

# Process to Achieve NVH Goals: Subsystem Targets via “Digital Prototype” Simulations

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## **ABSTRACT**

A process to achieve vehicle system level NVH objectives using CAE simulation tools is discussed. Issues of modeling methodology, already covered adequately in the literature, are less emphasized so that the paper can focus on the application of a process that encompasses objective setting, design synthesis, and performance achievement using simulation predictions. A reference simulation model establishes correlation levels and modeling methods that are applied to future predictions. The new model, called a “Digital Mule”, is an early new product “design intent” simulation used to arrive at subsystem goals to meet the vehicle level NVH objectives. Subsystem goals are established at discrete noise paths where structure borne noise enters the body subsystem. The process also includes setting limits on the excitation sources, such as suspension and powertrain.

## **INTRODUCTION**

Faced with the challenge to improve vehicle quality and reduce the program cycle time for new product introduction, CAE simulation has been used at DaimlerChrysler to assure improvements in vehicle NVH performance. Using simulation up front allows design decisions and risks to be weighed before costly

prototypes are built and before investments in production tooling are committed. Product development cycle times are approaching the point where only a single level of prototype, which is fully design representative, is available for hardware “what-if” studies before a program must proceed with production tooling investment. This shortened cycle time is made feasible through the emergence of CAE simulation methodologies that have proven to be representative of the actual physical hardware and applied to refine the engineering features of new vehicles.

The topic of this paper discusses a process for using simulation to guide a new product development to achieve goals in the area of structure borne NVH (Noise Vibration and Harshness). The process has evolved to the point that it parallels the physical hardware paradigm, where several levels of pre-prototypes evolved into several levels of prototypes, and so on, as the product improved toward its objectives. The difference being that the evolution occurs in CAE math models at much less cost and in a way that is quicker and more responsive to evolving customer needs, design requirements, and constraints.

The model requires a full vehicle representation so that all subsystem interactions are included. This requires sufficient detail in the models for suspension, powertrain, and body to predict response in the frequency range of interest. To simulate structure borne

NVH performance, the complete spectrum of NVH response must be considered including tactile shake issues in the low frequency range below 50 Hz, low frequency noise from 30 to 100 Hz, and high frequency noise up to 500 Hz.

To rate the tactile and noise performance in the low frequency range, design iterations are evaluated by comparing a full vehicle simulation directly to vehicle level targets (1.). This is cost effective since the computation only has to cover a smaller frequency range and utilizes the same model used for high frequency studies. In this range there are only a few fundamental system modes that are easier to diagnose. The concept of a subsystem target in this range involves global parameters including; the fully trimmed body first order modes, body-in-white modes, or body-in-white stiffness in rank order of their direct linkage to vehicle level performance. Targeting of the global vehicle modes of fundamental order is called “mode management” and will not be covered here since it has been described adequately in earlier work (1., 3., 9.).

The goal of this paper is to describe the process for setting subsystem targets for the major noise paths contributing to structure borne sound level in the frequency range above 100. Hz. This is the most difficult problem to diagnose and set targets for because of multiple contributing paths with many closely spaced resonances. The noise path targets for the body subsystem are limits on the noise sensitivity due to an individual load applied locally to the path, while for chassis and powertrain subsystems, the targets are limits on the excitation level to the path coming from these components. Once noise path targets are set, many design iterations can be evaluated using subsystem models. Poor path performance can be solved by: 1) improving the body structure using a trimmed body simulation, or 2) the displacement at excitation points from the chassis / powertrain can be reduced by using a stand-alone subsystem simulation. The full simulation is revisited only after significant improvements are made in the subsystem designs.

The process outline is as follows:

- 1) *Establish NVH Goals of new vehicle WRT a reference vehicle in hardware.*
- 2) *Verify reference vehicle simulation methodology.*
- 3) *Model “Digital Mule” of the design intent vehicle.*
- 4) *Evaluate performance of “Digital Mule” WRT goal.*
  - a) *Analyze key contributing paths.*
  - b) *Rebalance paths to set goal for “Digital Prototype”.*
- 5) *Iterate / Trade-off / Optimize new design to reach subsystem noise path goals.*
- 6) *Confirm goal achievement yielding a “Digital Prototype” design released for build.*

Just as in the physical hardware paradigm, the process begins with physical hardware needed for NVH target setting and is discussed in the next section.

## NVH TARGET SETTING

The first step in any new vehicle program is to set the goals to be achieved. The goal must be tied to a customer need that will position the new product competitively in the market place. Customer satisfaction in the area of NVH usually translates into a vehicle that is vibration free and quiet. A typical starting point for target setting is to have corporate management, designers, NVH specialists, and customer clinics involved in driving and rating several products similar in class to the new product to be designed. The result of this evaluation is a determination of the desirable NVH attributes that will distinguish the new product from the competition.

## SUBJECTIVE TO OBJECTIVE CONVERSION

It is standard practice, among automotive OEMs, to use a 10 point scale to rank the NVH performance of vehicles similar to the SAE subjective rating standard (1.). The subjective ratings must be converted into objective measurements. Then, as the design reaches completion, progress towards target can be verified and quantified using controlled laboratory testing. This test verification; however, can not be performed until hardware is available. A method of conversion based on human response to tactile vibration and sound level was documented in earlier work (1.) and is summarized in Table 1. The formulas express the subjective ratings in terms of tactile velocity level or A-weighted sound pressure level.

<b>Subjective to Objective Relationship</b>		
	<b>NVH Quantity</b>	
	<b>Tactile Level</b> mm/sec	<b>Sound Level</b> dBA
<b>Subjective Rating Equation</b>	$R = 8.19 - 4.34 * \text{Log} (V)$	$R = 13.6 - 0.175 * \text{SPL}$
<b>% Change Corresponding to 1.0 Rating Improvement</b>	<b>-41. %</b>	<b>-48. %</b>

Table 1: Subjective to Objective Relationship

While the formulas imply that an absolute rating can be computed, they are only used to compute changes in rating with respect to (WRT) a reference baseline. The formulas in Table 1 predict that a change in rating of +1.0 subjective points corresponds to a decrease of 41% in tactile velocity level or a 48% reduction in sound level. This corresponds to a general rule of thumb that a halving of amplitude represents a “significant” change in perception of NVH. A full subjective rating point improvement on a 10 point scale

can reasonably be considered as significant and observable by most customers. These formulas are used in the process to rank the NVH performance of the new product WRT a reference as the design unfolds.

## BENCHMARKING

As mentioned before, several competitive products are usually benchmarked for NVH quality to help position the new product. The NVH goal setting process described here requires that a reference vehicle be included in the rating process. Additionally, since simulation will be the basis for rating the NVH performance of the new vehicle, a complete simulation model of the reference vehicle must also be available. This reference should be in a class similar to the new product since the expectation of the customer and design management varies with price class. However, a vehicle in a close class can also be used as a reference since the human ability to perceive NVH quality can reasonably be considered invariant.

Typically, the competitive and reference vehicles are rated subjectively WRT the current product, if one exists. An example result is shown in Table 2 as a relative rating differential. In some cases the current product and the reference vehicle may be the same. For each NVH load condition a vehicle from the evaluation fleet is chosen to be the benchmark for the desired NVH performance.

<b>Results from a Typical Benchmark Process</b>				
	Subjective Ratings			Objective Measure Target
	Differential Rating WRT Current Product			
	Benchmark Vehicle	Reference Vehicle	Benchmark WRT Reference	Reduction WRT Reference
Road Shake	+ 1 ½	+ ½	+ 1	4.6 dBL*
Road Noise	+ ½	+ ¼	+ ¼	1.4 dBA
Idle Shake	+ 1 ½	0	+ 1 ½	6.9 dBL
Idle Boom	+ ½	0	+ ½	2.9 dBA
P/T WOT Noise	+ 2	+ ½	+ 1 ½	8.6 dBA

\* Note: Tactile dBL is based on a level  $V_{ref}$  of 1.0 mm/sec from the equation  $Level = 20 * \log (V / V_{ref})$  where  $V$  is velocity in mm/sec.

Table 2: Results from Benchmark Target Setting

Since, the benchmark is rated WRT the current product as well as the reference vehicle, then the benchmark can be rated WRT to the reference vehicle. In the simplest case, the target for the NVH performance of the new product is taken as the improvement needed to match the benchmark as measured WRT the reference vehicle.

The next step of the process requires the attainment of objective measures for each of the NVH

load conditions. Controlled laboratory tests must exist for each NVH condition to be measured for performance. This is required to have reasonable accuracy and repeatability in the attribute measurement and so a simulation, which closely approximates the key intent of the test, can be derived. The benchmark vehicle and the reference vehicle are tested in the lab resulting in the objective NVH performance level WRT the reference that is desired for the new product as shown in Table 2.

The relative objective for NVH performance WRT the reference, as determined from the lab test, should correspond reasonably close to the relative subjective rating as determined by the conversion formula in Table 1. If it does not, a suitable scale factor is inserted in the formula for each NVH load to create an exact correspondence. This assures that when the predicted subjective level from the formula is at goal, the absolute value of the benchmark NVH level has been attained. The introduction of a scale factor is not particularly significant, since the main purpose of the formula is simply to be able to rank design evolution at intermediate levels of goal achievement using a subjective measure. Stated another way, the NVH target can only be said to be met when a measurement of the final design in the lab has reduction in NVH levels as indicated by the last column in Table 2. For the typical data shown in Table 2, the objective data in the last column was computed directly from the formulas using the benchmark WRT reference subjective values and expressed in dBL for tactile level or dBA for sound level.

## REFERENCE VEHICLE MODEL

An NVH model of the reference vehicle is required so that the NVH performance of the new vehicle model can be rated WRT the targets established in the benchmarking process. While the level of technology has evolved significantly in the area of NVH modeling and simulation (2., 8., 9.), it is generally accepted that the best use of the models is for trend prediction rather than absolute vibration level predictors.

Kompella and Bernhard (7.) in a study of 99 production sport utility vehicles, showed that the band of variability for structure borne noise was on the order of 10 dBs from 40 to 150 Hz and as much as 20 dBs from 150 to 500 Hz. Clearly, this points to the need for a considerable number of tests to address the adequacy of the simulation model. A variation band of 10 dBs is quite large and may be more than the desired noise improvement goal. While this represents a concern for the adequacy of the model, it is equally problematic to the development engineer attempting to determine modifications to a limited number of physical prototypes with this potential band of variation.

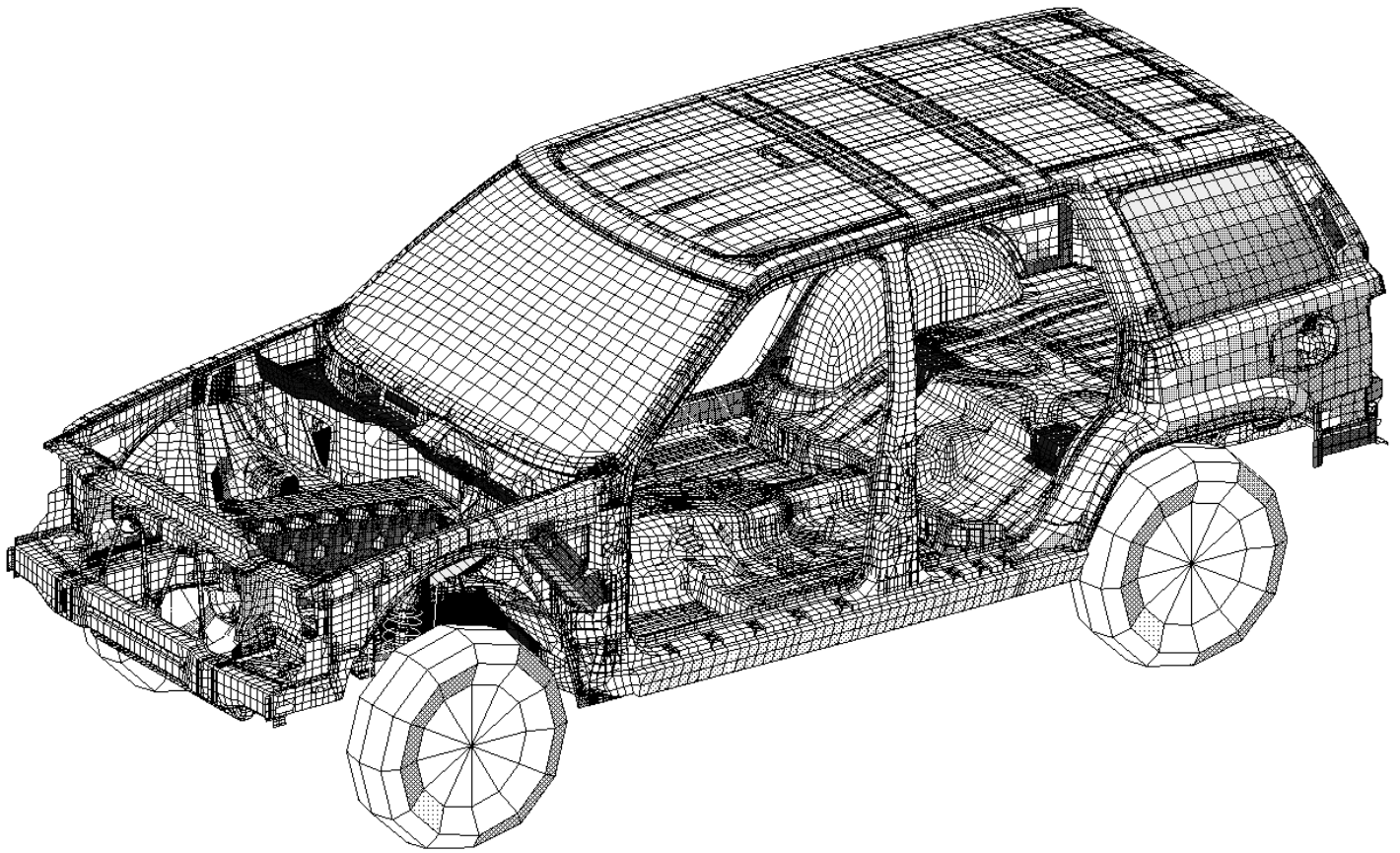


Figure 1: Reference Vehicle Simulation Model

This may point out the advantage of making design decisions from A-B trend predictions since there is no manufacturing or assembly variation. There may, however, be variation in modeling discretization and assumptions from one modeler to another leading to variation. This type of variation can be controlled with “best practice” modeling guidelines. “Best practice” guidelines must evolve over time and continuously improve. They are determined by the model fidelity that is required to bring the prediction level within the band of variation of the test level.

The reference baseline model (which is the foundation of the goal achievement process) is only required to be a directionally correct trend indicator of NVH performance. If the simulation prediction were within the band of variability of the test data, this would be an indication that the trend requirement was met. Assuming test variation on the order of that found by Kompella, the reference simulation model shown in Figure 1 was within this band of variation. Additionally, since the reference baseline model has presumably been used to guide the design of a previous generation, the trend prediction capabilities are likely to have been established through structural A-B comparisons on actual physical hardware during the development phase.

Since the reference model will be compared to the new design using a model, the target achievement

process requires that both models have similar discretization and level of detail. If any technology is improved in the modeling best practices and used in the new model, then it must also be updated in the reference model. If this process is followed then the trend prediction capability will be maintained.

Figure 1 shows the reference vehicle model used during the process described here. It has about 500,000 degrees of freedom. Targets for major noise paths are to be obtained and goal achievement evaluated, thus requiring models to include sufficient detail to represent all attachment bracketry down to representations for the sleeves in the rubber isolators. Isolators are typically modeled as point elasticities but it was found important to include rate effects from frequency and operating preloads. Rotational rates as well as translational rates were also important.

