

Analytical and Experimental Approach to Acoustic Package Design

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ABSTRACT

The interior noise signature of passenger vehicles is a significant contributor to a customer's perception of quality. The vehicle acoustic package can be an important piece to the acoustic signature, and can be utilized not just to reduce the sound levels inside the vehicle but also to shape the sound such that it meets the expectations of the customer. For this reason the definition, design, and development of an acoustic package can be vital to meeting vehicle-level acoustic targets. In many situations this development is conducted experimentally, requiring the availability of prototype vehicles and acoustic package components. Of more value is the ability to develop components early in the design phase, leveraging analytical tools to define component-level requirements and targets to meet the vehicle-level targets, and ultimately meet the final customer expectations.

This paper presents efforts made to further combine the benefits of experimental and analytical approaches to acoustic package design. The benefits of which include the ability to predict interior sound levels for alternative acoustic package configurations early in the design phase, allowing for listening studies to verify component and vehicle-level targets. Additionally, the performance of alternative designs can be quantified in the frequency domain and using sound quality metrics, while minimizing the necessity for physical testing. A current market vehicle was utilized for this development, in which experimental measurements were developed and conducted for optimum cooperation and utilization of analytical tools. The acoustic package was characterized to predict the sound levels for alternate acoustic package designs, listening studies were performed and metrics were calculated for each configuration to verify performance against the vehicle-

levels targets, and developed solutions were verified through experimental testing.

INTRODUCTION

As vehicle development cycles continue to be compressed and customer expectations continue to increase, additional efforts are required from the engineering community to develop high quality vehicles in a relatively short time frame. To accomplish this, standard development practices must be updated to continue to improve vehicle quality and performance while continuing to decrease development time.

Utilization of analytical tools is a highly efficient method to reduce development time while continuing to improve vehicle quality and performance. One typical concern with analytical models is the accuracy of the predictions specifically regarding full vehicle acoustic predictions. To address this concern, emphasis must be placed upon developing engineering processes and test methods such that they are most beneficial to both the experimental and analytical communities.

APPLICATION

A vehicle sub-system that can significantly benefit from improved cooperation between experimental and analytical methods is the vehicle acoustic package. The acoustic package is composed of materials located in strategic locations within the vehicle specifically designed to either absorb or block sound transmitted into the cabin, and in-part defining what the end customer hears while operating the vehicle. This noise signature experienced by the customer can have a significant impact on the perception of quality for the vehicle, and can be developed not just to reduce sound levels, but

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designed to shape the sound to meet the expectations of the customer.

Development of an acoustic package typically occurs throughout a vehicle development cycle. Initial assumptions are made for the definition of which types of materials are needed and at which locations, typically based on past experiences and/or previous model year vehicles. Final design criteria for the acoustic package components are often determined through experimental testing conducted to validate achievement of vehicle level targets.

A more efficient method for development of an acoustic package is to define the final component design criteria early in the vehicle development cycle using analytical tools without relying on experimental testing late in the process. Ideally the experimental testing should be used only to confirm the achievement of vehicle level targets, not to define component-level targets.

To reach this goal, current experimental testing should be conducted in a manner in which the data can be used to help improve the accuracy and confidence in analytical tools. This will help to transition a process that is not as reliant on experimental testing, and thus the availability of vehicle hardware.

CURRENT METHODS

STATISTICAL ENERGY ANALYSIS (SEA) – SEA is an established, energy based method for analytical vibroacoustic problems such as acoustic package design (1). For an SEA model, the structure under analysis is partitioned into coupled “subsystems” and the stored and exchanged energies between them are analyzed. The models utilize a power balance between the coupled subsystems in which the power flow is analyzed from subsystem to subsystem (2).

The definition of the subsystems is of critical importance for accurate predictions (3). Each subsystem must be capable of vibrating/behaving independently from other elements/subsystems. A simple SEA model for the prediction of powertrain noise could be composed of three large subsystems, the engine bay space, the dash structure, and the passenger space. Each subsystem behaves independently, and the power flow from subsystem to subsystem is analyzed.

For this simple model, the engine subsystem provides the acoustic input as well as some acoustic absorption. Power flow into the dash subsystem must balance with the power flow out of the dash system. Some energy will be dissipated through absorption/damping, and the rest will be either reflected back into the engine subsystem or transmitted into the passenger subsystem. The energy transmitted into the passenger subsystem will be partially absorbed by the vehicle interior, while the remaining will be perceived as sound by the occupants.

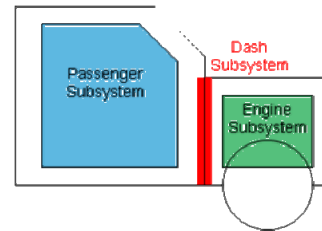


Figure 1: Simple SEA Model Subsystems

This methodology is utilized for models of higher complexity however the same underlying assumption of balanced power flow remains.

The presence of acoustic leakage can have a significant impact on an SEA model. For parts in which leakage is known to have a major impact, the effects often need to be quantified via test methods. The leakage is then applied to the model for a specific design of the part (4). For these reasons steps must be taken during hardware evaluations to quantify the acoustic leakage, specifically for components/areas which typically have high acoustic leakage such as front-of-dash pass-through holes.

EVALUATION OF IN-SITU MATERIAL PROPERTIES - Acoustic characterization of individual sound package materials is typically performed at the component or material level by suppliers per standardized test methods. Typical component level tests include sound absorption or sound transmission loss, depending on the composition of the material under test.

Acoustic absorbers are materials that control, or minimize, the amount of sound reflected from a surface. The effectiveness of an absorber is measured by the sound absorption coefficient (α), which is related to the ratio of acoustic energy absorbed by a material to the acoustic energy incident upon the material (eq. 1). Tests are typically conducted in an impedance tube per standard ASTM E1050 (5) or in a reverberant room per standard ASTM C423 (6).

$$\alpha = \frac{\text{energy absorbed}}{\text{energy incident}} \quad (1)$$

Acoustic barriers are materials that block the transmission of sound from one zone to another. The effectiveness of a barrier is measured by the Sound Transmission Loss (STL), which is the ratio of acoustic energy transmitted by a material to the acoustic energy incident upon the material (eq. 2). Tests are typically conducted per standard SAE J1400 (7) or ASTM E90 (8).

$$STL = 10 \log_{10} \left(\frac{1}{\tau} \right) \quad (2)$$

for: $\tau = \frac{\text{energy transmitted}}{\text{energy incident}}$

Characterizing the acoustic performance of sound package materials provides useful information that can be utilized by SEA models. This data, however, is a property of the material, not a property of the manufactured component with the intended shape or dimensions. Any cutouts or holes present in the manufactured component will have a significant effect on either the absorption coefficient or sound transmission loss. For this reason it is often useful to validate the component-level material testing with experimental in-situ data.

EXPERIMENTAL TEST METHODS - Experimental methods for measurement of in-situ transmission loss typically involve measurements (at the powertrain, tire patch, etc.) using an array of microphones to characterize both sides of the item under evaluation. For the example of a front of dash acoustic treatment, the source and receiver sides would be characterized in this way. An acoustic source could be placed in the engine compartment (actual powertrain or an acoustic source) and the acoustic signature would be compared on the “source” side and the “receiver” side to determine the in-situ transmission loss.

One drawback to this method is that it does not lend itself well to integration with methods utilized by analytical tools such as SEA models. This test method provides a global transmission loss from source to receiver. SEA models, however, utilize multiple local transmission loss functions to generate predictions.

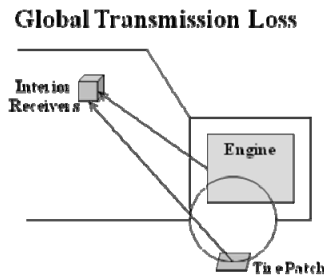


Figure 2: Global Transmission Loss

Local Transmission Loss

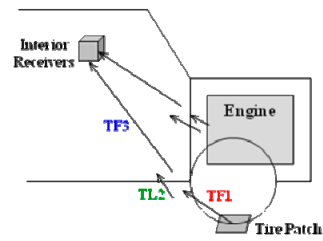


Figure 3: Local Transmission Loss

Of more interest is the ability to characterize the local transmission loss functions for the acoustic package components experimentally in a method that allow direct utilizations of analytical tools. Use of this methodology allows for improved prediction of interior sound levels for various acoustic treatment configurations.

