



Optimization of the Sound Package of a Truck using Statistical Energy Analysis

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Statistical Energy Analysis is used to analyze the air-borne noise transfer path for many applications. In a separate paper, we have presented the work performed to develop and validate the SEA model of a truck. In this paper, we describe how we used this SEA model to optimize the truck sound package. We first provide details on how the noise control treatments are modeled using multi-layer poro-elastic materials. We also explain how we identified the material properties of the treatments—Biot properties—from impedance tube measurements. We then present the optimization setup we created to either improve the sound pressure level at the driver headspace at constant cost or to reduce the sound package overall cost at constant sound pressure level. The optimization results are presented and discussed. We also share the results of the validation testing. In this project,

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we measured the vehicle noise performances before and after implementation of the optimization sound package. The comparison between simulation and test results demonstrate the accuracy of the method and confirm that the method proposed is effective for sound package optimization.

1 INTRODUCTION

In the last few years the sound quality and noise related issues have become extremely important for automobile manufacturers. The market trends indicate that the customers demand for products with superior performance and better sound quality at lower cost¹. One of the most efficient methods to reduce the noise inside the vehicle's cabin is by the use of materials with high sound absorption and/or insulation characteristics. These materials are applied on to the vehicle's body in layers and are referred as Noise Control Treatments (NCTs). A collection of these applied NCTs is known as a sound package. The perceived quality, of a sound package, is often quantified in terms of Sound Pressure Level (SPL) measured at the driver's ear location.

A middle size truck's sound package is optimized with two objectives: (a) improved performance at the same cost and (b) reduced cost while the performance of the sound package remains same. The performance is measured in terms of SPL at driver's headspace. The total cost of the sound package is computed based on price/kg of multiple NCT stacks.

External excitation sources, such as engine, generate noise that can cause inconvenience to the driver. To reduce the noise level, NCTs are applied on interior and exterior side of the cabin's body in white. By strategically optimizing the thickness and coverage area of NCTs, the performance of sound package is enhanced. In this project we primarily focused on air-borne sound transmission path to the truck's cabin space.

For this simulation, a Statistical Energy Analysis (SEA) model of truck's cabin is created in VA One. The Biot properties of NCT layers are identified based on impedance tube testing and the commercial software FOAM-X. The acoustic excitations from experiments are then applied on the SEA model of the vehicle. The SEA modeling of truck's cabin is briefly discussed in Section 2.

VA One's "Design Optimization Tool" is used to optimize the performance and the cost of the sound package. The optimization strategies and constraints are further discussed in Section 5. The VA One simulations yielded the optimized thicknesses for different layers of the applied NCTs. These results are then validated through experimentation. In the final sections of this paper, it is established that SEA based techniques can be effectively used to optimize a vehicle's sound package.

2 STATISTICAL ENERGY ANALYSIS

Statistical Energy Analysis or SEA is a simulation method for vibro-acoustics developed in the early 60's. SEA is based on conservation of energy in the system. Using a SEA model created in VA One the middle size truck's sound package will be analyzed and optimized. The basis of SEA computations can be expressed through following equations^{3,4}:

$$\omega[\eta]\{E\}=\{P\} \quad (1)$$

$$P_{in} = P_{out} \quad (2)$$

$$P_{out} = P_{transmitted} + P_{dissipated} \quad (3)$$

where,

- ω is the frequency,
- $[\eta]$ is the loss factor matrix,
- $\{E\}$ is the modal energy as vector,
- $\{P\}$ is the input power as vector,

P_{in} is the input power,
 P_{out} is the output power,
 $P_{transmitted}$ is the transmitted power, and
 $P_{dissipated}$ is the dissipated power.

Power balance equations (Eq. (1) to (3)) relating the net power flow between the different subsystems are solved for each subsystem to determine the subsystem energy. This subsystem energy can be converted into a variable such as average sound pressure level for acoustic spaces or vibration level for plates and beams.

The SEA model of the truck is subdivided in: (a) structural subsystems, (b) acoustic cavities, (c) junctions. The structural subsystems represent the physical components such as roof, floor, pillars etc. The interior cabin space and exterior ambience around the cabin are modelled as acoustic cavities. Junctions are means of transfer of energy from one system to the other.

The structural definition of the SEA model is generated based on the Finite Element (FE) model of the truck's cab. These structural entities are defined as flat panels or curved shells. For beaded panels, the modal correction factors are applied to amend the modal densities. After the structural entities are modeled the NCTs are applied on the base panels (or body in white). In the Figure 1, the FE to SEA model conversion is presented. The SEA modeling is further discussed in a separate paper by the authors⁵.

