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An Interactive Approach to the Design of an Acoustically Balanced Vehicle Sound Package

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ABSTRACT

Each time a new vehicle is developed, engineers face the challenge to develop the ideal sound insulation package. The goal is to attenuate powertrain, wind and road/tire noise from entering the vehicle while complying with cost, weight and packaging constraints. The design process is greatly facilitated if the engineer has effective tools to rapidly quantify how various sound insulation components contribute to the overall NVH performance of the vehicle.

This paper discusses how an interactive vehicle acoustical design tool can be developed that assists the designer in making rapid decisions as to how to balance the performance of the various sound package components. The acoustical design tool is unique for each vehicle, and must take into account design decisions such as type of powertrain, body style, and numerous other factors in order to correctly predict the performance of the total package. Any good modeling tool must also take into account inputs from a reasonable range of operating conditions.

A very good model for the acoustical behavior of the vehicle can be developed using data from measurements made while operating a sample vehicle at the target operating conditions. The authors will present a method for utilizing measurements together with some simple equations to predict the result when components of different designs are exchanged. The process of generating the needed data for this method from experiments on a vehicle is admittedly time consuming, if all of the possible design variations are to be considered. An alternative that the authors present in this paper is for the case in which a correlated Statistical Energy Analysis (SEA) model exists for the vehicle being considered. A great time savings is realized when the same acoustical behavior information about the vehicle can be extracted by running analytical experiments in the SEA model. The authors assert that even if an SEA model must be developed from scratch and correlated, this approach is preferable over the experimental approach.

Once developed, an interactive design tool of the type being discussed has ongoing benefit to product development engineers by giving them a handy way to asses future design changes. If sound insulation components are later sacrificed in the interest of reducing vehicle costs or weight, the model can accurately portray the implication of the changes on sound levels in the vehicle. A case study is presented that demonstrates the use of this tool and its accuracy.

INTRODUCTION

Vehicle sound package designers have the goal to design vehicle parts that contribute to meeting NVH targets while being well “balanced”. “Well balanced” implies that extra expense and weight have not been added into one area of the treatment package while others are under treated. Many technical experts have been befuddled by the experimental process of installing significant sound package enhancements, only to be disappointed that only slight reductions to cab-interior sound levels are produced. The challenge of developing upgrades to the sound package of well balanced vehicles is that a significant improvement is not achieved without changes to many parts at once.

The physical laws that govern how sound insulation packages behave in vehicles are simple and well understood. Analytical approaches, like statistical energy analysis (SEA) have been employed for the past several years, but have enjoyed limited success in practice as viable tools to arrive at balanced vehicle sound packages. There are several drawbacks in practice to the use of SEA and most other methods. First, there is only a fraction of the vehicle development community that trust such analytical methods. Secondly, for SEA and experimental techniques, the exercise to “try out” each round of design changes is considered too time consuming / expensive with the typical compressed design schedules at today’s auto makers. The experience of the authors is that a more common practice is to choose the content of a previous or similar model as a starting point. Then an experienced engineer will physically “try out” a very limited set of favorite components. The final design is the best of the options tried. Alternately, a Tier 1 sound package supplier "tries out" the set of materials / components that are favored by management for sale and recommends the best of a very limited population of options.

The authors have implemented an interactive design tool in Microsoft Excel that shows how the ensemble sound levels in the cab react to the installation of various insulators. Because of its intuitive and interactive nature, this tool assists sound package engineers to rapidly develop a balanced sound insulation package for the vehicle. The interactive and graphical nature allows management / decision makers to see the benefit / penalty in real time. We have named this approach: the sound package balancing tool, or "SPB tool" for short.

THE SPB TOOL APPROACH

A numerical recipe has been developed, and is here presented, that does a good job of approximating the summation of noise sources that excite the cabin of a vehicle. The inputs to this "recipe" can be derived either from experiments using an actual vehicle, or numerically, using a statistical energy analysis (SEA) model. As we have described earlier, the benefit of combining SEA and the SPB tool is the ability to interactively and immediately demonstrate the effect of design changes to decision makers.

A schematic of this numerical recipe is shown in Figure 1. Multiple sources act in parallel to contribute sound energy ($\sim p^2$) to the vehicle cab.

