 shows the time histories of the sound pressure generated by two different seat adjusters at one ear of a binaural head positioned on the driver seat while the seat is moving forward. The average dB(A) of the two signals is within 0.5 dB, while the sound quality of the two signals is very different. You can clearly see amplitude modulation in the “bad” sample, while by contrast the envelope of the time history of the good sample is flat.

Noise from DC motor-powered mechanisms tends to vary with time, since the transmission of motion from the DC motor to the actuator is typically realized by means of a system of gears and flex shafts. So side loads and misalignments are quite common; compounded with gear imperfections, they are the main causes of modulation, pitch changes and rattle noises.

The top SQ dimensions of DC motor mechanisms are:

- *Loudness* – can be measured by either loudness or dB(A) or even SI (Speech Interference).
- *Pitch change during travel* – this can be indirectly measured by monitoring the variation of the RPM(t) or by using specific metrics such as speed variation. If the mean of RPM(t) changes too much during travel, the mechanism is perceived as being weak and of poor quality. Ideally the mean RPM should stay constant during travel.
- *Low-frequency modulation* – this can be either amplitude or frequency modulation and can be measured by fluctuation strength, or in case of frequency modulation only, by specific metrics such as FSFM<sup>7</sup> or standard deviation of the RPM(t) function.

The difference between pitch change and low-frequency modulation is illustrated in Figure 6 and 7. Figure 6 shows the low-passed RPM(t) of four different actuator mechanisms during travel. The large difference between the top and bottom functions correlates very well to the preference of the associated sounds, because the sound with the top RPM(t) sounds more like a model airplane taking off than what you expect a normal seat adjuster to sound like. In another case (Figure 7), the mean RPM(t) is fairly constant but modulated, which is the main difference between the two RPM(t) functions shown here.

These two sound quality attributes – pitch change and modulation – are independent of each other, and their root causes are different. The modulation is induced by gear imperfections generally amplified by side-loads and the frequency of the modulation (amplitude frequency) always corresponds to the gear ratios in the system. But the pitch change during travel is caused by misalignment, adverse mounting or binding of the structure as it is mounted in the vehicle, so that the load seen by the motor changes during travel. The consequence is that the motor speeds up or

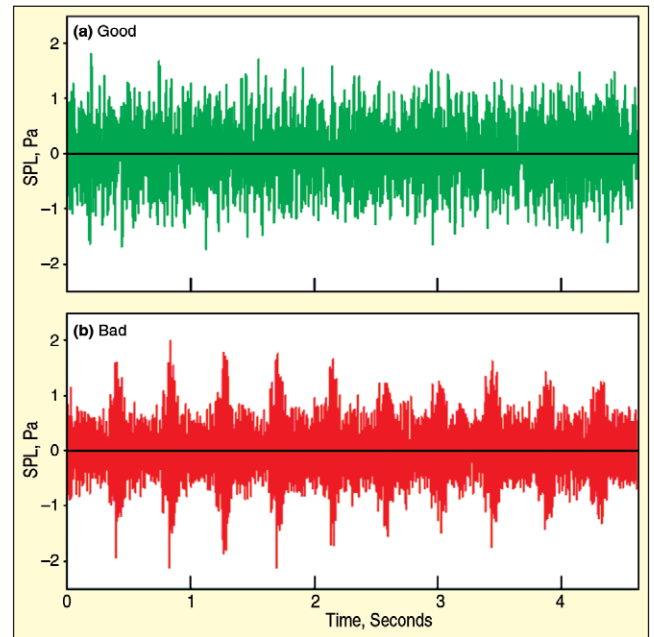


Figure 5. Time history of sound pressure of good and bad seat adjuster during horizontal forward motion.