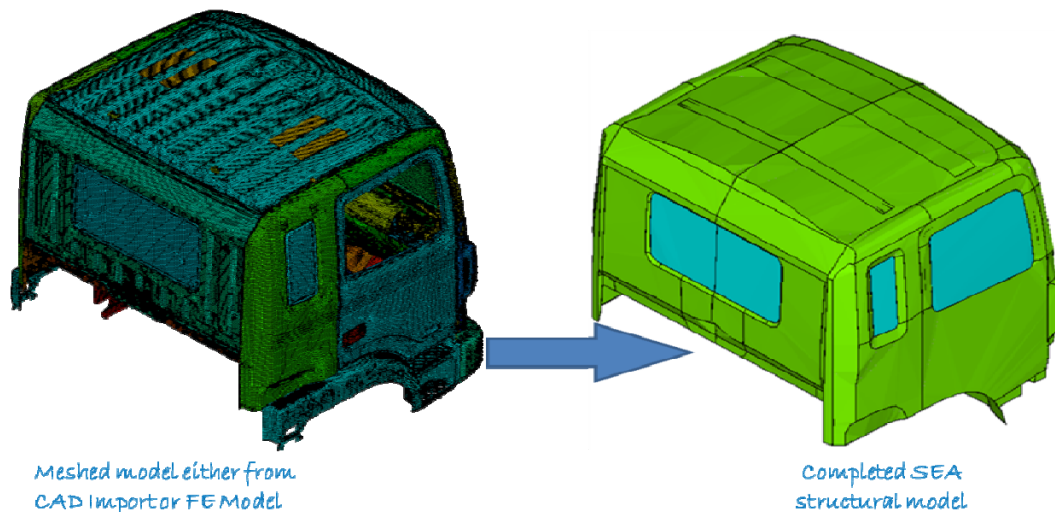


Fig 1—Creation of SEA model from FE Model

The interior cabin space is sub-divided to extract SPLs in multiple locations, for example waist-space, headspace, console etc. The driver headspace is the most important cavity in this presented analysis because the performance of the sound package treatment is quantified based on the estimated SPL in this cavity. The truck was tested in a hemi-anechoic room. To model the sound field around the vehicle external cavities are created. The external cavities are also sub-divided to gather valuable information at locations of special interest such as under floor, in front of the main windscreen and the side of the doors. The acoustic power, from tests, is then applied on the external cavities. Finally, these external cavities are connected to sinks, or Semi-Infinite Fluids (SIFs), to simulate free-field propagation as in the hemi-anechoic room. In Figure 2, truck's major cavities are presented.

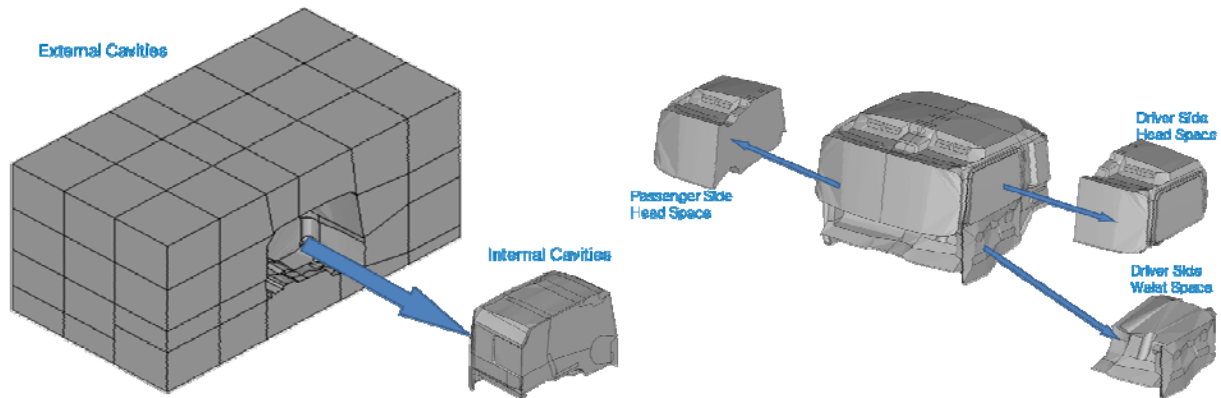


Fig 2—Internal and external cavities (Driver side only). The picture on the right presents the major internal cavities.

