

NVH Challenges for Low Cost and Light Weight Small Cars

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ABSTRACT

In worldwide automotive markets, the migration of customers towards smaller cars having compact, fuel-efficient design is well established and accepted as an engineering challenge by global automotive OEMs. Tata Motors of India has established a precedent by developing an ultra low cost and light weight car (the Nano), and has thereby created a new market segment for such cars that are more affordable to most of the population. This is now becoming established as a brand of low cost, safe transport in both rural and urban market segments. Despite the market moving towards such compact, fuel-efficient designs, customers are unwilling to lose many of the vehicle attributes to which they have been accustomed in previous types of entry-level cars. Addressing this marketing requirement places some significant challenges before the designers of this type of car.

This paper considers some of the fundamental technical challenges faced in delivering acceptable NVH performance in a light weight, low cost car. One of the most significant issues is the use of engines with lower cylinder counts than conventional cars, leading to strong impulsiveness and lower firing frequencies. These can become problematic when mounted in vehicle structures that have a high interior volume in proportion to their mass and are often not able to meet established norms for benchmark vibro-acoustic performance. Other matters considered include the high ratio of power train mass to total vehicle mass and the higher ratio of laden to un-laden mass. Such vehicles are also generally intended for manufacture by lower skilled workers in regions with little or no automotive assembly heritage, so they must be designed for ease of “right first time” assembly.

Using the example of this product, some of the possible solutions to these challenges faced by the NVH team are

examined. The paper will show that it is feasible to deliver market-acceptable NVH behavior despite the strong constraints inherent in such types of vehicle, by means of lean and innovative design.

INTRODUCTION

In passenger cars, NVH performance is one of the important attributes that define the perceived quality of the vehicle. In addition to meeting mandatory present and future regulatory requirements and required cost & weight targets, any new vehicle must meet or exceed customer expectations for many different attributes including NVH. Such expectations are escalating every year due to high levels of competition in the almost all automotive segments; none more so than the small car field. Here, despite the overriding demand to provide vehicles at low selling price, NVH standards have advanced significantly in recent years and consumers are no longer prepared to accept large compromises despite the simple physics and economic equations that suggest such cars are always going to suffer higher levels noise and vibration.

It was against this background that the engineering team faced the challenge of setting targets and proposing design solutions capable of delivering acceptable NVH performance within the ruling constraints of an ultra-low cost, light weight vehicle architecture. The difficulty was magnified by the absence of any true benchmark vehicles against which to set targets; at the time of conception, the target selling price was approximately 50% of the next lowest cost vehicle in the Indian market. As the basic packaging decisions were taken, it was clear that the NVH engineers would need to adopt innovative approaches to be able to create a car that would still appeal to the buyer.

The minimalist philosophy mandated that the car could only weigh some 600kg despite having four doors and space for

four adult passengers, thus the powertrain and all other mechanical elements had to follow a path of extreme downsizing with little reserve of performance. One of the pivotal decisions was to place the engine at the rear to liberate maximum inner space for occupants, denying the NVH team the normal benefits of good acoustic isolation through a conventional dash panel. The challenges were further intensified by the selection of a compact twin-cylinder layout for the engine compared to the conventional use of three- or four-cylinder units.

As the project progressed, issues became separated into three categories:

- Legislative compliance with pass-by noise standards;
- Customer requirements for interior noise and vibration;
- Exterior sound quality

In this paper, specific examples covering some of the challenges encountered during the development are discussed together with their solutions.

MAJOR NVH CHALLENGES AND THEIR SOLUTIONS

Challenges faced during development encompassed many of the components and sub-systems of the vehicle. Since overall vehicle NVH is the integrated response of all these elements, and each area was subject to different constraints relating to balanced achievement of the attribute goals, this paper has been divided into sections covering three major aspects.

- Body NVH
- Powertrain NVH
- Overall NVH

I. BODY NVH

1. BIW Structure Optimization

Since the cost of a vehicle is directly related to its weight, and since the BIW and trim are major contributors to the total weight, there was a strong focus throughout the project on keeping the weight of these major parts as low as possible. Measures such as the use of thinner gauge steel for panels and limiting the application of stiffeners to only selected locations based on strict durability and functional requirements were routinely used. In order to improve modularity for assembly and service, the power train was elastically mounted on a separate lightweight sub-frame (cradle), which was bolted to the BIW welded structure.

To control the in-cab noise and vibration of the vehicle, it is necessary to deal with structure-borne energy by management of the major sources and transfer paths. Here, the main paths included several mounting brackets for the powertrain, the

suspension attachment points and the cradle attachment to the BIW. Each attachment point was designed to meet appropriate dynamic stiffness and noise transfer function (NTF) targets for reducing the transfer of energy to the BIW structure. NTF measurements were done to calculate the contribution from various attachment points of mounts, cradle and suspension to the driver ear locations. [Figure 1](#) shows the NTF comparison of a prototype, a production and a typical benchmark vehicle, where it is clear that the NTF of the prototype was higher by 10-15 dB compared to the typical benchmark data. An improvement of 5-10 dB in NTF was achieved by increasing attachment stiffness by changing some of the BIW joints and adding local stiffness to the structure. Panel contribution analysis was also done to rank the critical panels based on their surface area and vibration velocities. The improvement in the stiffness by careful selection of thickness, joint structure, and ribbing pattern led to reduced response of body panels with minimal weight and cost addition. Although the objective performance in these areas is still inferior to the benchmark level, these modifications have helped in meeting the NVH requirement of the customer.

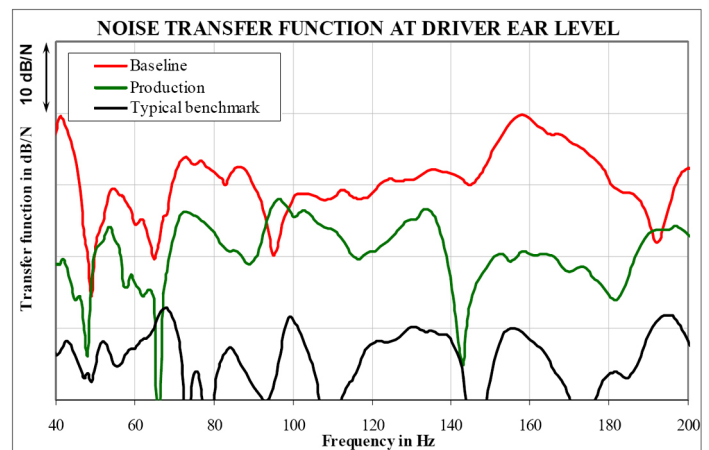


Figure 1. NTF comparison on baseline, production and a typical benchmark vehicle

2. Low Frequency Boom Noise

Low frequency boom noise is one of the most irritating perceptions inside the passenger compartment and this need to be addressed in the earliest possible design stage [1]. A low frequency boom was identified in early prototypes, in the operating range of 2000 to 2400 rpm especially in the 3rd and 4th gears, identified to be caused by first engine order excitation (1EO) at 40 Hz. By using techniques such as structural modal testing, transfer path analysis, and panel contribution analysis the root causes of the boom excitation and noise radiation were identified. [Figure 2](#) shows the structural mode of BIW shape at 40 Hz. It is distinctly indicating a local mode of the front roof area and roof header,

