Automotive Sound Quality – Powertrain, Road and Wind Noise

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This is the second article in a series on the subject of sound and vibration quality. The first (May 2007) covered the sound and vibration quality target development process. This focuses on the automotive industry and specifically on sound quality issues in vehicles (vibration quality will be covered separately) related to powertrain, road and wind noise. The next article will discuss sound quality criteria for the remaining automotive components/sub-systems [accessories, BSR (buzz, squeak & rattle), brake, static sounds]. I need to remind the readers that my goal is to provide a review of knowledge and techniques, well knowing that it will not be exhaustive and that I will miss a lot of things. I apologize in advance and I would like to ask readers to e-mail me with comments, questions and suggestions for the next articles in the series. This article provides a brief summary of objective parameters or metrics used for each sub-system/component in a vehicle. The description of the techniques used to derive either 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 detailed (references are grouped by system and chronologically within each system). Finally, the article is limited to the sound inherent in a vehicle during its operation, so it does not address issues such as sound quality of car audio or active noise control systems.

Sound Quality and Vehicle Harmony

Vehicle sound and vibration quality is a very broad subject, since our interaction with the vehicle is fairly complex. Audio and tactile feedbacks are combined with visual cues and ever-changing driving and boundary conditions. In industrialized societies, where the use of passenger cars has been prevalent for the last several decades, we have developed precise expectations for the "feel" of a car, and these expectations drive, along with cost and fuel consumption, our purchasing decisions. Despite the fact that the world has become "flatter" so to speak, these factors (feel/look, cost, fuel consumption) assume widely different values depending on geography and culture. When I moved to the U.S. from Italy in the early '90s, I purchased a totally "manual" car; that is, no power windows, seats, manual transmission, and I was very happy to be driving a relatively small, noisy, four-cylinder car (very similar to what I had been driving in Italy). After living here and driving American cars, my expectation has indeed changed. In the meantime, though, overall vehicle quality has improved tremendously, which is consistent around the world. I never cease to marvel at the quietness of European cars with diesel engines or of Korean vehicles at idle. Vehicle manufacturers have clearly put a lot of effort into specific attributes of their product to better align the product to customer expectation.

Noise and vibration play an important role in what is called the overall harmony of the vehicle. The term harmony is often used to describe the relationship between *form* on one extreme of the spectrum and *function* at the other extreme, and is associated to the oft-heard statement of "form follows function." In other words, today's vehicles have to perform all the functions that drivers and passengers expect while providing a comfortable and enjoyable environment. It is the job of human-factors experts to bridge the gap between form and function and establish a target balance between these two elements for each vehicle class and type.

The role of noise and vibration factors on the vehicle harmony elements is summarized in Figure 1.[1] Some NVH elements affect comfort, such as gear whine, boom, tire and wind noise. Others like engine noise in acceleration and ride and handling have a more direct impact on overall appeal.

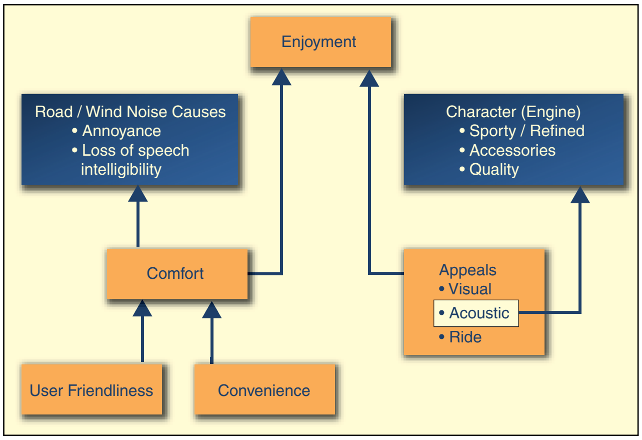


Figure 1. Impact of NVH on overall vehicle harmony.

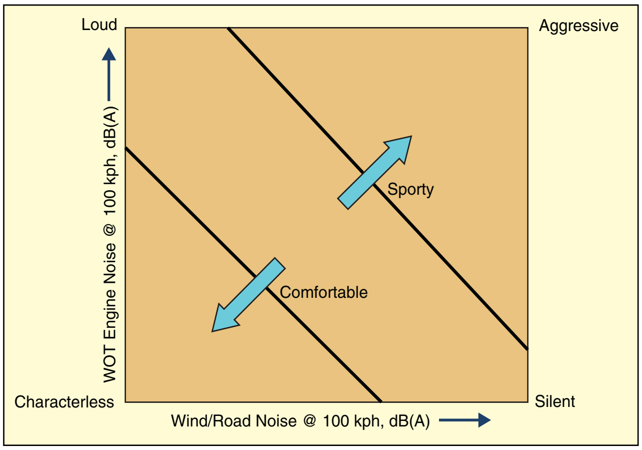


Figure 2. Example of brand sound design (adapted from Reference 2).

- **Detectability** – component shoujld not be detected in normal driving conditions
  - Transmission, gear, A/C compressor, alternator, fuel pump, tires, power steering, etc.

→ *Tone-over-masking criteria*

- **Acoustic Image** – component expected to make audible noise, but it has to match customer expectations
  - Character: Engine
  - Quality: Accessories (door closure, seat adjuster, power window, windshield wiper)
  - Comfort: road and wind noise

→ *Brand sound*

Figure 3. Automotive SQ concepts.

Automotive companies around the world have invested considerable resources in the past 20 years to understand what role sound and vibration play in a customers' perceptions and to establish realistic targets to ensure commercial appeal. In fact, in the past, the NVH of a vehicle would present collateral damage to other design choices. Now, NVH design is often tightly integrated with vehicle development starting in its early stages, when the NVH attributes are designed to express a very strong brand identity. An excellent example of brand sound design, or designing the sound around the brand name of the vehicle, is illustrated in Reference 2. Here the author describes the process developed by BMW to design the sound of the vehicle as an attribute expressing strong brand identity. The BMW sound portfolio, as it is called, is summarized in Figure 2, where the two main noise attributes at 100 km/h (engine noise and wind/road noise) are plotted against each other. The two diagonal lines represent the thresholds for definite sporty (to the right) and definite comfortable (to the left). Therefore if BMW were to design a new sedan, it would be positioned in the middle region.

To translate these concepts to engineering targets, it is useful to classify sound and vibration quality (SVQ) components based on the complexity of the approach their solution requires. Specifically, I like to group automotive SVQ issues in detectability and acoustic/feel image, as described in Figure 3.