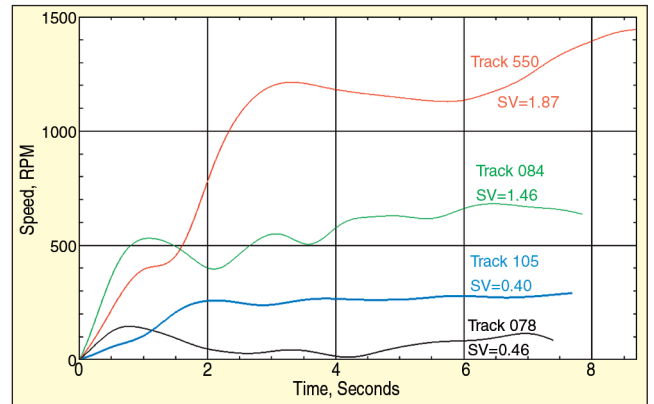


Figure 6. Speed variation of different horizontal adjusters.

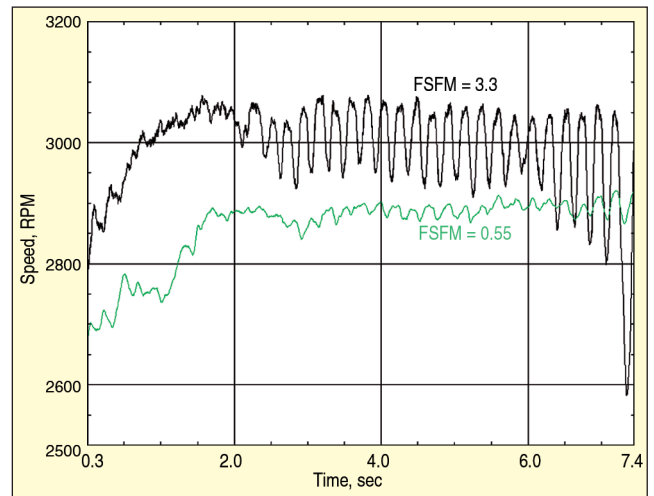


Figure 7. FSFM of two different horizontal adjusters.

down in response to the load change. My impression is that this latter attribute (pitch change) has been addressed by mechanism suppliers, because it seems that speed variation has not been a big sound quality issue in DC motor mechanisms in recent years. However, since these subsystems often still use poorly designed and/or manufactured gears, the modulation (or “wow-wow,” sewing-machine-type noise, etc.) is still an adverse sound of this type of mechanism.

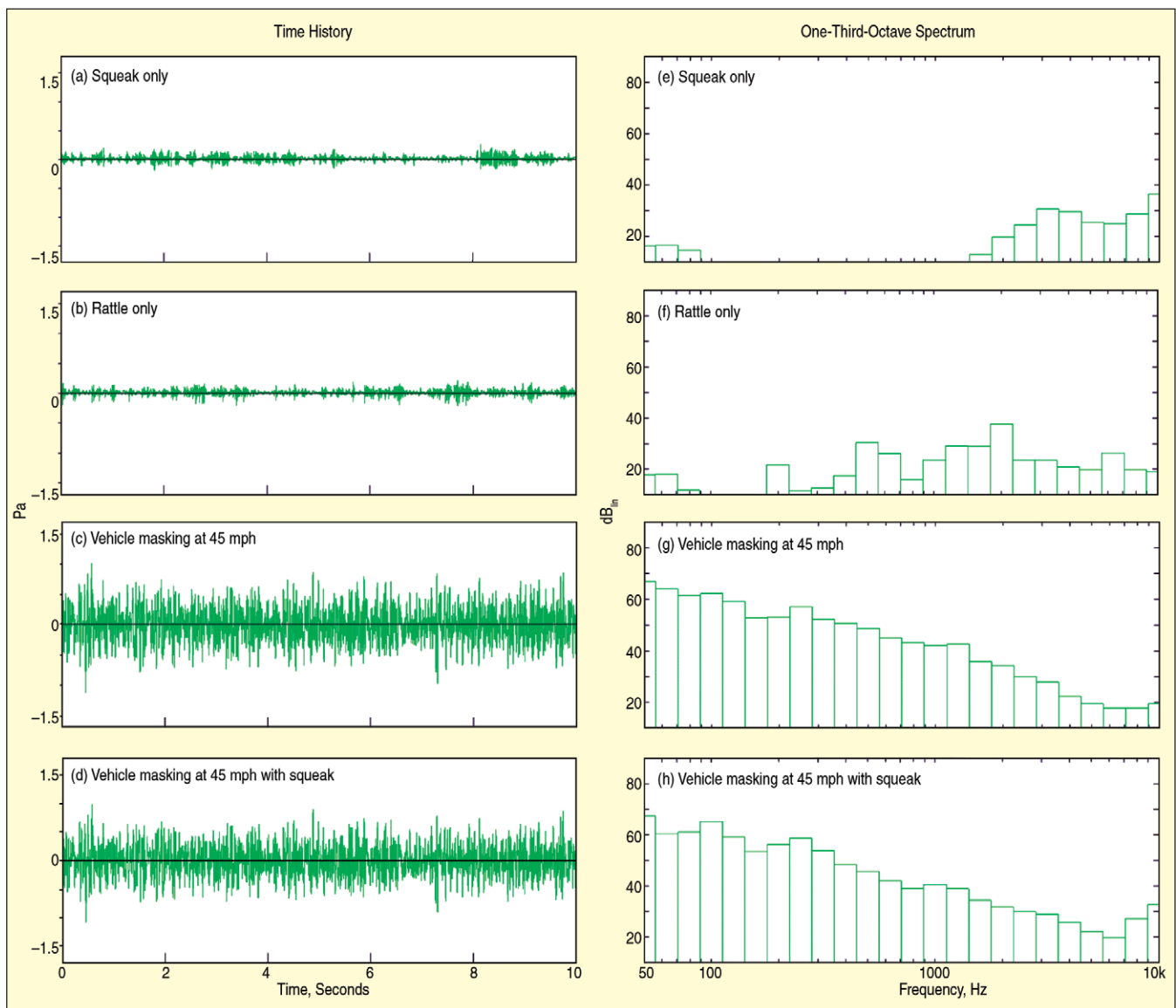


Figure 8. Time history and spectra of rattle and squeak.

In summary, the metrics used for DC-motor mechanisms are:

- Loudness
- FM and FSFM
- Speed variation or other metrics of motor RPM(t)

### Buzz, Squeak and Rattle

It is very difficult to represent our perception of BSR (buzz, squeak and rattle) by using sound quality metrics. First of all, BSR events are typically quiet but are noticed because the background noise is low and/or because they sound different. As stated previously, any change in the noise or any noise that is different from what we expect is noticeable. One of the challenges in establishing metrics to measure perceivable BSR events is that classical metrics are broadband in nature and were not derived with this type of noise in mind. The elementary sounds used in psychoacoustic experiments, like sine waves, narrow and broadband masking, chirps and burst random signals are very different from actual BSR noises.

A second challenge is the very low signal-to-noise ratio of BSR auditory events, which means that overall level metrics, such as  $dB_{lin}$ , dB(A) or loudness, do not typically catch BSR events unless they are extremely loud. In fact, a very noticeable rattle may not register at all on the loudness or dB(A) scale. Figure 8 shows the signal-to-noise ratio of rattle and squeak events as compared to measured background noise in a luxury sedan at 45 mph. The time history of squeaks and rattles shows their transient and impulsive nature but also their extremely low level relative to vehicle

background noise.

For example, once the squeak file is mixed with vehicle background noise, the resulting time history is undistinguishable from the original vehicle masking. Yet the squeaks are clearly noticeable when listening to the mixed file. The 1/3-octave spectra corresponding to each time history do not provide any further information, other than the fact that the SPL of rattles and squeaks is much lower (by 40-50 dB for frequencies up to 1-2 kHz) than vehicle masking and that they have comparable levels only at higher frequencies.

A third challenge to the objective characterization of BSR events is that because of their transient nature, they do not lend themselves well to FFT analysis. Average spectra, will not capture the onset of a faint rattle unless the averaging is done on a very short temporal window. Again the spectra in Figure 8 demonstrate this point. However, time-frequency analyses are very useful for BSR events and are the basis for the extraction of objective parameters. In Reference 16, the author recommends using a statistical measure of specific loudness(t) functions.