3 NOISE CONTROL TREATMENTS

The noise control treatments provide mechanisms to eliminate or reduce the unwanted noise and vibration. For a panel the NCT provides damping mechanism and for an acoustic cavity a NCT facilitates sound absorption. These NCT have multiple layers and each of them consists of at least one poro-elastic material –such as foam and glass wool. The challenging task is to measure/estimate the Biot properties of these porous materials.

To estimate the Biot properties, the vehicle’s entire sound package is peeled off and then NCTs are trimmed to extract samples for the impedance tube testing. The normal incidence absorption coefficients are measured and these coefficients are then used indirectly predict the Biot properties. We used FOAM-X to extract the Biot property of individual layers of NCTs. The material and stack information for each layer, in tabulated format, is presented below.

The middle size truck’s NCTs are sub-divided in five main categories:

- (1) Center Floor
- (2) Side Floor
- (3) Headliner
- (4) Side and Rear Trim
- (5) Engine Insulator

3.1 Floor NCTs

The floor treatments are applied on the interior panels of the cabin. The two layer construction of floor NCTs consists of a decoupler layer (foam) and a layer heavy (or barrier). The barrier layer is significantly heavy compared to the decoupler layer. The foam layer has a variable thickness ranging from 12 mm to 25 mm. The Biot properties are identified for the following thicknesses: 12 mm, 18 mm, 21 mm, 24 mm and 25 mm.

Using the Multiple Noise Control Treatment (MNCT) option available in VA One the variable thicknesses are incorporated in the SEA model. The barrier is modelled as isotropic material and its thickness is 3mm. In some regions of the floor a “spray-on” damping treatment (or “silent material”) is applied. The NCT definition of the floor is presented in Figure 3. Based on the predicted Biot properties, the transmission loss is predicted (Presented in Figure 4).