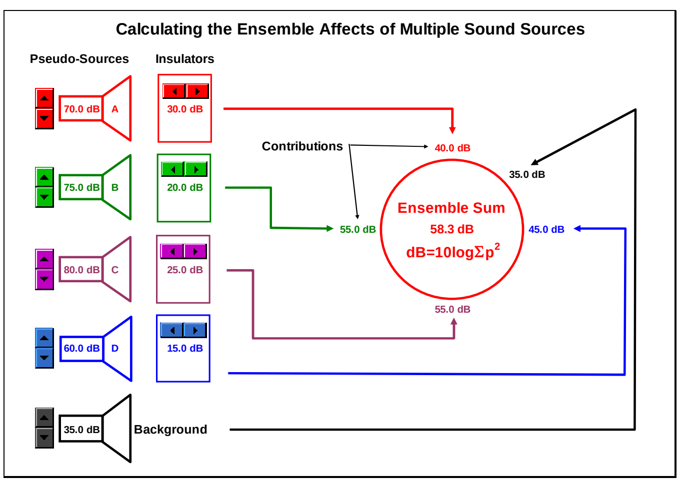

Figure 1: Schematic of Pseudo-Source Method

These sources are referred to throughout this paper as "pseudo-sources". Each one can be thought of as the summation of noise energy from all external sources exciting a particular subsection of the cab interior surface area that bounds the cab air space. A different set of pseudo-source values results from each different operating condition. As Figure 1 shows, these pseudo-sources act through insulators whose attenuation factors are known in dB. The insulators are assumed to operate over the entire area of the same subsection of cab interior surface area as the associated pseudo-source. The contributions made by each pseudo-source through their respective insulators p_i for the n sources is given by Equation 1, where p_e is the space averaged sound

$$\frac{p_e^2}{p_0^2}=\sum_{i=1}^{n}\frac{p_i^2}{p_0^2}+\frac{p_b^2}{p_0^2}$$

Equation 1

pressure of the ensemble of sources in the vehicle cab and p_0 is the threshold of hearing {2.0 x 10^{-5} Pa}. p_b is the contribution from the "background sources", defined to be the cab sound level when all surfaces are maximally treated.

The shape, area, and number of the cab interior surfaces that are used in the design tool is arbitrary, however the utility of the SPB tool is facilitated if they coincide with typical sound insulation parts. The number of cab interior surfaces chosen should be limited to 15 or less to maintain tool simplicity. Typical cab interior surfaces are shown in Figure 2. The accuracy of the design tool is

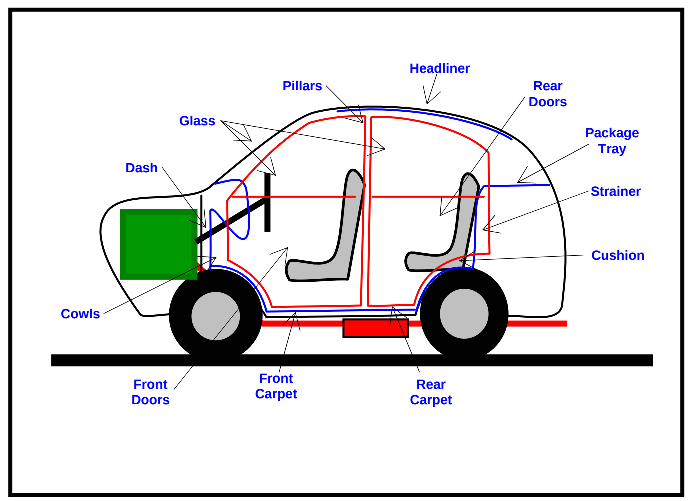

Figure 2: Typical Cab Interior Surface Definitions

improved if the sum of the cab interior surface areas is close to the total surface area of the cab air space. This forces the contributions from the background sources lower and enables the more accurate measurement of quieter pseudo-sources. A good rule to follow is to ensure that the background levels are less than 10 dB louder than the quietest pseudo-source.