The sound/vibration quality concerns related to detectability issues are generally easier to investigate, because they are one dimensional in the sound quality space. Think of axle whine as an example; the whine is due to one narrow-band frequency that first becomes audible, then annoying, since its level increases over the rest of vehicle noise (also called masking). In this case, the sound quality problem is: “what is the maximum allowable level of noise coming from the axle that will not cause a sound quality complaint or will not be clearly perceived by the driver?” The solution clearly depends on vehicle masking, which is vehicle and operating condition dependent, and from the difference in level between axle noise and masking. Simply put, if the axle noise reaches a high level, it is detected and is objectionable.

On the other hand, the acoustic image of the vehicle is multidimensional, in that multiple components that are time and frequency dependent interact and combine to create an overall vehicle sound. The NVH system having the most impact on the vehicle’s overall image is with no doubt the engine. Over the last few generations, in industrialized societies where the automobile has become such a prominent part of our lives, we have grown accustomed to expect different acoustic signatures from different vehicles. There is no doubt in my mind that appreciation for vehicle sound quality is an acquired taste, (like Korean Kimchi, which I have grown to appreciate only after many visits to Korea). I believe that in societies where automobiles have been the main means of private transportation for decades, drivers and passengers have very specific expectations for vehicle sound quality. The exciting news is that all this is going to change; with the advent of alternative powertrains and of vehicles with different acoustic signatures, our expectations will also change. This obviously poses new challenges for automotive engineers but it also presents an opportunity for some innovative thinking.

Hybrid Vehicles

The image concept is undergoing a profound change with the advent of hybrid vehicles. Conventional hybrids such as Toyota’s Prius have become a common sight, and major vehicle OEMs are developing a next generation of hybrids that can be plugged in to extend their electric range and greatly improve fuel economy.[4] Entirely electric vehicles are also available on the market,[5,6,7,8] while other companies work toward building the electric vehicle support network and infrastructure.[9] The sound and vibration signature of electric and hybrid vehicles in general is quite different from vehicles powered by internal combustion engines, but so are customers’ expectations, since the degree of “greenness” of the vehicle weighs the fuel efficiency/fuel independence more heavily than look and feel.

From a sound quality standpoint, there are two main design challenges:

- Interior noise, which needs to provide an image of quality and “cool”
- Exterior noise, first to ensure safety and next to be used for brand recognition

Quoting one of the several excellent papers authored by N. Otto[4] at Ford, “the lack of engine noise in electric vehicles is a double-edged sword” As we will see, this is true for both interior and exterior noise, since the internal combustion engine is a source of masking for all other sources.

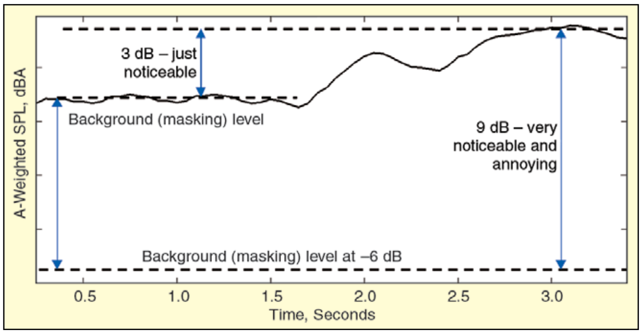


Figure 4. Change in level due to component start in two different masking scenarios.

In the vehicle interior, when there is no engine, there is no masking, and the noise from all other noise sources (pumps, compressors, fans, etc) becomes suddenly very noticeable. Therefore, the first issue that needs to be addressed is the detectability of all accessories/subsystems, especially when they start and stop. This is illustrated by Figure 4, where the dB(A) function vs. time for a pump on event is displayed (the event occurs at about 1.5 s). With the engine running, the event produces an increase of about 3 dB and, while noticeable, it is not judged to be reason for concern. But if we assume that the background noise was 6 dB lower (and this is a very conservative estimate of the difference between internal combustion engine and electric vehicle masking, which may actually be around 15-20 dB) and the pump had the same contribution at the receiver (that is, same source and same path), the delta level at the start of the pump would be around 9 dB(A), which is unmistakably noticeable and annoying.

One also has to consider that with an internal combustion engine, most of these accessories are driven by the engine (and therefore have expected speed ratio and patterns of harmonics), but in a vehicle powered by an electric motor, the speed of pump/fan/compressor may be unrelated and may spread over different frequency ranges.

The electric motor will also generate noise, but typically in a much higher frequency range than an internal combustion engine. Its noise can be more easily attenuated by careful design of transmission loss and acoustic absorption of vehicle floor/dash/trunk (depending on the layout of the powertrain).

Two interior noise components that are unchanged are road and wind noise. Not only are their relative contribution to overall interior noise larger in electric vehicles but also they may be the only elements providing acoustic feedback to the driver with regard to vehicle speed and acceleration. Since they cannot be suppressed completely, the overall sound quality balance of the electric vehicle has to be designed around their temporal pattern and frequency characteristics. One strategy adopted by manufacturers of electric/hybrid vehicles (and also by manufacturers of vehicles with cylinder deactivation) is the injection of pleasant, “cool” powertrain sounds.

The exterior noise of hybrid vehicles also poses new design and testing challenges. First of all, electric/hybrid vehicles at low speed (in a parking lot) tend to run on the electric motor only, so they are extremely quiet. Pedestrians use auditory as well as visual cues as warning signals that a vehicle is approaching. Current regulatory requirements aim at limiting the noise emitted by a vehicle in its loudest mode of operation (see pass-by test in ISO 362), and there is still no provision for ensuring that quiet vehicles can be heard by pedestrians. This is of utmost importance for the blind community, which obviously relies exclusively on auditory cues for detecting approaching vehicular traffic.[6] With this issue in mind, the automotive industry in North America has formed a Society of Automotive Engineers subcommittee to investigate this growing concern and develop recommendations. The most commonly devised solution is for the electric vehicle to generate exterior noise by means of loudspeakers mounted on its front section. But the question arises on which sound should be generated: beeps, bells, white noise, the sound of an engine or other option? What features of a sound make it detectable in an outdoor soundscape? How could the intrinsic directivity of the vehicle as it drives by be used to create or optimize a "cone of sound" aimed at lateral pedestrians? Several teams of researchers, automotive engineers and legislators are currently working on this issue. I have no answer to these questions.

Finally, if a solution is implemented that generates sound at the exterior of the vehicle, depending on vehicle speed and driving condition, the vehicle OEMs can also use this as an opportunity to increase the recognition of their brand. In this scenario a pedestrian would not only detect an electric vehicle which is approaching at low speeds, but would also recognize it to be a Tesla, Toyota, or Ford, depending on the sound it generates.

