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Automatic Detection of Buzz, Squeak and Rattle Events

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ABSTRACT

In the world of BSR (Buzz, Squeak and Rattle) testing, there is a high level of sophistication regarding the test machines employed to excite the items under test as well as the techniques used to ensure that the test is representative of real-life operating conditions. However, the object of the measurements, i.e., the identification of transient acoustic events classified as Buzz, Squeak or Rattle, is mostly a subjective procedure with classification in terms of Sound Pressure Level in dB(A) or Stationary Loudness. These "standard" metrics have proven, in general, unreliable in assessing the importance of individual transient events, and inappropriate to describe the vehicle signature from a BSR standpoint. This paper presents a methodology that has been developed for the BSR test of a vehicle using a road simulator to:

1. Demonstrate the feasibility of an automated system of detection of BSR events that can replace the "subjective" detection

2. To establish "vehicle BSR" indices that can be used to assess design targets and specifications.

INTRODUCTION

Today, automotive OEMs are dictating that components and sub-systems supplied by their vendors be free from audible squeaks and rattles. Without a more detailed specification, Tier 1 and Tier 2 suppliers are forced to carry out subjective evaluations, in order to get their customer to approve the design. Although the tests can vary in complexity from full vehicle simulation to component level tests, they all still require a subjective evaluation to determine a pass or fail.

The level of expertise in the noise and vibration field varies dramatically when comparing the decision makers associated with establishing BSR requirements. OEM's and Tier 1 and 2 suppliers have on their staff highly skilled NVH professionals, frequently with MS and PhD. degrees and years of experience. However, unless the program is at an early development stage or in a "fire-fighting" mode, program engineers are typically responsible for approving the designs. Program engineers have a wide range of engineering skills, but few have a high level of NVH experience. Furthermore, once the product is in production, quality engineers and line operators may be given the same responsibility of evaluating the BSR performance of their components or vehicles, and their NVH expertise is limited too. Along with the disparity of training and expertise levels, often the BSR decision makers use different detection and measuring tools as well. If all parties involved had objective BSR detection and measuring tools throughout the product development process, this would greatly enhance their cooperative efforts in defining targets as well as the consistency of the hardware validation process.

CURRENT TECHNOLOGY & REQUIREMENTS

All automotive OEMs and a majority of Tier 1 suppliers use a combination of full vehicle simulation test rigs and component level test stands for subjectively evaluating Buzz, Squeak and Rattle events. This technology stemmed from the durability labs, where full vehicle simulators and multi-axis simulation tables based on servo-hydraulic actuators have been used for many years to expedite life cycle testing. Examples of this type of test machines are displayed in Figures 1 and 2 below.

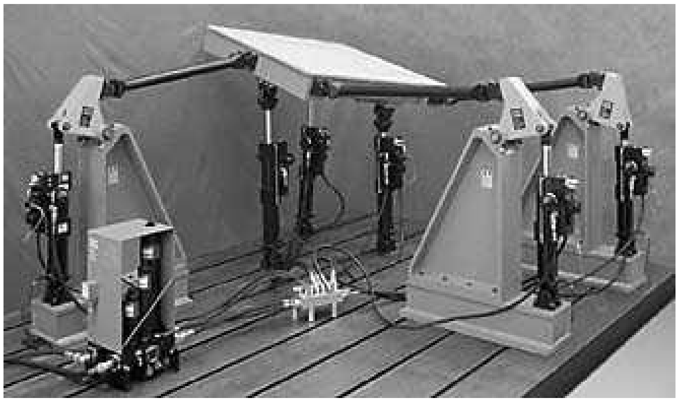

Figure 1: MTS Multi-Axis Simulation Table

Figure 2: MTS 320 Road Simulator, Magna Automotive Testing

FULL VEHICLE SIMULATION – In order to properly simulate on-road vehicle conditions, such as acceleration and/or strain, data are collected at various locations while the vehicle is driven around a test track or specific test course. The data are then post-processed in order to shrink the drive files down to the significant events. These drive files are played back through closed loop shaker control software to excite, via servo-hydraulic actuators, the four tire patches of the vehicle. The closed loop control is necessary to ensure that the accelerations and strains measured on the vehicle at the track are correctly reproduced on the test rig. Although drive files are used for most BSR and durability full vehicle testing, various sine sweep tests are used for benchmarking numerous vehicles for BSR performance, because the required time and added cost for developing drive files for each vehicle is not justified.