In order to predict the vehicle interior sound pressure using Equation 1, the contributions to cab interior sound pressure level (spl_i) due to each of the cab interior surfaces in an untreated state must be determined in decibels (dB). Once this is determined, a method has been developed to estimate the adjusted contribution when the surface is treated with a known noise barrier. One can calculate the sound pressure level contribution spl'_i from that cab interior surface through an insulator installed over that surface, using Equation 2, where I_f is the "attenuation factor" in dB of the insulator.

$$spl'_i = spl_i - I_f$$

Equation 2

The authors have developed a treatment database that includes 54 generic acoustical insulators, see Table 1. For each of these treatments an attenuation factor has been calculated. This was done using an acoustical material analytical model, several of which are commercially available. Physical characteristics like

Generic Insulation Options

No.	Description	No.	Description
1	6 mm Absorber	28	1.00# Barrier & 25 mm Decoupler
2	12 mm Absorber	29	1.00# Barrier & 31 mm Decoupler
3	18 mm Absorber	30	1.00# Barrier & 37 mm Decoupler
4	25 mm Absorber	31	1.25# Barrier & 6 mm Decoupler
5	31 mm Absorber	32	1.25# Barrier & 12 mm Decoupler
6	37 mm Absorber	33	1.25# Barrier & 18 mm Decoupler
7	0.25# Barrier & 6 mm Decoupler	34	1.25# Barrier & 25 mm Decoupler
8	0.25# Barrier & 12 mm Decoupler	35	1.25# Barrier & 31 mm Decoupler
9	0.25# Barrier & 18 mm Decoupler	36	1.25# Barrier & 37 mm Decoupler
10	0.25# Barrier & 25 mm Decoupler	37	1.50# Barrier & 6 mm Decoupler
11	0.25# Barrier & 31 mm Decoupler	38	1.50# Barrier & 12 mm Decoupler
12	0.25# Barrier & 37 mm Decoupler	39	1.50# Barrier & 18 mm Decoupler
13	0.50# Barrier & 6 mm Decoupler	40	1.50# Barrier & 25 mm Decoupler
14	0.50# Barrier & 12 mm Decoupler	41	1.50# Barrier & 31 mm Decoupler
15	0.50# Barrier & 18 mm Decoupler	42	1.50# Barrier & 37 mm Decoupler
16	0.50# Barrier & 25 mm Decoupler	43	1.75# Barrie & 6 mm -Decoupler
17	0.50# Barrier & 31 mm Decoupler	44	1.75# Barrier & 12 mm Decoupler
18	0.50# Barrier & 37 mm Decoupler	45	1.75# Barrier & 18 mm Decoupler
19	0.75# Barrier & 6 mm Decoupler	46	1.75# Barrier & 25 mm Decoupler
20	0.75# Barrier & 12 mm Decoupler	47	1.75# Barrier & 31 mm Decoupler
21	0.75# Barrier & 18 mm Decoupler	48	1.75# Barrier & 37 mm Decoupler
22	0.75# Barrier & 25 mm Decoupler	49	2.00# Barrier & 6 mm Decoupler
23	0.75# Barrier & 31 mm Decoupler	50	2.00# Barrier & 12 mm Decoupler
24	0.75# Barrier & 37 mm Decoupler	51	2.00# Barrier & 18 mm Decoupler
25	1.00# Barrier & 6 mm Decoupler	52	2.00# Barrier & 25 mm Decoupler
26	1.00# Barrier & 12 mm Decoupler	53	2.00# Barrier & 31 mm Decoupler
27	1.00# Barrier & 18 mm Decoupler	54	2.00# Barrier & 37 mm Decoupler

Table 1: Database of NVH Treatments

tortuosity, thermal characteristic length, viscous characteristic length, porosity, bulk density, flow resistance, Young's modulus, Poison's ratio and structural loss factor were used to predict the attenuation factor of each insulator.

The performance for a sampling of the insulators is shown in Figure 3. It should be noted that the attenuation factor of an insulator can also be experimentally measured. By using the SAE J-1400 test procedure, the airborne sound transmission loss (STL) of a body panel including the NVH treatment can be determined. For body panels the insulator tends to work as a unit with the steel by adding decoupling and barrier layers. The attenuation factor is simply the measured sound transmission loss of the multi-layer, built-up unit, with the TL measured from an experiment on the bare steel subtracted. It can thus be thought of as the "improvement in TL" gained on that area by adding the treatment to the minimally treated or "bare" condition of the panel.