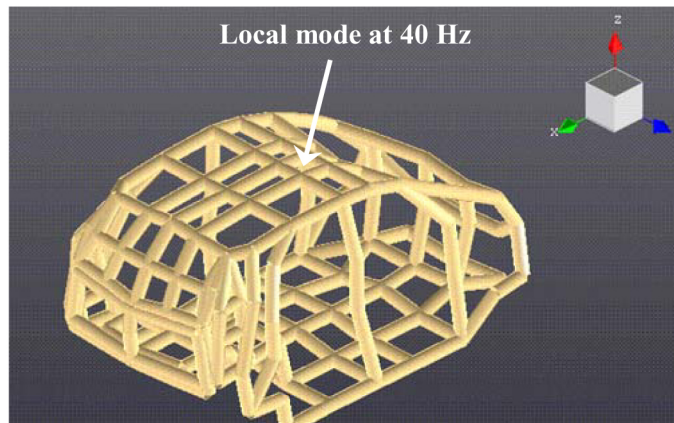


Figure 2. BIW local mode at 40 Hz

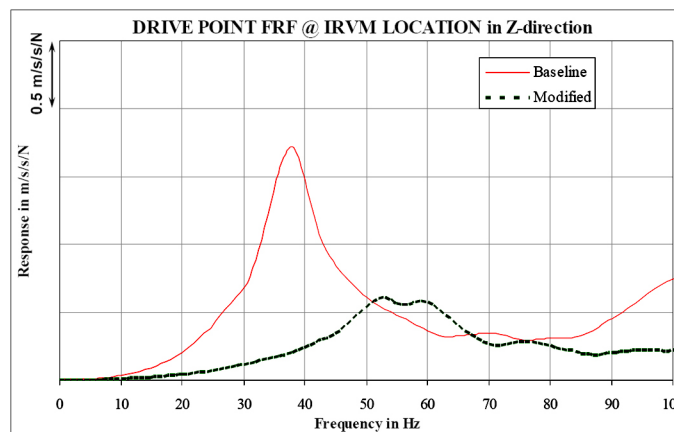


Figure 3. Drive point FRF at front roof location

whose mode shape and response is also coupled strongly with the interior cavity.

A simple test was conducted by making a rigid connection between windshield header and center floor; this was found to eliminate the boom noise and shifted the frequency beyond first order excitation in operating range. The same boundary conditions applied to a full vehicle CAE model produced an identical result, so having gained confidence in the CAE correlation, an optimized solution was developed after several iterations. The main modifications centered on increasing the section of windshield header and improving the joints between this member and the cant rails. Initial work shifted the mode to 44Hz which was still in the operating range, but by further stiffening of the B pillar (by increasing thickness) as well as adding gussets at the upper A-pillar, the roof mode was moved to 52 Hz which is sufficiently far away from the regular operating conditions of the vehicle. These modifications contributed a fourfold reduction of response amplitude when compared to the baseline configuration. [Figure 3](#) shows the comparison of FRF, measured at the mirror mount location on the header for baseline and

modified configurations. [Figure 4](#) shows the first engine order comparison of the in-cab noise during Third Gear Wide Open Throttle (3GWOT) measurements with and without structural modifications. Despite the cost and weight impact, these changes significantly improved the boom noise perception in the principal vehicle operating range. Reductions of between 4 and 14 dB(A) were observed at occupant locations during measurements with the proposed modifications.

3. Vehicle Sealing

Reducing the noise inside the passenger compartment, in addition to preventing corrosion and water intrusion, is one of the major reasons for using sealant products in vehicle construction [2]. Proper sealing between panels will help in reducing the airborne noise intrusion into the vehicle directly as well as that propagating through the frame work. [Figure 5](#) shows the effect of sealing on the transmission loss across a typical panel. The graph clearly indicates that even 1% leakage can reduce the transmission loss of the system by almost 20 dB. Proper application of weld sealant and mastic can control the leakage and assist in meeting targets. One of

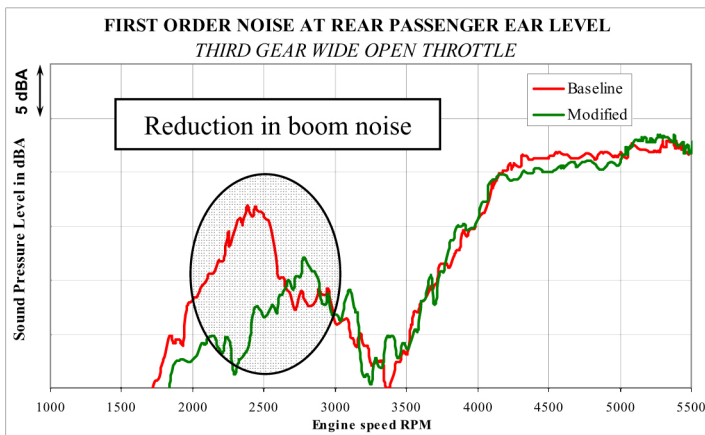
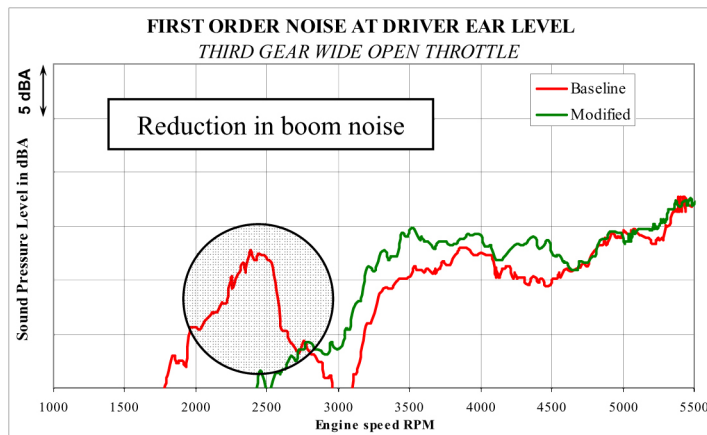


Figure 4. First order noise at driver ear and rear passenger ear level with improvements for boom

the performance criterion is the Equivalent Body Hole Size (EBHS) where the total leakage is represented as area in cm^2 for a defined flow rate and cabin pressure. Here, a target of 20 cm^2 at BIW level and 65 cm^2 at full vehicle level (both at $550 \text{ m}^3/\text{hr}$ flow rate) was adopted based on benchmarking of a range of vehicles.

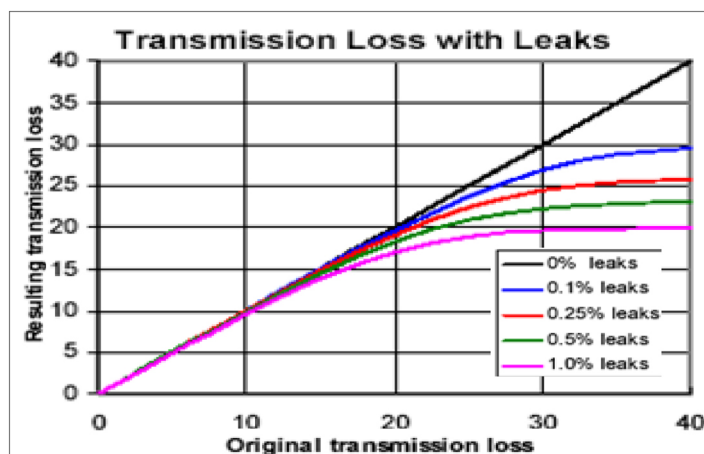


Figure 5. Effect of leaks on transmission loss

During the early phases of development, many bodies were measured using a purpose-built test rig and sealant application was optimized for to meet the BIW EBHS target. The quantity of sealant used on here is approximately 50% of that found in typical vehicles through careful design of the panel joints, helping in both cost and weight saving. In the production plant, regular quality audit checks on BIW structures include leakage measurement as well as normal dimensional checks to assure consistency.

Since a significant number of holes and cutouts need to be provided in BIW for drainage and pass-through of wiring harnesses cables and controls, grommets and covers are required to give positive sealing in the assembled vehicle.

The typical benchmark target for EBHS on full vehicle level in assembled condition is 70 to 80 cm^2 (measured at $550 \text{ m}^3/\text{hr}$ flow rate) for the conventional hatchback cars. The target was set at 65 cm^2 , since the absence of tailgate seal and the simpler features of the car were considered beneficial. Various leakage paths through door and engine cover sealing and through grommets and cutouts were identified and solutions were provided at all locations to meet the target. Expandable foam baffles were also introduced in the sill and cant rail locations to restrict the noise propagation through the body cavities (detailed in the next section). [Figure 6](#) shows the effect of EBHS on overall in cab noise

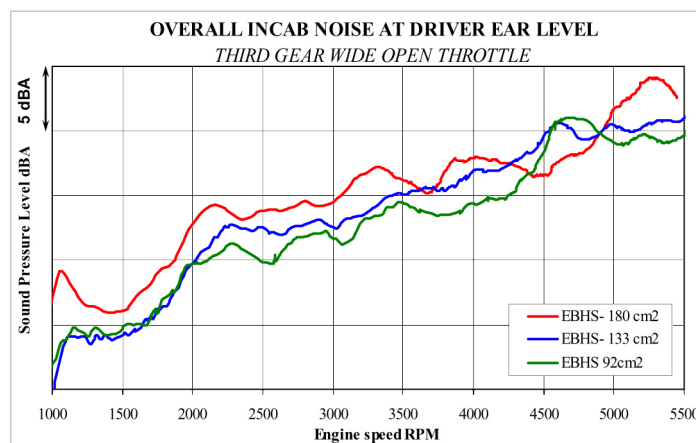


Figure 6. Effect of EBHS on the overall incab noise

Effective cabin sealing is in conflict with requirements for low door closing efforts, since better sealing prevents air from escaping once the last door is closed. After a series of experiments, it was determined that acceptable door shut loads were obtained as long as EBHS was not less than 55 cm^2 even without the use of complex over-pressure flaps that are usually employed. [Figure 7](#) shows the production scatter of EBHS in more than 240 vehicles, showing a consistent

achievement and good control about this value. There is an established leakage monitoring process on at least 2 vehicles per shift in the assembly plant, with corrective action taken if the values fall outside the normal range.

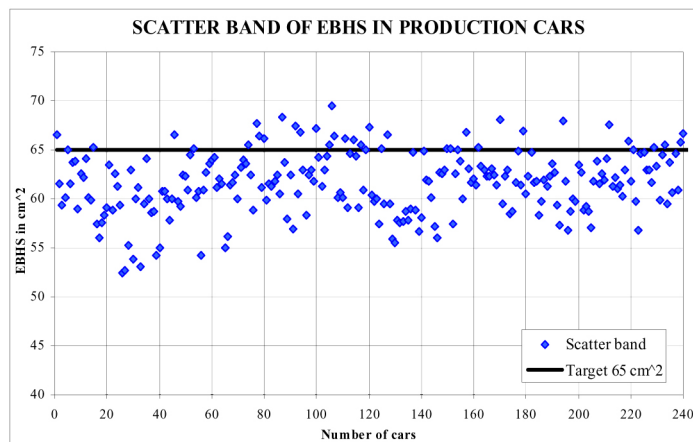


Figure 7. Production variation of EBHS value

4. Expandable Baffles

Baffle plates with heat-reactive expandable foam sealants are commonly used in automobiles. Use of these sealant materials has grown significantly as the demands to improve vehicle acoustic performance has increased. They are used to separate body cavities and to impede noise, water and dust propagation inside of body cavities, thus control mid- to high-frequency noise intrusion into the passenger compartment. Here there is a unique challenge with the engine air intake orifice is placed in the base of the C pillar cavity. Thus, low frequency attenuation is also a key requirement for the expandable baffle in this location.

During the development phase it was observed that the intake noise along with the engine noise, intrudes to the passenger compartment through an air extractor placed on the C-pillar, just above the air intake opening. It is therefore necessary to isolate the intake and engine noise from the passenger compartment for acceptable in-cab noise performance of the vehicle. Overall noise levels measured at passenger positions and near the engine intake were dominated by the low frequencies (below 500 Hz) due to harmonics of firing frequencies. The dominance of low frequency over high frequency was observed to the tune of some 10 or 15 dB(A) throughout the RPM range, thus dictating the uses of an effective sound barrier rather than a more normal absorption material.

In addition to the NVH requirements, there was a manufacturing constraint on the design of the baffle in this location. Since the outer surface of the C-pillar cavity is an exterior skin panel, a solid baffle cannot be welded to it, so it was decided to employ a specially developed expandable

acoustic baffle at this location. This comprised of heat-activated foam sandwiched between two rigid sheet metal plates fixed inside the cavity to be sealed. In this application, the carrier plate acts as a barrier while the foam offers some absorption as well as ensuring complete cavity sealing. The baffle is spot-welded onto the inner wall of the cavity prior to body side assembly and is then expanded during the passage of the BIW through the normal paint ovens.

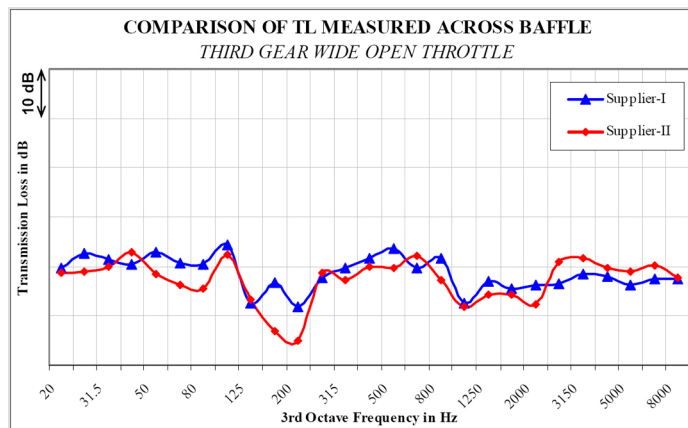


Figure 8. Transmission loss in vehicle level

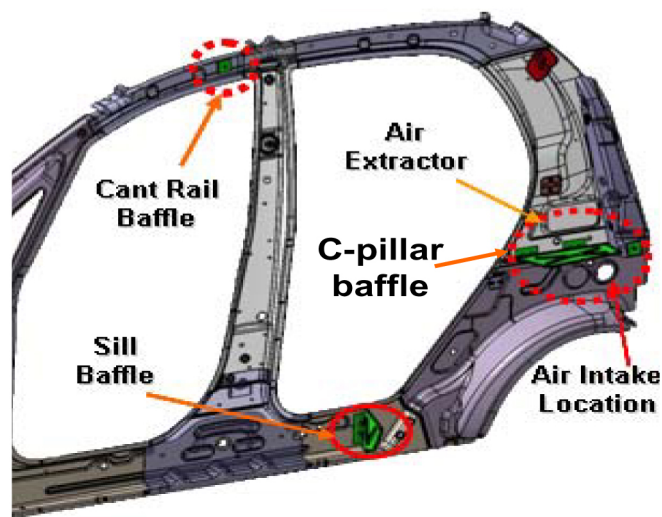


Figure 9. Expandable baffle locations in vehicle

Transmission loss measured across this C-pillar baffle is of the order 15 to 20 dB in the 20 to 8000 Hz frequency range when expandable foam is used. Initially there was significant variation observed in transmission loss of baffle samples from two different suppliers due to different design and fixing schemes to BIW inner panel. As this location is very critical from in cab noise performance point of view, considerable effort was expended to ensure that the design was made similar for both the suppliers. Figure 8 shows the averaged transmission loss measured across the baffle during