WORKING EXAMPLE: HEAVY-DUTY TRUCK

For this study, a heavy-duty Diesel truck platform was used to develop and refine test methods to improve the cooperation between the experimental and analytical communities. The goals of the study were to provide data to the analytical models to validate predictions and to utilize the collected data to predict interior sound levels for key alternate acoustic package configurations.

Major steps taken in the study, each of which will be discussed in detail, include:

- Vehicle characterization
- Front-of-dash pass-through leakage
- Component characterization
- Sound Synthesis
- Verification of predictions

VEHICLE CHARACTERIZATION - The acoustic package of a vehicle can be utilized to shape the acoustic experience of the end customer. Of great importance is to gain an understanding of what the customer expects to hear from a specific vehicle class, in this case for the heavy-duty Diesel truck market. The first step towards this goal was to gain an understanding of the current market both objectively with measured data and subjectively with customer assessments. This information was then utilized to understand which characteristics of the acoustic signature the customer likes and dislikes.

Objective measurements were conducted on three competitive vehicles in the heavy-duty Diesel truck segment. The purpose was to characterize the acoustic signature and determine the appropriate sound quality metrics to quantify the performance. For each vehicle, measurements were conducted at multiple operating conditions including idle, partial and wide-open throttle, and cruise events. Microphones were located at key user locations both for interior sound and exterior walk-around sound.

From the operating measurements listening studies were conducted to determine the subjective preferences. Sound quality metrics were then calculated and correlated back to the subjective assessments. For the idle load case, the key metrics identified were the overall A-weighted sound pressure level to capture the amplitude of the sound, articulation index to capture the ability to comprehend speech, and statistics on the transient loudness to capture the cycle-to-cycle variations of the Diesel engine and the perception of impulsiveness.

These metrics were then used as “pass/fail” criteria to determine if modifications to the acoustic package would be perceived by the end user and to verify that the resulting acoustic performance of the vehicle was competitive in the current market.

FRONT-OF-DASH PASS-THROUGH LEAKAGE – To support refinement of analytical models, a detailed analysis of the front-of-dash pass-through paths was conducted, including the following components:

- Electrical pass-through's
- Brake booster
- Steering intermediate shaft
- HVAC heater and AC lines
- Hood release

For each pass-through location measurements of the in-situ local transmission loss were conducted utilizing sound intensity measurements. A “window” technique (9) was used at each location to isolate the effects of each component, the results of which are displayed in Figure 4.

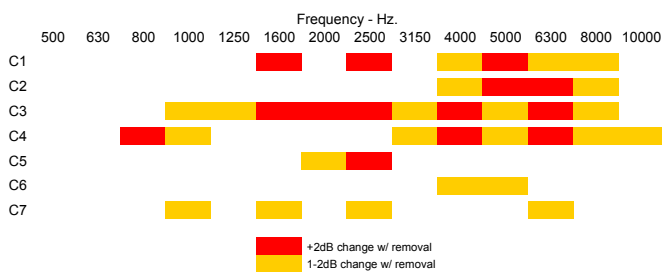


Figure 4: Summary of Effects of Removal of a Pass-Through Window

Through this analysis the contribution of the pass-through holes to the global in-situ transmission loss was determined.

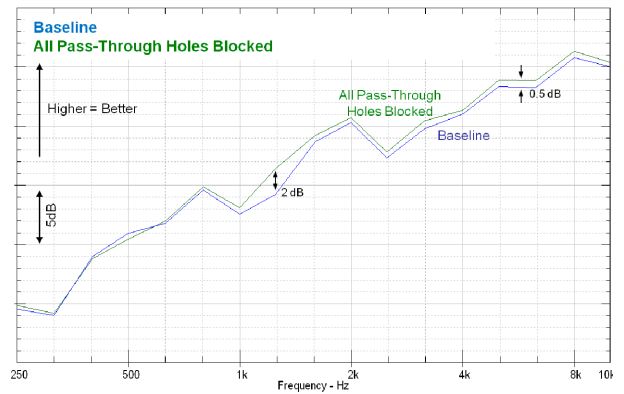


Figure 5: Pass-Through Holes - Contribution to Global In-situ Transmission Loss

COMPONENT CHARACTERIZATION - With an understanding of the critical frequencies and corresponding sound quality metrics that dictate customer perception, the next step in the process was to characterize each component of the released acoustic package to determine which components were affecting these critical frequencies.