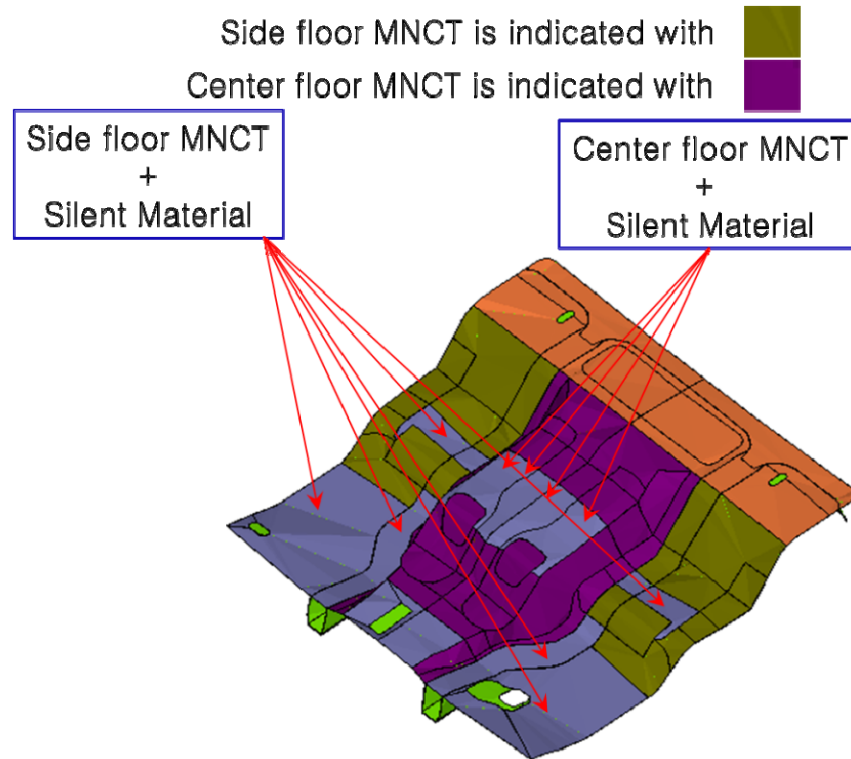


Fig 3—Floor NCT (Interior of the cabin) – The green regions are untreated

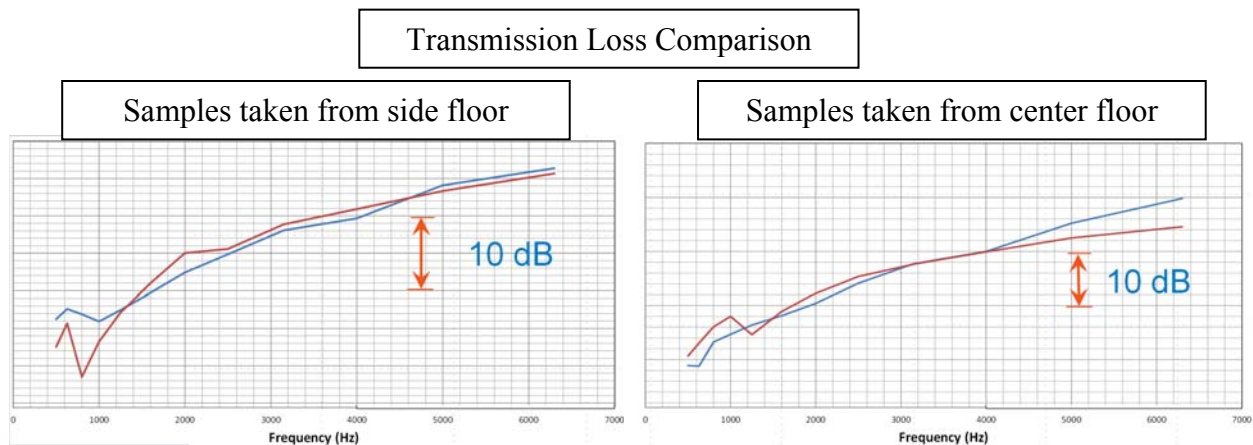


Fig 4— Comparison of Transmission Loss (TL) of the floor noise control treatments (blue curves are measured TL using the impedance tube and red curves are TL predicted using the FOAM-X based Biot properties)

3.2 Headliner NCT

The headliner consists of four layers. The first layer is a fibrous pad, the second one is a material with wood consistency, the third one is a thin layer of plastic foam and the fourth one is the impervious outer skin. The layer facing the interior cabin space is impervious hence the headliner has a low absorption. In Figure 5, the location of headliner NCT is presented. In the Figure 6 the predicted and measured transmission loss for the headliner are presented.

3.3 Side and Rear Trim NCTs

The side and rear trim have partial coverage of a two layered NCT. The decoupler layer is fibrous and the top acts as a barrier. The Biot properties of the fibrous layers are identified and applied as NCT. As the coverage is partial, the MNCT option of VA One is used again. In Figure 5, the location of side and rear trim NCTs is presented. Based on the predicted Biot properties the transmission loss is predicted and compared to measured transmission loss. The comparison of measured and predicted transmission loss for rear and side trim is presented in Figure 6.

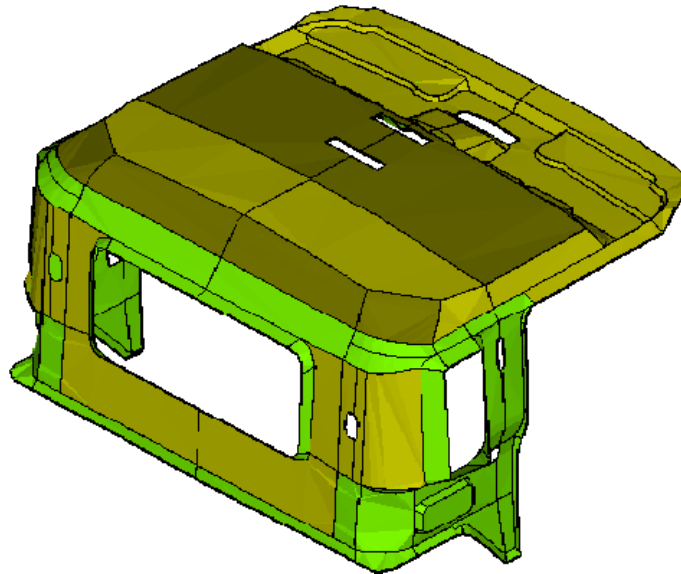


Fig 5—Headliner, side and rear trim NCTs – The green regions are left untreated.

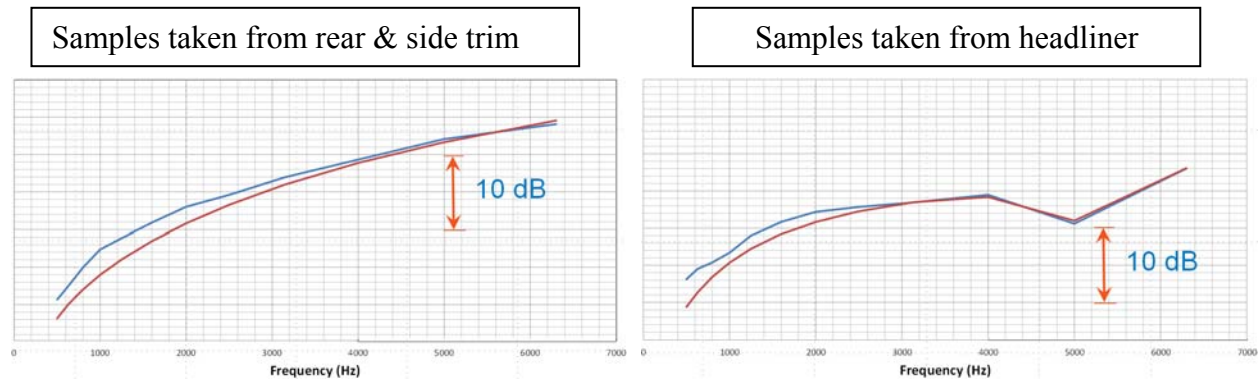


Fig 6—Comparison of Transmission Loss (TL) of the noise control treatments of side & rear trim and headliner (blue curves are measured TL using the impedance tube and red curves are TL predicted using the FOAM-X based Biot properties)

3.4 Engine Insulator NCT

The engine insulator is the NCT that is applied to exterior of truck's cab. The engine insulator consists of fibrous material with very thin scrim. The material was tested in impedance tube with the scrim, therefore, the Biot properties are indirectly determined for the combined stack. The insulator has variable thickness ranging from 15-20 mm. To incorporate this thickness variation, a MNCT is used in VA One. Figure 7 shows the bottom view of the floor the engine insulator.

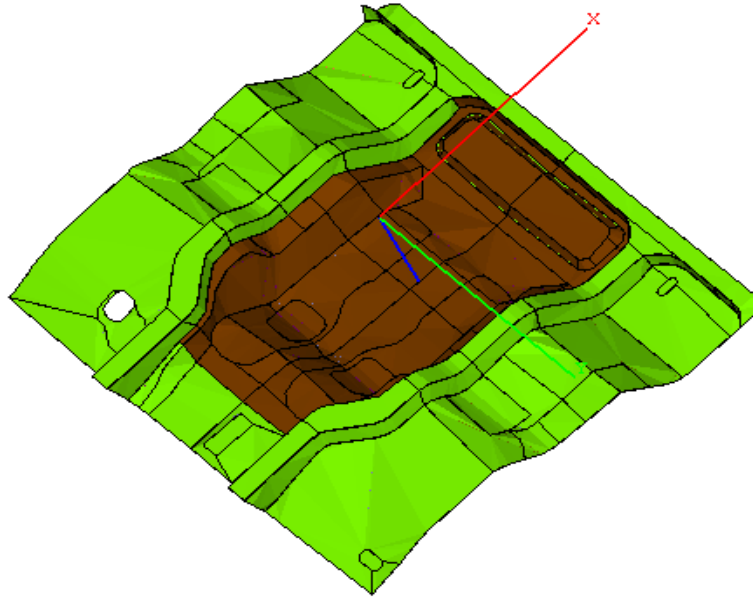


Fig 7—Engine insulator (applied on the exterior side of the floor). The green regions are untreated

4 APPLICATION OF LOADS & SINKS

In the SEA model the loads are applied on the cabin's external cavities. These loads are defined as acoustic power sources. The acoustic power spectrum is generated based on the Source-Path-Contribution (SPC) model. Source-Path-Contribution (SPC) is an experimental technique that allows decomposing the noise or sound pressure level at target locations into the individual contributions of each of the noise and/or vibration sources. This is an indirect method of estimating the source strengths. The measurements were performed on a chassis-dyno for multiple conditions including idle and 80 kph (kilometers per hour).

For the SEA model, the source strengths—modeled as volume velocity sources—are then converted to acoustic power. The estimated acoustic power is applied to corresponding external cavities. The SEA model is used to optimize the sound package for air-borne excitation sources only. The structure-borne sources are not considered in this analysis. A total of twelve acoustic power sources are identified (Presented in Figure 8). The engine sources when combined generate almost the same noise as all the sources combined. Based on this observation it could be concluded that the two engine sources—centerline and rear—are the dominant acoustic sources⁵. Therefore, optimizing the treatments applied on floor—internal and external—should be the point of focus.

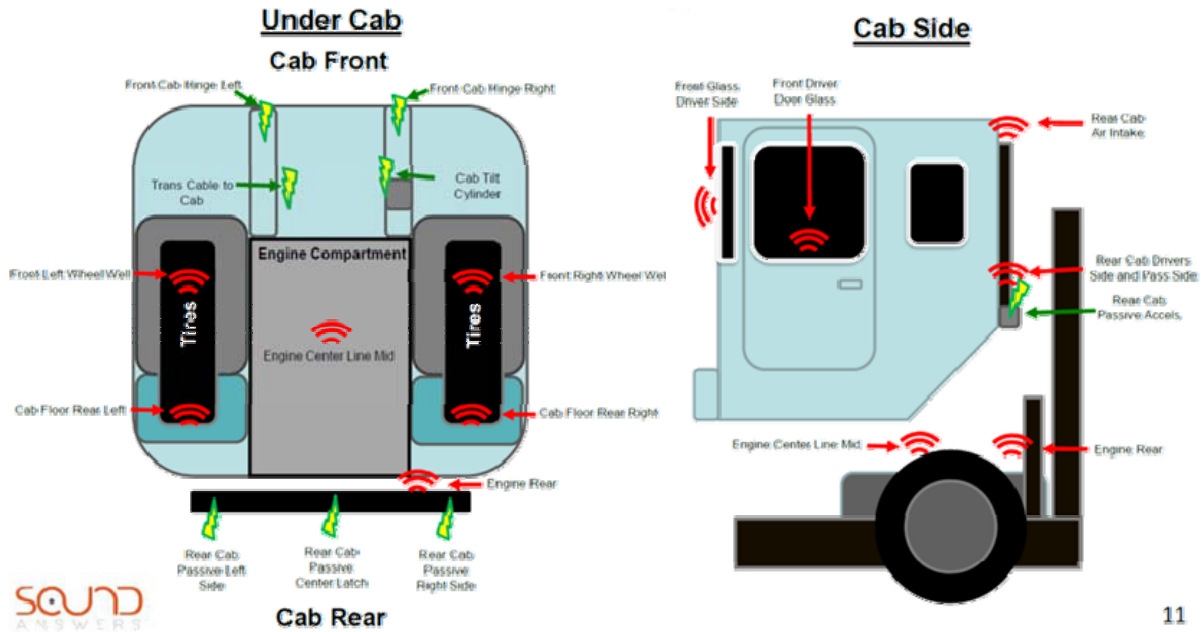


Fig 8—Identified excitations using SPC model (The acoustic sources are marked in red and structural sources are marked in green)

5 OPTIMIZING THE SOUND PACKAGE

The SEA model with all the air-borne sources, structural and acoustic subsystems is then utilized for the purpose of sound package optimization. The load case consisting corresponding to the 80 kph steady state operating conditions is considered to be the primary load case. The baseline model refers to the original configuration of the truck. In this study, all the baseline noise control treatments (discussed in Section 3) are optimized. VA One's Design Optimization Tool is used to execute the optimization task.

The optimization of the sound package, applied on baseline model, is performed with two objectives:

- Goal 1: Maintain the total price of the sound package and reduce the SPL at the driver headspace location
- Goal 2: Maintain the performance of the sound package—i.e. keep the SPL in driver headspace constant—and reduce the total price of the sound package

In the optimization using VA One's design optimization tool, following assumptions are made:

1. The headspace SPL will be considered as the measure of the performance of the sound package (cost function).
2. The optimization analysis is performed to reduce the overall headspace SPL in frequency range of 500 Hz to 1600 Hz
3. The thicknesses of the individual layers of the NCT are of constant thickness.
4. The barrier layer can be optimized to lower thickness.
5. For Goal 1: The coverage area of engine insulator is extended to the sides. If the thickness of the optimized insulator is close to zero, it indicates that there is no need of insulator at that location. To increase the absorption, the foam barrier treatment—same as floor—is extended under the mattress. (Presented in the Figure 9)

- For Goal 2: The coverage area of engine insulator is kept same as that of baseline model. (Presented in the Figure 9)

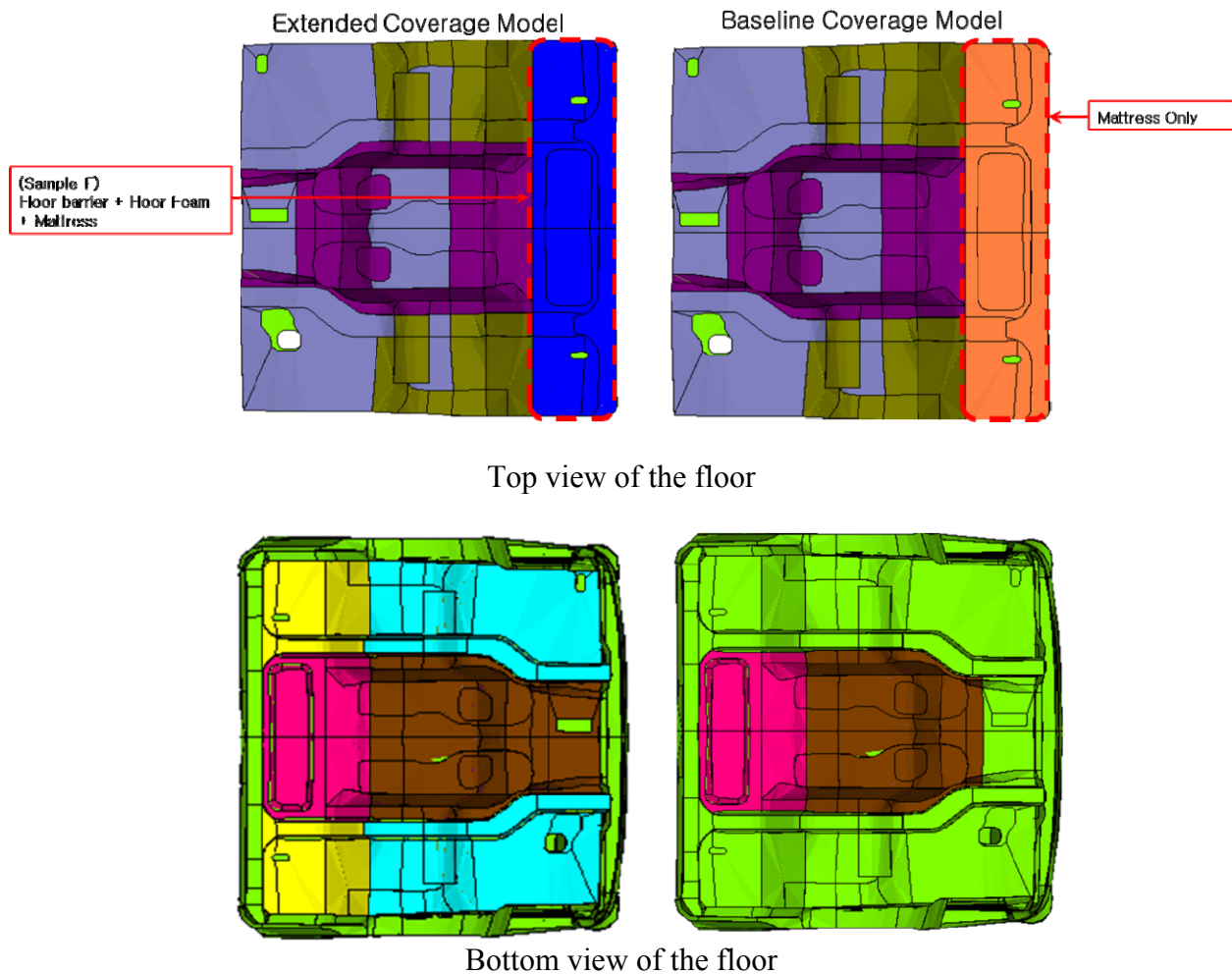


Fig 9—Extended coverage (for Goal 1) vs. baseline coverage (for Goal 2)

- For the optimization, the floor's decoupler layer cannot be thicker than 50mm and the insulation layer cannot be thicker than 25 mm.
- All the lower limits on thicknesses are set to be 1 mm except for the floor barrier layer. The barrier layer cannot be thinner than 1.5 mm due to stiffness constraints.
- For the optimization, above thickness constraints are applied along with the price constraint.

6 RESULTS

The VA One simulations generated optimized thicknesses for the vehicle's NCTs. With the extended coverage, the performance of the sound package is enhanced by 3dB at no additional cost. While, with baseline coverage, the price of sound package is reduced by 30% without compromising the performance.

To achieve the Goal 1—same price and better performance—the major NCTs on the floor are updated. The floor's decoupler layer's thickness is reduced and the foam layer's thickness is

increased. Note that the barrier layer is also one of the most expensive layers. The engine insulator on the center and rear are thickened for better noise insulation. For the side and wheel well—which are not covered in the original configuration—it is recommended to extend the engine insulator’s coverage. The cost reduction obtained by thinning the barrier, side and rear trims is spent on the floor treatments.