I see all this as an exciting challenge for innovative engineering work. We need to have an open-minded approach. Automotive engineers have the opportunity to shape the sound quality expectation of the users; i.e., the fact that we are used to vehicles with internal combustion engines should not influence electric vehicle designers to make the electric vehicles sound like an internal combustion engine. Maybe in a transition phase. But 50 years from now, probably no one will even remember how a gasoline engine sounds.

Internal Combustion Engine

In a vehicle powered by an internal combustion engine, the quintessential element defining the character of the car is the engine. In general, the isolation of the passenger cabin from the engine has improved significantly over the years; therefore, the issue now is more about the quality of the sound of the engine than its noisiness. Of note is the fact that the powertrain has been the first vehicle subsystem for which sound and vibration quality attributes have been extensively mapped by vehicle OEMs. This is highlighted by the fact that the majority of the important references on this subject date from the mid-'80s to the mid '90s.

The two main sound quality criteria for the powertrain are:

- Max loudness (or A-weighted sound pressure level) for overall noise and main engine orders (that is firing frequency and its first few even, odd and half-integer multiples), at idle and in hard and slow acceleration conditions.
- Linearity of overall noise and engine orders, that is the requirement for them to grow linearly with the RPM, with no significant peaks and valleys.[13]

An example of poor sound quality is represented by the data in Figures 5 and 6. In Figure 5, the two lines on the graph show the time-varying loudness measured in a compact four-cylinder engine vehicle at the passenger position during a slow partial throttle acceleration on a chassis dynamometer (red and green represent right and left ear respectively). The problem area, between 3800 and 5000 RPM is circled, showing strong deviations of up to ±4 to 5 sones from what would be the ideal trend (broken blue line). This is a problem area, since the overall level, in this case measured by time-varying loudness, exhibits a strong amplification as the engine sweeps through a certain RPM range (3800 to 4300 RPM), followed by a significant level reduction in the next RPM range (around 4500 RPM). Just by looking at this plot, we know that the overall impression of this vehicle will not be that of a smooth and refined ride. On the contrary, the vehicle will feel very "boomy."

In Figure 6, overall sound level and order slices from the same data are presented, showing that the reason for the poor sound quality between 3800 and 5000 RPM is the second engine order (labeled 2EO on the plot in red). By comparing the level of 2EO to the overall A-weighted sound pressure level (in black), it is clear that 2EO is the sole contributor to the perceived noise and that its level exhibits min-to-max excursions of up to 15 dB between 3200 and 5000 RPM.

An important fact of sound quality perception is that changes of any characteristics of the noise (level, pitch, modulation etc.) are noticed and may tune the driver's ears to a particular noise feature. In other words, a vehicle signature that is loud but grows linearly with engine RPM and vehicle speed will likely be more acceptable than a quieter signature that exhibits deviations of more than 6-7 dB from its mean under the same test conditions. This type of effect is called "boom" by vehicle engineers. Typically, the most annoying occurrences of boom are at steady state – at idle or cruise condition, when the frequency of excitation from the engine aligns or is very close to an acoustic cavity mode. Boom is not just triggered by the engine; it can also be triggered by a low-frequency mode from the tires or even by the motion of an accessory such as a power seat with the engine off.

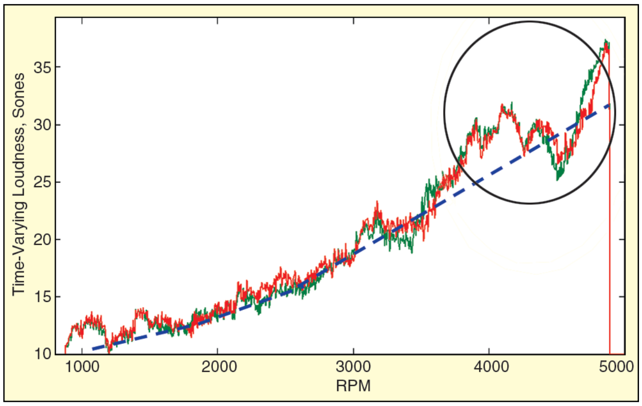


Figure 5. Example of poor powertrain SQ, time-varying loudness vs. RPM of vehicle interior noise during engine acceleration.

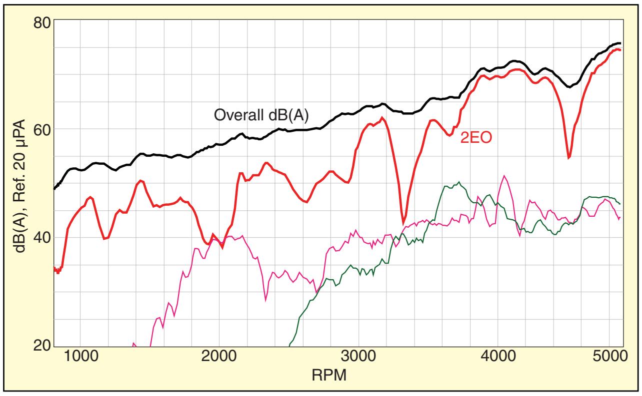
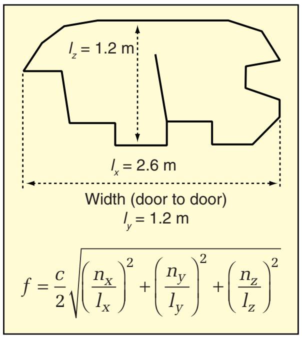


Figure 6. Example of poor powertrain SQ, order slices vs. RPM of vehicle interior noise during engine acceleration.



$$f = \frac{c}{2}\sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}$$

Figure 7. Resonant frequencies of room acoustics as applied to interior of vehicle.

The root cause of boom during vehicle acceleration is the excitation of the engine at its firing frequency, which is transmitted from engine and/or exhaust to vehicle body panels, which then excite acoustic cavity mode(s). Every cavity has acoustic resonant frequencies; the trick is in understanding the structural and acoustic modal alignment charts of the trimmed body and body in white, to decouple as much as possible one from the other and ultimately isolate the trimmed body as much as possible from the engine in the frequency range of the acoustic cavity modes. This is clearly not as easy to do as it is to talk about it.

Acoustic cavity modes are easily computed using acoustic finite-element approaches, but if you don't have access to these tools and want to get a quick estimate of their frequencies, you can also apply a very simple formula developed for small-room acoustics. Figure 7 shows the formula and the required geometric dimensions of the vehicle cavity. The resulting table of values will give you a rough estimate of the frequencies of the modes and of their frequency spacing/density, but of course it will not provide any information on the spatial pattern of the mode. (For this, a 3D acoustic simulation tool is essential.) For example, you can expect a typical four-door sedan to have around 10 to 15 acoustic modes approximately between 50 and 200 Hz. Larger cavities such as in minivans and trucks will have lower frequency modes, and sporty two-seat cars will have higher frequency modes.

Along with powertrain engineers, audio engineers are also very interested in acoustic cavity modes, since they have to tailor the location of loudspeakers to achieve the best overall performance of the audio. To do so, they need to know the spatial pattern of the main acoustic cavity modes. This is why you can easily find room mode calculators in audio system engineering websites (check www.mcsquared.com or www.harman.com).

In summary the sound quality, or refinement, of a vehicle powertrain is often objectively measured using the following metrics, which are evaluated for linearity as well as level:

- Loudness
- Tonality (includes boominess)
- Roughness and fluctuation strength

Diesel Engines

For diesel engine sound quality, you need to look at the technology advances made in Europe over the past 20 years. To my knowledge, the first exhaustive investigations of the characteristics of diesel engine noise and attempts to develop objective metrics for its perceived quality were done in the UK in the mid ’80s.[32] With the current market share of diesel-powered vehicles in Europe approaching 50%, much effort has been devoted by European vehicle OEMs to improve customer perception of diesel engine noise.[36]

In most passenger vehicles, diesel engine noise is acceptable at high-speed cruise conditions. The majority of the adverse reaction to diesel noise (“it sounds like a tractor”) occurs at low speed and idle. This is the condition where a diesel noise signature differs the most from the signature of a gasoline engine and also where its typical impulsiveness and irregularities are most noticeable. Other than sound pressure level (or loudness), the most peculiar acoustic features of diesel engines at idle are:

- Sharpness or high-frequency content (relative to low frequency)
- Tonality
- Impulsiveness (periodic), often referred to as “diesel knock”
- Irregularities (aperiodic), often referred to as “diesel clatter”

Figure 8 is an example showing the independence between loudness and irregularity. The three plots relate to idle noise measured in exactly the same location and condition in three different (but comparable) heavy-duty trucks. In the top plot, individual impulsive events with content up to about 1500 Hz can be seen clearly. In the middle plot, no impulsive events are shown, with approximately the same loudness as in the top plot. The bottom plot shows impulsive (and periodic) events with lower levels up to 1500 Hz. The subjective perception of the corresponding recordings (shown in the figure) agrees with what the data indicate.

Diesel acoustic signature originate from higher pressures in the diesel combustion process and higher forcing functions to the engine structures. Of these, three (loudness, sharpness, and tonality) are measured by steady-state metrics, while the impulsiveness and irregularities have to be assessed by using time-domain approaches. (European researchers use the term “dieselness” to describe these time-varying features of diesel engines.) Unfortunately, while clearly noticeable by the human ear, these are not easily captured by using traditional time-domain statistical analyses of the raw signal, such as crest factor, kurtosis, standard deviation, etc. The reason for this is that the very impulsive nature of diesel noise generates frequency spectra with significant broadband energy around and above the engine harmonic content; therefore, the raw signal is extremely rich and complex and requires some “focused cleaning” prior to metric computation.

Several algorithms have been developed to quantify “dieselness,” ranging from relatively easy (crest factor and standard deviation of impulse peaks[37]) to complex ones (localization and rating of events of compressed, post-masked excitation levels[39]). Regardless of the sophistication and complexity of the algorithms used, the basic approach to quantify diesel engine sound quality, both interior and exterior, is the same, and that is:

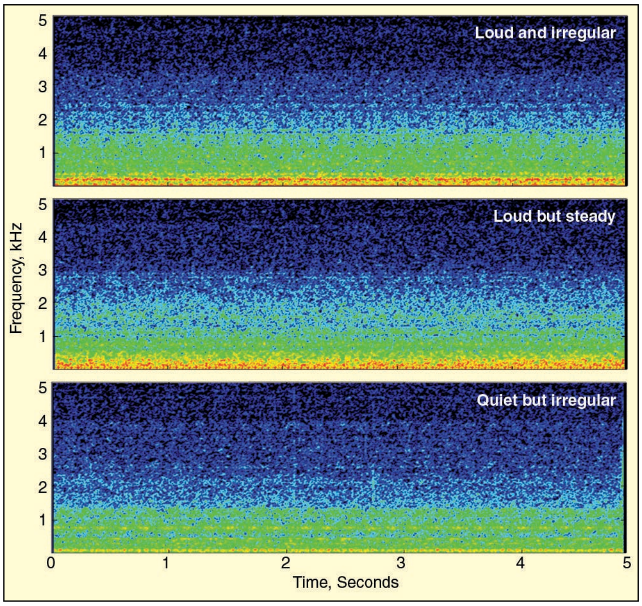


Figure 8. Spectrograms of diesel engine at idle inside three different super-duty trucks.

- Filtering the raw signals to focus subsequent analysis on a specific frequency range ($500 < f < 5$ kHz for diesel knock and clatter). This can be done by simply high-passing the recorded signal or alternately by running nonstationary loudness algorithms and extracting excitation level and/or specific loudness functions vs. time.
- Identification/localization of impulses (large deviations from mean) over processed functions by means of statistical parameters (crest factors, kurtosis, etc.) to quantify the impulsiveness of the signal.
- Distribution (standard deviation, percentile, etc.) of peaks of processed functions (overall or during one combustion cycle) to quantify the irregularity of the signal.
- Correlation to subjective perception (jury) to identify the best metric and define its target value (for acceptable/good diesel engine sound).

This is the fundamental approach that has been applied by vehicle OEMs around the world to quantify diesel sound quality. I am sure that company-specific metrics have been developed and are routinely applied in vehicle development. However, it is interesting to note that, despite these developments, the “judgment” of dieselness is still not fully understood. I am referring to an investigation[41] where 40 sounds from both diesel and gasoline engines were presented to two juries of people (one of naïve jurors, one of experts) who were asked the following question: “Is the sound you just heard from a diesel or a gasoline engine?” All jurors, experts as well as naïve, demonstrated an uncanny ability to discriminate diesel engine sounds, even the ones with less “dieselness,” from those of gasoline engines. The vehicle OEM who commissioned the study (BMW) then wanted to assess the correlation between jury results and four different metric algorithms of dieselness to identify the most representative one. The results show that the dieselness metrics deviate substantially from the psychoacoustic ratings, which clearly indicates that more research is needed.

The metrics commonly used for diesel sound quality are:

- Overall level: Zwicker loudness, composite rating of preference, dB(A)
- High-frequency content: sharpness, spectral balance
- Impulsiveness: kurtosis/standard deviation of sound pressure or loudness-derived functions vs. time or crank angle.
- Irregularities: amplitude modulation of peaks of band-passed amplitude/energy metric function vs. time, statistics of peaks of same function
- Tonality, pitch strength

Exhaust and Intake Tuning

Once overall quietness and linearity of orders from engine are addressed (main powertrain targets), it is often required to tune the interior sound to match the desired acoustic image. This is typically done by manipulating the acoustic performance of exhaust and intake systems. Exhaust/intake tuning refers to the art and science of balancing the requirements of engine sound and power performance to achieve the best possible compromise. An excellent review of intake and exhaust noise issues is in Reference 20.

The tuning of the exhaust note during acceleration is done by designing the desired sound at the tailpipe and accounting for its contribution to the interior receiver. However, it has to be noted that the ever more stringent European legislation on pass-by noise has significantly reduced over the years the capability of exhaust engineers to tune the exhaust for sound quality. In general, complying with pass-by legislation requires the use of silencers with relatively high insertion or transmission loss, that produce a quiet but not sporty interior sound. In practice, this means that often vehicle manufacturers who want to achieve a sporty interior sound have more room to maneuver by tuning the intake than the exhaust tailpipe noise.

Tuning in both exhaust and intake can be achieved by either completely passive means; i.e., with silencers of different performance, or by active means, that is by varying the geometry seen by the flow as a function of operating condition (flow rate, speed, etc.) or by a hybrid mix of these approaches. High-performance vehicles, especially from European OEMs, have used valves in the exhaust since the early '90s. By using valves, it is possible to use the same exhaust line, without additional muffler volumes. The great advantage of exhaust valves is also that they allow a high-performing vehicle to comply with the pass-by test, while at the same time achieving great sporty sound at engine RPM higher than the range experienced during the pass-by tests. An example of the effect on the interior sound of such a variable-geometry muffler is shown in Figure 9. Both spectrograms show the interior noise at DRE during a third-gear WOT (wide open throttle) acceleration from about 3500 to 8000 RPM. The top plot refers to the baseline (passive) muffler, and the bottom one to the variable-geometry muffler with a valve that opens past 5000 RPM (and therefore past the RPM range of the pass-by test) to provide less obstruction to the exhaust gases (and therefore less back-pressure and more noise).

Intake tuning is often done by either passive, active, semi-active or hybrid strategies.[31] The goal of intake tuning is typically to increase in a balanced way the harmonic content in the mid-frequency range – between 200 and 800 Hz. In practice, this means an increase of not only integer engine orders but also half orders, and a well designed balance of integer and half orders in this frequency range creates sounds with sporty, aggressive connotation. The level difference between half orders and integer orders is responsible for the roughness of the sound, and a rougher sound is generally perceived as being more aggressive, which is one possible connotation of sporty. But we need to note that two different groups of people may react to the same sound in an opposite way. This has recently been well illustrated in Reference 25, where a jury study with two different groups of jurors was conducted to investigate the effect on the perceptions of "pleasant" and "powerful" of the level and frequency range of integer and half orders. Not surprisingly, higher levels of integer orders were confirmed to increase the powerfulness of the sound, while higher levels of half orders were found to generate roughness. However, one group liked the rougher sound, because they found it powerful. But the other group did not like it, since they found it unpleasant. This demonstrates once again the importance of correctly mapping customer expectation when designing the sound quality of a vehicle. In an article by researchers at Honda R&D, the regression equation (model) for sportiness is provided in the following general form:[25]

$$Sportiness = coeff_1 \times OC + coeff_2 \times T + coeff_3 \times \Delta RPM$$

where OC is the level of order content, T is a tonality-type metric and ΔRPM describes the (probable) rate of change of the engine RPM. The specific metrics are obviously confidential, but the impression is that the idea of sportiness of a sound increases with the level of engine orders, with tonality and depends on the rate of change of the RPM. The challenge is to achieve sportiness without making the vehicle sound boomy or too loud.

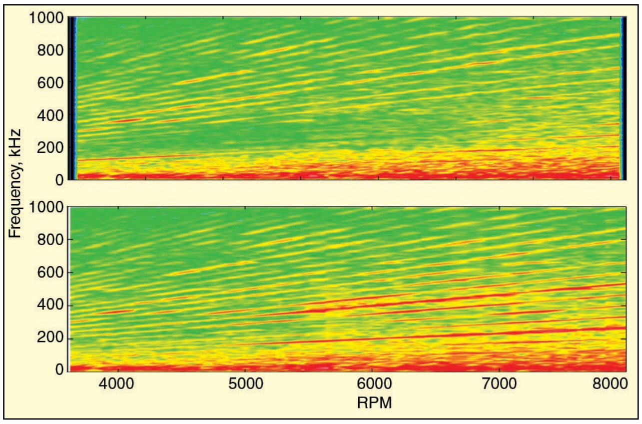


Figure 9. Interior noise in high-performance vehicle with baseline muffler (top) and variable geometry muffler (bottom).

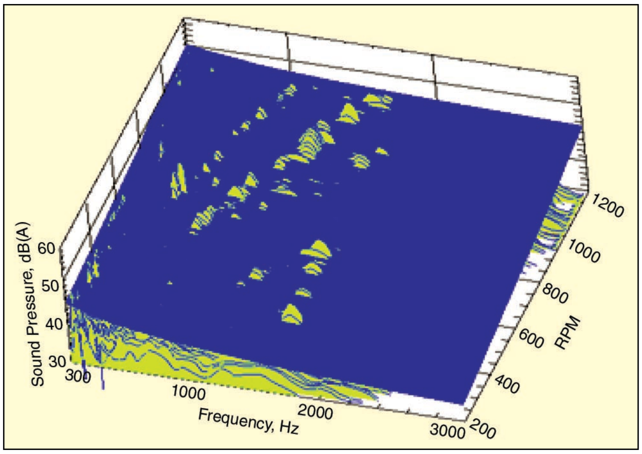


Figure 10. Tonal noise target surface.

In summary, the metrics used to assess intake/exhaust tuning are:

- Levels of engine orders vs. RPM
- Level difference between integer and half orders, especially in the 200-800 Hz range (shown in Figure 9)

Driveline

Unlike engine sound quality, which needs to be carefully designed for, typical driveline sound quality issues derive from gear mesh frequencies being heard as pure tones over background noise. From a sound quality standpoint, this is a much easier problem to deal with. For starters, the detectability threshold of pure tones over masking that have been established from psychoacoustic experiments apply fairly well to drivetrain-related tonal components. This is a case where the real noise is not much more complex than the elementary noises (sine waves, band-passed masking noises, etc.) used in psychoacoustic experiments. Furthermore, the detectability of tone over masking can be accurately measured by comparing A-weighted gear-mesh order slices to either overall noise or noise within the third-octave band centered around the tone. Finally, the number of pure tones due to driveline dynamics is generally limited to a few (fundamental gear-mesh frequency and maybe its first harmonic); therefore, more sophisticated broadband-type tonality metrics, such as tonality, tone-to-noise ratio, prominence ratio, etc., are not required.

A good approach to driveline SQ is described in References 45 and 46. In Reference 45, the authors provide a nice analysis of the perception of tonal components generated and/or radiated off the transfer case, transmission, differential and drive shafts. They derive three metrics for transmission tonal noise, all based on fundamental psychoacoustic findings but expressed by simple parameters, such as difference in level between tones and masking. The problem is in finding the maximum allowed level for the tone not to be noticeable against masking. This can be expressed in

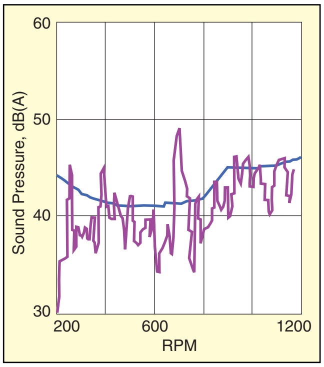


Figure 11. Measured gear-mesh order and target for masking function.

terms of a smooth 3D surface, like the curved plane shown in Figure 10, which represents the maximum allowed level for the tone as a function of frequency (X axis) and RPM (Z axis). Frequency components sticking out of this plane are clearly audible.

The metrics used to measure the audibility and annoyance of gear noises are surprisingly simple, such as a level difference between the A-weighted SPL of gear-mesh orders and either total noise or band-passed noise. This level difference is a function of the frequency of the tone and the frequency of the masking, which in turn depends on vehicle operating conditions.

One must note that, especially for a classical gear whine issue, the sound quality concern is not so much from the presence of a loud tone, rather from the fact that its' level varies with time/RPM. Generally in sound quality, change of noise is bad, because it focuses our attention on the noise itself. Often loud noises do not cause complaints simply because they are always present. While a gear whine that, as an example, onsets at exactly 45 mph and goes away at 55 mph, is very noticeable in slight acceleration like passing. For this reason, the maximum level allowed for the tone has to be expressed as a function of RPM, against which measured or predicted gear mesh SPL have to be plotted. The data in Figure 11 show an example of clearly audible gear whine at a prop-shaft speed of 700 RPM, because the measured order (in pink) exceeds by 7-8 dB the target curve (in blue).

- The metrics used for driveline sound quality are:
- Order slices versus RPM
- Tone-over-masking detectability thresholds

Tire/Road Noise

Tire/road noise has become increasingly important for overall sound quality perception due to the ongoing and successful reduction of powertrain and driveline noise. Road noise generally starts to be noticeable at vehicle speeds above 30 mph, but its contribution to overall interior noise is maximum between 40 and 60 mph and then decreases at higher speeds, where aerodynamic noise becomes predominant.

For this reason, tests for road noise are generally conducted at constant conditions, typically 50 mph and in coast down on different road surfaces. Road noise is generated by the interaction between the tire and the road surface and excites the vehicle through both structural and airborne paths (see Figure 12).

An example of good and bad road noise is provided in Figure 13. The FFT color maps represent the analysis of the sound measured at the right ear of a binaural head positioned on the passenger seat of a production sedan driven at 50 mph over a smooth asphalt road (vehicle, road and test conditions are the same between the two plots, the only difference is the tires). As clearly shown, the main difference occurs between 500 and 1300 Hz, which is the typical "tire-band" range. In this range, both broad-band and narrow-band (tonal) components may be present, due respectively to turbulent-type excitation at the tire patch and to tread pitch harmonics.

In this frequency range, the path followed by the noise from the tire patch to the interior occupants is airborne; i.e., through holes, leakage, and due to insufficient acoustic transmission loss of vehicle floor, doors, windows. In the case of Figure 13, since the vehicle is the same, the only difference is the acoustic source strength of the tire patch. In other words, the sound power of the tire patch is very different between the two tires. Tire/road noise may have significant acoustic contribution at low frequencies, and especially around 200 Hz, where tire acoustic cavity modes are present. Since the tire/road noise is generally transmitted only through structural paths (tire-to-wheel-to-tie-rod-to-suspension-to-body) for frequencies up to 200 Hz, the tonal components due to tire acoustic cavity modes are typically structure borne. Alongside the tire acoustic cavity modes, low orders of the tire rotation (related to the number of block elements around the tire) can affect the sound quality. Figure 14 is an example of poor sound quality at vehicle interior due to the presence of both a 14th order of rotation of the tire and two closely spaced tire acoustic cavity modes around 200 Hz.

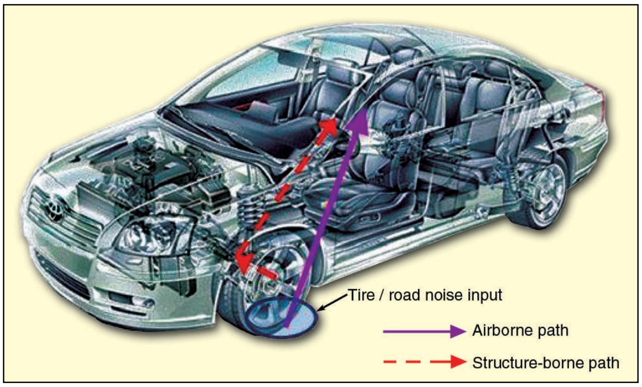


Figure 12. Road noise input and paths.

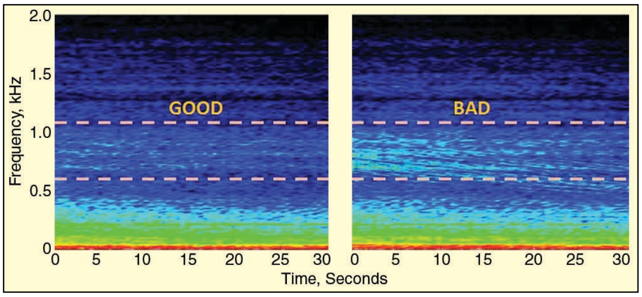


Figure 13. Example of good and bad road noise quality for "mid/high frequency" concern; time on X-axis (10s), frequency from 0 to 2000 Hz on the Y-axis, color denotes amplitude.

