

Automobile Powertrain Sound Quality Development Using a Design for Six Sigma (DFSS) Approach

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ABSTRACT

Automotive companies are studying to add extra value in their vehicles by enhancing powertrain sound quality. The objective is to create a brand sound that is unique and preferred by their customers since quietness is not always the most desired characteristic, especially for high-performance products.

This paper describes the process of developing a brand powertrain sound for a high-performance vehicle using the DFSS methodology. Initially the customer's preferred sound was identified and analyzed. This was achieved by subjective evaluations through voice-of-customer clinics using vehicles of similar specifications. Objective data were acquired during several driving conditions. In order for the design process to be effective, it is very important to understand the relationship between subjective results and physical quantities of sound. Several sound quality metrics were calculated during the data analysis process. A House of Quality (HOQ) matrix was created to characterize this correlation using the new metrics. Multiple sample candidate sounds were designed using sound design and simulation tools. A unique and preferred target sound was identified after an extensive double-elimination round of paired-comparison analysis of candidate sounds using an in-vehicle audio system. Final optimization was executed, with live jury, to demonstrate and verify the new unique and preferred sound.

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INTRODUCTION

DFSS, an acronym of Design for Six Sigma, is used to design a product or service from the ground up. The phases or steps of DFSS are not universally recognized or defined; hence every company defines DFSS differently. One of the most popular DFSS methodologies is called DMADV and it was used during this study. The phases of DMADV are defined as: Define, Measure, Analyze, Design and Verify [1].

Table 1 shows the DFSS phases that were followed during this project and their relationship with the brand sound quality development process.

A total of 6 high performance vehicles were used with similar engines and specifications.

Table 1. Design for Six Sigma phases [1]

DFSS Steps	Brand sound quality development
Define	Definition of project goals and customer requirements through voice of customer clinics and listening sessions
Measure	Objective sound data collection.
Analyze	Objective data analysis, sound metrics development and calculation. Correlation with subjective data. House of Quality development.
Design	Sound design using sound development and simulation tools based on the analysis performed.
Verify	Verification that the designed sound meets customer's needs and expectations.

PROJECT GOAL DEFINITION AND CUSTOMER REQUIREMENTS

The goal of this study was to develop a brand sound that will be unique and preferred by the customers. In order to achieve that, the customer's preferences were investigated through a series of subjective evaluations and listening sessions. Letters A through F were used for vehicle identification purposes.

Subjective Ride and Drive Customer Clinic

The selection of the population that participated in the ride and drive customer's clinic was performed based on the people's personal vehicles. Specifically, all the people that participated in the clinic own and drive regularly, an 8 cylinder high performance vehicle and are driving enthusiasts.

The subjective evaluation procedure included start-up, idle, part throttle and wide open throttle accelerations. A series of questions were asked during each evaluation category.

Questionnaire and Rating Scale

The customers that participated in the subjective evaluation clinic had to rate each question for each category and vehicle using a 1 to 5 rating scale with 1 being the worst and 5 being the best. At the end they also provided ratings regarding their overall impression of the vehicle sound using a 1 to 10 rating scale. Table 2 and 3 shows the evaluation categories with their corresponding questions and the overall impression questions respectively.

Table 2. Subjective Evaluation Questionnaire

Grouping	Question (1 – 5 rating scale)
Start-up sound quality	Perception of levels
	Dynamic nature of sound
	Objectionable noise present
	Brand character
Idle sound quality	Perception of levels
	Objectionable noise present
	Brand character
	Perception of levels
Wide open throttle sound quality	Objectionable noise present
	Dynamic nature of sound
	Brand character
	Perception of levels
Part throttle sound quality	Objectionable noise present
	Dynamic nature of sound
	Brand character
	Perception of levels

Table 3. Overall impression questions

Overall impression questions (1 – 10 rating scale)
How dynamic/sporty does the vehicle sound?
How pleasant does the vehicle sound (absence of objectionable noises)?
What is your overall impression of the vehicle sound?

