

Performance Cascading from Vehicle-Level NVH to Component or Sub-System Level Design

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ABSTRACT

Before a physical proto-vehicle is assembled, various components or subsystems are ready by Tier-I or II suppliers. During final design judgement of the vehicle thru' CAE or Mule-vehicle testing, performance target compliance need be assured for all these components to meet the Vehicle-level NVH targets. The work here studies some of the major components of a passenger car. Their individual NVH response can be critical to be cascaded for meeting the final targets for the vehicles running over roads. Conclusions of the study challenge some of traditional beliefs or generic targets. Often the component level response deviating from its own targets may not have an adverse influence on NVH of the vehicle facing multiple excitations from tyre/road, wind and power-train in a frequency band of interest. It is the sound balance of In-cab as perceived by human occupants or overall Pass By Noise at 7.5 m from the vehicle will govern an optimal design of components or subsystems facing cost and weight constraints.

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INTRODUCTION

Vehicle NVH refinement is a challenge before designers and manufacturers when "time to market" is short. Design targets for various components or subsystems need be set right much before first proto-vehicle is ready. A famous "V-diagram" [1] of vehicle development is simplified as shown in [Figure 1](#); it is 100 % applicable for NVH targets and validation.

Typical vehicle NVH targets are listed in [Table 1](#); some of them are well known to be evaluated at sub-system level; the list is not exhaustive; the target values X* in Table will depend on category, cost and market position of a car; for Luxurious ones, stringent targets are expected; detailed description is seen in [2].

This paper attempts to find out if this cascading is always in line with the desired goal of meeting vehicle level refinement as expected by customers. Out of various subsystems, here experimental work is presented on 3 major areas as shown in [Table 2](#) with cascaded performance parameters. Transfer Path Analysis (TPA) based target cascading with test and /or CAE data has been demonstrated in [3, 4]. Meeting fixed objective targets at a vehicle level may not necessarily be in line with subjective ratings of customers.

It is not always a quiet car they desire to drive; they need some feedback of rise in speed of the car thru' perception of wind noise as shown by a comfort study [5].

When a full vehicle is not ready, TPA of its In-cab noise & vibrations due to various sources of excitation is not possible. CAE modelling with test correlation need still maturity especially for air-borne noise paths though recently good attempts are seen in this direction [6]. On this background, design finalization of major subsystems or components of the vehicle will have to be taken with available parts if Tier 1 or 2 suppliers are ready much before the final vehicle assembly is made.

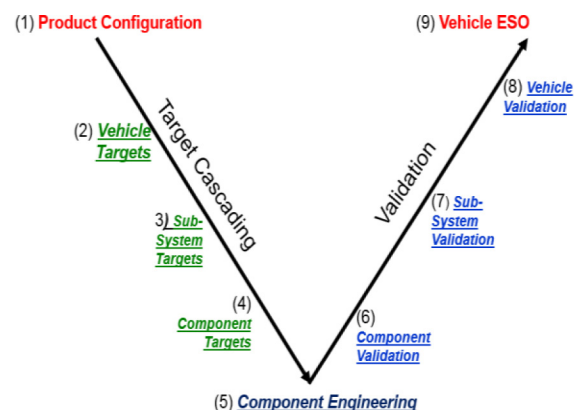


Figure 1. Vehicle performance cascading

Table 1. Vehicle NVH Targets

1.	Pass By Noise of a car < 74 dBA (IS 3028) or 72 dBA (ECE R51:03)
2.	Interior Overall (OA) noise at high speeds of road driving < X* dBA
3.	Seat vibrations at vehicle Idle < 0.09 m/s ² [ISO 2631-1] for a long exposure
4.	Articulation Index of In-cab noise at speeds above 100 kmph > 55 %
5.	Tyre/road rolling Noise of a car < 72 dBA (ECE R-117)
6.	Engine noise level < X* dBA at rated speed / load of a dynamometer
7.	Vibration Isolation Efficiency of engine mounts > 90 % at idling
8.	Sound Transmission Loss across firewall > 25 dB across all frequency bands
9.	First natural frequency of a car BIW global mode > X* Hz
10.	Intake orifice noise < X* dBA at various engine speeds
11.	Tail pipe noise rise < 5 dB per 1000 RPM of engine RPM

Table 2. Performance Cascading

Sr. No.	Area of vehicle NVH	Component / subsystem	Vehicle level influence	NVH target at subsystem level	Evaluation parameter at component level	Design Parameters
1	Flow Induced Noise	Exhaust system	*Pass By Noise, * In-cab noise *Sound Quality of exterior Noise *Engine back pressure *Floor vibration	(1) Tail pipe noise, (2) Silencer shell vibrations & its sound power	A. Transmission & Insertion Loss of silencer B. Vibration isolation efficiency of bellows and hangers C. Modal analysis of exhaust system	(1) Silencer volume & internal gas flow thru' expansion chambers and resonators (2) Pipe geometry (3) Dynamic stiffness of hangers and bellows (4) Location of hangers (5) Shell stiffness & damping
2	Structure borne noise	Body-in-white [BIW] – Powertrain & suspension attachment points	* In-cab booms *Floor vibration	*Dynamic stiffness and Noise transfer functions of body *Vibration isolation efficiency of engine mounts & suspension pivot-bushes	Global & local modes of body-flexure and its acoustic cavity Panel damping, radiation efficiency	A. Ribbing patterns B. Cross member stiffness, C. Surface-Damping: material, thickness and area coverage D. Rubber mount dynamic stiffness & damping
3	Air borne noise	Acoustic trims on Firewall, dash, floor, roof, bonnet	Articulation index of In-cab noise due to power-train, wind, road excitation	Acoustic Transfer functions for Trimmed bodies across each body panels	Sound absorption and/or Transmission loss of insulators	Thickness, material density of insulators, flow resistivity & other BIOT parameters

Here, complex interaction is illustrated for output of component level testing either on the vehicle or in isolation. For this purpose, an existing car with a 4-cylinder gasoline engine of 55 kW is used. Conclusions of the study are applicable to other subsystems of the vehicles affecting customer perception of ride comfort thru' NVH.

EXHAUST TAIL PIPE SOUND CONTRIBUTION

Generally a tail-pipe sound is considered as a parameter of exhaust system effectiveness from vehicle NVH point of view. But placing a microphone at a standard distance, viz., 0.5m at 45° close to the tailpipe mouth is also influenced by, driveline-tyre-road noise and many other factors such as combustion input of engine, exhaust system connection with body, silencer shell vibrations, etc.

Target lines can be put on overall (OA) levels, rise per 1000 RPM & 2nd & 4th engine firing orders (2EO & 4EO) of Sound Pressure Level(SPL) measured at the tail pipe as shown in Figure 2 for a car under consideration running in 3G-WOT (3rd gear wide open throttle) acceleration. But these targets hardly matter unless they have contribution towards the final vehicle level NVH with the other noise-sources present.

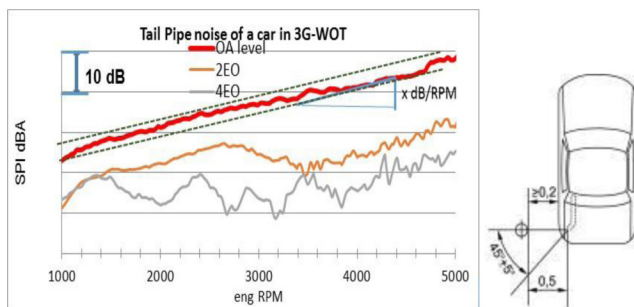


Figure 2. Tail Pipe noise in 3G-WOT

A quick method of knowing the contribution of the tail pipe noise is to suppress it by using a large volume of silencer at its end without affecting back pressure of the engine. There was no change in Pass By Noise (PBN) as per current method A of IS 3028 for a car under study; but the In-cab noise of OA in 3GWOT at RPEL (rear passenger ears' level) got reduced by 4 dB till 3000 RPM as seen in Figure 3. This was mainly due to reduction of 2EO SPL indicating that Insertion Loss (IL) of the silencer need be improved in the low frequency range till 100 Hz.

This would demand increase in volume of the silencer posing a challenge before packaging designers. However, when the Jury Ratings of a car running on the road were studied with and without the tail pipe noise suppressed, the current levels of In-cab noise were acceptable to them.

Later, sound quality analysis of the Tail pipe noise revealed that most of the parameters as perceived by humans were under the limit and/or comparable with those of benchmarking cars as seen in Figure 4. Hence suppressing its OA or 2EO SPL further did not give much benefit.

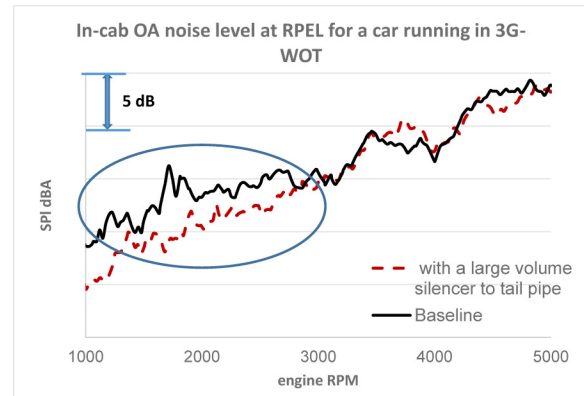


Figure 3. Tail Pipe contribution to In-cab noise

Here interface of the exhaust system with other subsystems of the vehicle plays a crucial role. If acoustic transfer function (ATF) between the tail-pipe and In-cab noise is assured to be below

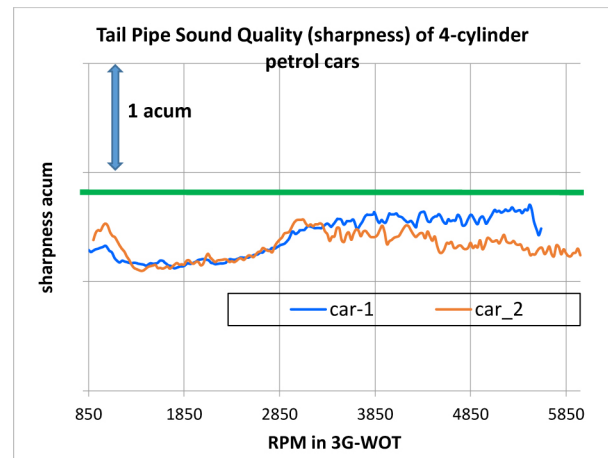


Figure 4. Tail Pipe sound quality

X^* dB ($\text{pa}/\text{m}^3/\text{sec}^2$) from 100 to 6000 Hz (X^* target value depending on body-sealing & vehicle class), then the In-cab noise is mildly affected by the noise from the tail-pipe. In that case, the supplier can work with a less stringent target for the tail-pipe noise unless the exterior sound of the vehicle is affected seriously leading to PBN rise or a bad quality of pull away noise of the vehicle.

SOUND ATTENUATION OF SILENCERS

Transmission Loss (TL) of a silencer with a speaker input agrees well with commercially available software for acoustic Finite Element Analysis, however in practice, with a pulsating gas flow from the engine exhaust manifold at high temperatures $> 600^\circ\text{C}$ & high speeds $> 15 \text{ m/sec}$, TL value significantly drops.

Insertion loss (IL) of the silencer as measured on the vehicle in 3GWOT with a difference in its tail-pipe noise from a case with a straight pipe replacing the silencer for the car was as per Figure 5. At different engine speeds, IL was close to 10 dB as an average over 1/3rd octave bands from 100 to 6000 Hz; whereas TL was measured to be $> 50 \text{ dB}$ for the same with a Kundt's Tube using a white noise of speaker.