Due to the inherent capital investment with a 4 poster, suppliers tend to use them in a dual-purpose mode, for both durability and BSR testing. Since both durability and BSR results can vary depending on climatic conditions (humidity and temperature), the 4 posters are usually placed in an environmental chamber, where temperature and humidity can be controlled. The trade-off for placing the rig in a standard environmental chamber is that the reflective interior walls may affect noise measurements inside the vehicle and prevent accurate acoustic measurements outside of the vehicle. Therefore, some OEMs and suppliers have invested in sound absorbent walls that can be used in environmental chambers. In order to detect BSR events at the vehicle level, an engineer or a technician is required to either sit in the vehicle or walk around the test rig during the tests. There have been attempts at setting target levels for BSR in terms of A-weighted Sound Pressure Level (SPL), but in case of a dispute, one generally reverts back to a human evaluator.

Along with interior sound pressure measurements, suppliers typically record acceleration and/or strain data on the floor pan and various locations on the seat systems. Although these measurements can be useful to gain an understanding of the structural resonances of the body and seat systems, they are generally used to correlate component testing to the full vehicle simulation.

COMPONENT LEVEL TESTING – Multi-Axis Simulation Tables, MAST, and 1 DOF pitch tables are used to study the BSR events at a component level. In order to simulate road conditions at the component level, the acceleration measurements for a particular section of a vehicle are correlated from the full vehicle simulation. As an example, for a minivan application, the vehicle is separated into three subsections: front, first row, and second row. These subsections allow the test engineers to accurately simulate the acceleration levels that can be significantly different from one section to another.

A basic pitch table can also be used for component level testing. Pitch tables are typically used because of their relatively low capital investment, and they can be used to determine significant characteristics about the structure. For example, a sine sweep test with a set input level could be used to determine the seat subsystem’s first resonance. This information can be used to determine the likelihood of a BSR problem at a system level at a much lower cost. However, it is important to point out that single DOF test rigs are not usually representative of real-life conditions.

Since component test stands are much smaller and cheaper than full vehicle simulators, the NVH labs can afford to have multiple test machines in different test environments, depending on the primary purpose of the test (durability or NVH). An NVH test stand will be typically installed in a “quiet” or hemi-anechoic room so that noise measurements can be made with a higher level of accuracy. In case it is necessary, the noise components from the test stand can be filtered out using analog or digital filters both in the frequency and in the order domain (this is required to eliminate tonal noise from the pump(s)). Current specifications recommend looking at the data in the time and frequency domains, and tagging anything over a target sound pressure level (dB). Although this is a good starting point for using objective measurements for detecting BSR, it is not 100% effective, and a human is typically used along with the measurements.

THE DEVELOPMENT STEPS

In order to develop automatic detection tools of BSR events, it is necessary to go through several investigative phases in order to try to replicate as precisely as possible the subjective process currently adopted by most NVH laboratories. So, what does the BSR engineer do today? Here is a typical scenario:

Do I hear any BSR events? – This is done by the engineer sitting in the vehicle being tested or standing next to the component on the shaker table.

If I hear some, how bad are they? – Clearly, from a practical standpoint, not all BSR events, which are detectable, are worth being chased down. As an example, those which are very low level and/or last only a few milliseconds are less likely to be noticed by the final customer therefore are “less likely offenders”. Therefore, we need to establish a threshold of acceptable BSR, which does not necessarily coincide with the threshold of detectability. Both thresholds will be expressed in terms of one or more sound quality or signal processing parameters.

How often will this BSR event occur? – A severe BSR event that does not occur very often has to be considered less important than a less severe event that occurs often. Therefore a BSR sensitivity matrix has to be developed for each relevant BSR event in which objective SQ metrics are “weighted” by other factors such as customer expectation and frequency of occurrence.