The specific loudness functions represent the loudness perceived in each critical band. Their impulsiveness and transient nature can be measured by using statistical measures such as standard deviation, kurtosis or crest factor. The basic idea is that of band-passing the signal so that transient events (rattles/squeaks) become evident in the time history of the filtered sound. This can be done simply on the raw sound pressure signal or on the loudness function in each critical band (specific loudness). Either way, this approach



has proven to be robust in several applications. The graphical visualization of BSR events buried in steady background noise can also be enhanced by using wavelet analysis.<sup>15</sup>

Finally, note that quantifying the perception of BSR events is even more complex at the component/subsystem level. First of all, realistic BSR events are difficult to reproduce, even with very sophisticated and expensive test machines. Second, the very same test machines used to excite the vehicle or the components also generate noise that acts as masking for the faint BSR events that need to be reproduced and measured. Therefore, two test strategies have been devised:

- The first and most popular relies on the use of very quiet and sophisticated excitation devices, allowing the use of broadband parameters to capture BSR events. In other words, the investment goes into the equipment for the excitation and reproduction of the BSR concern, while the measurement of it is fairly simple (such as loudness percentile values,  $N_{10}$  or other).
- The other approach does not require super-quiet test machines but relies on sophisticated (and therefore more difficult to develop and implement) measurements, such as digital filters, to allow for the extraction of BSR correlated parameters. With ever decreasing NVH resources, this has not been a popular approach, for obvious reasons.

The sound quality metrics used for BSR are:

- Loudness and loudness percentiles
- Kurtosis (rattles)
- Roughness (buzz)
- High-frequency band SPL (squeaks)

### Static Sounds

The sounds in this group are:

- Door closure, on-off switches, open-close trays/lids, turn signals, etc.
- Chimes, warning signals, horns.

In general, these sounds are not periodic in nature, rather they are transient and need to be addressed by using signal processing techniques similar to those described for BSR events. However, while BSR events should not be noticeable or detected, static sounds in this group are generally expected, and their acoustic feedback, typically produced when background noise is at its minimum, contributes to the overall image of the vehicle. Therefore, while the basic signal processing techniques are the same as those used to detect BSR events (since the events in this group are also transient in nature), the evaluation of the perception of the signal is very different.

Take the door open/close sound as an example. This is very important from a marketing standpoint, since it is the very first physical interaction between the customer and the vehicle. A sharp and ringing door closure will immediately create an image of “poor quality,” while a nice, muffled, low-frequency thud will give us the impression of solidity and refinement. The same applies to opening and closing the glovebox or the center console, etc. These sounds have to be carefully designed and monitored during product development to make sure they meet customers’ expectations.

I will focus this section on the sound of door closures, since this is the most important among those in this group (from a marketing point of view). Naturally, the same fundamental understanding of what is pleasant or annoying in a transient sound will apply to other events (but not necessarily the same metrics).

Figure 9 shows a comparison of waveforms measured from two door closing events. The amplitude and the time decay are similar, but the waveform to the left has significantly more high-frequency content than the one to the right. In this case, this indicates that the door to the right was judged worst because of higher sharpness value.

A nice discussion of door closure sound quality is found in Reference 21. The results reported here agree with my experience as well as with results from other researchers.

The sound quality of door closures is quantified by the following parameters:

- *Peak amplitude* – better described by loudness but I know of

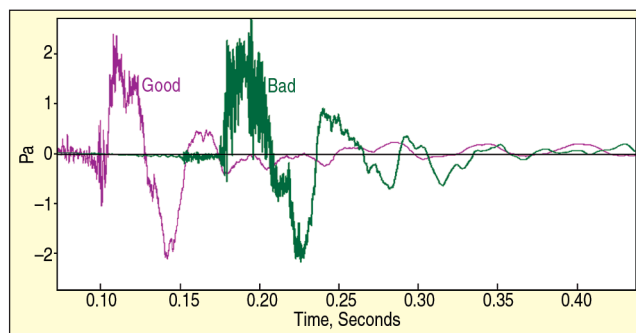


Figure 9. Time history of sound pressure of good (left) and bad (right) door closure; events have been shifted in time to facilitate comparison between waveforms.

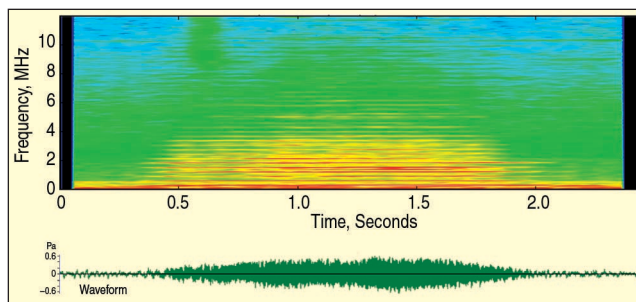


Figure 10. Example of disk brake groan noise.

several test specifications still based on peak dB(A) measured with fast time constant.

- *Sharpness* – or the balance between high- and low-frequency content. The psychoacoustic metric sharpness is often used for this purpose but also the difference between high- and low-frequency band SPLs. A useful alternate metric based on Zwicker loudness is the percentile frequency method by Fridrich.<sup>19</sup>
- *Ringiness* – that is the time it takes for the sound of the door to converge to background noise.
- *Impulsiveness* – type of parameters to detect rattles that may be triggered by the door impact and be mixed with ringing noise.

### Brake SQ

Noise from the brakes is typically classified as:

- Moan
- Groan
- Howl
- Squeal

In terms of sound quality, both moan and groan, while generated by different mechanisms, affect the low-frequency range, which is approximately between 100 and 500 Hz for brake noise. Groan typically occurs upon stopping the car or when the brake is gradually released and drag torque is simultaneously applied to the wheel. This is a condition of minimum background noise, and groan occurs when several tonal components emerge above background, creating a rough, growl-like, sound. An example of brake groan noise is shown in Figure 10.

Moan occurs during deceleration of the car when a constant pressure is applied to the brake block. Moan is less transient in nature than groan, and it is perceived more as a constant noise during the braking event. The perception of “moan” as opposed to “groan” is due to a single tonal component having a higher level than others and inducing a clear perception of its pitch. Howl is a tonal component that may occur during braking, similar to moan, but its frequency is higher (500-1000 Hz).

Finally, the most annoying of all brake noises is squeal, which usually occurs at frequencies above 1000 Hz, with the most annoying typically occurring above 5 kHz. Squeal is caused by high-frequency, free-bending oscillations of the brake elements, by forced response of the metal disc brake or vibration in the friction lining. Regardless of the squeal-generating mechanisms, squeal manifests itself as intermittent high-frequency noise, typically at several resonance frequencies (between 2 and 10 resonances) above

2 kHz and frequently up to 20 kHz.

From a standpoint of sound quality, an objective noise index (ONI) has been proposed for measuring the annoyance of brake squeal, and it takes into account both the maximum SPL of the brake noise event and its duration. An improvement upon this formulation, called the BONI-Squeal, has been proposed more recently, with a polynomial regression model for the annoyance of brake squeal established from the correlation between measured noise data and jury testing.<sup>26,28</sup>

In hybrid/electric vehicles, the brake event is often supplemented by a regenerative braking system that uses an electric motor as a generator to capture some of the braking energy to recharge the batteries. This event is realized in the vehicle axle as a load on the coast side of the hypoid gear. Historically, axles have been designed to transfer load on the drive side of the gear and are assumed to transfer little or no load on the coast side. For this reason, gear mesh noise under load has not been a primary design constraint for the design of the coast side of the hypoid gear. In addition to this, the IC engine is often deactivated during braking so the “axle noise” due to regenerative braking occurs when the vehicle masking is at a minimum. In addition to “axle noise” during braking, the motor control change described earlier (Figure 4) should be considered as the motor controller switches from a high-speed control strategy to a low-speed control.

The common features among the different types of brake noise are high level (typically above 70 dB(A) and up to more than 100 dB(A) in the most severe cases) and tonality, due to the presence of multiple narrow-band resonant frequencies. Generally, the higher the frequency of the noise, the more annoying the sound. This is also true for the duration of the event. In summary, the sound quality metrics that can be used to describe brake system noise events are:

- Max dB(A) over the entire frequency range, but also high dB(A) in specific bands; i.e., below and above 1000 Hz, etc.
- Number and duration of events.
- Tonality or prominence ratio or tone-to-noise ratio.

## Sound Quality in Vehicle Development

Hopefully this review has demonstrated that the sound quality of every system/subsystem or component in a vehicle can be objectively quantified. New-vehicle development today uses the knowledge acquired over the past two decades in the field of sound quality, and recent vehicle test specifications have in-vehicle sound quality targets for several subsystems and components.

It also needs to be added that sophisticated NVH simulators are available to establish in a controlled lab environment the target values or functions that need to be achieved by a vehicle to be competitive. Therefore, a lot of the “black magic” aspects of sound quality and of “second guessing” target development have been removed from the process. The most interesting (and useful) consequence of having realistic sound quality targets at vehicle level is that now realistic and consistent targets at the component level can be derived by following a systematic source-path-receiver decomposition of the vehicle system (see Figure 11).

This also translates to better component-level test specifications that can be implemented by suppliers. In my experience, once more meaningful test procedures are developed and implemented, the engineering teams at the suppliers have the opportunity to improve understanding of their product and the impact that design variables have on their product as well as on its interaction with the vehicle.

## Conclusions

In reviewing current SQ technology, it is clear that tools are available now to quantify the sound quality of any vehicle. The process is well defined, and there are many examples in the literature that can be used as a starting point. However, with this positive conclusion also comes a word of caution – sound models (the relationship between sound and vibration quality metrics and human perception) are not cast in stone. They are subject to

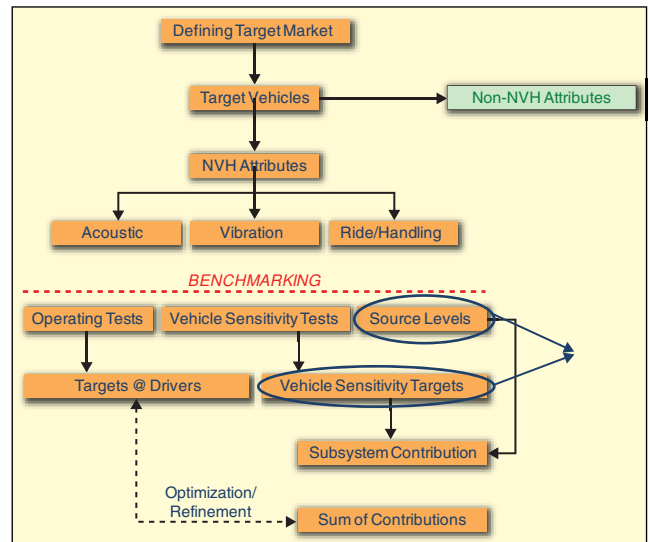


Figure 11. From customer expectation to engineering targets.

change with the introduction of different types of vehicles (think electric and hybrid, as an example).

An example of customer expectations changing over time can be seen in Reference 33, which shows how interior vehicle noise spectra at 100 kilometers/hour have changed over the years from the late '70s to the late '90s – (higher levels at low frequencies, much lower levels at high frequencies), so the author makes the case that a metric derived in the '70s (the Composite Rating of Preferences) should be modified to better account for the spectral envelope of current vehicles.

Technology turning points can trigger significant changes in consumer habits and their expectation of product performance. The same applies to sound and vibration quality expectations that will evolve with technology over time, and new SVQ targets will need to be defined. While this may be an unsettling thought for today's engineers, we should also be comforted by the fact that the process which has been improved and refined over the past decade by the auto industry provides a robust set of guidelines and strategies for efficiently deriving new targets.

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