

A Study on North American Customer Preference to Interior Noise using Sound Balance Analysis

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ABSTRACT

A new approach to achieve better customer perception of overall vehicle quietness is the sound balance improvement of vehicle interior sound during driving. Interior sound is classified into 3 primary sound source shares such as engine sound relative to revolution speed, tire road noise and wind noise relative to vehicle speed. Each interior sound shares are classified using the synchronous time-domain averaging method. The sound related to revolution order of engine and auxiliaries is considered as engine sound share, tire road noise and wind noise shares are extracted by multiple coherent output power analysis. Sound balance analysis focuses on improving the relative difference in interior sound share level between the 3 primary sound sources. Virtual sound simulator which is able to represent various driving conditions and able to adjust imaginary sound share is built for several vehicles in same compact segment. Objective sound evaluation targeting the North American customer is carried out using the virtual sound simulator tool in audio lab and it is verified that overall customer perception is improved by modification of sound balance between 3 primary sound shares. Through objective evaluation for the North American customer, the effectiveness of each sound source to each driving condition and customer perception of overall quietness and preference was found. In this paper the development guideline for interior for the North American market is suggested as well as effective countermeasures for improving sound balance.

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INTRODUCTION

Traditionally, the process of setting these targets is accomplished through vehicle and/or component benchmarking, and the groups responsible for each noise source work to achieve their respective development goals. While it is convenient for the engineer to measure success by the ability to achieve component level goals, the ultimate measure of success is the ability to satisfy and please the customer with the finished product. The customer evaluates the NVH performance not as a set of individual component attributes, but as the combined interaction between each noise source during a variety of operating conditions. This fact, coupled with the reality of component level compromise due to any number of limitations, can potentially lead to poor customer satisfaction. For these reasons, vehicle NVH target setting was studied from a holistic point of view, placing the focus on

achieving the appropriate balance between engine, road, and wind noise sources rather than the traditional method of reducing noise at the component level.

An NVH simulator was selected as an appropriate tool to evaluate, assess, and determine vehicle NVH targets necessary to achieve an appropriate "sound balance" for a compact class vehicle. Previous works [1, 2, 3] have demonstrated the NVH simulator's effectiveness at creating a realistic evaluation experience through the ability to experience noise phenomena along with a set of operating stimuli, such as visual effects, various road surfaces, powertrain loading, transmission gear ratios, etc. A virtual vehicle model was created for a target vehicle and segment competitors using experimental measurement data. Realistic modifications were then made to the target vehicle model in order to assess critical areas for the overall improvement of the vehicle's sound balance. Finally, these virtual models were evaluated by

customers on the NVH simulator, resulting in the identification of customer-driven impact areas to the improvement of vehicle sound balance.

SOUND BALANCE OVERVIEW

During a vehicle's operation, the driver experiences a variety of noise sources as illustrated in Figure 1. These sources are generally measured and evaluated through a set of specific driving conditions such as constant speed or wide-open throttle acceleration, depending on the noise source of interest. While the driver experiences the combined effect of each source simultaneously, it is necessary to separate each source's contribution in order to establish meaningful engineering targets. This is traditionally accomplished by conducting listening tests using fixed-condition data.

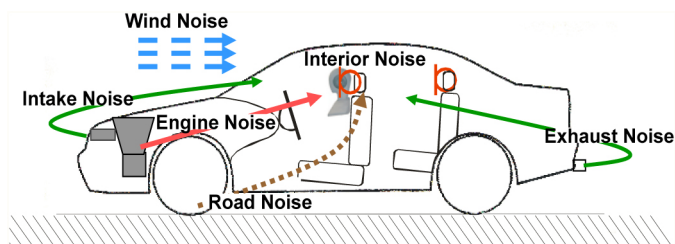


Figure 1. Primary Vehicle Noise Sources Present While Driving

Two main drawbacks to using these fixed-condition listening tests are the lack of visual/tactile context for the aural experience and the failure to experience how the interaction between different noise sources leads to the overall impression of the vehicle's NVH performance. The NVH simulator provides an ideal solution to this problem, as it allows for the separation and evaluation of component level noise sources while allowing the operator to experience the interaction between sources with a visual context. The NVH simulator then provides tools that can be used to modify each source component and evaluate the combined effect in the virtual environment. In this way, the balance of different noise sources present during typical driving conditions can be properly assessed.

The complexity of the noise source model depends on the desired output from the NVH simulator. For this work, the primary focus was to achieve a desirable balance between engine, road, and wind noise sources, so a fairly "coarse" model was used. Additional levels of detail were built into the engine and road noise models in order to gain a better understanding of "balance" within each of these noise sources. Figure 2 illustrates the breakdown of noise sources used in this work.

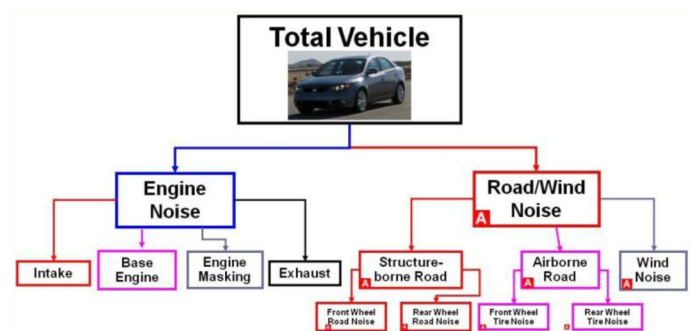


Figure 2. NVH Simulator Vehicle Noise Source Model

EXPERIMENTAL DATA MODEL

Experimental data was acquired in order to create the NVH simulator models described by Figure 2 for three different vehicles - a development test vehicle plus two competitors identified as having benchmark level "balanced" sound. Binaural microphone measurements were made at the driver's ear positions in order to create an accurate listening experience from the driver's point of view. Engine and Axle tachometers were used to identify order-related components originating from the engine or driveline. Multiple test conditions (loads, road surfaces, etc.) were measured for each vehicle in order to further enhance the realism of the virtual driving experience. Detailed descriptions of the source separation procedure used in this work have previously been documented by Williams, et al [4].

Engine Noise

The engine noise model was divided into four main components - airborne intake contributions, airborne exhaust contributions, the base engine - which includes both structure-borne noise and radiated airborne components, and engine masking noise - which refers to all non-order related noise generated by the engine. In order to separate the intake and exhaust contributions, acoustic frequency response function (FRF) measurements were measured between the intake/exhaust orifices and the receiver locations. These acoustic FRF's were used along with near-field source microphone measurements to estimate the intake/exhaust contributions. The acoustic FRF's were also used in the playback model to establish the appropriate phase relationship between these sources and the receiver location. After the intake/exhaust components are removed, the remaining order-related data is lumped together in the "base engine" source level component. The engine masking noise is the remaining data after all intake, exhaust, and order-related contributions have been removed, and was measured at various engine speeds in Neutral so as to exclude any wind noise or road noise effects. An overview of the engine noise extraction procedure is shown in Figure 3.

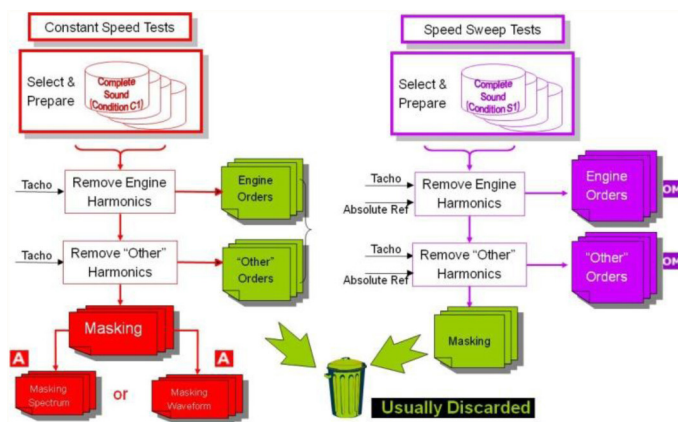


Figure 3. Engine Noise Extraction Overview

Road Noise

The road noise model was also divided into four components - airborne and structure-borne noise for the front and rear tires. In order to obtain the road noise component, multiple measurements were performed at various speeds on several road surfaces. After the order-related (engine and driveline) components were removed from the signal, the remaining noise represents the combined road and wind noise effect, so additional calculations were necessary to isolate the road noise components. Structure-borne contributions were estimated using the multiple coherence analysis method between wheel center vibration and the receiver microphone locations. Airborne contributions were also estimated using the multiple coherence analysis technique, this time between the microphones positioned at the leading and trailing edge of the tire and the receiver locations. The sum of the calculated structure-borne and airborne road noise contributions then equals the total road noise contribution.

Wind Noise

The wind noise model was estimated as the lump sum of remaining components left in the signal after the engine and road noise components were removed. An overview of the road and wind noise extraction procedure is shown in Figure 4.

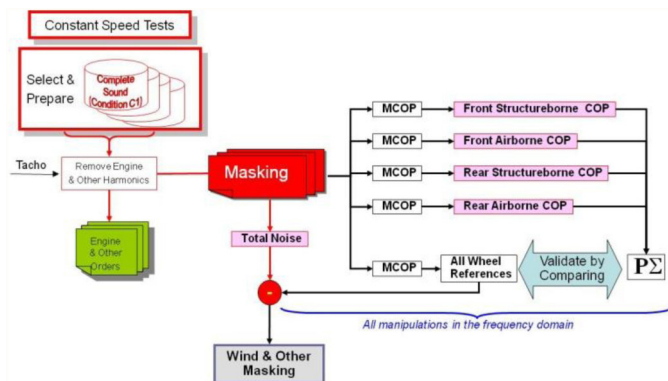


Figure 4. Road/Wind Noise Extraction Overview

SOUND BALANCE ANALYSIS

Once the virtual vehicle models were completed, a detailed analysis was performed to determine the weak points in the sound balance performance of the test vehicle. Engine, Road, and Wind noise levels were compared with the benchmark competitor vehicles for a variety of operating conditions.

Figure 5 displays colormap data obtained from 2nd Gear full load acceleration virtual tests conducted on the NVH simulator. Comparison of the test vehicle's engine noise with the class-leading competitor vehicles revealed some unique observations:

1. Order-related levels were much lower than competitor vehicles
2. The overall engine noise level of the test vehicle was lower than the competitor vehicles
3. The high frequency content (non order-related) was much higher than with competitor vehicles

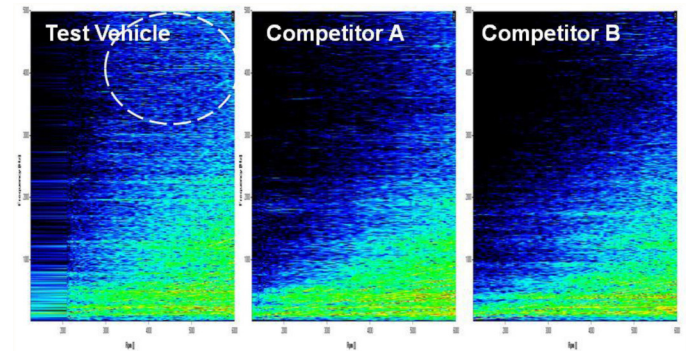


Figure 5. 2nd Gear full load Colormap - Test Vehicle vs. Competitors

A series of virtual road noise evaluations were performed at constant speed on a variety of different road surfaces. Figure 6 compares the road noise performance of the test vehicle and competitors on a coarse asphalt surface.

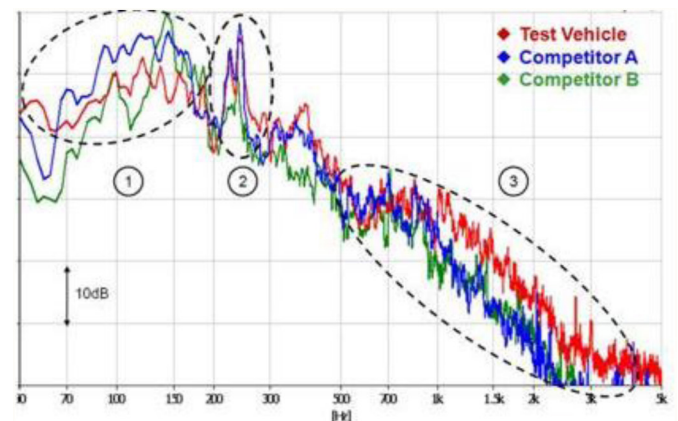


Figure 6. 30mph Road Noise on Coarse Asphalt

The following observations were made regarding the road noise performance of the test vehicle: