# Predicting Vehicle Interior Sound with Statistical Energy Analysis

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**Statistical energy analysis (SEA) is the standard analytical tool for predicting vehicle acoustic and vibration responses at high frequencies. SEA is commonly used to obtain the interior sound pressure level (SPL) due to each individual noise or vibration source and to determine the contribution to the interior noise through each dominant transfer path. This supports cascading vehicle noise and vibration targets and early evaluation of vehicle design to effectively meet NVH targets with optimized cost and weight. Here we discuss the SEA modeling assumptions used to generate a typical model of a vehicle cabin interior and surrounding structure. The distribution of acoustic absorption and its effect on the local interior SPL responses are addressed. Measurements of transfer functions to various points of the vehicle interior from exterior and interior acoustic sources and structure-borne sources for a typical vehicle are also presented and compared to SEA model predictions. Observations and recommendations about typical interior transfer function correlation, modeling limitations, and use of the SEA model as a design tool are given.**

Statistical energy analysis has been used extensively for both acoustic and vibration predictions over the past 50 years.[1] Early applications for aircraft and launch vehicles dealt with the problem of predicting structural vibration levels of parts that were subject to structural fatigue when excited by loud broadband acoustic sources. Shortly thereafter, SEA became a mainstream tool for predicting the structural response and radiated noise for ships and machinery from structural vibration sources. With the advent of commercial SEA software codes, in the 1980s and '90s SEA became a tool used to predict interior noise levels inside automobiles, heavy trucks, construction equipment, and aircraft for a wide range of acoustic and structureborne noise structures. [2-5]

SEA is most commonly used at higher frequencies (400 Hz and up) for this type of modeling, mainly because the size, damping, and modal density of the vehicle structures are more suitable to being modeled by SEA for these frequencies. However, because the subjective perception of acoustic performance and vehicle quietness is usually controlled by frequencies above 400 Hz and is typically dominated by noise levels between 1000 and 5000 Hz, it is sufficient in most cases to limit the range of study of acoustical performance to this frequency range.

Because SEA models are not dependent on geometric details, SEA vehicle models have proven to be most useful during the concept design phase, where test hardware is not yet available and CAD or FEA models are unavailable or incomplete and subject to changes that will greatly impact the results.[6,7] In the concept phase and early stages of design, an SEA model can return early predictions of vehicle NVH (noise, vibration and harshness) performance and an accurate assessment of the effect of changes to materials, sheet metal gage thickness, absorption and damping treatments including laminated and constrained-layer damping, barriers, changes to source levels, and other parameters that have a measureable influence on acoustic performance.

Full-vehicle studies as well as component-level studies using SEA may be performed. Full-vehicle models return overall levels from the summation of noise sources and transfer paths and provide a "virtual contribution analysis" that can be used to evaluate and set noise transmission targets for subassemblies of the vehicle. Component-level models may be used to evaluate whether a vehicle subassembly meets the noise transmission targets, and they often show the effect of individual parameter changes on the acoustic performance of the subassembly in greater detail than the full-vehicle models.

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*Figure 1. Standard inner- and outer-ear microphone positions to measure SPL for driver and front passenger locations.*

With the advent of larger and more detailed automotive, truck, and aircraft SEA models with vehicle interior noise as the primary prediction goal, the modeling details of the interior acoustic spaces have assumed greater importance. The goal of the SEA model is to accurately predict the sound pressure level (SPL) and especially the change in interior acoustic response at frequencies of interest due to changes in the source levels or of subassembly parameters. But as testing with multiple interior microphones demonstrates, the observed interior noise levels vary based on location. This variation may be large, depending on the source location(s).

To be useful for predictions of interior noise at different locations (driver's ear, passenger's ear, and rear passengers' ear locations), particularly for asymmetric noise sources, a predictive model needs to be able to account for the difference in acoustic response at different interior levels. This article addresses the modeling assumptions used in SEA to account for interior SPL variation and illustrates how careful calibration of the input power and inclusion of some direct-field effects complement and increase the accuracy of the vehicle interior noise predictions using SEA.

## Interior Vehicle Noise

**Observed SPL Response**. As a metric and performance target, the interior SPL at the driver's ear position is generally considered to be the most important indicator of vehicle acoustic performance. However, even this relatively straightforward metric is complicated by a noticeable difference in SPL between the inner and outer ear positions. In addition, the driver's ear position depends on the height of the driver and the seat position and angle, so that the driver's ear SPL is inherently more statistical in nature than may be implied by the term "driver's ear" and the unachievable ideal of a single, deterministic prediction of acoustic SPL at one particular fixed point in the vehicle cabin. Standard inner and outer ear microphone measurement positions are shown in Figure 1.

Other interior points are also important in evaluating overall vehicle acoustic performance, particularly the front passenger's ear positions (again both inner and outer ear) as well as the ear

*Figure 2. Microphones at lower positions to measure cabin SPL distribution and acoustic transfer functions involving lower interior positions.*

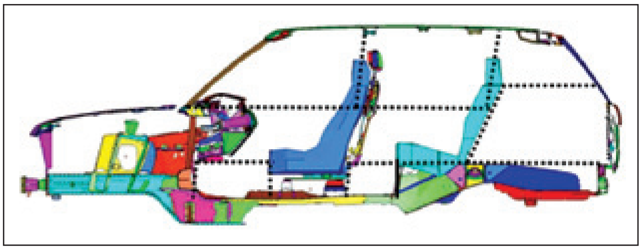

*Figure 3. Side-view illustration of typical subdivision of interior cabin airspaces in SEA Model.*

positions of occupants in the rear of the vehicle. Again, the exact location of these points within the vehicle interior depends on the passengers' height as well as the seat position and angle for passenger locations where the seat position is adjustable. In addition to these standard locations near the ear positions of the occupants, the SPL of the interior vehicle at lower positions near the mid-section or legs of occupants can be observed to have much different levels than at the ear positions. The SPL at these lower positions may not be as important for evaluating the subjective response of the occupants to the interior noise, but it is nevertheless important for evaluating the contribution analysis of the different vehicle subassemblies to the interior SPL at the ear positions and other locations within the vehicle. An example of these lower measurement positions is shown in Figure 2.

There are two different levels of test effort that may be applied to characterize the interior acoustic performance of a vehicle. Testing with microphones at just the ear positions of the driver and at one or more passenger locations checks the performance targets of a vehicle subject to various acoustic sources. But use of additional microphones to characterize the interior sound field gives information not only about whether the ear positions meet the acoustic target, but also indicates the contribution through different subassemblies of the vehicle and shows the dispersal of and variance of the acoustic energy and response within the cabin. This second type of measurement need not be done for every vehicle evaluation, but this type of comprehensive testing performed on a few representative vehicles gives great insight into the vehicle noise transfer paths and acoustic transfer functions and gives the ability to correlate an SEA model that may be used to support NVH design of a wide variety of vehicles of a generally similar body style.

**SEA Model of Interior**. A typical SEA full-vehicle model consists of a cabin interior subdivided into several acoustic SEA subsystems, SEA structural subsystems representing the various structural components, and exterior acoustic SEA subsystems adjacent to the structures. The subdivision of the interior SEA airspaces may be done in several ways; however, selecting interior acoustic SEA subsystem locations on the basis of the structural SEA subsystems to which they are connected and from which energy is transmitted is one accepted and consistent way to subdivide interior spaces. An example of a typical interior subdivision of the acoustic spaces is shown in Figure 3. In addition (not shown in Figure 3), the interior airspace is generally divided into passenger and driver side spaces so that asymmetries in response due to asymmetries in noise sources or transfer paths between the driver and passenger sides can be predicted.

The interior airspaces are connected to each other by coupling factors based on the area of the junction between two adjacent spaces and the impedance of the acoustic spaces.[8] Since the impedance of these acoustic subsystems is generally equal, the SEA coupling factors between the interior spaces is relatively high, and the coupling between the subsystems is considered to be "strong." Historical theoretical formulations of SEA theory have used a "weak" coupling assumption as a necessary condition for SEA theory to be applicable; however, more recent work has demonstrated that having conditions where a single mode does not dominate the response of a subsystem can replace the "weak" coupling assumption for SEA theory to be valid.[9,10]

Additionally, formulating the SEA coupling factors in terms of wave-based parameters rather than mode-based parameters also allows the theory to hold even when "strong" coupling is present. For the vehicle system modeled here, both conditions were met; no single mode dominated the interior acoustic responses for the frequencies studied and the formulation of the SEA coupling factors was wave based.[11] Models of the interior acoustic SEA subsystems have consistently demonstrated the ability to match the measured interior SPL levels at different locations based on proximity to the sources and dominant transfer paths as long as the correct local subsystem damping is specified.[4] The subsystem damping of the interior acoustic spaces is usually dominated by the absorption at the boundaries of the subdivided interior acoustic SEA subsystems.

The vehicle structure is generally subdivided into SEA structural subsystems on the basis of structural elements that have similar material and gage thickness that result in similar impedance and modal characteristics. The majority of SEA structural subsystems for automotive and aerospace vehicles are plate subsystems, although some beam and pipe subsystems are present (such as rails, rockers, and pillars) and are included in the models. When loads are asymmetric or when part of a structure has a damping treatment and the part is untreated, a structure may be further subdivided into additional structural SEA subsystems. However, it is generally desirable to not subdivide structures more than necessary so that the maximum modal density can be achieved in the structural subsystem and SEA assumptions can remain valid to as low a frequency as possible.

The exterior airspaces are generally modeled for the primary purpose of having SEA subsystems to which exterior input loads may be applied, such as tire noise, exhaust noise, wind noise, etc. The secondary purpose of modeling the exterior airspace is to provide a dissipation mechanism by which interior acoustic energy and vibrational energy in the structures can be transmitted or radiated to the exterior of the vehicle. Special care must be taken to realize that the exterior acoustic spaces, like all SEA acoustic and structural subsystems, are assumed to be diffuse and to have acoustic energy and response distributed equally in space throughout the subsystem.

The interior spaces and the vehicle structure generally satisfy this condition. In reality, however, the exterior airspaces rarely have the diffuse characteristic meeting this modeling assumption (except for the special case of testing in a reverberant chamber). Therefore, care must be taken to make sure that acoustic loads applied to the exterior acoustic airspaces are converted to the equivalent load for a diffuse field excitation, with transmission through the structure assumed to be at field incidence (angles in the range of normal to 78°). (This is discussed later in the Analysis Methodology section).

Also, transfer functions from interior locations and structures to nonadjacent exterior locations and transfer functions between exterior spaces in the SEA model are often poorly predicted due to the theoretical diffuse field assumption and the difference between SEA coupling factors and energy transmission versus the direct radiation and diffraction effects that usually control the exterior transfer functions. Measured exterior acoustic transfer functions or direct measurements of the exterior loads on the windows and other parts of the structure resulting from the various acoustic excitations are generally used to overcome this limitation. Analysts are generally advised to not rely on exterior transfer function predictions from SEA without further test confirmation or model refinement.

With the above modeling considerations in mind, an experienced analyst can create a full-vehicle model from a template or "from scratch" within a fairly short time and obtain useful interior level predictions for a range of noise sources as well as an indication of the relative contribution through the different sections of the vehicle. Theoretical changes to different parts of the vehicle may be modeled, and the effect on interior acoustic SPL versus frequency may be obtained in a matter of minutes in many cases with no need for detailed geometry. This prediction capability is especially useful during the concept design phase of a vehicle, where test hardware and other analytical tools are not available or ready for use.[6] SEA analysis also plays a key role at later stages of the vehicle development by exploring which design changes can achieve the component-level and full-vehicle acoustic targets. This complements and can greatly reduce the amount of test effort required. This type of modeling is also useful for cost-reduction studies, since the model can predict which reductions of a sound package are acceptable without significantly impacting the interior acoustic levels.[7]

Although SEA modeling can greatly reduce the amount of time and effort spent on testing, SEA remains complementary to testing, and a minimum amount of testing is needed to give confidence in the model parameters and predictions. The source levels and material damping and absorption in the model are especially difficult to predict theoretically and are important for SEA model accuracy. These are generally obtained by measurement, which may come from a component-level test or from a surrogate or previous-generation vehicle if the current vehicle is still in the concept phase. Although it is not necessary for each vehicle being developed, confirmation of the acoustic and structural-acoustic transfer functions via test allows an SEA model to be validated, leading to higher confidence in the model predictions for design changes as well as serving as a basis for NVH development of similar future vehicles.[4,12]

## Model Validation

**Testing**. The main goals of model testing are:

- To characterize the input power from sources.
- To characterize the subsystem damping of the most important structures and of the interior acoustic spaces (which manifests itself as acoustic absorption).
- To confirm the acoustic-acoustic and structural-acoustic transfer functions.
- To confirm that the model can predict the effect of a design change.

The test source used for this study was a high-frequency volume velocity source, and so the input power is the acoustic power incident on the vehicle from the source. This was measured by a microphone internal to the source and was confirmed via exterior microphones positioned near the source. The transfer functions were measured by multi-channel simultaneous recording of the window vibration responses and interior acoustic responses to the exterior acoustic sources at several locations.

Predicting the effect of design changes, which is necessary to confirm that the SEA model is both correctly predicting the contribution of the dominant paths and correctly predicting the effect of an individual parameter change, was confirmed by selectively covering the windows with heavy layers and by a set of tests comparing transmission through a laminated glass window to the transmission through a non-laminated glass window from a nearby source.

The high-frequency volume velocity source with a known, calibrated acoustic input power was applied at several locations centered outside the windows of the vehicles. The source locations for two positions, outside the front side glass and outside the windshield, are shown in Figure 4 and Figure 5, respectively.

Because the acoustic source acts as a point source for the frequencies from 500 to 6300 Hz and because the source is tested at

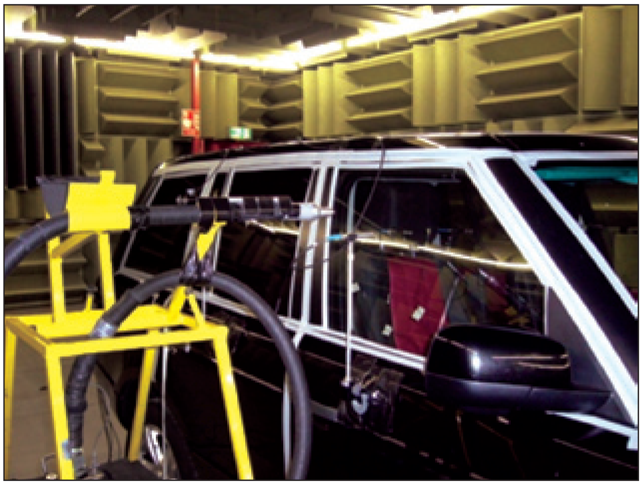

*Figure 4. High-frequency acoustic volume velocity source applied outside vehicle front side glass.*

*Figure 5. High-frequency acoustic volume velocity source applied outside windshield.*

a position normal to the center of the glasses, it is not appropriate in this case to directly apply the calibrated acoustic power from the source to the SEA model. The acoustic input level is calculated based on the source location relative to the glass in a manner described later in the Analysis Methodology section. The source reference microphone and the exterior microphones seen in Figure 4 and Figure 5 are used to confirm the acoustic power of the high-frequency volume velocity source.

For this study, transmission of the sound through the glass was the dominant mechanism of interest. The damping of the glass was a very important SEA modeling parameter and could be obtained via the measurements in one of several ways. The first method is to indirectly infer the damping of the glass by looking at the SEA-predicted interior SPL response due to the transmission through the glass and use the damping as the unknown parameter that can be adjusted within reason to obtain a prediction of the interior noise levels that matches the measurement. However, the correlation of damping using this method is often limited to higher frequencies near coincidence where radiation is a more dominant transmission path to the interior than mass law.

Using accelerometers on the glass allows the damping to be measured more directly by determining the loss factor necessary to obtain the measured structural response when the glass is excited by the high-frequency volume-velocity source with a known acoustic power. An example of the test setup is shown in Figure 6, and the measured acceleration response at three locations on the front side glass is shown in Figure 7, showing little spatial variability of the structural response. This was used to confirm the front side glass damping loss factor for the model, discussed in the Comparing Results section. The structural damping can also be measured directly with a shaker input with known structural

*Figure 6. Three accelerometers mounted on vehicle front side glass.*

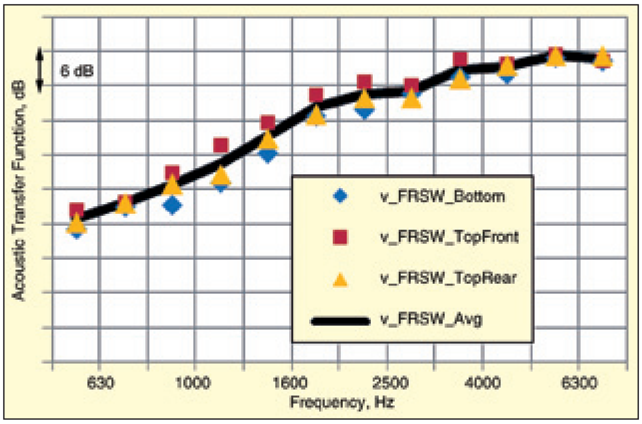


*Figure 7. Response of three accelerometers on front side window bottom, top front and top rear.*

input power or by decay rate testing. However, the high loss factor of the laminated acoustic glass and resulting fast decay made using the decay rate results difficult, and the above methods were instead used to determine the frequency-dependent glass damping loss factor.

The interior acoustic subsystem damping is directly proportional to the absorption, and the headliner, seats, and carpet are usually the dominant contributors to the total interior absorption. The interior absorption was obtained by component-level testing of the absorption of the interior trim. These values were then imported and directly used in the SEA full-vehicle model. A representative test of one of the interior trims (rear carpet) is shown in Figure 8. The measured absorption coefficient of the rear carpet that was directly imported into the SEA vehicle model is shown in Figure 9.

The acoustic interior microphones were described previously. In this testing, microphones were used to capture acoustic transfer functions from the exterior source to the inner and outer ear positions at four occupant positions: driver, front passenger, rear passenger left, rear passenger right. Six other positions at lower and rear interior locations were used to fully characterize the interior sound field, for a total of 14 interior microphones.

As discussed above, the measured interior SPL response varied strongly by location. Figure 10 shows the interior response at the 14 locations where an interior microphone was present. This large measured interior SPL response variability of nearly 24 dB at some frequencies and locations serves as an indicator that subdividing the vehicle cabin into several acoustic space subsystems is appropriate and that the SEA modeling approach described previously is justified.

Representative interior SPL responses for some of the specific interior locations are shown in Figures 11 to 13. For the excitation case of the high-frequency volume velocity source outside the front right side glass, the measured inner and outer ear position SPL for the front left and front right vehicle occupants are shown in Figure 11 and Figure 12, respectively. The front left inner and outer ear responses are generally the same, indicating that there is little spatial variation at this location. In contrast, the front right inner and outer ear responses are markedly different; the outer ear position shows levels 3 to 6 dB higher than the inner ear position, indicating that the direct field contribution from the side glass comprises an important part of the total measured SPL for this location and needs to be accounted for in the analytical prediction, as has been suggested in previous studies.[10]

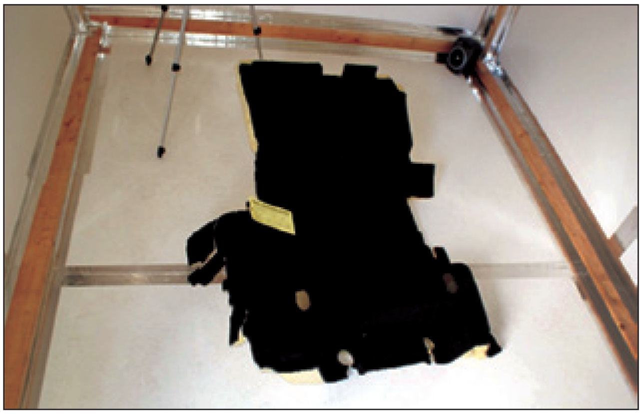

*Figure 8. Measurement of rear carpet absorption in small reverberant chamber.*

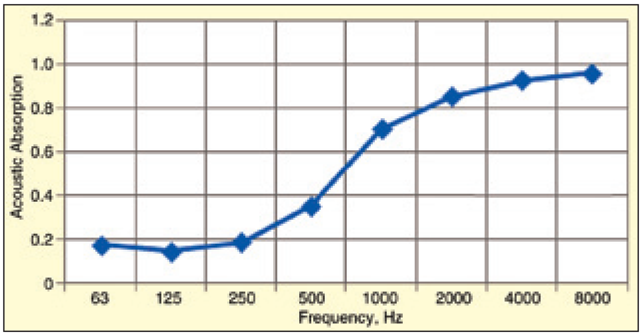


*Figure 9. Measured rear carpet absorption coefficient from testing (applied to vehicle SEA model).*

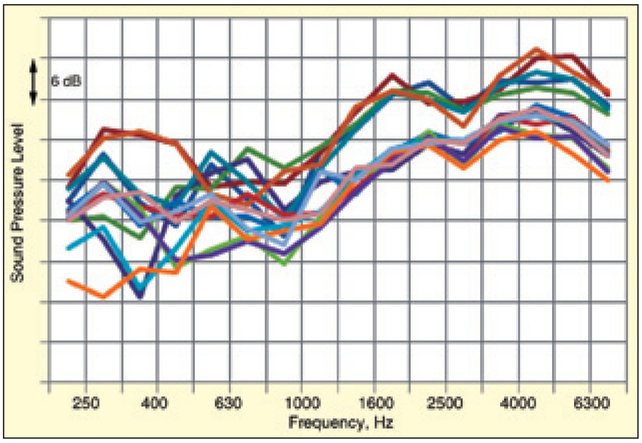


*Figure 10. Measured interior SPL responses at 14 microphone locations for source positioned outside front side glass.*

The SPL response for the same excitation at the front right lower locations, namely the midsection and leg positions, is shown in Figure 13. The midsection location generally has slightly higher response levels due to closer proximity to the side glass. But the levels are fairly similar, which is expected given their distance from the front side glass and relatively close location relative to each other (see Figure 2).

To have confidence in SEA model accuracy, it is usually necessary to validate not only a baseline configuration, but also a series of design changes where permutations of individual parameters of transfer paths allow comparison to the SEA and show whether the effect of the design change can be predicted.[3] The SEA param-

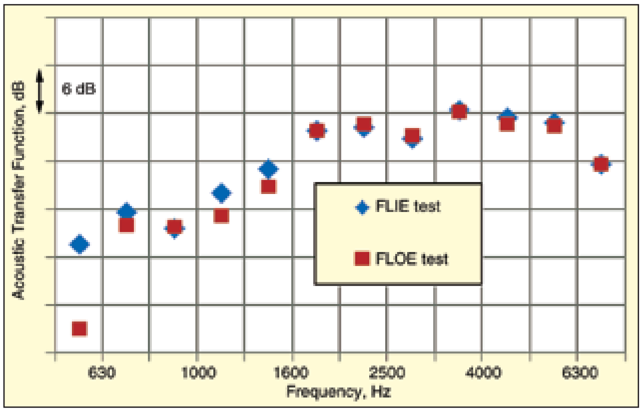


*Figure 11. Measured SPL for front left inner ear (FLIE) and outer ear (FLOE).*

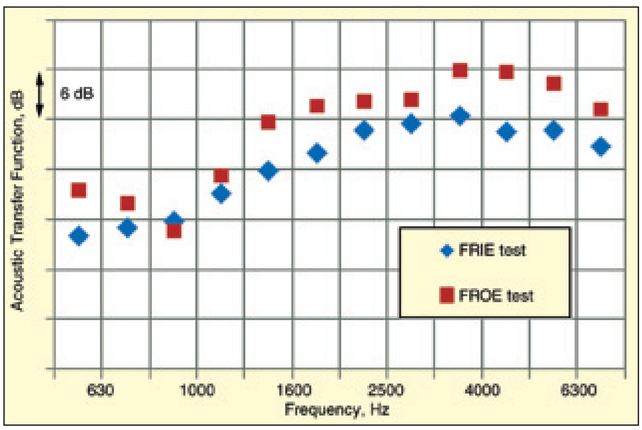


*Figure 12. Measured SPL for front right inner ear (FRIE) and outer ear (FROE).*

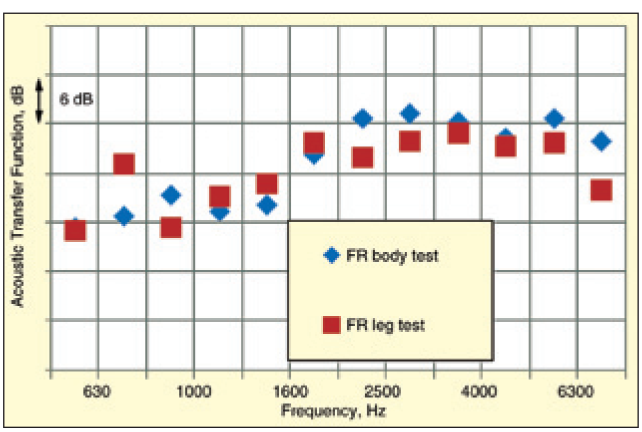


*Figure 13. Measured SPL at lower front-right (FR) locations.*

eters are not always obvious and compensating errors can occur that lead to reasonable correlation to a baseline model but retain errors in the model that manifest themselves when the baseline condition is changed.

High accuracy of the SEA model to predict the effect of a single design change is expected. Inability to predict the direction and magnitude of the change for the frequencies of interest is an indication that the baseline SEA parameters or dominant transfer paths are not being correctly specified or predicted in the SEA model. Testing of the baseline condition as well as configurations with design changes reveals these errors and provides the opportunity to correct and refine the SEA model so that it is properly modeling the most important SEA parameters and has the ability to predict the effects of individual design changes and combinations of design changes.

Windowing testing as shown in Figure 14 is a good way to ensure that the SEA model is correctly modeling the transmission through the dominant transfer paths. With the dominant path blocked, the interior noise is due to the next-most-dominant transfer paths or flanking paths. The SEA model should predict the effect of blocking the most dominant path with a heavy barrier impermeable to sound transmission. If not, then the relative contribution of the main transfer path and next-most-dominant paths is not correct and the model requires revisions.

*Figure 14. Use of heavy layer to confirm effect of blocking dominant transmission path.*

Another practical testing design change is to change the damping or absorption of an important SEA subsystem of the vehicle. Adding or reducing the interior absorption at some locations is an effective way to test the model and is relevant to the different interior noise levels that may be expected for various levels of trim for the vehicle.[12] For this study, a laminated door side glass was replaced with nonlaminated glass so that the effect of the transmission to the interior with a glass with different damping loss factor could be evaluated and the SEA model validated for this change.

## Analysis Methodology

The framework of the analysis for this study was the use of a standard SEA full-vehicle model to generate the results.[8,11] The main considerations for accuracy were proper characterization of input power, damping, and absorption, as described below. For some of the locations that were determined to have a significant contribution from the direct field, further study with an additional contribution from the direct field was considered and calculated in a manner described later in this section.

Because SEA is an energy-based method, the proper specification of exterior input loads in terms of a precise power input is important for prediction accuracy. A high-frequency volume velocity source is ideal for having an input that is omnidirectional at high frequencies and it also provides a calibrated amount of acoustic power. However, it is important to recall that in SEA the subsystems are assumed to be diffuse, and that some adjustment to the input power is needed so that the radiated acoustic power from the source is converted to the correct equivalent exterior SPL for a diffuse acoustic space that is assumed to transmit noise through the structure from normal to 78° (also known as field incidence).

By assuming that the high-frequency volume velocity source is a piston of small area, the acoustic pressure at the surface of the vehicle structural subsystems (such as the glass) may be calculated by the relationship:[13]

$$p(r,t) = \frac{\sqrt{2}\, j f \rho_0 u_0 \pi a^2}{r}\left[\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right]e^{j\omega(t-r/c)} \qquad (1)$$

where:

- $j$ = imaginary unit
- $f$ = linear frequency, Hz
- $\rho_0$ = fluid mass density
- $u_0$ = RMS piston velocity of source
- $a$ = radius of source
- $r$ = distance between source and receiving point location
- $J_1()$ = Bessel function of first order for cylindrical coordinates

$k$ = wave number
$\omega$ = radian frequency
$t$ = time in seconds
$c$ = wave speed of fluid

This equation takes into account both spreading effects and directionality effects from the source to the vehicle surface.

The surface pressure levels calculated using this formula can be converted into the equivalent diffuse field SPL, which is important because different incidence angles have different transmission coefficients, and an acoustic source normal to the glass often has a different range of incidence angles than the range defined by field incidence. If this effect is not accounted for, the transmission through the glass may be overpredicted or underpredicted at certain frequencies even though the correct surface SPL based on Equation 1 is specified as the input load.

The damping of the glass was calculated by means of the method described above in the Testing section. The predicted glass vibration response for a known acoustic input load was compared with the average accelerometer measurements. The damping loss factor is the unknown parameter that is determined empirically as the value for which the prediction and measurement of the glass vibration agree, as seen in Figure 15.

With the correct acoustic input power, structural damping, and acoustic damping (interior absorption values), the SEA interior responses can be predicted with confidence. As seen above in the test data, however, at some locations in the vehicle interior that are near the source and the dominant transmission path, such as the front right inner and outer ear locations when the source is placed outside the front right side glass, there is additional variation between two close locations that cannot be accounted for using an SEA model alone.

There are usually a few locations for which the direct field needs to be accounted for, but these locations may be critical (i.e., driver's ear positions). For these locations the direct field is not negligible compared to the reverberant field and needs to be included in the prediction of SPL to account for the difference in SPL.[10] Equation 2 describes the acoustic pressure of an interior location as a function of a direct radiation term and a reverberant field contribution:[13]

$$|p|^2 = W\rho_0 c\left(\frac{1}{4\pi r^2} + \frac{4}{R'}\right) \quad (2)$$

where:
$W$ = acoustic power, watts
$\rho_0$ = fluid mass density
$c$ = wave speed of fluid
$r$ = distance between source and receiving point
$R'$ = room constant in square meters, defined as:

$$R' = \frac{S\bar{\alpha}}{1-\bar{\alpha}} \quad (3)$$

where $S$ is the absorbing surface area and $\bar{\alpha}$ is the average sound absorption coefficient of the absorbing surface area.

The first term in the parentheses in Equation 2 is the direct-field contribution, and the second term is the reverberant-field contribution. Absorption or $T_{60}$ measurements may be used to obtain the value of $R'$. The distance of the interior point $r$ from the source or dominant transmission path(s) allows Equation 2 to be used to indicate if the direct-field term is not negligible compared to the reverberant field term and needs to be included in the analysis for more accurate acoustic response prediction at a given location.

In this study, the direct field was shown to be not negligible and needed to be included for both of the inner and outer ear locations closest to glass with a nearby acoustic source (see Figure 17). However, including the direct-field contribution was not needed for the majority of the interior points of interest for which the SEA prediction alone proved to be sufficiently accurate.

## Comparing Results

Using the calculated input load at the exterior acoustic SEA subsystems, the correlation between SEA prediction and test was good. The representative set of comparisons between measurement and analysis presented below were all for the case of the acoustic

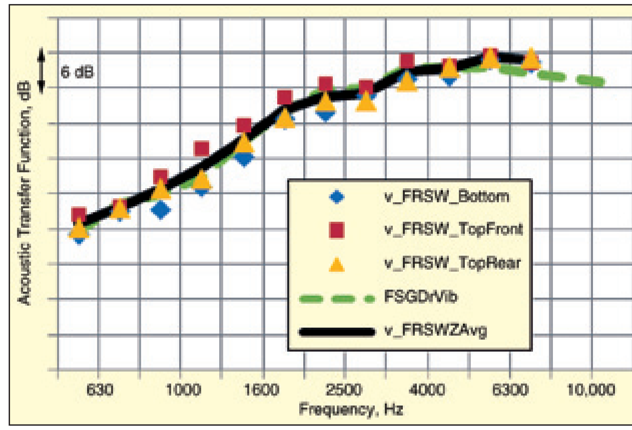


*Figure 15. Measured acceleration with three accelerometers vs. SEA prediction at front side window.*

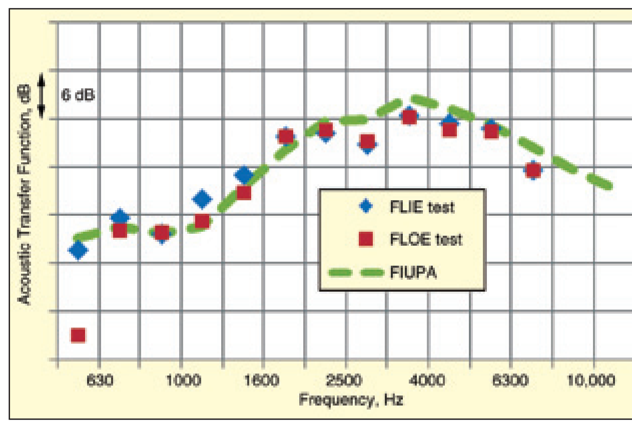


*Figure 16. Measured SPL vs. SEA prediction for front left inner and outer ear.*

excitation at a standoff distance of 300 mm outside the center and normal to the front right side glass. A good first comparison was between the measured and predicted structural response of the glass. The measured glass vibration allowed confirmation of the damping loss factor of the glass and the structural-acoustic junction parameters of the model. The glass vibration levels from three accelerometers on the front side glass and a comparison to vibration prediction from the SEA model are shown in Figure 15.

The front side glass response measured by the three accelerometers in Figure 15 is for a highly damped glass and, as expected, shows little point-to-point variance between accelerometers. The SEA prediction is seen to agree very closely with the measured average acceleration response from 500 Hz and higher, including the higher frequencies where glass radiation is the main contributor to interior noise and has a high degree of sensitivity to the glass damping. The validation of this structural-acoustic transfer function from exterior acoustic space to the glass gives additional confidence in the predicted SEA acoustic-acoustic transfer functions from exterior to interior locations.

For an acoustic excitation outside the front right side glass, the prediction of the front left ear location is the same for inner and outer ear because no direct-field contribution was added to the SEA prediction. This location was far enough from the source and excited front right side glass that the direct-field contribution was minimal compared to the reverberant-field contribution, as seen by the similar acoustic response for inner and outer ear (see Figure 11). The SEA prediction was in very good agreement from 500 to 6300 Hz, rarely more than 1 to 2 dB off from the measured average SPL (see Figure 16).

For the same excitation case, the SEA prediction of the acoustic response of the front right ear location is somewhat less than the measured inner and outer ear SPL when no direct field contribution was added, as shown by the broken green line in Figure 17. However, when the theoretical direct-field contribution is calculated from Equation 2 and added to the SEA acoustic response prediction, the resulting predictions (broken red and blue lines

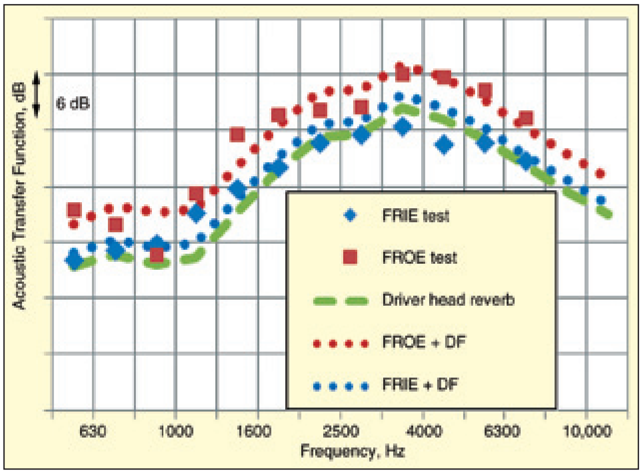


*Figure 17. Measured SPL vs. SEA + direct field prediction at front right inner and outer ear and driver head reverberation.*

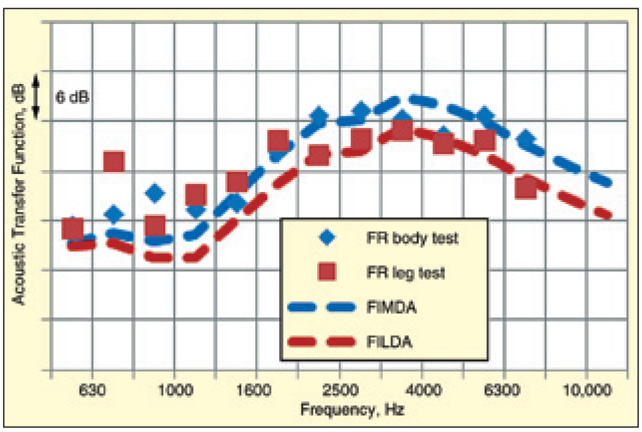


*Figure 18. Measured SPL vs. SEA predictions at lower front-right locations.*

in Figure 17 for outer and inner ear locations, respectively) are in good agreement with the measured inner and outer ear SPL.

Finally, the SEA prediction of the front right lower locations confirms that the SEA full-vehicle model can identify the variation of SPL at other locations in the vehicle due to distance from source and local absorption effects. Figure 18 compares the predicted SPL to the measured SPL at the body (midsection) and leg (lower) positions. The accuracy using just the SEA model for prediction is reasonable and is especially good at the most important frequencies of 2000 Hz and higher. The direct-field contribution was not necessary for these locations; all locations at more than a very short distance from the source and dominant glass show an acoustic response dominated by the reverberant field for most vehicle measurements.

This baseline correlation, along with correlation with changes due to windowing with heavy layers and comparing the transmission through laminated to nonlaminated glass, give confidence in the validity of the SEA model and its ability to predict the effect of further individual parameter studies and combinations of changes. Following the validation, a wide range of design studies can be done with high confidence in the results and can greatly reduce the test effort and quickly provide useful indications of which changes to the vehicle and sound package can most efficiently be made to meet acoustic performance targets.

## Summary and Conclusions.

By subdividing the vehicle cabin into several acoustic spaces, an SEA model can account for the side-to-side, front-to-back, and upper-to-lower variations of interior vehicle SPL that are shown in measured test data from external acoustic sources. The predictions are generally accurate for the different interior locations provided that the input power is correctly measured and calculated. An acoustic point source such as a high-frequency volume velocity source is suitable for confirming the acoustic transfer functions of an SEA model; however, care must be taken to account for the difference between the actual source characteristics and the usual diffuse field acoustic load input common for SEA models. The "strong" coupling between the subdivided interior acoustic space SEA subsystems is permitted because of the assumption that individual modes are not dominating the responses and by the use of wave-based SEA coupling factors.

For many locations in the vehicle cabin at a minimum distance away from the dominant transfer paths and sources, the reverberant acoustic response predicted by the SEA model is in good agreement with the measured and expected SPL. However, for some locations close to the dominant transfer paths and sources, the summation of the theoretical direct-field contribution with the SEA model result can generate a prediction closer in agreement to the measured SPL. This is especially true for outer ear locations when noise transmission through a glass is a dominant contributor to the interior noise, and is also true to a smaller extent for inner ear locations near a glass.

Theoretically, a greater amount of interior absorption reduces the reverberant-field contribution. Therefore, the direct-field contribution can play a greater role, and it may be necessary to include this effect in the analytical prediction for vehicles that have a large amount of interior absorption. Therefore, including the theoretical contribution of the direct field may be more important for luxury vehicles and higher-end trim versions of vehicles that can be expected to have a larger amount of total interior absorption than for an entry-level or baseline trim version of a vehicle.

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