Understanding NVH Basics

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Introduction

Designing for NVH (Noise, Vibration, and Harshness) is a process that requires the integration of customer product expectations with the vehicle design and development process. To the customer, NVH is defined in terms of how the vehicle "feels" with regards to vibration levels at the seat, toe pan, and steering column, and how the vehicle "sounds" with regards to the perceived loudness and quality of the interior noise. To the design and development engineers, NVH is defined in terms of measurable tactile and acoustic responses.

The following sections of this paper will describe the conversion of subjective customer expectations to objective measures which can be arrived at through vehicle system NVH simulation and testing. In addition, the process of establishing vehicle and subsystem design targets will be covered along with some basic principles of designing for NVH.

Vehicle Subjective and Objective Target Setting

Target Setting Process

Increasing demands for improved NVH performance in passenger vehicles has led to renewed interest in determining measures of what represents a pleasing environment to the customer. One of the first steps in the development of a new vehicle is to determine the NVH characteristics to be targeted. Existing reference vehicles are selected using customer ride clinics, expert ride evaluators, and design management. This process identifies one or more vehicles which have the NVH qualities, or image, desired for the new vehicle. The image vehicles are then subjectively rated to target the relative improvement needed for a new vehicle with respect to a baseline vehicle (i.e., new proposed vehicle is to be 1/2 point better than the baseline design) [1].

Next, the image and baseline vehicles are tested for objective quantities such as tactile vibration and acoustic noise levels. The process establishes the NVH performance relationship between subjective and objective measures. At Chrysler, this relationship has correlated well to an objective/subjective rating system based on human sensitivity to vibration. The NVH targets at the vehicle level are used to arrive at subsystem targets using a process described later in this paper.

The goal of this section is to relate subjective ratings on a ten point scale to typical objective measurement practices both of which are commonly utilized by the auto industry. As trade-offs for NVH, cost, weight, and manufacturing are confronted, use of the rating system provides a quantitative measure that ranks the effect of design alternatives upon subjective perception.

The 10-Point Rating Scale

A common basis for comparing many classes of items is the ten-point rating scale. Guidelines for a 10-point scale developed by the SAE [2], Figure 1, were originally used to rate noise and ride comfort of automotive tires. This scale has been commonly adapted by the auto industry to rate vehicle performance in the areas of ride, handling, NVH, performance feel, and those areas that relate to the perception of the transport experience.

Tactile Vibration Criteria

The vibration criteria to be discussed here will focus on vibration that is "felt" by the customer. This occurs where the passenger comes into contact with the vehicle at the feet, seat, arms, and hands. In the typical passenger vehicle, the frequency range of this vibration is from 0 to 25 Hz and is termed the "shake" region (Table 1).

There has been significant research conducted and various indicators have been derived to rate human sensitivity to vibration. Goldman [3] conducted research to characterize human sensitivity to sinusoidal vibration amplitudes as a function of frequency and acceleration levels as shown in Figure 2. Three broad categories each with upper and lower bands suggest that 10 levels are indicated which align with the subjective 10-point scale.

1	2	3	4	5	6	7	8	9	10
Unacceptable				Borderline	Acceptable				
Condition Noted By									
All Observers		Most Observers		Some Observers	Critical Observers		Trained Observers		Not Observed
1	2	3	4	5	6	7	8	9	10

Fig. 1: SAE 10-point rating system

NVH Characteristic	Frequency Range (Hz)
Ride	< 5
Shake	5 - 25
Harshness	25 - 100
Boom	25 - 100
Moan	100 - 150
Noise	150 - 300

Table 1: Typical NVH issues and frequencies

The lines suggested as representing 5.0 and 6.0 ratings have been denoted on Figure 2. It is clear that if we were to use these acceleration level lines as our rating criteria then the amplitude limit would vary with frequency. However, if we convert to a velocity basis (integral of acceleration) then the level is more constant with frequency and approaches constant velocity as the perception threshold is reached.

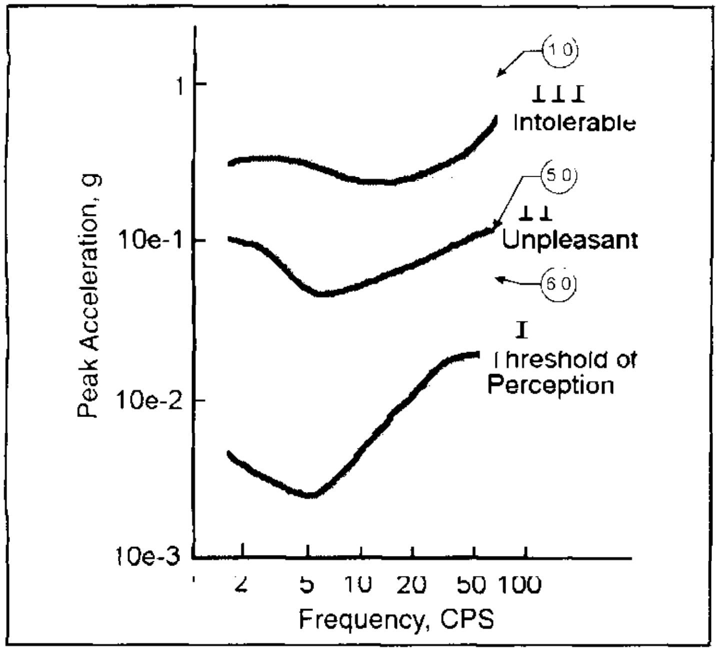

Fig. 2: Human sensitivity to tactile vibration

Based on the above assumption, a simple constant amplitude limit for velocity response can be derived. Using the data on the 5 and 6 rating lines, a formula can be derived as follows:

Tactile rating equation:

$$SR = 8.19 - 4.34 * \log(V) \qquad (1)$$

where: SR is the subjective rating, and V is the tactile velocity level expressed in mm/sec.

This criteria is likely to vary depending on the expectations of the customer (and design management) for a given class of vehicles.

For example, a luxury car may receive a 5 level rating from a subjective evaluation which might correspond to a 6 level band of an intermediate size vehicle. This indicates that lower vibration is "expected" in the luxury class for the same subjective rating.

Acoustic Response Criteria

The sound levels to be considered here will be those experienced by the passengers within the interior cavity under normal operating conditions. There is an overlap from 25 to 50 Hz where the NVH experience is both "felt" and "heard" and then the sound response will begin to dominate. From 50 to 300 Hz, the noise will typically be dominated by structure-borne sources. Again there is an overlap until air-borne sources become dominant at about 500 Hz and above. These are only general rules and exceptions inevitably exist.

The structure-borne noise below the 125-Hz region is a very important one since most noise energy is present there. This is because a typical vehicle will have its fundamental (first order) modes in this region which must be carefully engineered to avoid unpleasant noise levels. Also, this is the range that can be most easily simulated using computer models of vehicle systems with typical computer resources available to the auto industry.

The criteria to be developed here will be based on loudness of pure tones [4]. The choice is based on the fact that a large number of NVH concerns are single source problems especially in the lower frequency structure-borne region. These single sources create noise periods that are objectionable at well-defined frequencies and thus similar to pure tones.

It should also be noted that these criteria are appropriate for comparing the results of acoustic predictions from a computer simulation model. This follows from the fact that most simulations are single source sinusoidal excitations which have a pure tone as output [5].

The Equal Loudness Contours of Pure Tones are shown in Figure 3. The contours represent the sound pressure limits of distinguishability of human hearing for constant sound pressure contours measured in units of phons. Similar to the tactile relation, ten levels can be identified to represent the subjective 10-point scale. The 5 and 6 rating levels have been identified in Figure 3.

At this point we should note that our criteria appear to be complicated by the fact that the level varies with frequency. By implementing the A-weighting factor, the noise limit for each level becomes nearly constant with frequency.

Basing the computation on a range from 20 to 125 Hz and after A-weighting, the average sound levels are approximately 49.1 and 43.4 dBA for the 5 and 6 subjective levels respectively. This gives the following equation for relating acoustic subjective to objective ratings:

Acoustic rating equation:

$$SR = (-0.175) * SPL + 13.6 \qquad (2)$$

where: SR is the subjective rating, and SPL is the A-weighted sound pressure level in dBs.

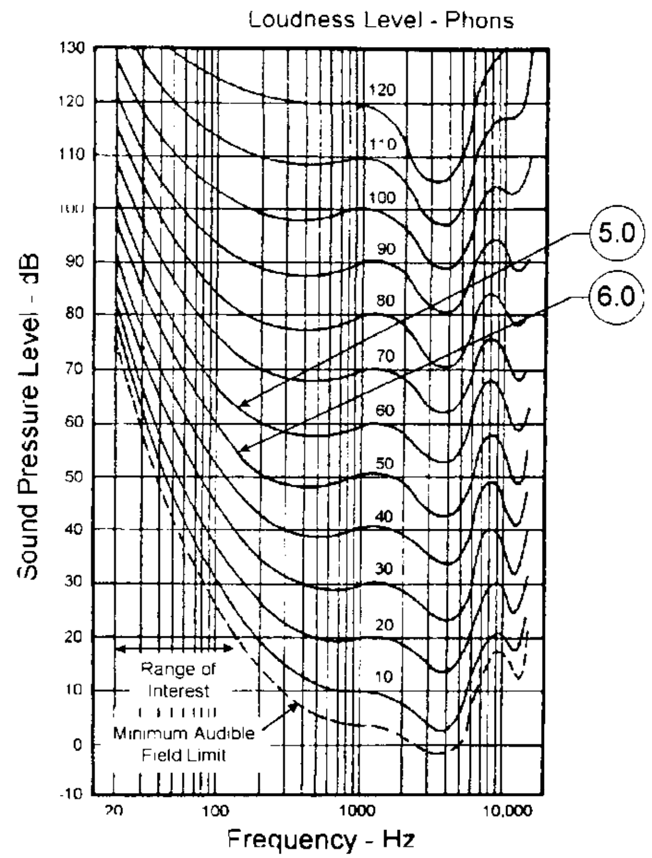

Fig. 3: Human sensitivity to pure tones

Application of the Criteria

The development of the tactile and acoustic subjective to objective rating equations results in quite simple relationships. However, when attempting to describe human subjective response, the results are often not very predictable.

It is instructive to look at these relations not as absolute criteria but to consider what they predict about relative changes. In fact, during most vehicle target setting for NVH, as indicated earlier, goals are set for a differential improvement in one vehicle over another.

Using the tactile and acoustic rating equations previously developed, we find that a change of +1 rating point is a 41 percent reduction in tactile response and a 48 percent reduction in sound pressure. This relates well to a rule-of-thumb that a halving of the response will result in a significant perceptible improvement. Similar results have been shown by other authors [1].

Designing for NVH

Basic Principles

Automotive NVH issues involve tactile and acoustic responses. Seat shake, toe pan vibration, and steering column shake are examples of typical tactile responses. Acoustic responses include sound levels at driver's ear and rear passenger ear locations. Noise sources can be characterized as either air-borne or structure-borne. Vibration energy transmitted to the structure through the suspension bushings and powertrain mounts results in structure-borne noise. Noise resulting from the energy radiated by the surfaces of powertrains, tires, and exhaust systems is characterized as air-borne noise. This paper will focus on structure-borne noise.

Most of the noise energy in a typical automobile is below 125 Hz [6]. Noise and vibration concerns below 125 Hz must usually be dealt with by major structural changes such as additional cross members, reinforcements, and beam section sizes. Above 125 Hz, vehicle interior noise is usually the main concern and can be dealt with by local design modifications such as panel beads and damping treatments.

Designing automotive structures for NVH performance begins with defining the NVH targets for the full vehicle as described previously. These targets are established based on customer and market objectives for the product and are usually expressed in terms of subjective ratings (e.g., SR = 7 for idle shake). Typical NVH issues, and frequency ranges, which need to be addressed in the design process are summarized in Table 1.

Road, tire, and powertrain load conditions used in NVH analysis are summarized in Table 2. Vehicle system design for NVH involves minimizing the tactile and acoustic responses to these inputs to achieve the desired NVH performance. Forces to the body structure from suspension and powertrain excitations are effectively reduced by designing for isolation. Isolation is achieved when the excitation frequency is greater than 41 percent of the natural frequency of the system as shown in Figure 4 [7,8].

Road Induced	Tire Induced	Powertrain Induced
Road Shake	Tire/Wheel Unbalance	Engine Idle Shake
Rough Road Noise	Tire Force Variation	Engine Lugging Boom
		Driveline Unbalance

Table 2: Load conditions for NVH simulations

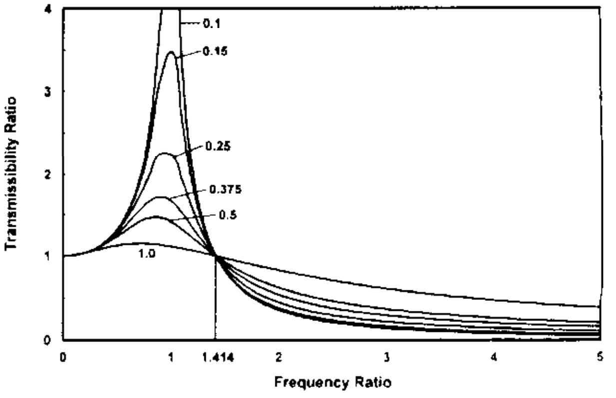

Fig. 4: Transmissibility ratio vs. frequency ratio

Suspension (unsprung mass) hop and tramp modes are usually in the 12-15 Hz range, while the sprung mass ride frequencies are typically in the 1-2 Hz range. As a result, the suspension effectively isolates the body from road disturbances at frequencies above the ride frequencies.

Powertrain mounting involves isolating the powertrain from the body and chassis. For a 4-cylinder engine, the second order gas torque is the dominant excitation. Idle isolation at 700 rpm requires that the engine modes be below 16 Hz.

While design for isolation results in reducing the magnitude of the forces transmitted to the body structure, the remaining transmitted forces acting on the body structure excite the flexible modes of the body structure to produce tactile and acoustic responses of the structure. It is not always possible to design for isolation, for example, when the body, or body with frame, modes approach the suspension hop and tramp modes, the vehicle response will be subject to dynamic amplification. A vehicle with modes which lie near the suspension hop and tramp modes (frequency ratio near 1.0 in Figure 4), will experience greater dynamic amplification of the transmitted forces than a vehicle with higher frequency bending and torsion modes (frequency ratio near 0.5). How the resulting vibration is perceived by the occupant depends on the frequency range as given in Table 1.

For good NVH performance, the body structure must be stiff to minimize noise and vibration, to maximize handling performance, to minimize the body contribution to squeaks and rattles, and to provide an overall "put-together" feeling. The body structure must also have sufficient stiffness at the suspension attachments and powertrain mounts to take advantage of the isolation and damping provided by the suspension bushings and powertrain mounts. As a general rule, the body stiffness at these attachments must be 5 to 10 times the stiffness of the bushings and mounts. Otherwise, the body structure becomes part of the mounting system. Figure 5 shows the effective system stiffness for various body/bushing stiffness ratios. For a body stiffness at 5 times the bushing stiffness, the overall system stiffness is about 83 percent of the bushing stiffness. A body stiffness at 10 times the bushing stiffness results in an overall system stiffness of 91 percent of the bushing stiffness.

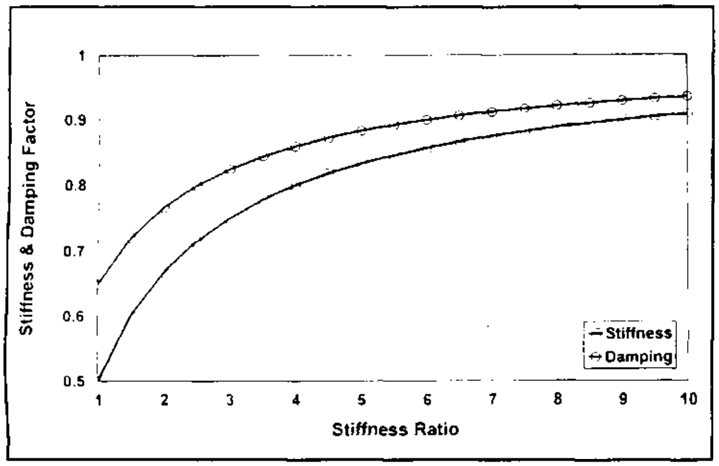

Fig. 5: Stiffness and damping factors vs. body/bushing stiffness ratio

Figure 5 also shows that increasing the body/bushing stiffness ratio results in increasing the overall system damping. Suspension bushings and engine mounts are more heavily damped than the body structure at the attachments. As the body structure becomes stiffer relative to the bushing, more of the strain energy is transferred to the bushing. As a result, the overall system damping approaches the higher bushing damping as the body structure becomes more rigid. Simply stated, work the rubber and not the body to achieve the maximum isolation and damping benefits from the bushings and mounts.

Subsystem Target Setting

Once vehicle system subjective NVH targets are defined, the next step in the process is to define objective full vehicle response characteristics which meet those targets. An estimate of the objective targets is provided by using the tactile and acoustic rating equations developed earlier. An example of the objective targets is illustrated in Table 3. Objective response characteristics are also determined by measuring the tactile and acoustic responses of comparative vehicles which are known to meet some, or all, of the subjective NVH targets. A comparison of the subjective and objective results is used to validate and refine the tactile and acoustic rating equations. These equations can then be used to predict changes in vehicle subjective rating from analysis results well in advance of hardware availability.

Load Condition	**Subjective Target**	**Objective Target**
Smooth Road Shake	7.5	1.4 mm/sec
Rough Road Shake	7.0	1.9 mm/sec
Idle Shake	8.0	1.1 mm/sec
Idle Boom	8.0	32.0 dBA
Road Boom	7.5	34.9 dBA

Table 3: Vehicle response targets

The above objective measures can be duplicated with controlled laboratory tests to establish a process to rate new prototypes when they become available. Additionally, full vehicle computer simulations approximating the controlled lab tests can be developed and used to refine new prototypes in advance of hardware build. Computer simulations allow many more design alternative ("what if") and optimization studies than would be possible with testing alone. Also, the simulations can evaluate the robustness to process variation load conditions, such as wheel, powertrain, and driveline unbalances that would not be possible to test within the development cycle time frame.

After establishing the required response characteristics at the vehicle level, subsystem performance targets can be established from an analysis of the major vehicle subsystems. A frequency separation chart, such as the one shown in Figure 6, is a useful tool for displaying subsystem targets. The frequency separation chart shows how the subsystem targets line up with the chassis and powertrain modes, interior acoustic modes, and excitation sources. As was the case for the full vehicle, subsystem targets can be established based on measurements of the subsystems from comparative vehicles, and from analysis of the simulation model subsystems. Typical subsystem performance parameters, ranked in order of priority, would include:

1. trimmed body bending and torsion natural frequencies
2. body acoustic impedance in the form of P/F transfer functions measured at the chassis and powertrain attachment points
3. body mobility in the form of A/F transfer functions measured at the chassis and powertrain attachment points
4. body-in-white (B-I-W) bending and torsion natural frequencies
5. B-I-W static bending and torsional stiffness.

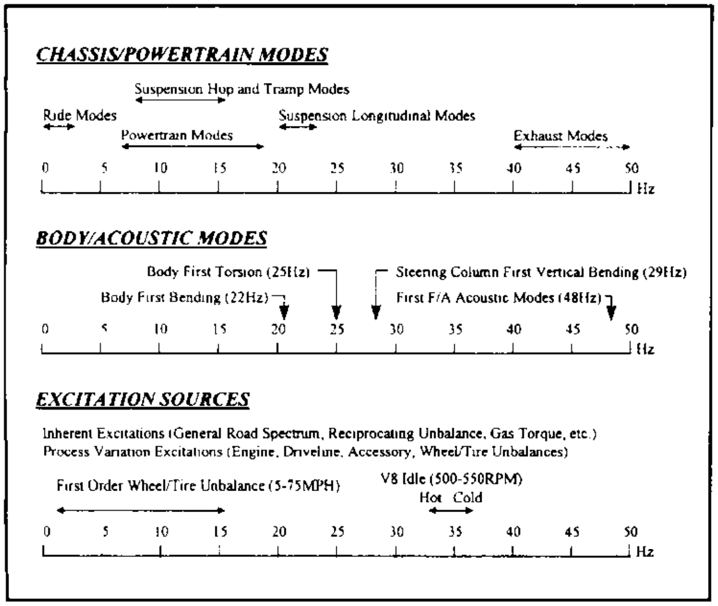

Fig. 6: Frequency separation chart

To summarize, customer and marketing objectives, along with comparative vehicle evaluations, are used to define vehicle subjective targets. These subjective targets, along with comparative vehicle tests and concept vehicle simulations, are used to define the vehicle objective targets. Finally, the objective targets, along with subsystem tests and simulations are used define the subsystem targets. This process of starting with customer and market objectives to arrive at subsystem targets is illustrated in Figure 7.

It should be emphasized that meeting the subsystem performance targets does not necessarily imply that the full vehicle NVH targets will automatically be met. The subsystem targets are just a device for measuring the relative performance of different designs before proceeding to the vehicle system level. In other words, subsystem targets provide a means of assessing the merits of different design alternatives. If a subsystem does not meet its target, then the subsystem must be re-evaluated at the system level to determine its impact on the vehicle system NVH targets. If the impact is significant, then the performance targets of the other subsystems must be adjusted to compensate for the lack of performance. Occasionally it is found that the under-performing subsystem is a "weak link" that will prevent achievement of the vehicle level goal. An effective simulation and optimization capability provides the tool to sort the design trade offs within the vehicle development time frame.

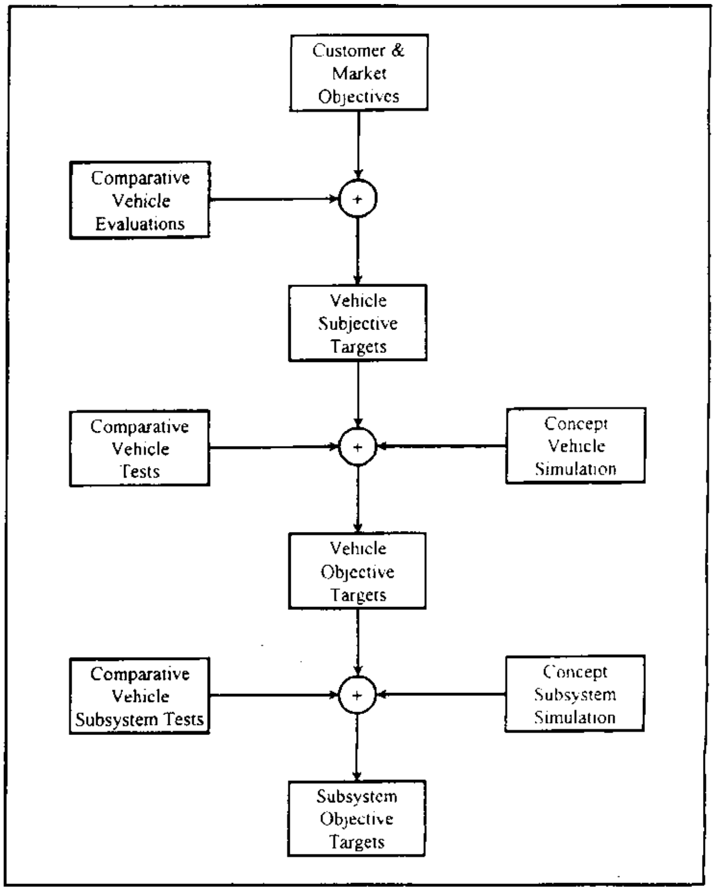

Fig. 7: Target setting process

Conclusion

The preceding has outlined a process for taking customer and marketing objectives, combined with comparative vehicle evaluations, to arrive at subjective and objective vehicle system design targets. These vehicle design targets are further broken down into subsystem and component design targets. Basic design principles, such as designing for isolation, frequency separation, and body stiffness ratios are used in the process to achieve the desired design objectives.

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