Subjective Results

Averages from the entire population were calculated for each vehicle and each driving cycle as well as for the overall impression questions.

According to the customers, vehicle B was a clear winner for most of the questions. It was rated highly for most of the questions and it is preferred for brand sound quality due to its dynamic and sporty sound content. On the other hand, vehicle B was rated poorly for pleasantness due to the objectionable high frequency whining sound.

The 1 - 5 rating scale questions were used for the development of a House of Quality matrix that will be presented and explained later. Figures 1, 2 and 3 include the average results from the overall impression questions.

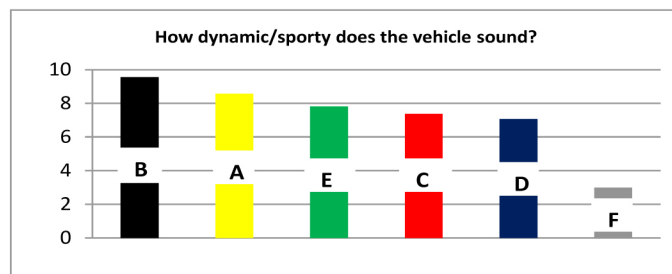


Figure 1. Average ratings for question, "How dynamic/sporty does the vehicle sound?"

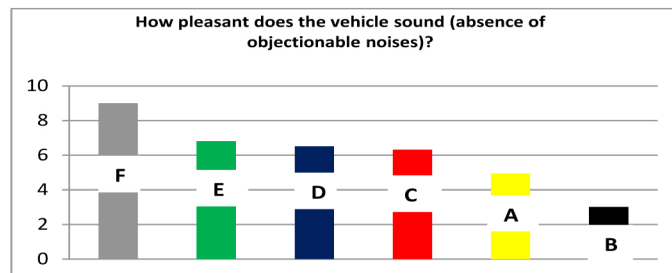


Figure 2. Average ratings for question, "How pleasant does the vehicle sound?"

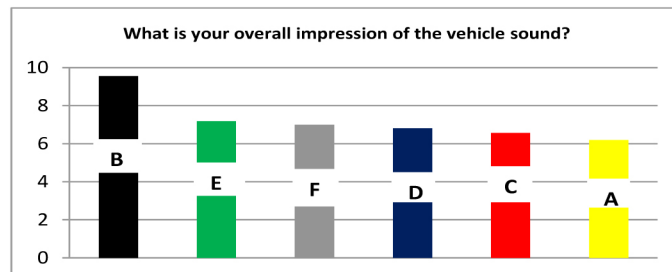


Figure 3. Average ratings for question, "What is your overall impression of the vehicle sound?"

Listening Session

A listening session was conducted using the recordings from the data acquisition process. A comparison between each vehicle sound individually was completed regarding dynamic character and brand sound quality by NVH engineers. Figures 4 and 5 summarize the results from the listening session.

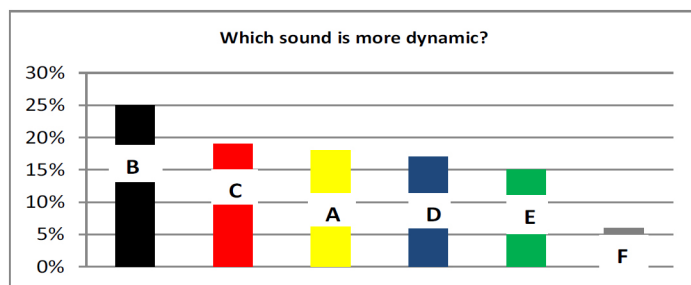


Figure 4. Individual comparisons for dynamic sound listening session

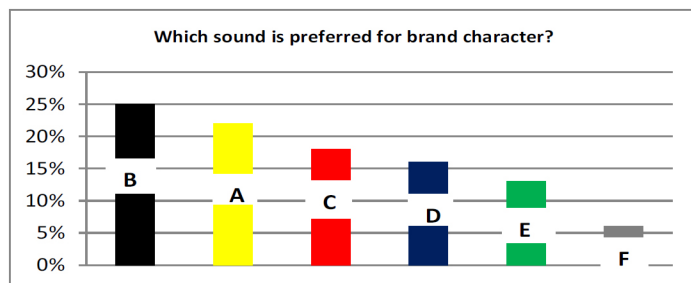


Figure 5. Individual comparisons for preferred brand character listening session

Sound of vehicle B was preferred for dynamic content and brand character that correlate with the subjective ratings acquired from the voice of customer clinic.