Where is it coming from? – The engineer starts to walk around or move his/her head to localize the source of the rattle.

Let’s see if it goes away – This is the fix, which confirms the source or the path. The engineer starts touching different components with the objective of localizing the source of the annoying BSR event.

The question is: which are the steps of this process that can be automated? The objective of this paper is to demonstrate that detection and assessment of BSR events (the first three of the steps outlined above) can indeed be carried out by objective, engineering methods. As for the source localization phase, a significant amount of work has been done by several researchers to demonstrate the feasibility of different techniques (microphone arrays etc., ref. 1). Of course, the engineer is still needed to verify and fix the problem, which is a task where his or her expertise and skills are required.

THE DETECTION OF BSR EVENTS

The first step in developing a BSR measuring tool is to define how it will detect the occurrence of BSR events. The detection has to be done using processed data derived from the noise measured with the microphone(s). Microphones (one or typically more than one) will be mounted inside the vehicle or next to the component under test, in positions typically occupied by the BSR engineer during the subjective evaluation. During the feasibility study described in this paper, a binaural head was positioned in the driver’s seat of a Sport Utility Vehicle. The use of a binaural head, which best represents the way human ears perceive noise, was driven by the fact that one phase of this project involved a correlation study between measured signals and subjective perception. For the correlation study, the authors wanted to make sure that the sounds used for playback were of the highest fidelity possible (i.e. most realistic). Furthermore, the use of two or more microphones can be used to gather information on the direction the noise is coming from, which helps when trying to correlate in-situ subjective evaluations to results of off-line jury tests. However, it is anticipated that, especially for component level tests and for end-of-line inspection stations, single microphone(s) are adequate for the measurement of the signals to be processed by the BSR measuring system. In these cases, a correlation study will be required to compare the data resulting from noise measurements carried out with different transducer systems (ref. 2).

In the feasibility study performed by the authors, the time history of the noise signals (acquired with a binaural head and sampled at 44.1 kHz) was first saved to disk (i.e. as .wav file), and then it was analyzed both in the time and in the frequency domain.

It is necessary to differentiate the analysis and treatment of different types of BSR events, since buzz, squeaks and rattle have different time and frequency features. We will focus in this paper on the detection of rattle events, which are characterized by groups of individual impacts in the time domain whose frequency content spreads over a broad range. The choice of dealing first with rattle events derived simply from considerations of complexity of the task, and rattle events were judged by all authors to be “easier” to detect and describe than buzzes and squeaks.

An example of a typical noise signature with rattle is given in Figure 3. At the top of the figure, the FFT spectrogram of the signal between 0 and 8.5kHz (Y axis) is displayed for a duration of 10 seconds (X axis), the color representing the amplitude. The curve underneath the spectrogram displays the level versus time of the 0.5-

8kHz frequency band. This is a very clear case, with a lot of rattle events, which can be easily seen on both graphs.

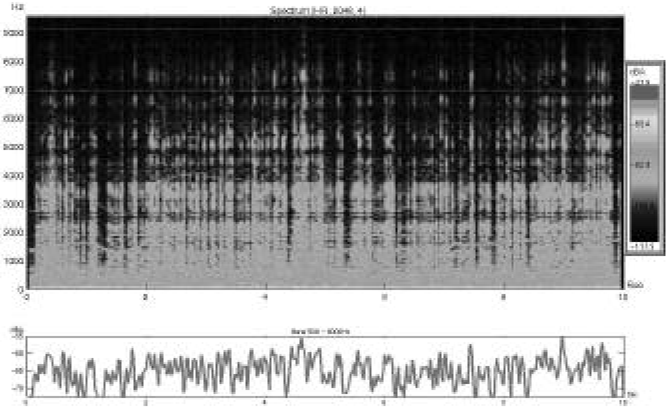

Figure 3: FFT spectrogram of vehicle interior noise with rattle

In order to develop the detection algorithm, we started by looking at some "elementary" test signals, that is rattle induced inside the vehicle by a sine sweep excitation. While it is well agreed upon in the BSR community that road profile and/or random type excitation are used to assess compliance to OEM targets, tests with sine sweep excitation are often used to identify problem areas as well as to benchmark different vehicles.

During the tests described in this paper, the binaural head was positioned in the driver seat of a luxury SUV, with complete interior trim, which was positioned on a MTS 320 Road Simulator (Figure 4). Doors and windows were closed. The data acquired were the two microphone signals from the binaural head, and the excitation signal as a reference. In the case of the sine sweep, the excitation signal was used as a phase reference and acquired as a tachometer. All data were acquired with the MTS Sound Quality software.

Figure 4: Test Setup

The sine sweep was defined between 0 and 30 Hz, and the test consisted of a complete cycle of sweep up and down at a rate of about 1 Hz/s. The relative phase was changed among the sine sweep signals fed to the four hydraulic pumps that drove the actuators, and data was acquired in the following test conditions:

- **Hop** – Front to Rear excitation: the front wheels are excited 180 degrees out of phase from the rear wheels.
- **Tramp** – Twist excitation: the driver side front wheel and passenger side rear wheel are excited 180 degrees out of phase from the passenger side front wheel and driver side rear wheel.
- **In Phase** – Vertical excitation: all wheels are 0 degrees out of phase.
- **Wobble** – Side-to-Side excitation: the driver side wheels are 180 degrees out of phase from the passenger side wheels.

The noise signals were then analyzed by using a combination of MTS Sound Quality and MTS I-DEAS Test software. The signals acquired with a sine sweep excitation (which was also used as phase reference) were also filtered to remove the lower harmonics (orders) of the excitation frequency.

Figure 5 and 6 show the FFT spectrogram of the noise measured during the sweep down at tramp and in-phase conditions.

Figure 7 and 8 show the loudness at left and right ear as a function of time and as a function of the frequency, respectively, of the sweep at hop sweep down condition.

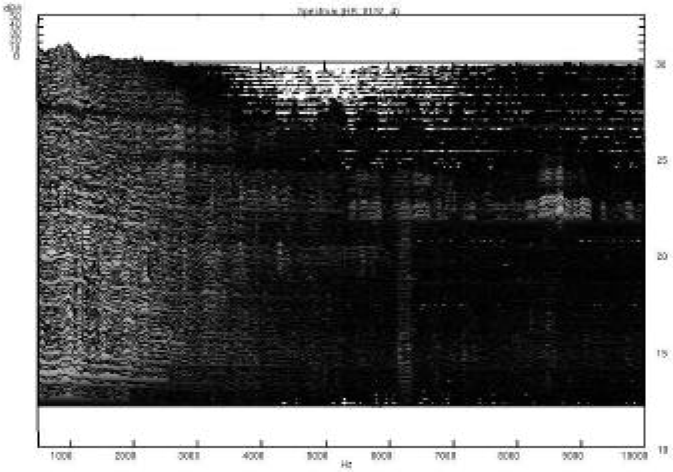

Figure 5: FFT spectrogram of vehicle interior noise at tramp

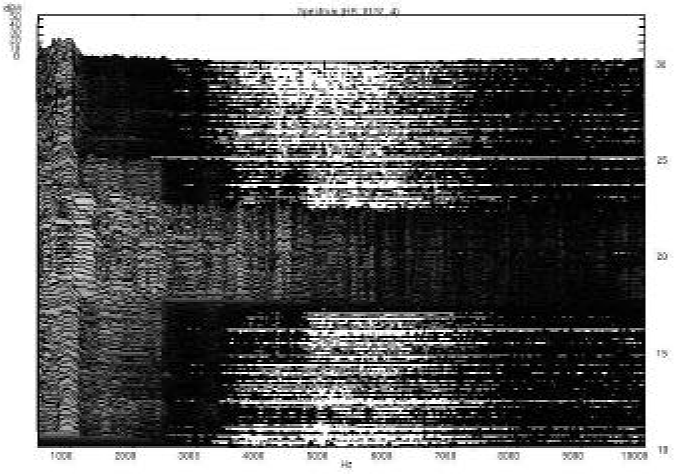

Figure 6: FFT spectrogram of vehicle interior noise at in-phase

Three events exhibit relatively higher loudness, and seem to emerge from the loudness functions:

1. The first event (between 5 and 8 seconds, Figure 7) is a high level, relatively long duration event, with same loudness at both ears. This strongly suggests dominant low frequency content, and therefore not a rattle but a resonance.
2. The second event (between 12 and 16 seconds) is a lower level, high interaural difference event, which suggests higher frequency content, and therefore could be associated to a BSR event.
3. The third event (between 18 and 25 seconds) is a high relative level, long duration, with significant difference between left and right ear. The event could actually be made of two events, of different frequency content, therefore, while it could be associated to rattle, it requires a closer look in the time and frequency domain.

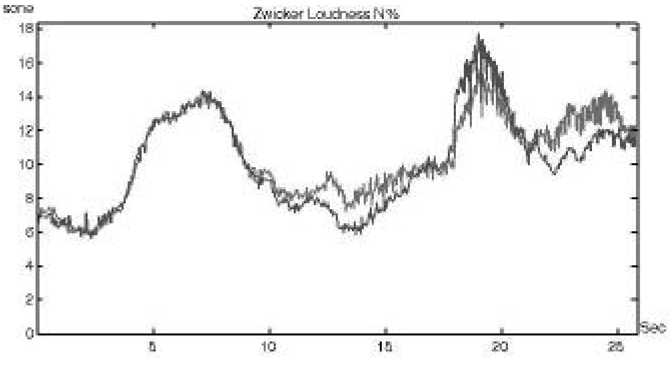

Figure 7: Loudness function versus time for left and right ear of the binaural head during hop sweep down

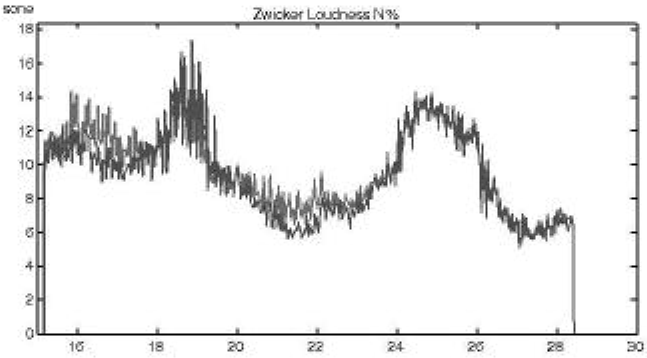

Figure 8: Loudness function versus excitation frequency for left and right ear of the binaural head during hop sweep down

The same conclusions relative to the three events can be derived by looking at the loudness functions in Figure 8, where the X-axis displays the frequency of the sweep.

The results of the analysis of the processed functions were then compared to the results of the subjective evaluation performed by the authors on-site during the test and off-line by playing back the recorded signals through headphones. The listening sessions confirmed the existence of two events perceived as rattle.

The authors' assumption that a lot of information can be extracted by looking at the temporal variation of functions as opposed to their average values seemed to be confirmed. Different parameters can then be used to characterize this temporal variation, the simplest available being the distribution percentiles. Statistical percentile levels have been historically used in environmental acoustics to assess the impulsiveness of ambient noise, and in the sound quality field to characterize the perceived loudness. Other recent works have pointed out the importance of using percentile levels to better describe the variations of loudness associated with transient events such as BSR events (ref. 3).

Figure 9 displays the frame kurtosis function versus time for the same signal of Figures 7 and 8. Kurtosis is a statistical parameter (the 4th moment of the distribution of the time history data points), which is often used to quantify the degree of impulsiveness present in a signal. In this case each point on the kurtosis function represents the kurtosis of the distribution of the 8192 data points in each frame, therefore the function is called Frame Kurtosis.

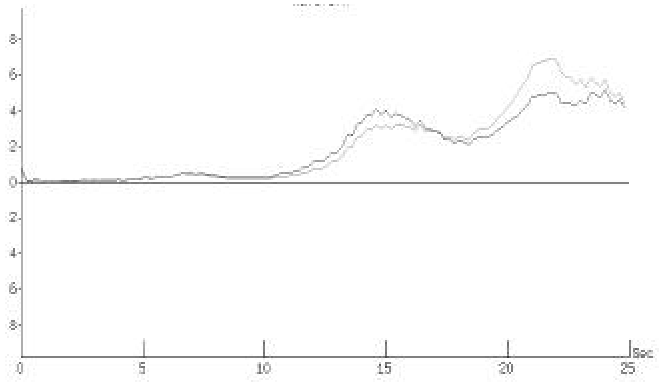

Figure 9: Frame Kurtosis function versus time for left and right ear of the binaural head during hop sweep down

As a reference, the kurtosis value of random noise is 3 and the 0 line in Figure 9 represents this reference value. In general, kurtosis values higher than 4 indicate high degree of impulsiveness. From the function in Figure 9, the first event (between 5 and 8 seconds) exhibits far less impulsiveness than the second (between 12 and 16 seconds) and the third one (between 18 and 25 seconds). The Kurtosis function is therefore used, in this case, to “identify” the rattle among other events of relative high loudness. Therefore, the authors concluded that based on a representative database of BSR events, a robust algorithm based on existing sound quality and signal processing parameters can be developed to detect the occurrence of BSR event.

Once one or more functions are identified whose temporal behavior correlates with the occurrence of rattle (as subjectively perceived), the next step is to characterize each of these functions by one or more single numbers that can be used to measure the rattle.

THE BSR SOUND QUALITY INDEX

An interesting observation from the functions displayed at the previous page is that while the Frame Kurtosis seems to be a powerful indicator of the occurrence of the rattle events, it may not necessarily be highly correlated to the perception. In other words, one function may be more useful to detect the rattle (kurtosis) and another one to “measure” it (loudness). In general, a combination of functions may be needed to detect and measure the BSR event.

In order to define the BSR index it is necessary to perform a series of subjective evaluations (or jury tests). Jury tests are necessary to define the threshold of detectability for the rattle, and in this case the sounds presented may be generated by superimposing rattle to masking noise and varying their relative level. Figure 10 shows in succession three samples of time histories in which the level of background noise is progressively reduced while the level of the rattle is maintained constant. This technique is very useful to assess realistic levels of detectability and acceptance of specific events over background, masking noise.

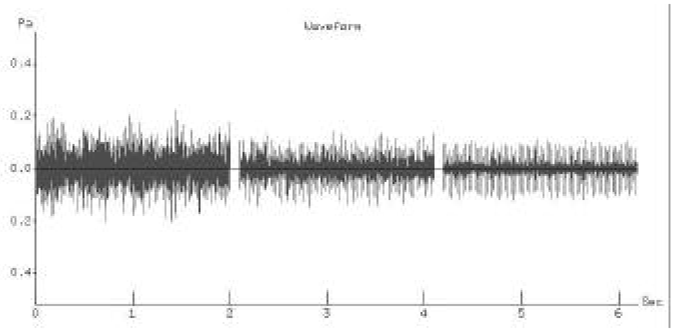

Figure 10: Time histories of rattle plus masking noise with varying level of masking noise (descending)

Another jury test may be required to understand which types of BSR events are most annoying and why (i.e. rattles of different frequency content, of different duration, of higher or lower temporal density and so forth). The results of the jury test will be a ranking of preferred BSR events and a list of dominant sound quality features.

An example of a BSR Sound Quality Index function, derived from the data presented in the figures above, is displayed in Figure 11. The BSR Sound Quality Index function, computed from a combination of sound quality metrics functions and signal processing parameters, is plotted versus time along with the threshold of acceptable rattle, which has been set to a value of 1. Whenever the function exceeds the threshold, it indicates the existence of a rattle, which can be clearly perceived by the occupant.

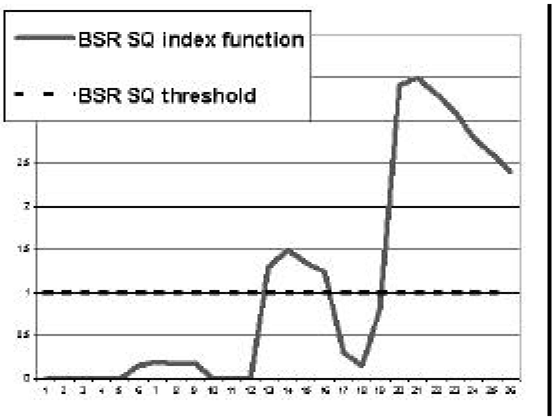

Figure 11: Example of measured BSR Sound Quality Index function and associated threshold value

THE BSR SENSITIVITY INDEX

The BSR Sound Quality Index is a measure of the perception of the BSR event. Other considerations however come into play when assessing the severity of the rattle and therefore the need for subsequent action. For example, a BSR event that is very noticeable but occurs rarely might be less important than a less noticeable BSR event that occurs frequently. Furthermore, certain sub-components are, because of manufacturing tolerances, more likely sources of rattle than others and may be responsible for a higher percentage of warranty costs. Therefore, a BSR Sensitivity Index, a function of the BSR Sound Quality index and of economic/business factors, can be established and used to assess priorities of subsequent engineering actions of BSR control and reduction.

The BSR Sensitivity Index can be further refined by taking into account the frequency of occurrence of the rattle, in other words the likelihood of the occurrence of the event in normal driving conditions. An example of a sensitivity matrix used to generate the BSR sensitivity index is provided in Table 1 below (ref. 4).

Event	Total Reported per 100 units	% Total Offenders	BSR SQ Index	BSR Sensitivity Index
1	90	90%	.65	13.5
2	5	5%	3.5	1.8

Table 1: Example of BSR Sensitivity Matrix

An example of BSR sensitivity Index for the data in Figure 11 is displayed in Figure 12 below. The BSR Sensitivity Index for the two rattle events of Figure 11 is displayed, assuming that the event occurring between 12 and 16 seconds, while of lower BSR SQ index, occurs in 90% of the tested vehicles, while the event between 18 and 25 seconds occurs in 5% of the vehicles.

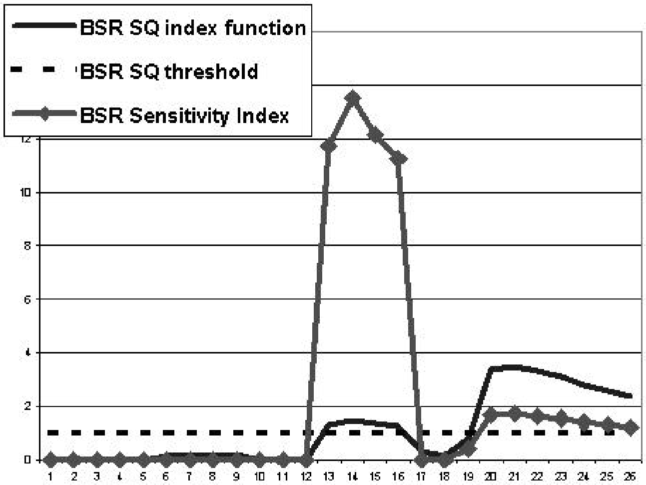

Figure 12: Example of measured BSR Sound Quality Index function, BSR SQ threshold and BSR sensitivity Index

CONCLUSION

Existing sound quality metric functions can be successfully used to detect the occurrence and measure the severity of BSR events instead of human subjects. This has been demonstrated for rattle events measured inside a SUV on a MTS 320 road simulator. The developed algorithms and tools can be easily integrated into existing off-the shelf sound quality software packages to facilitate the work of OEM and Tier 1 suppliers to validate hardware from a BSR standpoint. The same detection tools can then be easily adapted for use at inspection stations at the end of an assembly line in a manufacturing facility.

The same approach, but most likely not the same algorithm, has to be used when dealing with buzzes and squeaks. Both type of phenomena exhibit peculiar time and frequency characteristics, which have to be fully explored in order to identify objective functions that correlate with the their subjective perception.

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