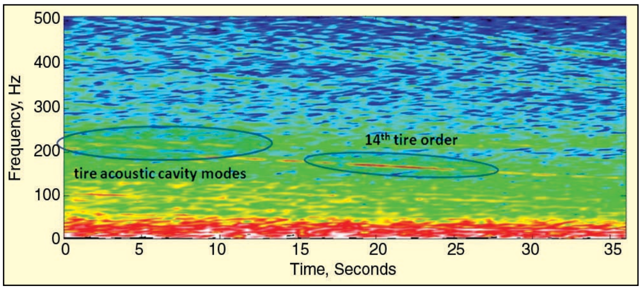


Figure 14. Example of poor sound quality due to low-frequency tire noise.

In cases of strong phase alignment between tires, modulation may also occur and contribute to the overall perception. However, this does not occur often, and modulation is not typically an objectionable attribute of road noise.

The perception of road noise is therefore mainly affected by:

- Tonality in the low-frequency range, which can be measured by tonality-related metrics such as tonality, tone-to-noise ratio, prominence ratio, etc.
- Broad-band air-rush-type of noise in the mid frequency range (500 to 1300 Hz), which can be measured by using broad-band, amplitude-related parameters such as the articulation index, A-weighted SPL or loudness. In cases where the level in the tire band is noticeable and yet it does not significantly impact a broad-band parameter such as ASPL or loudness, then it is necessary to increase the resolution of the analysis and compute some spectral envelope type of metric to relate the content in the tire band to the overall content of the signal. I often find that a target expressed as maximum SPL in each 1/3 octave band as a function of vehicle speed works better than an overall value such as the articulation index, speech intelligibility or loudness.

I have to point out that this is the result of my experience, and does not align with some of the other assessment methods for an-

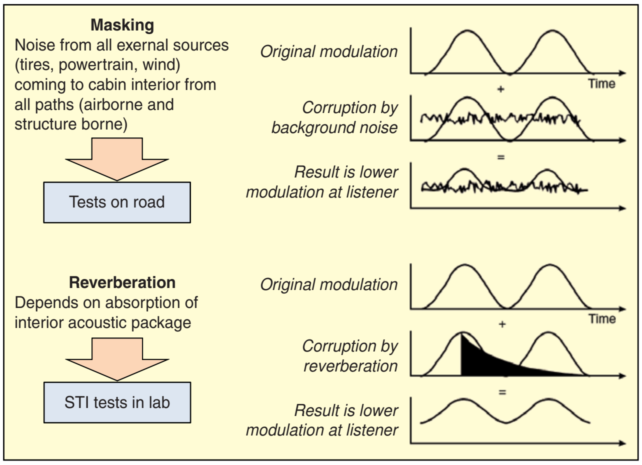


Figure 15. Forms of speech corruption.

noyance due to excessive road noise. As an example, Reference 49 describes the procedure followed to derive a tire noise model based on loudness, roughness and fluctuation strength. It is possible that the noise recordings included in the jury test described in that paper had significant amplitude fluctuation, which explains the presence of fluctuation strength in the model. However, this has not been my experience with vehicles and tires sold in North America. Ultimately, road noise is a comfort factor and should be loud enough to provide acoustic feedback of vehicle speed but not at all annoying and noticeable.

The metric most often used to assess road noise performance is the articulation index, which is a global parameter aiming at establishing the masking effect of background noise relative to the capability of listeners to detect articulated words. It is always measured with the vehicle driven in accelerating and cruise condition and it is based on a 1/3-octave-band spectrum analysis of the overall noise measured at the driver/passenger head position. The main drawback of AI is that it includes both the effect of the noise/vibration coming from the exterior inputs (the tires) and that of the acoustic boundary condition of the cabin (reflection, absorption). For a more efficient vehicle development, it would be useful to separate the forced response of the vehicle from the interior acoustic boundary conditions, and establish separate targets for path sensitivities and for the interior acoustic package. This is of relevance especially considering the increased need for good speech intelligibility inside today's vehicles with entertainment centers and voice activation capabilities.

The metric that links the speech intelligibility performance to the acoustic characteristics of the cabin interior is the speech transmission index (STI).[48] STI is a physical quantity that measures the capability of a given environment to transmit unaltered speech from a talker to a listener. The basic assumption is that the understanding of speech is based on the appreciation of the amplitude modulation, which is intrinsic to the speech. If the amplitude modulation of the speech is lost or reduced when the sound travels from the source (talker) to the receiver (listener), then the comprehension at the listener is compromised. The presence of masking noise can reduce the modulation depth of the transmitted speech signal, and so does the amount of reverberation in the environment (Figure 15). The change of the modulation from the talker to the listener is measured by the modulation transfer function (MTF), which is measured at several octave band center frequencies and for different modulation frequencies. The MTFs are then combined in a weighted sum to produce the STI, which is normalized between 0 and 1.

How to test for STI in a vehicle cabin? Luckily several references are available in the literature with excellent descriptions of the procedures tried and lessons learned.[51] Since the use of STI for automotive interiors is fairly recent, there are still no standard tests, however from the lessons learned, one can easily develop a controlled and possibly simplified test procedure. To measure STI in a vehicle interior, one typically needs a "talking head," which is a binaural mannequin with a loudspeaker in its interior and a mouth opening. While researchers and hardware vendors have been investigating the directivity of the human mouth and developing hardware to achieve the highest possible degree of correlation, a simpler and perhaps less accurate, but still very useful, approach is that of using a normal binaural head, insert inside its torso an off-the-shelf loudspeaker and use its front-mouth cavity to generate noise in the environment. One or more "receiver" binaural head can be used to measure the binaural sound at the receiver positions (second or third row). A set of signals, octave-band wide, with different modulation frequencies is fed to the source binaural head and the response measured at the listeners positions. This artificial excitation test can be done in the lab, with no excitation to/from the vehicle, but also on the road, when actual masking is present. Other approaches try to simplify this procedure by using simpler parameters, such as the speech interference level (SIL) and preferred speech interference level (PSIL) to correlate to speech intelligibility.[51]

The sound quality metrics used for road noise are:

- Loudness, articulation index and dB(A)
- Tonality/tone-to-noise ratio/prominence ratio
- Roughness/fluctuation strength
- Speech intelligibility and (indirectly) speech transmission index

Wind Noise

Wind noise is the predominant component of interior vehicle noise at speeds above 100 kph. It is typically tested at steady vehicle speeds between 100 and 160 kph, either on the road or in a wind tunnel.

Wind noise refers to the following noise and conditions:

- Aerodynamic noise made by the vehicle as it moves at high speed through a steady medium (air). This is related to the aerodynamic (or drag) coefficient of the vehicle, which is a function of the vehicle shape and its cross-sectional area.
- Aerodynamic noise due to turbulence through "holes," which is correlated to how tightly sealed the vehicle is (around doors, hood, windshield etc.).
- Aerodynamic noise due to exterior varying wind conditions, such as cross-wind on a highway. This is different from the previous two, since this type of wind noise is fluctuating.
- Very low-frequency (10 to 20 Hz) beating noise occurring when either a rear window or the sunroof are partially open. This is due to the Helmholtz resonance of the vehicle cabin, which is excited by the air flow along the boundary of the window or sunroof opening.

The last two types of noise are also often referred to as wind buffeting or wind gusting noises. The frequency spectrum of steady wind noise is typically broadband and heavily biased toward the low frequencies (31.5 to 63 Hz). Gusting noise due to cross-wind, as an example, is impulsive and has content at higher frequencies (above 300 Hz or so).

Perception of steady-state wind noise (such as the first two types listed above) is well characterized by Zwicker loudness.[54] Other researchers have complemented the use of Zwicker loudness with the binaural cues provided by recordings made in the vehicle with an artificial binaural microphone.[55] The binaural cues can be used to localize the provenance of the wind noise.

As for time-varying wind noise, such as from wind gusts, a gusting metric has been proposed by Ford researchers.[58] The metric is based on Zwicker loudness excitation and detects "gusting events" by assessing the relative changes in the excitation level. It is therefore independent from the absolute value of loudness. Using Zwicker loudness and this gusting metric, the researchers developed a linear regression model capable of predicting the annoyance due to both steady-state and fluctuating wind noise.

For the rear window or sunroof buffeting, the metric typically used is simply the peak level of the sound pressure at the resonance. An example of rear window buffeting is shown in Figure 16, where the top plot depicts the time history of the sound pressure at the ear of a rear passenger during a light acceleration from 40 to 50 mph (note the fairly sudden onset of the resonance), and the bottom plot shows the FFT spectrum of the same signal at resonance.

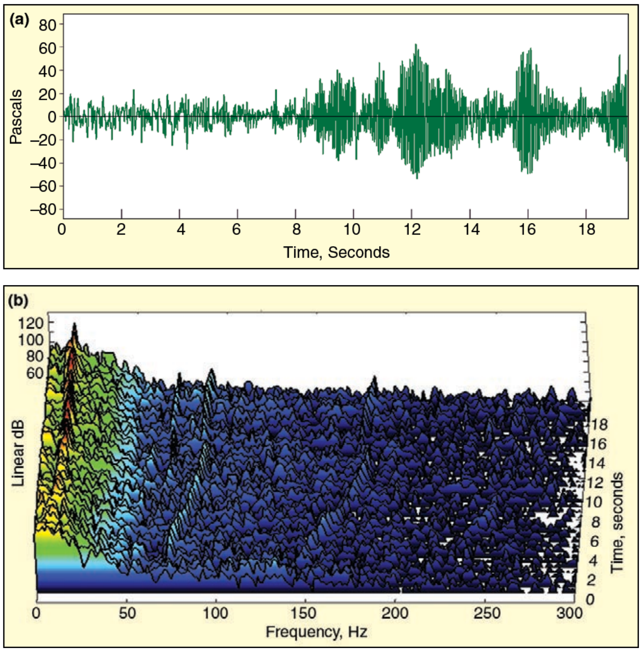


Figure 16. Rear-window buffeting; peak at 15 Hz.

In summary, the metrics used for wind noise are:

- Zwicker loudness for all steady-state wind noise
- Changes of loudness relative to steady state for gusting/cross-wind conditions
- Peak level (not A-weighted) for Helmholtz-driven buffeting

Vehicle Exterior Noise and Pass-By

Pass-by testing has nothing to do with sound quality. It is strictly a mandatory test to ensure that a vehicle's exterior noise at specified operating conditions is below a defined threshold value. This threshold value is expressed in dB(A), and it is the max value recorded while the vehicle is driven from entrance to exit of the pass-by course. In recent years in Europe, however, vehicle OEMs have started to focus on exterior vehicle sound quality and not just in relation to diesel engines but also for gasoline vehicles. I am aware of a couple of research projects on this subject: Sound Quality of Vehicle Exterior Noise (SVEN), sponsored by the European Community, and the German project Silent Traffic, sponsored by the German Ministry of Education and Research. In both, one main goal is to establish methods to develop sound quality targets for a vehicle exterior in recognition of the fact that in urban and residential areas, vehicular traffic is a very important contribution to the overall soundscape. Furthermore, vehicle exterior noise could be used by vehicle manufacturers as an element of brand recognition that can shape over time the expectation of the customer. That is, if a pedestrian likes the sound quality of Car A, he or she may decide to purchase that car over other candidate vehicles.

I have not personally worked on this aspect of vehicle sound quality yet, since I believe this is at least for now an issue arisen mainly in Europe due to the strong government push for reduced community noise and improved quality of the soundscape. From what I am aware of on the subject, I can summarize the following:

- The test conditions have to include realistic scenarios, not just the pass-by test procedure. Recommended test procedures include: vehicle driving by the receiver microphone at 70 kph steady; vehicle approaching at 50 kph steady, starting to brake at –25 m, come to a full stop in front of the microphone, drive away at moderate acceleration (to simulate the traffic light scenario).
- The results of subjective testing are preliminary so far and no definite sound quality preference models for exterior vehicle noise have been derived. However, the following parameters have been suggested:[64] boom index – A-weighted sound level below 250 Hz; difference between loudness at $f < 2000$ Hz and loudness at $2000 < f < 5000$ Hz; sharpness (t); and prominence ratio, to measure the impact of tonal components.

Conclusions

By reviewing the current knowledge on this subject, it is clear that technology and tools are available now to quantify the quality of any vehicle sound. 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, which is that sound quality models (the relationship between sound quality metrics and human perception) are not cast in stone. Rather, they are subject to change with the introduction of different types of vehicles (think electric and hybrid as examples).

An example of customer expectation changing over time can be seen in Reference 66, which shows how interior vehicle noise spectra at 100 kph have changed over the years from the late '70s to the late '90s (higher low frequencies, much lower high frequencies). So a metric derived in the '70s (the composite rating of preference) should be modified to better account for the spectral envelope of current vehicles.

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