A Survey of Sound Quality in the United States Automotive Industry

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Abstract

The concept of sound quality (SQ) has been used in the U.S. automotive industry since the 1980's. Early studies were part of an effort to understand why some vehicles sounded better (and sometimes quieter) than other vehicles even though they had a higher A-Weighted sound pressure level (SPL). This led to the use of juried tests and many measures other than A-weighted SPL to quantify noise. The first studies were often dedicated to developing SQ methodologies and were generally focused on the evolving tools of sound quality in an effort to show how they could be used to solve problems. Sound quality has matured over the years and the principles of SQ are now used in nearly all aspects of automotive NVH in the U.S. The latest trend in sound quality is the development of virtual environments to simulate driver and passenger noise before prototype vehicles are available.

Introduction

Sound quality is used in nearly every area of automotive noise control in the U.S. Everything from engine noise to power seat track noise has been analyzed using juried tests and metrics that reflect the nature of the sound instead of merely it's overall A-weighted sound pressure level. Vehicle specifications on both a component level and a vehicle level are often written with sound quality in mind.

This was, of course, not always the case. For many years the A-weighted SPL was the primary unit of measure for any acoustic specification. Juries were also used, but these were nearly always expert engineering groups that used a rating scale (1 –10 scale). While this provides useful information, it may not reflect the feelings of the demographic group that will be purchasing the product.

Sound quality grew from an understanding that A-weighted sound pressure level only reflects the loudness of a sound (and there are other measures that are better correlated with subjective loudness). It is obviously impossible to characterize a complex sound with a single number. Many parameters must be considered. In addition to loudness, we must take into account frequency and amplitude variation over time, spectral balance, tonality, and many other attributes.

A good way to determine which of these attributes are important is via a juried test. Many early studies on sound quality included a juried study. Now that sound quality has become more mature, the required parameters for good sound quality are better known and there is less juried testing. Juried evaluations are, however, still run particularly when new noise problems are being diagnosed.

This paper examines published literature on sound quality in the U.S. auto industry over the past 16 years and comments on the developments that have taken sound quality from a novel idea to a method that is commonly applied to a wide variety of noise control problems. A survey of current practices in sound quality is also presented. Finally, a categorized listing of papers presented at the SAE Noise and Vibration Conference is presented.

References to SQ in U.S. Automotive Literature

The Society of Automotive Engineers (SAE) holds a Noise and Vibration Conference every two years in Traverse City, Michigan. The history of SQ in Detroit can be traced by looking at the papers published at this conference (see appendix A). Note that this is not an exhaustive listing of all papers published on sound quality in the U.S. Many papers are published at other SAE meetings, in the Journal of the Acoustical Society of America, the Journal of the Institute of Noise Control Engineering, Noise-Con Proceedings, Inter-noise Proceedings, and many other places. There was also a Sound Quality Symposium (SQS 98) that was held in 1998 in conjunction with Noise-Con 98 in Ypsilanti, Michigan. There will be another in 2001 in Detroit as part of Inter-noise 2001. There have, however, been over 140 papers published at the SAE Noise and Vibration conference that use at least some of the concepts of sound quality and they will be examined to trace the development of the technology in the U.S. automotive industry.

A 1985 paper by engineers from Toyota is often considered the first paper on sound quality published at the SAE conference, *A Study of Noise in a Vehicle Passenger Compartment During Acceleration* [1]. There were, however, a number of other papers on subjective ride quality and juried testing at the 1985 meeting.

At the 1987 SAE conference engineers from Nissan, Lucas, Head Acoustics, and Yamaha published papers on sound quality. By 1989 there were 5 papers and a special session on sound quality. These special sound quality (subjective response) sessions have continued as a regular feature of the SAE conferences.

The number of papers has continued to grow over the years (see figure 1) though as sound quality matures the number of papers appears to be leveling off.

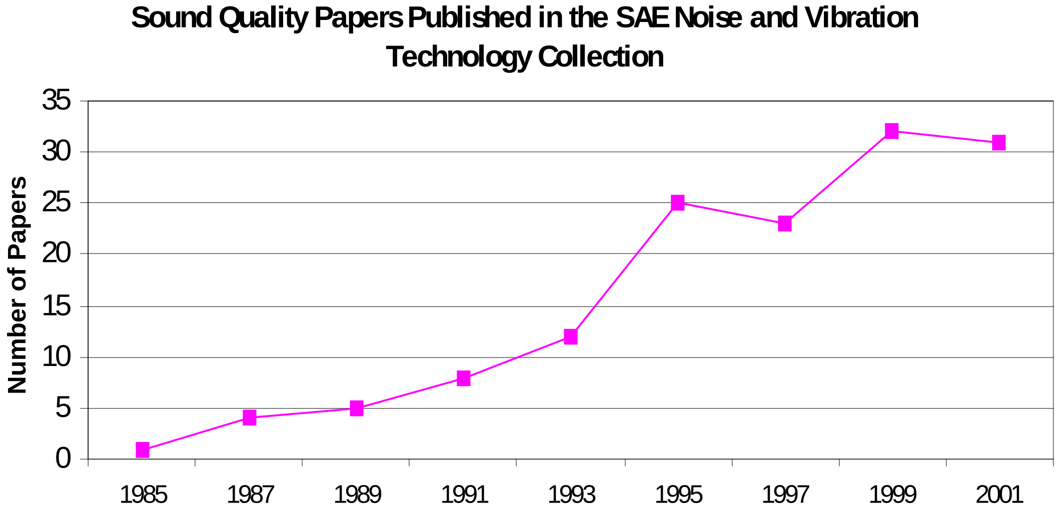

Figure 1: The number of papers published in the SAE Noise and Vibration Technology Collection. Nearly all of these papers were presented at the SAE Traverse City Sound and Vibration Conference

It is difficult to categorize sound quality papers because many papers are concerned with several areas. For instance, a number of papers cover the development of a methodology and then present a case study showing how that methodology was used to solve a particular problem. This is particularly true for the earliest papers on sound quality since the methodology was not well known at that time. Despite this difficulty it is clear that the subject area of the papers has changed over the years. The early days of sound quality were generally filled with papers related to methodology and to powertrain related noise (with special interest in diesel, intake and exhaust noise).

Many of these early papers illustrated the imperfect correlation (and in some cases lack of correlation) between A-weighted SPL and a desirable sound quality. These papers established the basis of a sound quality methodology (subjective evaluation and/or juried testing, the use of additional and alternate metrics rather than A-weighted SPL, and the combination of those metrics to achieve an objective tool that correlated with subjectively determined quality). While these principles are completely accepted now, they were very innovative less than 20 years ago. The early papers also presented methods for conducting juried evaluations to a noise control community that had not been familiar with them.

The papers are categorized in Appendix A and the number of papers in each category is listed in Table 1. Note that the number of methodology papers would expand greatly if all the papers that contain methodologies were listed in that category. The methodology category is used for those papers where methodology development is the main purpose of the study. Otherwise, the papers are listed elsewhere.

Papers related to methodology peaked in 1995 with a total of nine though a large number of methodology related papers continue to be published (seven in 2001).

Powertrain related papers have and continue to be an important part of the sound quality literature in the automotive industry. Powertrain noise was the first area investigated using sound quality tools and is still one of the most important.

	1985	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	Total
Methodology		1	1	2	6	9	5	8	7	**39**
Engine / Powertrain Noise	1	2	1	3	2	3	5	5	2	**24**
Diesel Engine Noise		1	1		1	1	2	2		**8**
Transmission and Gear Whine / Rattle				1			1	3	4	**9**
Induction / Exhaust Noise			1			4	1	3	2	**11**
Impulsive Noise / Door Closure				2	1	2	3	3		**11**
Mechanism / Component Noise					2	3	2	1	1	**9**
Vehicle Simulators								1	6	**7**
Buzz, Squeak, and Rattle							1	2	3	**6**
Sound Package / Path Noise Control						1	1		3	**5**
Facilities						1	2		1	**4**
Wind						1		1	1	**3**
Misc.			1					3	1	**5**
Total	**1**	**4**	**5**	**8**	**12**	**25**	**23**	**32**	**31**	

Table 1: Distribution of Sound Quality Papers by Subject

A recent development in sound quality is the interest in simulators for noise and vibration work. These simulators are intended to provide a representative environment where one virtual vehicle can be compared to another and where vehicle interior noise and vibration can be judged before hardware is available. As automakers decrease the development time for new vehicles it becomes increasingly important to understand noise and vibration problems before hardware is available. When these devices are used in conjunction with full vehicle models (such as FEA and SEA models) it is possible to create changes to a vehicle’s structure and noise control treatments and simulate the affects for a jury to evaluate. There were six papers presented at the 2001 SEA conference on simulators.

Methodology

Instrumentation - Automotive sound quality recordings are nearly always made with binaural mannequins, though component and mechanism noise is sometimes measured with a single microphone. The first SAE paper describing this was written by Klaus Genuit in 1987 [2]. The idea of a binaural recording device was novel at that time. Binaural heads provide the most lifelike re-creation of the original listening environment. They also provide listening cues that are lost when a recording is made with a single microphone. Though the technology has evolved along with digital technology, the basic principles remain unchanged and there have been relatively few recent papers published on hardware (with the exception of vehicle simulators which are covered under a separate section).

Juried Testing - Early papers described the use of juries to define the subjective nature of sound quality. Engineers from Ford, GM, and Head Acoustics wrote an SAE paper with guidelines for the use of juries in 1999 [3]. Though there are many different approaches to juried testing, the basic principles are now generally understood by a significant portion of the noise control community.

In 2001Zhang, Kaiser, and Hopkins [4] presented a method for determining the hearing threshold for sounds generated by a stepper motor in an instrument panel. This is an interesting problem because there may be a number of sounds that are objectionable at any audible level. In this case the signal may inaudible because it is masked by engine noise. The authors desired to know the level at which it becomes audible in the presence of the engine noise.

The authors describe a technique for determining the masked threshold for a given noise. With this technique the subject is presented with two sounds. One is the signal and masking noise. The second is the masking noise alone. The order of the two is random. The subject must choose which sound contains the signal. The test is conducted twice for the same signal level. If the response to both trials is positive, then the signal level is lowered, otherwise it is raised. Eight reversals are recorded and either the mid points of the reversals or the average of the peaks is taken as the threshold level. To improve resolution, the step size (change in signal level) is halved after the first negative response.

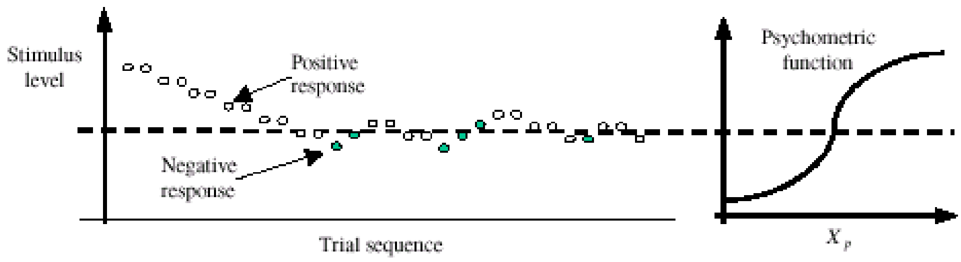

Figure 2. Illustration of the adaptive procedure used to determine the masked threshold of stepper motor noise in an instrument panel [from 4]

Metrics – The number of metrics continues to grow and many are not general, but are based on particular noise problems. These can be speed related, order related or related to the level in a particular band of frequencies. The most widely used general metrics are loudness (from ISO 532B), time varying loudness, fluctuation strength, roughness, sharpness, kurtosis, and tonality.

In most cases engineers utilize the metrics that are found in whatever analyzer they happen to own. Otto and Bloomer [5], however, describe a situation where this was not sufficient and they developed their own fluctuation strength (FS) metric to define the performance of electric motors.

Otto and Bloomer were not satisfied with the correlation between subjective impressions of fluctuation strength and a commercially available FS metric. In some cases the metric indicated high levels of FS when there was little fluctuation in the sound. In other cases the metric indicated low FS when the signal in fact had a high fluctuation. In addition, they found that the FS metric did not predict equally for different types of motor sounds (seat motors vs. pedal motors, for instance).

Otto and Bloomer's implementation uses a standard model for FS, but utilizes empirically determined parameters. This was found to give much better agreement for the types of motor sounds generally found in vehicles. Figure 3 shows the relationship between subjective impressions of fluctuation strength and the commercial metric as well as their new metric.

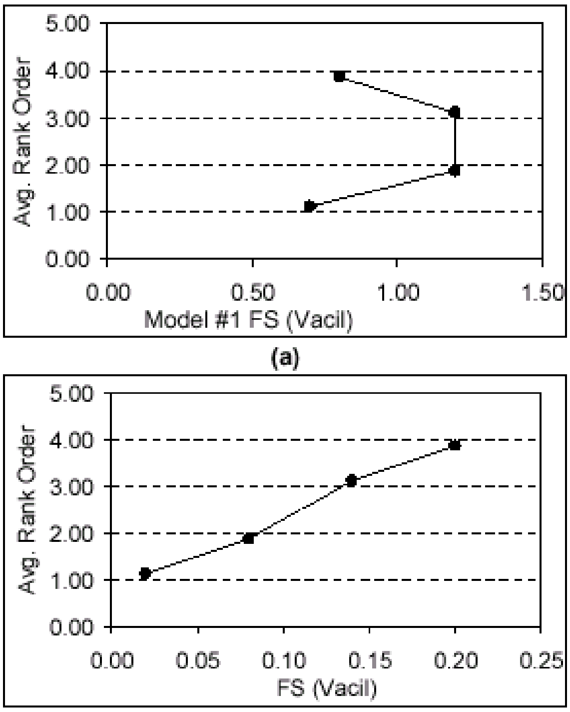

Figure 3.Electic Motor Study: Average subjective rank order of fluctuation as function of Fluctuation Strength (1 = Least Fluctuating, 4 = Most Fluctuating). (a) Commercial Model; (b) proposed model [from 5].

Powertrain Related Noise – Induction Noise

If all of the powertrain related areas are considered together, this is the area where the greatest number of papers has been published. These papers range very widely in application from diesel sound quality to transmission whine.

A paper was published at the 2001 meeting [6] regarding active noise control of induction noise. This is an area where there has been a lot of anticipation. It has been hoped that active noise control will be able to reduce noise and also modify its character to provide better sound quality. While the 2001 paper does not address sound quality in much detail, it mentions this possibility and describes a system (Figure 4) to actively control induction noise.

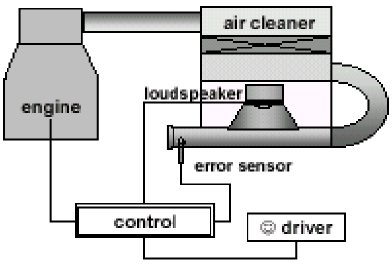

Figure 4. An active noise control system applied to an automotive intake [from 6]

Impulsive Noise / Door Closure Noise

Door closure sound quality is a very important area. Door closure noise is heard twice by the driver each time he or she drives the car and it is an important part of a prospective customer's showroom experience. There have been a steady number of papers on impulsive noise and door closure sound quality.

A paper published in 1999 [7] looks at the measurement of door closure noise, the key objective parameters in door closure quality, and at the physical structures that contribute to the noise. The noise is measured outside of the vehicle. Exterior measurements are somewhat simpler since there a smaller demands made on the dynamic range and low frequency performance of the microphones outside the vehicle vs. inside the vehicle. These sounds were recorded and played for a jury. The jury found a significant difference among the sounds. Those differences were also reflected in loudness and sharpness measurements for these noises (Figures 5 and 6).

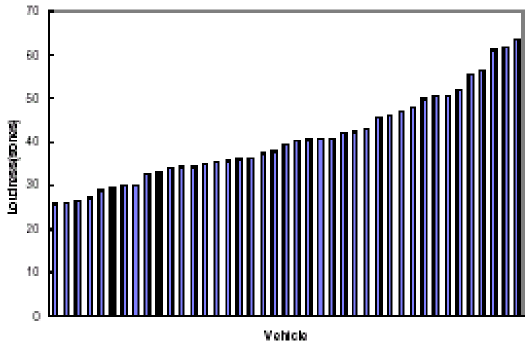

Figure 5. Loudness Distribution of Door Slams Across Vehicles [from 7]

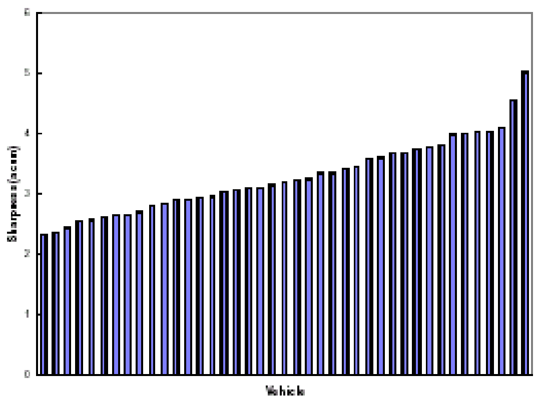

Figure 6. Sharpness Distribution of Door Slams Across Vehicles [from 7]

Loudness and sharpness provided the best correlation to the subjective quality of the noise. Ring-down (the persistence of noise in some bands after the initial impulsive event) and rattles can also be important factors in door closure sound quality.

The root cause of these sound quality problems were identified and a number of general solutions were suggested. These solutions addressed both the noise generating mechanisms themselves and the most significant paths and radiators. This paper represents one of the current trends in sound quality work since it identifies the physical sources of noise as part of the study. This illustrates how sound quality is no longer an isolated function carried out by a special group, but is an integral part of solving general noise and vibration problems.

Vehicle Simulators

Vehicle simulators are clearly the latest direction in automotive sound and vibration quality assessment. There was one paper on this topic in 1999 and there were six in 2001. An important use for theses systems is the study of vibration. Sound playback can be accomplished with headphones or speakers, but vibration playback obviously involves a much more sophisticated system.

There is also a feeling that context is important when presenting subjective data. That is, non-expert listeners need to experience the vehicle noise and vibration playback in a way that is close to the experience in a real vehicle. Assessing sounds in an office or listening room environment (though very useful for NVH experts) is difficult for non-expert listeners.

A complete noise and vibration simulator was described at the 2001 SAE conference [8]. This simulator provides a 220-degree wrap around screen for visual simulation, binaural noise playback via headphones or loudspeakers, and a six degree of freedom vibration playback system. The system simulates wind, tire/road, and engine/driveline noise. These are dynamically variable and change in response to the vehicle speed, engine speed, throttle position, road type, and any special events occurring during the simulation. Special sounds such as potholes are recorded at certain vehicle speeds and must be played back at that speed.

This system can be used to recreate recorded vehicle sounds and vibrations so that current production and prototype vehicles can be evaluated. It can also be used to assess changes in performance as determined by CAE analysis. In this case the CAE analysis predicts frequency response functions for a baseline and “proposed” condition. The ratio of these frequency response functions is calculated and used to create a filter which is applied to the time domain input to the simulator. As vehicle development timetables become shorter it seems likely that there will be increased need for this type of “virtual prototype” analysis.

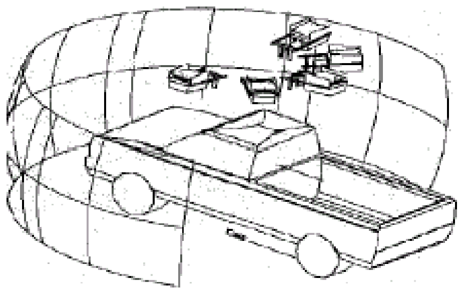

Figure 7. Visual Display System for a noise and vibration driving simulator [from 8]

Survey of Current Practitioners of Sound Quality

A number of engineers working in the sound quality area were interviewed for this paper. While certainly not exhaustive, their comments are an anecdotal sampling of sound quality in the U.S. automotive industry.

There are considerable differences among the U.S. car manufacturers and among the automotive suppliers in their use of sound quality. Some aspects, however, are universal. Nearly all sound quality measurements are conducted with binaural mannequins. Single microphones are sometimes used for analysis of noises, but listening evaluations are very rarely conducted with a single microphone. It is also very common to use measures that are not part of the standard list of metrics (loudness, fluctuation strength, sharpness, etc.) to characterize noise. These can include measures that are not psychoacoustic in nature such as motor speed.

These trends were mentioned by the participants in the survey:

- CAE simulations are being integrated into sound quality studies. This leads to the creation of “virtual” prototypes.

- Telematics and voice quality for talkers and listeners will likely become more important as hands-free telephones and voice recognition systems become more common. This is a new and somewhat different application for sound quality.
- Brand image will be characterized using sound quality parameters (among many others).
- Impulsive noise has been difficult to characterize, but is very important. Its importance will likely continue in the future in terms of injector noise, diesel noise, door closures, switch noise, and many others.
- Sound quality is now being put into the hands of the product and project engineer rather than being done by a separate "sound quality" group. This change is relatively new and is still evolving. In some cases sound quality measurements are being used on the assembly line as a quality control check for components.
- Vehicle level sound quality information is being cascaded into specifications for components. Some engineering targets are based on sound quality information.
- The use of sound quality is growing among the automotive suppliers.
- For many organizations there is somewhat less use of juried studies, but this is not true for all.
- The SQ process is continually evolving and many companies find that they must alter their models as noise sources become quieter and more refined.
- For some organizations, expert evaluation is quite common, but for others expert evaluation is avoided. Some people believe that an expert jury may overemphasize noise and vibration issues as compared to a naive group of subjects.
- The various sound quality analyzers provide somewhat different measurement results since they use different methods to calculate SQ metrics. This can be an issue when trying to work from company to company or even from department to department within a company.

Conclusion

Sound quality has become a very useful tool to investigate noise and vibration problems in the U.S. automotive industry. In less than 20 years, it has come from a new idea to a proven concept in automotive NVH. Perhaps the reason that it was quickly accepted is that its usefulness is so easily understood.

Listening to noise and understanding the qualities in the noise that are unacceptable is the first step in solving a problem. For many years, the A-weighted SPL was considered good enough to quantify noise problems. This is reasonable since loudness is usually the most important parameter for most noise problems and A-weighted SPL is often reasonably well correlated with loudness. As the overall noise levels drop, however, other parameters become more important and must be considered.

For the immediate future virtual prototypes appear to be an important new direction as automakers continue to compress vehicle development programs. These virtual prototypes can be used to set targets at the beginning of a program and to predict the performance as noise sources and sound and vibration control treatments change.

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