To achieve the Goal 2—same performance at reduced cost—the coverage of all the NCTs is kept the same as that of the baseline model. Similar to the Goal 1 objective, the major cost reduction is achieved by reducing the barrier thickness of the floor, and reducing the thicknesses of the headliner, side and rear trim. The rear floor engine insulator is reduced in thickness to 16mm and the thickness of the center floor engine insulator is increased. Therefore the price of the engine insulator almost remained the same. For the interior floor NCT, it is recommended to have a decoupler layer of 23mm.

In Table 1, the optimized prices of each NCT—in percentages w.r.t. their optimized sound packages—are presented. It becomes evident that the headliner, side and rear trim NCTs are the least effective. The floor treatments are the ones which drive the performance of the sound package. For both objectives, the price reduction is achieved by reducing the thickness of the barrier layer. The engine insulator—high grade material—is very effective in noise insulation but is very expensive too. From the optimization trends, it is suggested to focus on the floor foam and the engine insulator.

The barrier layer is not very effective therefore for both price and performance optimization, the barrier thickness can be reduced to 1.5 mm. The headliner and side-rear trims are also not effective as the major noise source is the engine and the primary source path is through floor. The simulations suggest to completely remove the headliner and side-rear trim’s fiber layers as they are least effective. But for sources not encountered in these tests, such as wind noise, these treatments may be critical. It is recommended, for practical reasons, to keep these treatments.

Table 1—Cost comparison/update of the NCT treatments

Noise Control Treatment	Price of Baseline NCT w.r.t. Baseline Sound Package's Price	GOAL #1	GOAL #2
		EXTENDED COVERAGE MODEL	BASELINE COVERAGE MODEL
		Price of the the Optimized NCT w.r.t. Optimized Sound Package	Price of the the Optimized NCT w.r.t. Optimized Sound Package
Sample A -- Side and Rear Trim	27.4%	12.4%	17.6%
Sample B -- Headliner	15.3%	14.9%	21.2%
Sample C -- Side Floor	26.6%	11.0%	22.5%
Sample D -- Center Floor	18.6%	15.3%	19.0%
Sample E -- Engine Insulator	12.1%	41.7%	19.8%
Sample F -- Additional Barrier + Foar	0.0%	4.4%	NA
SUMMARY			
Total Price Reduction		0% Baseline Price (No Change)	30% Reduced Price
Performance Improvement (Driver Side Headspace SPL in dB)		3 dB Reduction Improved Performance	0 dB Baseline Performance (No Change)

6.1 EXPERIMENTAL VALIDATION

The simulation based recommendations have been validated. The original materials—applied on the truck—were not available for validation tests. In the absence of original materials, to update the thickness of foam and fibrous layers, “off the shelf” materials are used. For these ad-hoc materials the Biot properties are again predicted and applied in the VA One model. With these updated materials, the SPLs are predicted and compared against measurement results.

In the following table 2, the reduction in SPLs is compared. VA One predicted a drop of 1.2 dB in SPL—with off the shelf materials—and in the tests the measured SPL drop in the frequency band of interest is 1.7 dB. The SPL reductions are in-line with the recommendations. This validates the model and the ability to predict the effect of design changes.

Table 2—Experimental validation of VA One based recommendations.

Goal #1		
Same price and improved performance		
	Recommended Treatment (With HMC original materials)	Applied Treatment (With off the shelf materials)
Simulations (VA One)	3 dB Drop	1.2 dB Drop
Experiments	-	1.7 dB Drop

For the objective Goal 2, the NCT coverage is the same as the baseline vehicle. VA One predictions indicated that the price of the sound package will be reduced and the headspace SPL will remain the same. When the thicknesses are updated to the recommended thicknesses of Goal 2 it is confirmed through the tests that there is no change in overall headspace SPL. Hence it can be validated that the Goal 2 can be met with VA One based recommendations.

7 CONCLUSIONS

SEA based methodologies and VA One’s Design Optimization Tool have been successfully used to optimize the sound package of a vehicle. Two sound packages were generated that met the optimization requirements. The engine sources are the dominant sources for air-borne noise. For this reason the headliner, side and rear trim NCTs are the least effective. Also, the floor heavy barrier layer can be reduced to its minimum of 1.5 mm. To improve the performance of the sound package, the engine insulator needs to cover the wheel well and side floor.

Using the sound package designed for same cost and increased performance (Goal 1), the headspace can be made 3 dB quieter. While, using the second sound package—same performance and reduced price—the cost of the entire sound package can be reduced by 30%.

This project successfully demonstrates the process and methodology to optimize the sound packages using SEA based tools.

8 ACKNOWLEDGEMENTS

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