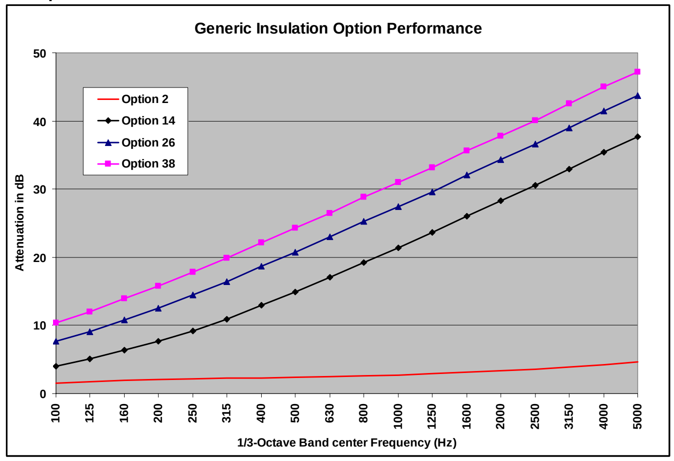

Figure 3: Effectiveness of Selected Treatments

Some of the cab space boundary surfaces are not steel panels, but are complicated structures, such as the dash, seats and windows. The same principle can be applied to give treatment options in these regions. A "stripped" condition must be defined, which represents the minimally treated surface. Then a variety of optional treatments can be developed that have attenuation factors assigned based on their impact on the cab interior sound level. For instance, greater glass thickness options can be treated as the bare glass with an "attenuation factor" for the thicker glass options. Likewise, other NVH treatments, such as adding acoustic absorptive material or improving air seals will show up in the "attenuation factor" term automatically as an improvement in the cab sound level as compared to the bare condition, achieved by applying the treatment.

Using SEA to develop the pseudo-source and attenuation factor terms has the excellent advantage of allowing all of these separate variables to be independently controlled. The experimental method involves a large number of "put and takes", testing and retesting with the various treatment options installed and removed.

For the parts of the cab boundary that are simple steel panels, that can use the treatments of Table 1, a handy shortcut is available to estimate the TL of the steel panel. The theoretical sound transmission loss (STL) in dB, for a homogeneous limp panel is given by Equation 3. m is the surface density (body steel = 7.3 kg/m^2), and f is the frequency of interest in Hz. This is a reasonable rough estimate for the TL of bare steel over most of the frequency range.

$$STL = 20\log(mf) - 47.2$$

Equation 3

Equation 2 is used to calculate the contribution that each pseudo-source makes through the insulator which is specified for installation over that cab interior surface during the modeling process. The contributions are then converted into sound pressures using Equation 4.

$$\frac{p_i'}{p_0} = (10)^{\left(\frac{spl_i'}{20}\right)}$$

Equation 4

Finally, the ensemble sound pressure in the cab, due to inputs from all of the treated bounding areas, with whatever insulator options you choose installed over each of the cab interior surfaces, is calculated. This is done by using the p_i' (or treated pressure contributions) calculated using Equation 3 and Equation 4 as the p_i terms in Equation 1. The summation of these terms, the ensemble sound pressure p_e is then converted into a prediction of cab sound pressure level using Equation 5.

$$spl = 10\log\left(\frac{p_e^2}{p_0^2}\right)$$

Equation 5

AN SPB TOOL FOR A MEDIUM SEDAN

We set out to develop a balanced sound package design for a new vehicle. We have chosen a medium sized sedan as our example. To develop an SPB tool using SEA, a suitable model must be developed or obtained. If SPB tool data is to be developed experimentally, a suitable test vehicle must be selected for the diagnostic tests. The following section will describe the process of developing the SPB tool input data using experimental methods. However, it is understood that this data could likewise be developed by running the corresponding analytical experiments in the SEA model. The data in this paper was in fact developed using an SEA model.

In many practical circumstances, the “baseline” vehicle doesn’t actually exist, and a surrogate vehicle that is “close” acoustically and mechanically, must be used for the study. Prototypes or mule vehicles are frequently utilized, wherein the powertrain, suspension and body are updated to better approximate a new design.

Frequently, the vehicle is tested while operating on a chassis rolls dynamometer inside a hemi-anechoic test chamber. This ensures highly repeatable test conditions, and enhances accuracy. One or more operating conditions must be chosen which will allow the tool to explore the key NVH attributes. If more than one operating condition is chosen, a separate SPB tool must be developed for each one.

We chose the 70MPH smooth level road condition to work with. The tests begin with a baseline study, with the vehicle equipped with a production trim and insulation package. Data taken on an NVH chassis rolls provides for input from road/tires, powertrain, exhaust, but not wind noise. This is usually acceptable.

This is followed by stripping the interior trim & acoustical insulation components to render the vehicle in a minimally trimmed “bare” condition. Next a very heavy, high performance sound insulation {1 – 2 lb/ft^2 barrier with a 1” - 2” thick decoupler} is installed over all of the cab interior test surfaces and tested. This is defined as the “MaxPack” condition. A noise measurement using MaxPack treatment gives the p_b background contribution of Equation 1.

Cab interior sound pressure levels during the MaxPack condition can be 6 dB(A) or more below baseline levels. Speech intelligibility often improves by over 5%, see Figure 4. Next, individual components of the MaxPack

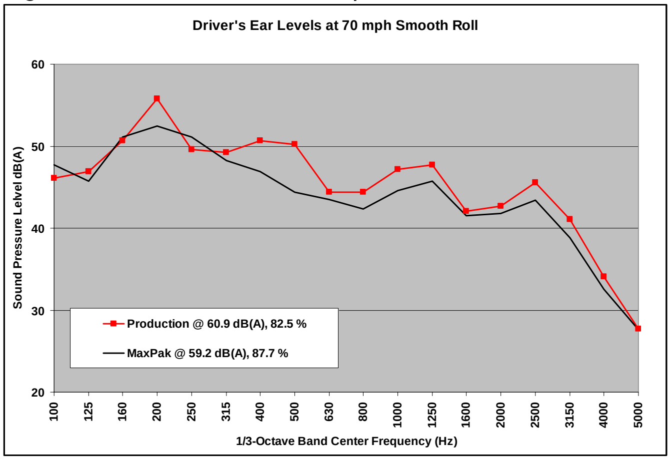

Figure 4: MaxPack & Baseline SPL

treatment are removed to expose cab interior surfaces and the cab sound level is again measured. In most cases, the MaxPack component is removed to reveal a “bare” surface. This treatment change results in a significant increase in cab sound pressure levels, see Figure 5. Sound pressure level changes above 400 Hz

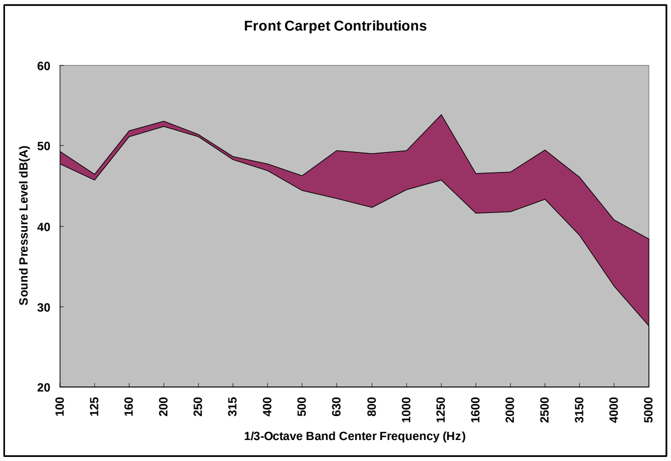

Figure 5: Effect of Removing MaxPack Treatment from a Single Pseudo-Source

in this example are well above 5 dB, while those below 400 Hz are around 1 dB, compared with the MaxPack condition. By rearranging Equation 1, the sound pressure p_i contributed by the uncovered cab interior test surface (i), can be calculated as shown in Equation 6. p_e in Equation 6 is the cab sound pressure measured with a single area of MaxPack removed.

$$\frac{p_i^2}{p_0^2} = \frac{p_e^2}{p_0^2} - \frac{p_b^2}{p_0^2}$$

Equation 6

By systematically removing the heavy insulation over each cab interior test surface, the sound pressure contributions of each pseudo-source is determined. Figure 6, shows the contributions for our medium sedan target vehicle. Note that the contributions from the pseudo-sources are evaluated over a broad frequency range, from 500 – 5,000 Hz. For display purposes, the SPB tool is usually developed to display results over fairly broad frequency ranges, usually a low, medium and high frequency prediction.

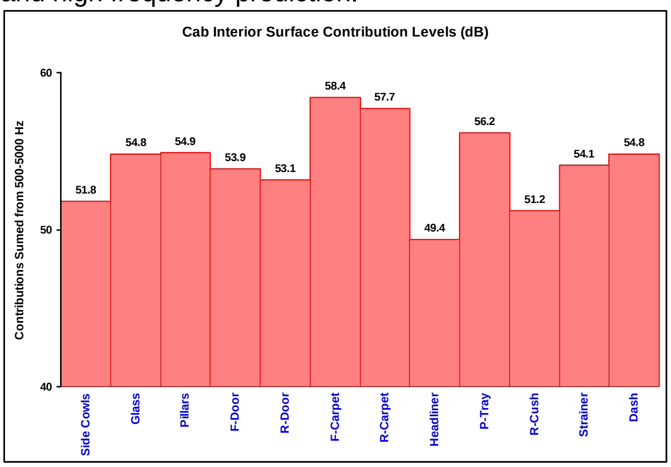

Figure 6: Contributions of Stripped Pseudo-Sources

Finally, all of the MaxPack insulation is removed to measure the effect when all of the cab interior surfaces contribute to the cab interior sound level in a minimally treated condition. This condition is called the “stripped” condition. Figure 7, shows the A-weighted sound pressure levels measured in a typical vehicle for the Baseline, MaxPack and Stripped conditions.

The final pieces needed to finish our sound package balancing tool are a set of optional treatments with various levels of performance for each of the cab interior surfaces. Each of these must be measured or analytically simulated to develop a prediction for the attenuation factor of the treatment.

We have chosen to implement the relatively simple equations of this method in a spreadsheet format. Macro tools exist that allow the user to select treatment options, and have the cab interior sound pressure chart immediately update based on the chosen treatment.

User selections are made using visual tools such as a slider bar or buttons to highlight the selection from among a rich database of acoustic treatments. Figure 8 shows an example display of selections where the treatment selected is identified in the table under the “Installed Insulator” heading.

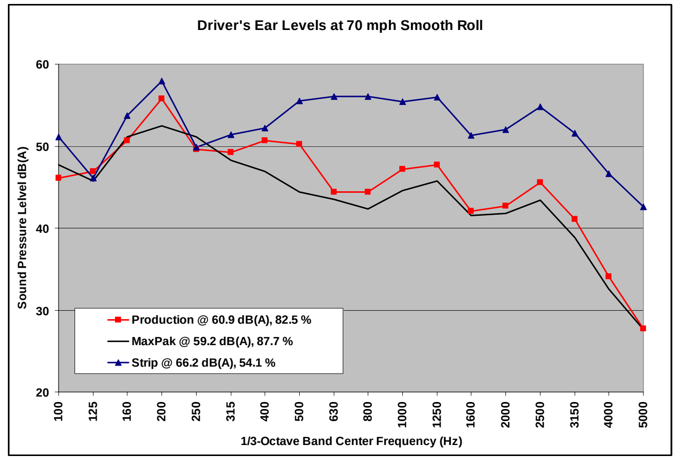

Figure 7: Cab SPL of Stripped, Baseline and MaxPack Treatments

Note that other effects such as air leakage can be taken into account as well, and be adjusted in the SPB tool.

3.00% Leaks

	Installed Insulator	#	Σ=>	Kg 21.4
Dash	37 mm Absorber	6		1.40
Strainer	0.25# Barrier & 37 mm Decoupler	12		3.27
Rear Cushion	18 mm Absorber	3		0.66
Package Tray	0.50# Barrier & 25 mm Decoupler	16		2.65
Headliner	6 mm Absorber	1		1.23
Rear Carpet	25 mm Absorber	4		2.09
Front Carpet	25 mm Absorber	4		2.02
Rear Doors	0.25# Barrier & 37 mm Decoupler	12		2.94
Front Doors	37 mm Absorber	6		1.85
Pillars	0.50# Barrier & 6 mm Decoupler	13		2.66
Glass	No Treatment	0		0.00
Side Cowls	31 mm Absorber	5		0.60

Figure 8: Example Display of a Chosen Treatment Selection

The relative effects of these selections on each pseudo-source may be displayed in a bar chart, as shown in Figure 9. The location of the stripped condition is

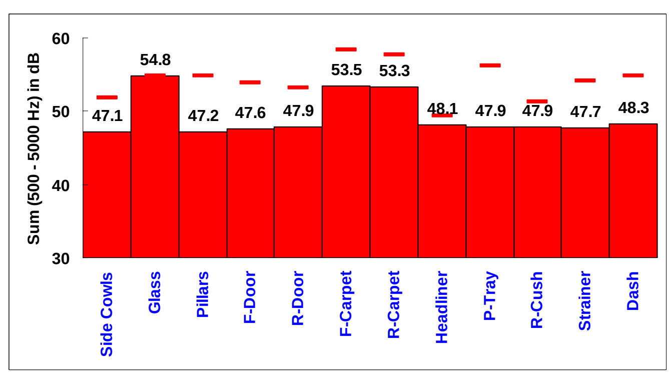

Figure 9: Pseudo-Source Levels resulting from the Chosen Treatment Set

indicated by the horizontal line above each bar. In this example we have adjusted the treatments to show a sound package design that is nearly balanced. Contributions to cab sound level from most sources are of very similar amplitude, over this frequency range, for this load condition. The challenge comes that the glass is untreated, and is the single largest source. Treatments for glass tend to be costly, and are not often considered, except in luxury vehicles. Figure 10 gives the resulting cab interior SPB tool prediction for this treatment set. The front and rear carpet are the second and third largest sources.

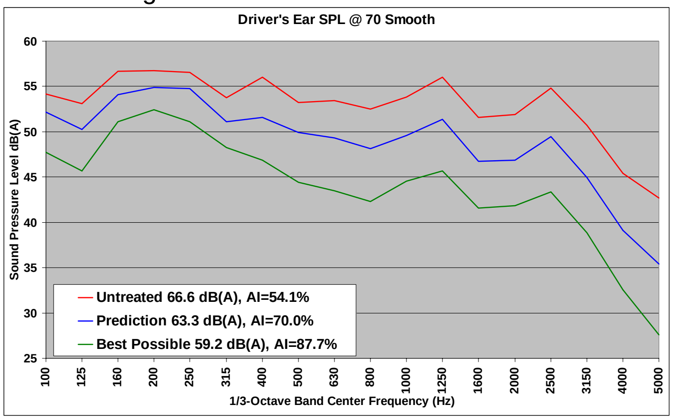

Figure 10: Cab SPL Resulting from the Chosen Treatment Set

Treatment of these pseudo-sources can have some positive impact on the result. Improving both carpet treatments by 6.4dB can be achieved by a change in treatments as illustrated in Figure 11 and Figure 12.

3.00% Leaks

	Installed Insulator	#	Σ=> Kg 30.5
Dash	37 mm Absorber	6	1.40
Strainer	0.25# Barrier & 37 mm Decoupler	12	3.27
Rear Cushion	18 mm Absorber	3	0.66
Package Tray	0.50# Barrier & 25 mm Decoupler	16	2.65
Headliner	6 mm Absorber	1	1.23
Rear Carpet	0.75# Barrier & 6 mm Decoupler	19	7.77
Front Carpet	0.50# Barrier & 6 mm Decoupler	13	5.46
Rear Doors	0.25# Barrier & 37 mm Decoupler	12	2.94
Front Doors	37 mm Absorber	6	1.85
Pillars	0.50# Barrier & 6 mm Decoupler	13	2.66
Glass	No Treatment	0	0.00
Side Cowls	31 mm Absorber	5	0.60

Figure 11: Improved Treatment Set

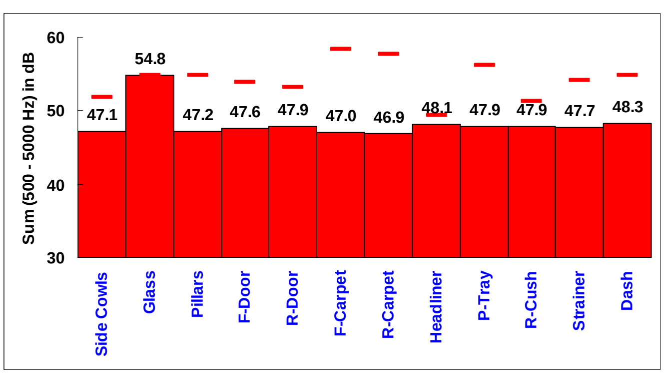

Figure 12: Pseudo-Source Levels Resulting from the Improved Treatment Set

The resulting cab sound pressure level dropped by 0.8dB(A) overall, as is seen in Figure 13. This is a relatively modest improvement for the amount of change made to the carpets. The SPB tool gives a clear explanation of this lack of effectiveness. Figure 12 shows that the Glass pseudo-source is dominating the sound input. Without treatment of the dominant source in an otherwise well balanced treatment set, very little can be done by the sound package designer.

In the above design example, we used the relative level of the pseudo source contributions to guide our balancing exercise. This process works as well for the lowest level contributors. If one or several pseudo-sources is significantly lower than the rest, this becomes a good candidate for degradation of the treatment in

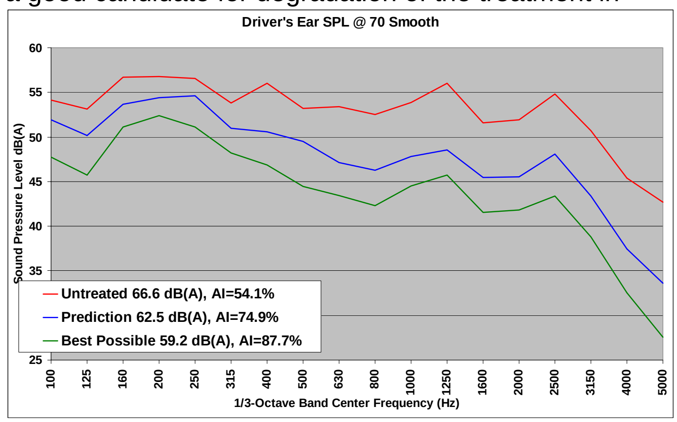

Figure 13: Cab SPL Resulting from the Improved Treatment Set

favor of saving cost and weight. Note that we have aided this exercise by adding treatment weight estimates in the far right column (see Figure 8 and Figure 11).

The ability to modify treatments and see the result immediately is likely to be much more helpful to decision makers than the results from slower modeling or measurement methods. As mentioned earlier, this is seen by the authors as a very useful post processing and display tool for SEA results. It is also very instructional to decision makers to see the MaxPack vs Stripped lines compared to performance achieved by a reasonable set of parts, rather than some hypothetical target line.

The mathematics of this approach, though approximate, have the benefit that the end points (MaxPack and Stripped) are the results of measurements or more careful analyses. The result is that any errors are bounded, and the transitions between treatment levels are constrained to be directionally correct.

CONCLUSION

The authors have presented a reasonable approach to the development of a tool that gives sound package designers an interactive way to display the NVH impact of design options to decision makers. As illustrated in the right column of Figure 11, non-NVH issues such as the total added weight of the sound package treatments may be included in the output for evaluation.

The development of the input data for this tool can be time consuming when it is taken from measurements, yet it is still a preferable way to present design options. The authors have suggested that the use of an SEA model to create the input data deck for this tool would yield a time and cost savings. The presented sound package balancing tool is recommended as an excellent way for designers to present decision makers with useful and timely design guidance.

REFERENCES

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