Most components were modeled using shell elements and include body structure, body brackets, and most suspension links. Some reduced degree of freedom models, such as powertrain, were included, however, they are derived typically from full detailed representations. The level of detail was required so that predictions of high frequency phenomena, such as wide open throttle (WOT) powertrain noise, could be made to 300 Hz. Noise predictions require an acoustic cavity

model as shown in Figure 2. The powertrain and chassis are shown in Figure 3.

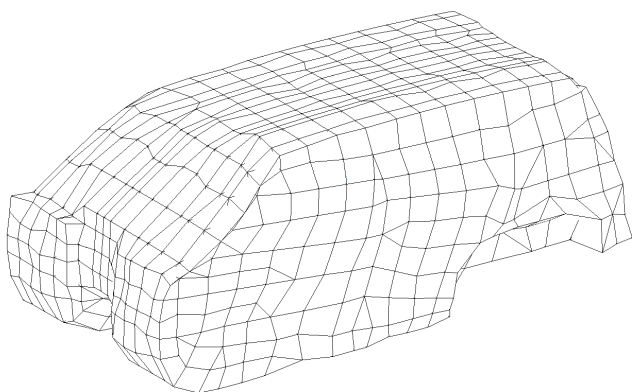


Figure 2: Interior Acoustic Cavity Model

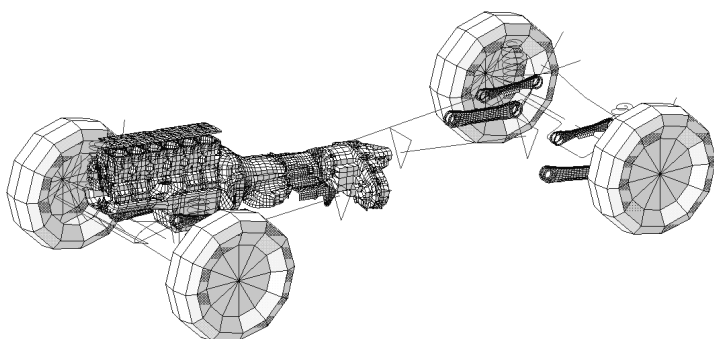


Figure 3: Reference Vehicle Chassis and Powertrain

### ***“DIGITAL MULE” VEHICLE MODEL***

The challenge of the target setting process is to create a representative model that captures the design intent of the new product at the early stage before enough design data is available to build the model. In some cases the reference vehicle may be close enough to the new design such that it can be used for noise path subsystem target setting directly. But in many cases, as was true for the example used in this paper, the architecture had noise path configurations that were significantly different than the reference vehicle.

Recall that the target setting model has to have the same detail level as the reference model. For the example described here, this means a full shell body representation, as well as FEA suspension components, and including FEA or modal powertrain models. The state of technology for mesh generation and FEA model creation has advanced to make this possible within the program timeframe. A four to six man team, depending on skill level, can put together a model with a detail level of the reference vehicle in about 30 to 40 days.

Since, the design data is scarce, the model is usually pieced together from existing models. The

models are shrunk, widened, cut, and pasted to form a complete vehicle from several sources, very similar to the way pre-prototypes used to be built in the hardware build-and-test paradigm. The engineering group called this a “mule” vehicle, implying that it would be depended upon for much of the initial vehicle development work without the beauty or agility of the first prototype. This is the source of the name for the first working vehicle model in the target setting process, referred to here as the “Digital Mule” vehicle.

### ***DESIGN INTENT CONFIGURATION***

The “Digital Mule” must be representative of a realistic production automotive vehicle regardless of the source of its parts. To derive realistic targets it must also be representative of the design intent configuration. In the early stages, the design intent may only be a basic wheel base package layout, a weight goal, and a few preliminary assumptions defining the basic architecture such as the following:

- Front Suspension with Steering Layout
- Rear Suspension and Final Drive Configuration
- Powertrain Configuration
- Unibody Construction

This level of description is enough to start design synthesis. Suspension attachment points are fixed based on type of layout and to achieve fundamental handling properties. This data is available early and determines the noise paths into the body structure. Subsystem targets for these major noise paths are the result of the target setting process and are the primary foundation for achieving the full system NVH objectives.

### ***“DIGITAL MULE” SYNTHESIS***

When the program is at the earliest stage, only a broad definition of the design is available as stated by the design intent. It is this stage where simulation guidance can be most effective since the results of CAE analysis, if timely, can be used to stake a claim on package space.

Ideally, functional NVH requirements evaluated using simulation should be the primary driver for synthesis of the “Digital Mule” to be used for NVH target setting. Cross functional requirements such as crashworthiness and handling must also be considered for their effect on the basic architecture; however, the synthesis should be weighted towards NVH requirements since the Digital Mule will be used to set noise path targets.

Due to the program timing constraints, there is only time enough for one level of Digital Mule with which to set NVH targets (similar to the vehicle development process in hardware!). Therefore, it is vital that the vehicle is constructed to have most of the noise paths at

high performance levels. To this end, some iterations of the critical noise paths, known from experience, are required at the body level before proceeding to build the full vehicle. Noise path analysis is simulated using a fully trimmed body model (3.). Assumptions of carry over trim mass items from the reference or similar model are adequate for this purpose.

All paths should meet some minimum level of noise path performance. General rules of thumb exist for desired performance levels. A criteria for body dynamic stiffness to be 5 to 10 times that of the corresponding rubber isolator in the path (1.) and a criteria of maximum mobility of -10 dBL (see Table 2 for the tactile dBL formula) have been used (6.) . The model should be checked against these criteria to assure that the subsystem noise paths have good NVH characteristics.

In the powertrain noise example discussed in this paper, it was expected (as determined from experience), that the transmission crossmember would be one of the dominant paths. Intuitively, this occurs because the crossmember is anchored at its ends and loaded in the center of the span, which is otherwise unsupported. The key design issues controlling performance are beam section, span length between supports, and end conditions, all of which were examined by Achram et.al. in Ref. (3.) The rule of thumb criteria specifying a crossmember dynamic stiffness 5 to 10 times that of the mount isolator was used to iterate on the design until the crossmember reached a rate of 7.5 times that of the isolator. Additionally, where mobility performance was below that of similar paths from the reference model, noise path iterations were performed until the levels were matched.

Best Practice guidelines for NVH design are additional principles which guide the Digital Mule synthesis (3.). At some point during the synthesis, the construction can reach an impasse where a basic package constraint may be compromising a key noise path. At this point, it is recommended that the analyst and designer work proactively to remove the constraint so the build can continue with high performance paths. This is accomplished with the cooperative understanding that the Digital Mule is used only for target setting. It is imperative that the Digital Mule be built with adequate noise paths. The final design of the new vehicle may evolve to relieve the package constraint, and if it does not, then the path performance of the Digital Mule serves as a benchmark to be accomplished in the final design inclusive of the constraint. Insight gained from studying the hardware from the benchmark vehicles can often be useful in cases of impasse since it can be used to assure that the proposed design for the noise path of the Digital Mule has a basis that is feasible for mass production. The target achievement process has rebalancing remedies for paths that can not meet the NVH target performance which will be discussed later.

Sufficient noise path performance is a goal for the Digital Mule to bring the full system NVH performance close to the vehicle NVH target levels. However, the Digital Mule performance can be above or below the vehicle goals and still be used to set subsystem noise path targets. If the vehicle level target is exceeded for some NVH conditions, then correspondingly the subsystem performance targets will be set below the Mule’s performance levels and conversely. This part of the process is discussed later.

With the body structure and trim completed, consideration was made for the chassis and powertrain. The powertrain was available from existing simulations in modal model form, just as used in the reference vehicle. Suspension layouts were used to make FEA control arms and links. Axles were carried over from existing models. The final Digital Mule model had body, chassis, and powertrain models with the same level of detail as the reference model.

### “DIGITAL MULE” SIMULATION

Next in the process is a consideration of the NVH conditions to be simulated. This must include the full spectrum of NVH load conditions that will encompass the real world environment experienced by the actual vehicle to be designed. This breaks down into two main sources, one excited by loads from the suspension, and the other from the drivetrain.

#### Load Condition Description

There are two types of typical loads; 1. Inherent, and 2. Process Variation as shown in Table 3.

<b>NVH Load Conditions</b>		
	<b>Inherent</b>	<b>Process Variation</b>
<b>Suspension Induced</b>	Tar Strip Impacts	Tire/Wheel Unbalance
	Rough Road Surface	Tire Force Variation
<b>Driveline Induced</b>	Engine Fuel Combustion and Reciprocating Unbalance	Driveshaft and Halfshaft Unbalances
	. Idle-in-Gear	Torque Converter Unbalance
	. Constant Speed Cruise . WOT Acceleration	Axle Gear Mesh Variation

Table 3: NVH Load Conditions

Inherent loads are present for all vehicles and can be determined by measurement or calculation. An example of an inherent load from the powertrain is combustion gas pressure due to fuel ignition and an example of a suspension load would be from road surface irregularity. Process variation loads result from build variation and rotating unbalances. Tire/wheel unbalance and driveshaft unbalance are two examples.

The vehicle is designed using the specified maximum allowable unbalance so as to be insensitive to these forces where ever possible.

It can not be over emphasized that the full range of NVH load conditions must be simulated and compared to target as the design evolves. If only the driveline or the suspension induced loads were evaluated, there would be some noise paths that would not appear to be significant. Also, as design decisions are made, it is often observed that there is a conflict between achieving performance in one area and losing in another. The goal of the process defined here is to create a balance between the conflicting issues and result in a near optimum design at the limit of performance in each category.

All of the load conditions were evaluated in the target setting process described here; however, the process was weighted towards the Inherent load conditions. This occurs primarily because the subjective ride evaluations center around events that are usually induced as a result of discrete events such as hitting a tar strip, running over a section of rough road, or performing a WOT acceleration. This process is also easy to make comparisons among competitive products with A-B ride evaluations. The study of process variation for a condition like wheel unbalance, for example, is somewhat harder to duplicate out on the test track and is even more difficult to evaluate among competitive products. The process variation loads are, however, easier to measure and duplicate with lab measurements.

While all of the loads were evaluated with the Digital Mule, only an example from powertrain noise will be discussed here since it is considered to be the most complex. It was felt that the road noise excitation case has been well developed in earlier work (4.) as well as the low frequency tactile shake cases (3., 9.). The powertrain noise case is complicated by the need to consider multiple engine orders of the load involved in the excitation. For example, a V6 engine with a 90 degree block angle would have significant gas pressure torque orders of at least 3<sup>rd</sup> and 6<sup>th</sup> and inherent reciprocating unbalances of 1<sup>st</sup> and 2<sup>nd</sup> orders. The inclusion of higher order effects such as crankshaft flexibility leads to a sophisticated simulation to get the proper excitation coming from the powertrain subsystem. The powertrain example discussed in this paper was a variation of this type of V6 engine.

#### Vehicle Performance WRT Target

Once all load cases for the Digital Mule were established, the model was analyzed to obtain the vehicle level NVH responses for all load conditions. These NVH responses were then compared with 'the vehicle level target' to find the vibration or noise reduction levels needed to meet goal. For example, the Digital Mule vehicle level simulation indicated the powertrain noise was 2. dBA higher at 4200 RPM than the vehicle upper band target as shown in Figure 4.

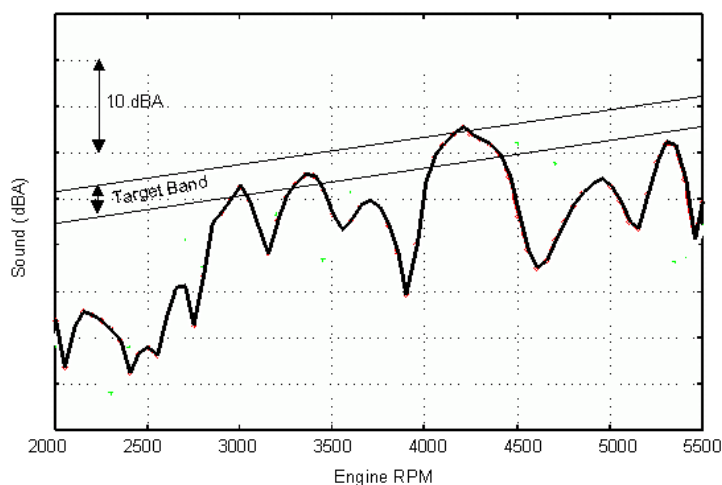


Figure 4: Overall Sound at Driver's Ear for "Digital Mule"

### **SUBSYSTEM TARGET SETTING**

The factors that control structure borne noise generation are as follows:

- The Input Level from the Excitation Source.  
If the input source is the powertrain, this might be the displacement of the powertrain mount locations. If the source is the suspension, then the displacement of the suspension linkages are the inputs. These source displacements will be referred to later as excursions.
- The Attenuation Efficiency of the Isolator.  
This is influenced by the stiffness or inversely, the compliance of the mount configuration and its damping.
- The Dynamic Structural Integrity and Noise Sensitivity of the Body at the Isolator Attachment.  
This is measured as the passenger ear sound level transfer function per unit force applied on the body in each direction (P/F). This has been shown to be related to the velocity transfer function response per unit input force applied on the body and measured in the direction of the force (V/F). This velocity response (V/F) will be referred to as the mobility.

Each of these factors must be considered and target values established to create a well balanced vehicle system. The level of input experienced depends on the NVH loadings that will be encountered during service; therefore, a full spectrum of loads must be considered to uncover all the NVH concerns.

### **CASCADE SUBSYSTEM TARGETS FROM VEHICLE PERFORMANCE**

After the vehicle level NVH status of the Digital Mule vehicle is determined with respect to the target, the next step is to establish the subsystem targets, which will lead to achievement of the vehicle targets. Fig.4 indicated that the powertrain noise of the Digital Mule is

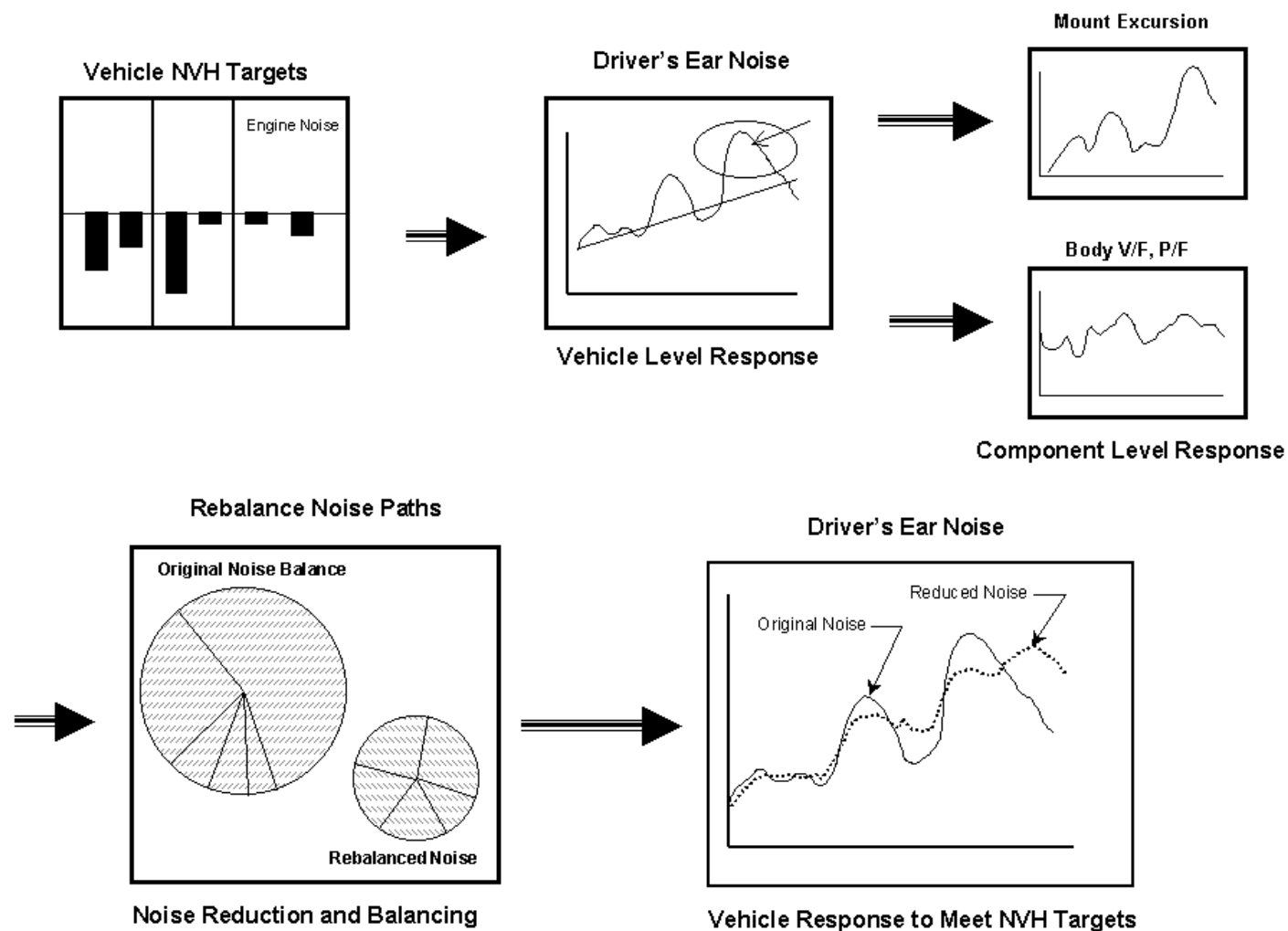


Figure 5: NVH Subsystem Target Setting Process

2. dBA higher than the target. The subsystem targets for the new vehicle are based on the Digital Mule simulation obtaining a 2.0 dBA reduction in noise.

The subsystem target setting process is shown symbolically in Figure 5. First, the new vehicle level targets were established. Then the Digital Mule vehicle level simulation indicated that the powertrain was 2. dBA higher than the target. The third step was to perform the noise path analysis to rank each path's contribution and determine the root cause of the dominant paths; i.e., whether the contribution comes predominantly from: 1) an input force or from, 2) an unacceptable path transfer function. The fourth step is to rebalance the noise paths by setting the subsystem targets to reduce each path's contribution and to make their participation more evenly distributed. Rebalancing is depicted in Fig.5 as a big pie of total noise level, with some dominant noise contribution pieces, becoming a small pie with even noise contribution pieces. Finally, the powertrain noise vehicle level target is attained by achieving all of the subsystem targets.

#### Noise path analysis

Since the new vehicle must meet all vehicle level NVH targets, the subsystem target setting should consider all loadcase conditions. Therefore, the noise path studies must be performed separately for road, powertrain, axle noise, etc.

The basic concept of noise path analysis assumes that the total noise level  $P$  received at the driver's ear, or passenger's ear, is equal to the summation  $P_{sum}$  of all of the partial pressure  $P_i$  of each noise path, which is described as follows:

$$P \approx P_{sum} = \sum P_i \quad (1)$$

The partial pressure  $P_i$  of an individual path is equal to the input force  $F_i$ , from suspension or engine to body, multiplied by the acoustic transfer function  $(P/F)_i$ , as shown below: (3.)



$$P_i = F_i * (P/F)_i \quad (2)$$

Here  $F_i$  and  $(P/F)_i$  both are obtained from the simulation results of the Digital Mule vehicle.  $F_i$  is a force from suspension, engine, or exhaust system to the body through the bushing attachment point.  $(P/F)_i$  is an acoustic transfer function for an individual path, that defines a sound pressure level at the certain location inside the vehicle, such as at driver's ear, excited by a unit force at a particular bushing attachment point on the body. A noise path analysis calculates a total noise level  $P_{sum}$  from the partial pressure  $P_i$  of each noise path by using the equation (1) and (2). Then a ranked contribution list of noise paths can be obtained.

Since phasing of the various paths causes some noise cancellation, the summations are made without phase. This is intended as a worst case conservative assumption to focus the design process on the improvement of all high level paths since phase cancellation can not be depended upon in the final product.

Table 4 is an example result from the Digital Mule powertrain noise path study. From the Digital Mule vehicle modeling, it was found that the total powertrain noise  $P$  was 2. dBA higher than target  $P_{target}$ . Since the total powertrain noise  $P$  at the driver's ear, obtained from the vehicle level simulation, is approximately equal to the summation  $P_{sum}$  of the noise paths, the noise from some of the paths must be reduced. This can be described as:

$$P_{target} \Rightarrow P - 2\text{dBA} \approx P_{sum}' = \sum P_i' \quad (3)$$

where  $P_i'$  are the new set of subsystem performance limits or targets for the noise paths that will achieve the desired vehicle level reduction of 2. dBA.

Ranking	Name of Path	Noise Contribution
1	Transmission Mount	58.0 %
2	Left Engine Mount	29.0 %
3	Front Right Upper C. Arm	5.5 %
n	...	...
Total	All Paths	100. %

Table 4: Ranking of Powertrain Noise Path Contribution

### Root Cause Analysis

The root causes for each main noise path must be determined to reduce their noise contributions. From equation (2), we know that the partial pressure of an

individual path depends on the input force level

$F_i$  and its acoustic transfer function  $(P/F)_i$ .

$(P/F)_i$  has been shown to be related to the body point mobility  $(V/F)_i$  at the bushing attachment point in a paper by J. Dunn (6.) along with criteria. Although the body trim treatment and body cavity will also effect  $(P/F)_i$ , the process defined here concentrates first on  $(V/F)_i$  for structure borne noise reduction. The focus on V/F allows the design task to concentrate on obtaining good performance at the local attachment level first before consideration of the P/F. This is justified since poor mobility at the attachment will often dominate the response like a weak link and make downstream compensation in the P/F unobtainable.

The input force  $F_i$  is a function of the bushing stiffness  $K_i$  and the relative displacement of the bushing. Here  $(K_{ratio})_i$  is introduced which is a dynamic stiffness ratio of the body attachment to bushing.  $(K_{ratio})_i$  is a factor that influences the bushing isolation efficiency and affects the input force level. Reducing the incoming displacement will reduce the force level. Displacement on the powertrain side of an isolator, called an excursion, has shown to be insensitive to isolator rate. This was confirmed with a sensitivity study using the full vehicle model but may only be valid for the frequency range studied in this paper since this only involves a few fundamental modes of the powertrain. Suspension link excursions are more influenced by isolator rate, however, NVH issues with these parts usually involve a fundamental link resonance (rigid body or flexural) that must be shifted out of the range of operation thus reducing the input excursion. The assumption that the input excursion is the root cause of an NVH concern to be addressed, if unclear, can be tested later with the full vehicle simulation by monitoring the excursions while design alternatives are weighed or by performing a sensitivity study as was done for the powertrain.

These relationships can be described as:

$$P_i \propto (P/F)_i, (V/F)_i, F_i, (K_{ratio})_i \quad (4)$$

It was expected that these four factors effect the partial pressure of a path. If the factors of the main noise contribution root cause are identified, then targets can be set for them. Once these subsystem targets are reached, then the system will achieve the vehicle level NVH targets.

### Generic Subsystem Performance Rules

As mentioned earlier during the Digital Mule synthesis, there are some rules of thumb used to determine if the above mentioned factors are

reasonable. For example, the body acoustic transfer function  $(P/F)_i$  should be smaller than 60 dBL (5.) and the body point mobility  $(V/F)_i$  must be below -10 dBL (6.) (see Table 2 for dBL formula). The input force has certain guidelines also. The dynamic stiffness ratio of body attachment to bushing  $(K_{ratio})_i$  should be larger than a factor such that the bushing can isolate the input excitation effectively.

The generic rules are only guideline indicators of NVH performance and allow flexibility in the range of acceptability depending on the specific path's contribution. For example, consider how to judge a typical  $(K_{ratio})_i$ . A certain range of  $(K_{ratio})_i$  values are used to determine the performance from good to unacceptable.

For example:

$$K_{ratio} < 1.0 \Rightarrow \textit{danger}$$

$$< 1.0 K_{ratio} < 5.0 \Rightarrow \textit{caution}$$

$$K_{ratio} > 5.0 \Rightarrow \textit{OK}$$

The powertrain example, mentioned earlier, will be used to illustrate subsystem noise path target setting. It can be seen that the dominant sources of powertrain noise into the body are the top two contributing noise paths shown in Table 4. Looking at the first noise contribution path, the transmission mount, the rules of thumb indicated that  $P/F$  and  $V/F$  were acceptable but that the force level was too high.  $K_{ratio}$  was also checked and it was acceptable. Further simulation results indicated that the transmission mount displacement on the powertrain subsystem (called an excursion) was high compared to excursions observed in the reference baseline model. Based on this, a goal to limit the excursion coming from the powertrain subsystem was established. The powertrain excursion was not affected by the isolator which was 1/10 as stiff as the body side dynamic stiffness. Therefore, a reduction in excursion of 20% would also reduce the transmitted force by 20% and give a corresponding reduction in the noise path contribution.

For the second path, the left engine mount, the input force level was reasonable,  $K_{ratio}$  was good; however, its  $V/F$  and  $P/F$  were unacceptable. For this path, a subsystem goal was set to limit the  $V/F$  and  $P/F$  sensitivity in order to reduce its contribution to vehicle level noise.

View Forced Modeshape

Forced modeshape animation is a powerful tool for root cause analysis of a dynamic system. The above

section mentioned that the excursion of the transmission mount was high, so it was desirable to find the root cause. The Digital Mule vehicle model was run for a response modeshape (sometimes referred to as an operating deformed shape or an applied force response mode) at the frequency of concern at 140 Hz. The shape observed was a complex motion of the powertrain dominated by high excursion of the transmission mount as expected. The high excursion caused the high input force of the transmission mount from the powertrain to the body. This led to the need to set a powertrain subsystem excursion target for the transmission mount to reduce the noise contribution of this path. Another forced modeshape animation for the poor  $V/F$  of the engine mount revealed excessive motion of the engine bracket mounted on the body. This indicated the need to set a  $V/F$  mobility target for the body subsystem.

View Natural Frequency Modeshape

The forced modeshape animation showed the high motion of subsystems or components at the frequency of concern. Additionally, it is necessary to study component natural frequency modeshapes and set resonance frequency targets to decouple the modes from other subsystems or from the excitation frequency of the input load.

For an example, a high input force from a suspension control arm was identified through a noise path analysis as a high contributor. The operating modeshape of this arm was identified, through the forced mode animation, to be torsion in nature. The natural frequency modes of the components can be computed within the full vehicle model; however, it is impractical to store and view the resulting modes, in the 1000's, due to high body modal density. For this reason, all arm mode frequencies and modeshapes in the frequency range of concern were studied with the arm supported by its bushings fixed to ground. Finally, a mode frequency target was set in order to move the rigid body and flexural arm modes out of the frequency range of concern.

### Rebalancing Path Contributions

Up to this point, the noise path analysis has identified the main contributing noise paths, e.g., the transmission mount and the left engine mount for the powertrain noise. Next, the noise path contributions are rebalanced by establishing subsystem targets to achieve the vehicle level noise reduction target of 2.0 dBA for powertrain noise.

First, the targets were established for the two main noise paths. The excursion of the transmission mount of the new vehicle was to be limited to 20% of the excursion of the transmission mount of the Digital Mule vehicle. Then,  $V/F$  of the engine mount was set to be 1.0 dB lower than the Digital Mule's. Based on these

improvements, the new summation  $P'_{sum}$  of all paths was calculated including the new partial pressures  $P'_i$  assumed for the two main noise paths, resulting in a rebalanced noise contribution list. It was found that the new  $P'_{sum}$  was still higher than the vehicle level target. A study of the new noise contribution list indicates the next rebalancing calculation. Suppose for the next iteration that the third, fourth and fifth path become the main noise paths. Then, the four factors  $(P/F)_i, (V/F)_i, F_i, (K_{ratio})_i$  of these three paths are checked and the targets are set through the similar procedure. Symbolically, as in Fig. 5, the goal of the process is to make the noise pie smaller and smaller by reducing the highest contributing pieces until the vehicle level target is reached and the distribution is more even.

Iterating through the rebalance noise contribution process eventually leads to a new summation  $P'_{sum}$  of all paths which meets the vehicle target level. This final set of path performance levels defines the subsystem targets. The subsystem targets established based on the Digital Mule vehicle were as follows:

#### For Powertrain Subsystem Excursion

- Reduce Transmission Mount Excursion by 20%

#### For Body Subsystem Mobility

- Reduce Engine Mount V/F by 1.2 dBL

Only two items were identified for improvement to reach the vehicle level objective since the Digital Mule model was nearly at target. However,  $(P/F)_i, (V/F)_i,$  and  $(K_{ratio})_i$  of all other paths must be maintained at Digital Mule vehicle levels to reach goal. The Digital Mule's design features, therefore, serve as a benchmark for the new structure.

## **DESIGN EXECUTION AND REFINEMENT**

The following discussion pertains to execution and refinement of the first design intent vehicle for hardware build. The Digital Mule vehicle concepts and defined targets serve as the basis for the design implementation process.

### **FIRST DESIGN OF RECORD**

The first Design of Record (DOR) vehicle has all the subsystems defined and ready for modeling including provision for evolving design constraints like packaging, assembly, etc. The content is derived from the Digital Mule concept, where possible, to retain many of the good NVH principles used earlier in synthesizing this target setting vehicle.

The performance of the first DOR is then evaluated relative to the targets for all the NVH load

conditions described earlier. The critical load conditions for which vehicle performance is below target are further analyzed. The under-performing noise paths are identified by comparing to subsystem targets. This process is discussed in the next section using the example of powertrain WOT overall noise for a V6 engine. The powertrain noise was not meeting target for the first DOR at 4200 RPM as shown in Fig. 6.

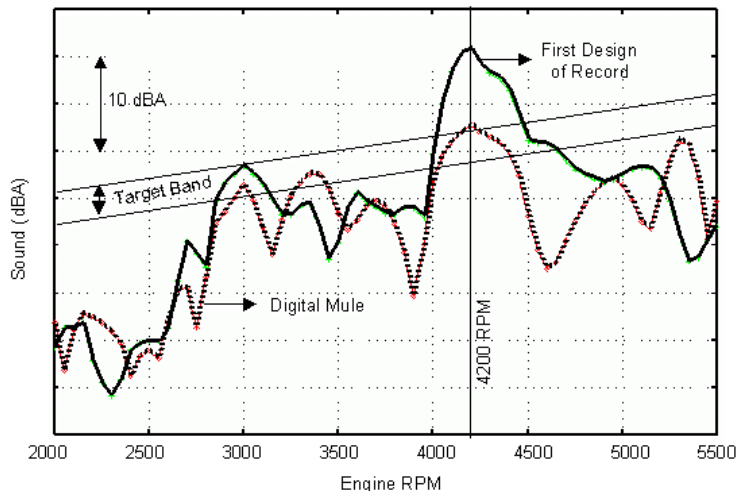


Figure 6: Comparison of Overall Sound at Driver's Ear between "Digital Mule" and "First Design of Record"

Comparatively, the powertrain noise for the Digital Mule vehicle nearly meets target (within 2. dBA) as shown in Fig. 6, thus validating the "NVH Best Practices" used in synthesizing the Digital Mule model.

## **SUBSYSTEM COMPARED TO TARGET**

A diagnostic process is applied to the critical subsystems which are below target level performance. This process includes transfer path analysis and forced mode animations at the noise peak frequencies of concern. The example of the aforementioned powertrain noise is discussed next to explain this process.

The V6 powertrain WOT overall noise for first DOR exceeds target at 4200 RPM as shown in Fig. 6. The overall sound at driver's ear is obtained by summing the responses from second order reciprocating unbalance and third and sixth gas pressure torque order contributions from the V6 engine. The order contribution analysis indicates that the second order component is dominant at the 4200 RPM noise peak as shown in Fig. 7. The sixth order gas pressure component is not shown as it is not significant compared to the second and third order components over the RPM range. Forced mode animation at 140 Hz (Second order frequency equivalent of 4200 RPM) indicates poor mobility at the transmission mount body attachment location which is related to the body structure subsystem and also high transmission mount excursion which relates to the powertrain subsystem.

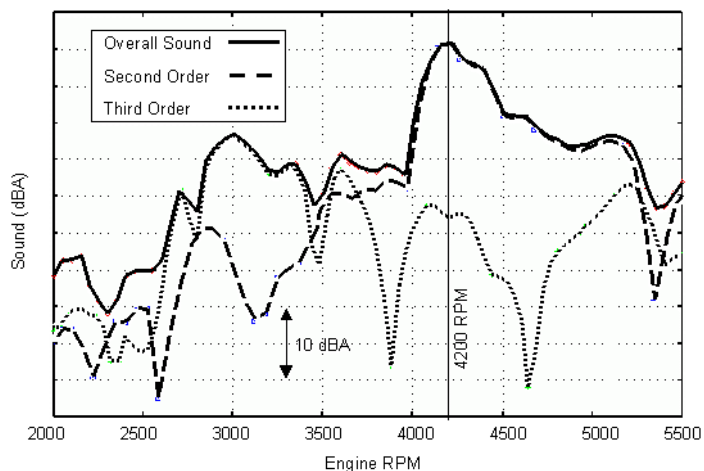


Figure 7: Order Contribution of Overall Sound at Driver's Ear for "First DOR"

Mobility studies (V/F) on the body structure subsystem at the transmission mount location reveals an amplitude peak (Fig. 8) at 136 Hz which directly corresponds to the overall powertrain noise peak observed at 4200 RPM. This narrows down the focus of attention by identifying the critical powertrain noise path on the body structure. Forced mode animation of transmission mount mobility peak at 136 Hz suggests the body crossmember supporting the transmission mount to be the key component. The lower transmission mount mobility response for the corresponding Digital Mule vehicle is also shown in Fig. 8. The results point to some of the vital design features that were included in the Digital Mule crossmember, as explained earlier and detailed in (3.), but which needed better execution in the first DOR. Iterations were performed until the features were incorporated into the DOR crossmember in terms of feasible redesign proposals. The next section will show the result of some of these redesign proposals as subsystem iterations.

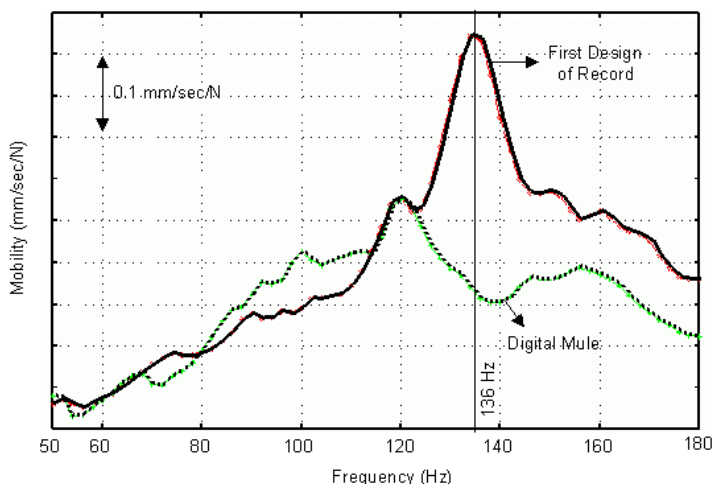


Figure 8: Comparison of Transmission Mount Vertical Mobility between "Digital Mule" and "First DOR"

Similarly, the high transmission mount excursions associated with the powertrain subsystem, shown in Fig. 9, is attributed to structural improvements needed within the powertrain assembly.

## SUBSYSTEM ITERATION

Several feasible component redesign proposals are identified to address poor subsystem performance. In the case of the body, the subsystem is a fully trimmed body and interior acoustic cavity. An iterative process is then used where these proposals are digitally incorporated in the subsystem model and their performance evaluated WRT previously defined subsystem targets. The intent of the process is to identify an optimum redesign package for key components that will eventually achieve subsystem goals. In several cases, the Digital Mule vehicle serves as a reference and provides useful insights into a component that needs redesign.

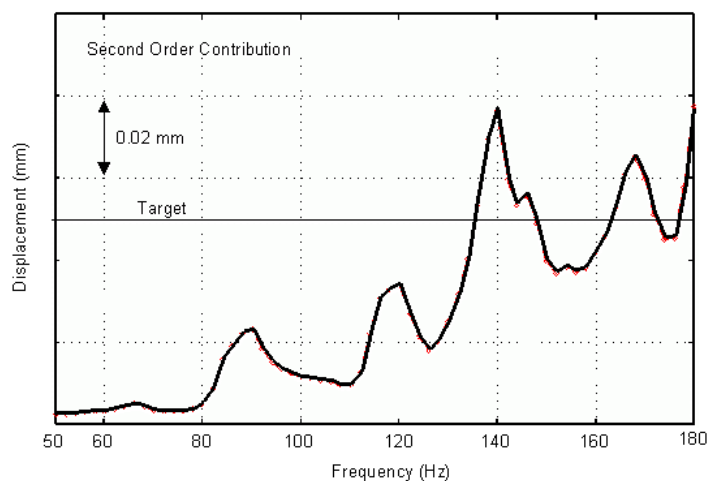


Figure 9: Transmission Mount Vertical Excursion for "First DOR"

For instance, the stiffness of DOR body crossmember described above is improved by providing sturdy end attachment structure and reinforcements within the crossmember section. The mobility (V/F) study of this body subsystem final iteration at the transmission mount attachment is shown relative to that of the design of record body as shown in Fig. 10. Clearly, the maximum amplitude of the mobility response has been significantly lowered and also the distinct resonant peak seen on the design of record response has now vanished. Also, a more uniform mobility response was seen for the final iteration design which was desired. The body subsystem target for the critical noise path indicated above was thus achieved.

Iterating on the body subsystem design to meet a subsystem goal is a very effective process that allows quicker job turn around, more iterations in a given time period, and easier interpretation of results than if iterations were done using the full vehicle model. With the alternative approach of iterating at the system level,

there is more risk that improvement in one subsystem may be masked by another under performing, “weak link”, subsystem that takes over as the dominant root cause. Because of the requirement to understand the root cause of the noise, the subsystem target setting, discussed earlier, assures that all the “weak links” in the systems are addressed thus enabling goal achievement at the system level.

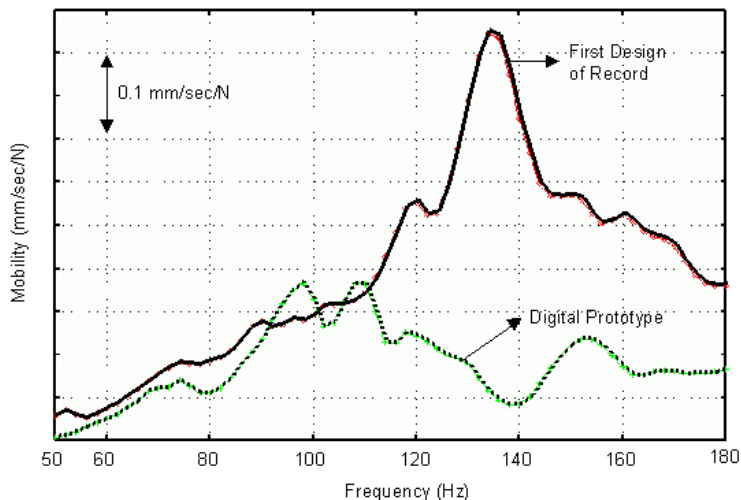


Figure 10: Comparison of Transmission Mount Vertical Mobility between “First DOR” and “Digital Prototype”

It should be obvious, that if this dual “weak link” scenario exists in the final hardware, it represents a nearly insurmountable task to diagnose and solve using conventional testing techniques. This is especially true since available testing time is also compressed due to shortening design lead times. The hardware countermeasures at this late stage are fewer and are more costly to implement also.

A similar iterative procedure was used on the powertrain subsystem to reduce the transmission mount excursion. The reduction in the transmission mount excursion for the final iteration design, shown in Figure 11, achieved the powertrain subsystem target. Two design strategies were employed to reduce the excursions. The addition of a dynamic absorber (shown) or the addition of bending braces were equally effective. As mentioned earlier, to achieve the full system goal, both the powertrain subsystem and the body subsystem were required to meet their goal thus preventing either one from becoming a dominant “weak link” in the system.

### SUBSYSTEM TRADE-OFFS

In many instances, subsystem goals may not be attainable owing to a multitude of design constraints. In such cases, a subsystem “trade-off” is used so as to not compromise system targets. The trade-off may occur between two or more subsystems in terms of relaxing the target of one and compensating that by redoing the targets on the other(s). In the preceding example, it is possible that the powertrain subsystem mount excursion

targets are not achievable. But the resulting high excursions could be balanced by reduced body subsystem mobility at the mount attachment. This could be achieved by providing for an even stiffer crossmember than shown earlier. If the isolator rate is fixed and no excursion reduction is possible, a limiting condition may be reached where the body subsystem can not compensate with a reasonable structural trade-off. This is true if the path is a dominant weak link in the system. Special countermeasures, such as dynamic absorbers, may have to be employed in this case.

### DIGITAL PROTOTYPE

Once a design content is identified from the subsystem iterations which meet the noise path targets, the refinements are incorporated into the first DOR vehicle model and a system simulation confirms that vehicle level targets are achieved. The resulting vehicle model is referred to as the “Digital Prototype” to indicate that this will be the content of the first vehicle to be built into hardware. Ideally, the hardware prototype verifies the predicted performance of the Digital Prototype model.

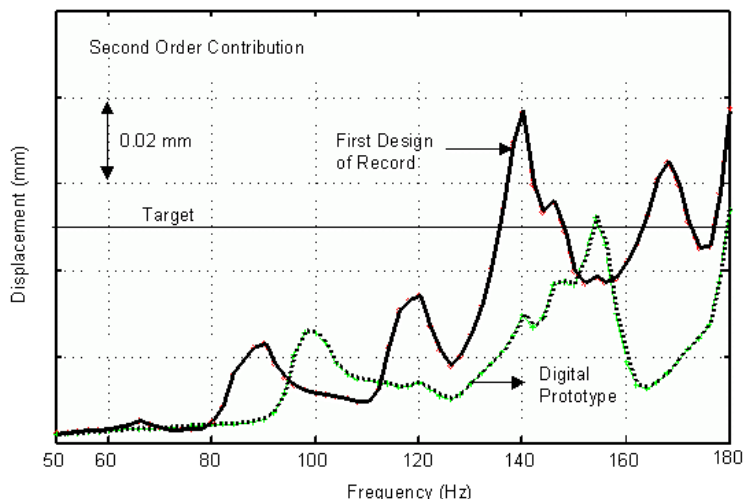


Figure 11: Comparison of Transmission Mount Vertical Excursion between “First DOR” and “Digital Prototype”

At this juncture, the NVH Target Achievement process has accomplished the major task of identifying and implementing a viable design content in the vehicle that meets the vehicle system level NVH goals. The design is released to fabricate tooling for the first generation of hardware prototypes. For the preceding powertrain noise example, the evaluation of the digital prototype vehicle relative to the target is shown in Figure 12. It can be seen that the vehicle has achieved and exceeded the vehicle powertrain noise goal established for the order related structure borne noise considered. This process can be repeated for road noise and the other NVH load conditions where subsystem noise path performance is the dominant concern.

It is typical for the new vehicle design to continue its evolution even before prototype hardware

testing starts thus indicating the need for further simulation. The Digital Prototype model is retrofitted to reflect further evolving changes in the design and the guidance continues all the while assuring that system level objectives are achieved. Further, design optimization studies to reduce cost and weight are also processed through the revised model. Once again, the previously described system-subsystem cascading target process is used to evaluate the updated digital models and on a smaller scale, component and subsystem redesigns are achieved to help meet subsystem and eventually vehicle system level objectives.

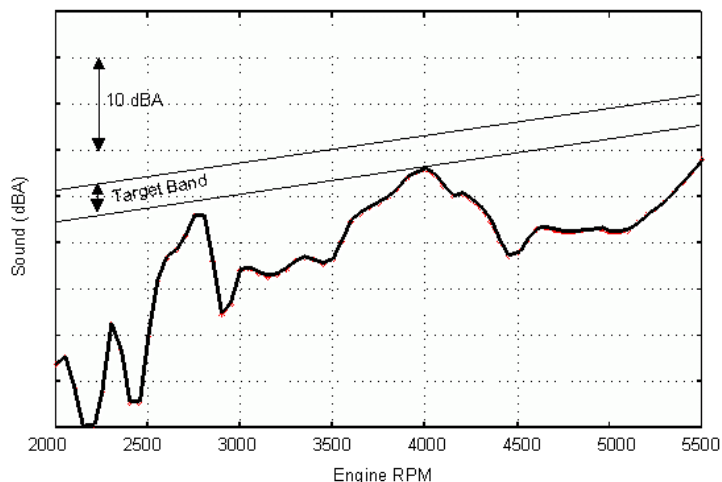


Figure 12: Overall Sound at Driver's Ear for "Digital Prototype"

Later when the physical prototype is available, new NVH related issues, revealed from prototype evaluations, are incorporated into the Digital Prototype assumptions so that cost effective solutions can be obtained. The new simulation assumptions carry into the next vehicle program to assure that the process continuously improves.

## CONCLUSIONS

A process has been defined where vehicle level NVH objectives were determined from a benchmarking exercise and converted into objective measurable parameters. The vehicle level NVH parameters, tactile vibration and noise, were evaluated using a full simulation "Digital Mule", formulated from NVH "Best Practices" and the reference baseline modeling methods. Response levels from the reference baseline model are used to project the level of goal achievement attained by the Digital Mule when subjected to inherent powertrain and suspension load conditions. A cascading from the top-down process was defined that set goals for subsystem NVH performance to meet the vehicle level goal in terms of vibration source excursions, noise path mobilities (V/F), and noise path sensitivities (P/F) based completely on simulation predictions. Subsystem noise path goals provided the required performance level, such that subsystem iterations, guided by simulation,

proceeded until the needed level was achieved. An example for powertrain WOT noise confirmed the direct link between attainment of the subsystem goals and achievement of the vehicle level objectives. The final model results in a "Digital Prototype" meeting vehicle level NVH goals and cross functional constraints to be built in hardware for performance verification.

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