Acoustic package components evaluated in the study included interior and exterior dash treatments, dash panel pass-through treatments, cowl and tunnel treatments, interior trim components, bulb seals, and carpet and underlayment treatments.

A trimmed body vehicle was utilized to characterize each piece of the acoustic package. White noise excitations were applied using a volume velocity source at the vehicle interior, and measurements were conducted at multiple locations to characterize the local transfer functions between source and receiver. Measurement locations included interior microphones at the customer positions, path microphones along the vehicle body, and powertrain microphones at the engine and transmission.

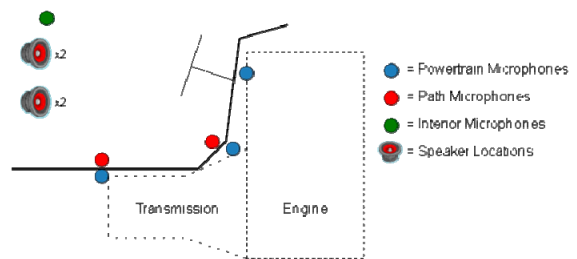


Figure 6: In-situ Transmission Loss Test setup.

Transmission loss measurements were conducted along with sound intensity/power scans at each of the acoustic package locations to calculate the sound power through each treatment. Measurements were made for a baseline configuration along with each component of the

acoustic package individually removed. This provided information for the performance/impact of each piece measured in-situ. This “windowing” method was utilized to evaluate each treatment to reduce the effects of leakage and to more accurately characterize its in-situ performance.

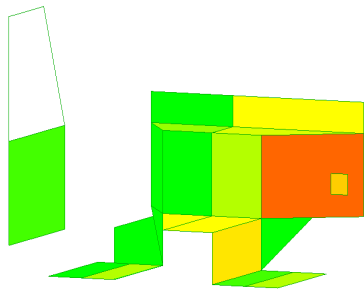


Figure 7: In-situ Sound Intensity Scan of IP, Dash and Right Door (Vehicle Interior)

Each in-situ evaluation of the acoustic package components provided data for the impact of a single component to the overall sound levels at the receiver locations, as well as changes to each of the local transmission loss functions. These local transmission loss functions can then be directly utilized by SEA models for improved correlation and predictions.

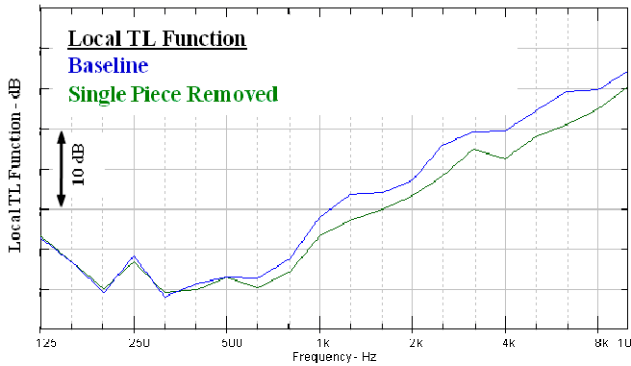


Figure 8: Local TL for Component Removal

Characterization of each component of the acoustic package provided an overview of the in-situ impact of each piece. This information can then be utilized to predict the interior sound pressure levels for alternate configurations of the acoustic package, included component removal and/or modifications to component level performance.

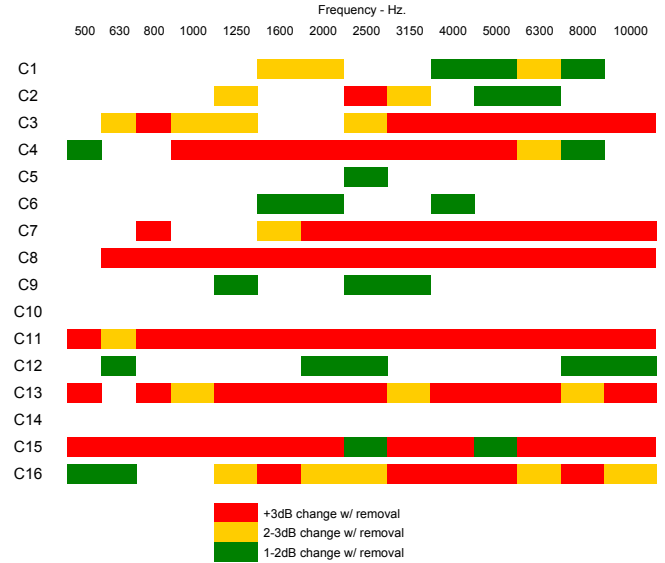


Figure 9: Summary of Effect of Removal of Each Component on Frequency Range of Sound at Receiver

SOUND SYNTHESIS - A tremendous benefit of utilizing experimental tools and methods in combination with analytical tools in the development of an acoustic package is the ability to predict sound level prior to the availability of a full vehicle. Proper predictions allow for playback of sound for listening studies, calculation of sound quality metrics both in the time and frequency domains, as well as prediction of sound levels for alternate acoustic package configurations. This type of information can be used to determine which components of the acoustic package can be further optimized, and to identify critical locations within the vehicle that need to be further treated to meet program targets.

The prediction of interior sound levels can be conducted as follows:

$$SPL_{rec} = \sum_1^{\# \text{ subsystems}} [SPL_i * TL_i * TF_i] + \text{Masking} \quad (3)$$

Where SPL_{rec} is the predicted sound at the receiver, SPL_i is the measured sound at the interface of a subsystem, TL_i is the local transmission loss, TF_i is the transfer function from the path microphones to the receiver, and Masking is the noise which is not due to the subsystem under test. As indicated by equation (3), the interior sound pressure levels are a function of the sound pressure at the interface of the source subsystem convolved with the local transmission loss function across the interface and the transfer function of the passenger compartment. The resultant is the time-domain sound pressure level response at the interior of the vehicle.

Source Sound Press Levels (SPL) - For the heavy-duty truck working example, predictions were made for the idle load case. In this situation the primary acoustic source was the powertrain. This source noise remains a constant regardless of the interior acoustic package configurations and can be characterized experimentally or analytically.

Experimental measurements of the powertrain source noise can be conducted in-situ with the appropriate hardware, or utilizing component level measurement techniques such as SAE J1074 “Engine Sound Level Measurement Procedure.” (10) The engine hardware is typically available early in the vehicle development cycle allowing for early experimental acoustic characterization of the powertrain.

For the working example, the engine acoustic signature was characterized in-situ using multiple microphone locations around the engine and transmission at the interface with the vehicle body.

Acoustic Package Transmission Loss (TL_i) - The transmission loss across the acoustic package is the main variable for the prediction of interior sound levels. This transmission loss can again be characterized for each piece of the acoustic package either experimentally in-situ, analytically, or through utilization of material performance data.

For the working example the transmission loss was measured experimentally in-situ to validate analytical predictions. The global transmission loss was calculated from the local sound intensity/power measurements and each of the local transmission loss measurements.

The acoustic package global transmission loss function becomes a sum of each of the component transmission loss functions:

$$\frac{1}{TL_1} = \frac{1}{TL_1} + \frac{1}{TL_2} + \frac{1}{TL_3} + \dots \quad (4)$$

Path to Receiver Transfer Function (TF_j) - The acoustic transfer function from the vehicle body to the interior receivers (driver, passenger, rear passenger, etc.) can be characterized experimentally with availability of the appropriate hardware. Analytical tools such as SEA models, however, are very well suited for these calculations. The acoustic cavity is divided into key volumes and predictions can be made from a specific boundary, such as a key panel at the front of dash, to each of the receiver volumes.

For the working example, the transfer functions from the path microphones at the boundaries of the passenger compartment to each of the receiver microphones were measured experimentally to validate the analytical predictions. An acoustic source was placed at the receiver locations and the transfer functions were

measured between each receiver and each “path” location.

For the predictions of interior sound levels, this transfer function remains constant assuming constant interior treatments (headliner, carpet, etc.).

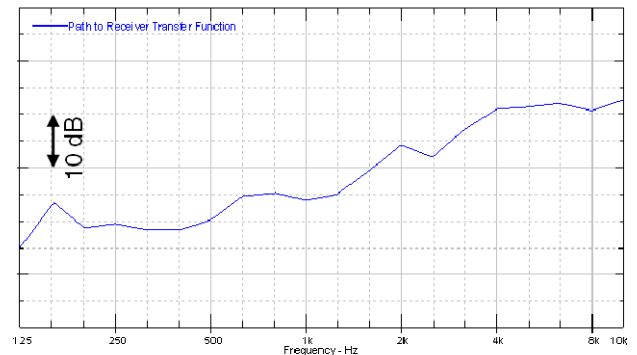


Figure 10: Path to Receiver Transfer Function

Masking - A masking term was utilized in the acoustic predictions to account for the structure-borne contributions and general masking not captured during the airborne artificial excitation methods. This term was composed of low frequency contributions and allowed for the predicted sounds to more closely reproduce the in-vehicle acoustic experience during listening studies.

ACOUSTIC PREDICTIONS - Each of the terms described above can be determined experimentally, analytically, or in combination to predict interior sound levels for a given acoustic package configuration. Through modifications to the local transmission loss term for each component, the resulting predicted sound levels can be computed. This yields a predicted sound level in the time-domain that can be used for listening studies and to compute sound quality metrics for comparison against program targets.

For the heavy-duty truck example the sound levels were predicted for each piece of the acoustic package individually removed. This was accomplished by modification of the appropriate local transmission loss term, which in turn affects the global transmission loss of the acoustic package.

The resulting predictions were then compared against the baseline configuration through calculation of the sound quality metrics defined earlier and to determine if the modification would result in degradation to the acoustic experience for a customer.

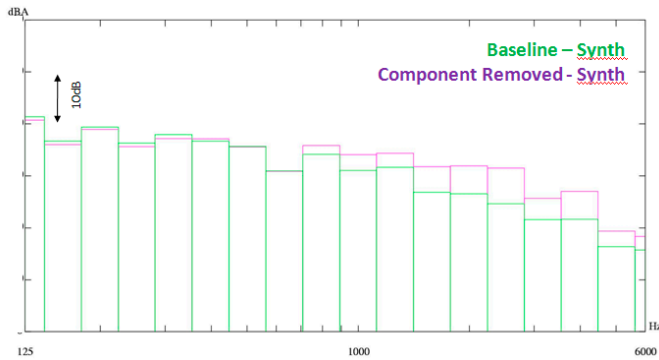


Figure 11: Example of Acoustic Predictions

This methodology can be used to predict the effects of removal of multiple treatments simultaneously, as well as for modifications to individual treatments. A material property change to a component will result in a change to its local transmission loss. The modified term can be substituted back into the calculations to predict the vehicle-level performance change for a proposed material change (size change, location change, etc.).

VERIFICATION OF PREDICTIONS – To validate the developed processes, experimental test methods, and acoustic predictions, vehicle level hardware evaluations were conducted for several configurations of the acoustic package. The quality of the acoustic predictions was judged through subjective listening studies and calculations of sound quality metrics for each hardware configuration.

The resulting 1/3 octave frequency spectra for the hardware evaluations and the acoustic predictions are displayed in Figure 12 and Figure 13.

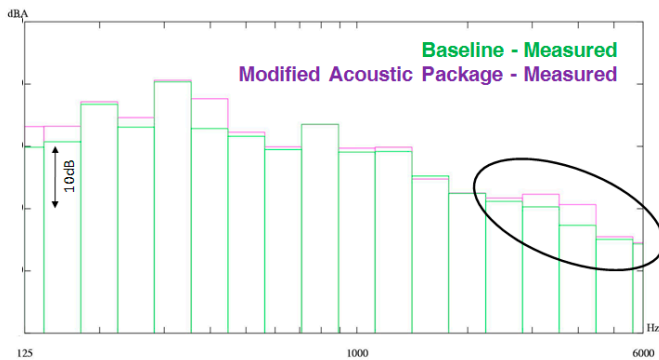


Figure 12: Measured SPL with Acoustic Package Change

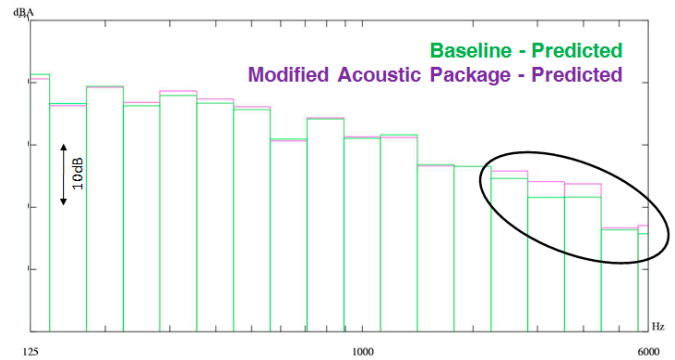


Figure 13: Predicted SPL with Acoustic Package Change

Based upon the results from the listening studies and metric calculations, good correlation was achieved between the predicted and measured signals. Frequency-domain differences between the baseline and modified acoustic package configurations were similar for the measured and predicted signals, and the calculated sound quality metrics yielded similar effects.

CONCLUSION

Increased cooperation between experimental testing methods and analytical modeling techniques can help to improve the development time of vehicle systems such as an acoustic package. By conducting experimental measurements in methods that are of most use to analytical tools, time-efficient modeling efforts can be used to aid in the development of the acoustic package.

Leveraging analytical tools can also allow for accurate and efficient prediction of interior sound levels for acoustic package development. Listening studies can be performed to assess subjective preferences and the effects on frequency-domain and sound quality metrics can be quantified without the necessity of a full vehicle.

Through utilization of these methods, component-level performance requirements can be defined and delivered to the supply base early in the vehicle development phase, minimizing the necessity for physical testing to define component-level targets.

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REFERENCES

1. *SEA Model Development Considerations for Cost-Driven or Developing Market Vehicles*. **A. Rodrigues, C. Musser**. s.l. : SAE, 2007. SAE 2007-01-2308.
2. *The Use of in Vehicle STL Testing to Correlate Subsystem Level SEA Models*. **T. Connelly, J. Knittel, R. Drishnan, L. Huang**. 2003. SAE 2003-01-1564.
3. *Energy-based Vibroacoustics: SEA and Beyond*. **Sarradj, E.**

4. *SEA Modeling of A Vehicle Door System*. **Q. Zhang, A. Parrett, C. Wang, D. Wang, M. Huang**. 2005. SAE 2005-01-2427.

5. *Standard Test Method for Impedance and Absorption of Acoustical Materials Using A Tube, Two Microphones and A Digital Frequency Analysis System*. **ASTM**. ASTM E1050 - 08.

6. *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*. **ASTM**. ASTM C423 - 08a.

7. *Laboratory Measurement of the Airborne Sound Barrier Performance of Automotive Materials and Assemblies*. **SAE**. SAE J1400.

8. *Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements*. **ASTM**. ASTM E90-04.

9. *A Tool for Predicting Interior Sound Package Treatment in a Truck*. **P. Saha, T. Henry, J. Chahine, G. Demrose**. s.l. : SAE, 2001. 2001-01-2807.

10. *Engine Sound Level Measurement Procedure*. **SAE**. SAE J1074.

11. *Acoustic Materials Workshop*. **SAE**. 2003. 2003 SAE NVC.

12. *Development of a Luxury Vehicle Acoustic Package Using SEA Full Vehicle Model*. **M. Huang, . Krishnan, T. Connelly, J. Knittel**. 2003. SAE 2003-01-1554.

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