MEASURE AND DETERMINE CUSTOMER NEEDS

The 6 vehicles were tested and interior sound data were acquired during several driving conditions. Testing was performed on a smooth evaluation road during ideal weather.

Test Process

The instrumentation that was used included two microphones for driver's right and left ear; one binaural head positioned in front passenger's seat and an optical tachometer for engine speed measurements. Pedal position was also captured using CAN.

The operating conditions included full load and part load sweeps; conducted in drive, fixed 2nd and 3rd gears; and coast downs. Interior sound was recorded during these conditions. Idle and start-up sound was captured as well.

Frequency and Order Content Color-Maps

A Fast Fourier Transformation (FFT) versus engine speed was initially performed in order to understand the signature of the interior sound of each vehicle. This was depicted using color-maps that can reveal the frequency and order content of each sound.

Figures 6 shows the interior sound signatures of vehicles B and F. B was the vehicle that was preferred for dynamic content and brand sound quality, and F was the one that was rated the lowest by both customers

and NVH engineers. By looking at the sound signature of vehicle B we can see fractional low order content as well as dominant fundamental 4th order (firing order). We can also observe resonances at 250 Hz, 500 Hz and 750 Hz. After more listening sessions it was discovered that these resonances play a very significant role to the sound character of vehicle B. Specifically the 250Hz and 500 Hz resonances, amplify significantly the first 8 fractional orders giving the vehicle a rough and rumble sound that is desired for a high performance 8-cylinder vehicle. The 750 Hz resonance amplifies higher orders that also have a positive outcome to the sound quality of vehicle B.

On the other hand, vehicle F was considered to be quiet, with a refined sound quality, a basic characteristic of a luxury vehicle. That is the reason that vehicle F was rated the highest for pleasantness during the voice of customer clinic.

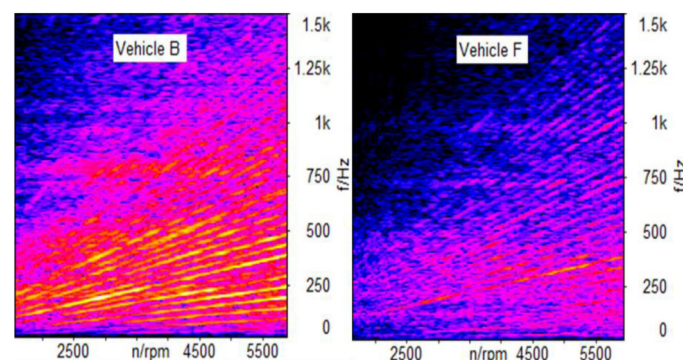


Figure 6. Interior sound signatures of vehicle B and F

OBJECTIVE DATA ANALYSIS AND CORRELATION WITH SUBJECTIVE RATINGS

After acquiring objective sound measurements from the 6 vehicles, specific sound quality metrics were calculated and correlated with the subjective ratings acquired from the voice of customer clinic and the listening sessions for each category and driving condition. This correlation was summarized using a House of Quality matrix that was utilized for the sound design process later.

Sound Quality Metrics

The sound quality metrics that were calculated can be seen in [table 4](#).

Table 4. Sound quality metrics and corresponding units

Sound Quality metric	Unit
Overall Sound Pressure Level	dB(A)
Zwicker Loudness	Sone
Roughness	Asper
Tonality	tu (tonality units)
FEV Pleasantness	#
FEV Dynamic	#

Overall sound pressure level (SPL) dB(A) [2],[3]

The overall SPL was computed in the time domain using the following steps: