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Determination of In-Cab Sound Paths Using Sound Intensity

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Abstract

To determine appropriate treatments to reduce the airborne sound paths into a vehicle's interior, information regarding the contribution of each path to the interior sound level and the spectrum is required[1, 2]. Historically, this has been determined through windowing studies. In this type of study, all of the potential sound paths are treated with heavy decoupled barrier materials. Sound levels are then measured with the vehicle operating and then with one treatment area at a time removed (a window is opened letting sound enter from one area). At the conclusion of the tests, the contribution from each area to the sound level at a measurement position is known. In this paper, we present an alternate measurement method that combines sound intensity measurements with limited windowing. Here, the major noise paths are treated similar to the windowing process, but now the sound power of each open window is measured using sound intensity. The sound power is then propagated to receiver locations based on the in-cab room constant. By using this technique, the number of windowing treatments can be reduced, which significantly reduces the testing time. This technique also makes it easier to model the effects of adding interior sound absorption.

1. Introduction

Although the windowing technique can work well for many applications, there can be many drawbacks. The time required to appropriately treat the vehicle interior and perform all of the tests can be long. Sound pressure levels must be made at all receiver positions of interest during the testing. It is difficult to model the effects of added sound absorption, and care must be taken to treat all of the possible noise paths. If, for example, one of the dominant paths is the windshield, it becomes very difficult to treat this source during on-road testing. Another issue occurs with relatively low production volume vehicles. Testing is often performed on a vehicle that will later be sold, so great care must be taken not to damage any of the interior finishes. By measuring the sound power level of each of the open windows using a sound intensity system in addition to the sound level at a receiver position, such as the operator's ear, these drawbacks can be significantly reduced.

Measuring in-cab sound intensity levels is not new[3-7]; however, its use in combination with limited windowing, especially outside of the passenger car industry, appears unique. The use of limited windowing simplifies the acquisition of accurate data and in large vehicles makes it possible to acquire on-road as well as stationary data. Without limited windowing, sound intensity measurements must be made very close to each surface to achieve the necessary signal-to-noise ratio (δ_{PI}, pressure intensity index). With near field sound intensity measurements, the reactivity of the sound field must also be taken into account. Using limited windowing improves the signal-to-noise ratio of non-dominant paths, which allows the intensity measurements to be made at a greater distance from the surface, thus reducing the potential for non-propagating acoustic modes to dominate the measurements.

2. Measurement Theory

With this procedure, a cab interior is typically divided up into 16-20 surfaces and each of the dominant sound paths (floor, engine cover, dash, etc.) is then treated. Limited testing may be necessary to define the paths that will require treatment. The sound power level of each of the surfaces is calculated using equation 1. While the negative sound intensity is useful for understanding the sound field inside the cab, we are only interested in the sound that propagates from the measurement surfaces to the various receivers. Therefore, only the positive sound intensity is accounted for in this equation.

$$\text{Sound Power } (L_w) = \text{Positive Sound Intensity } (L_I) + 10*\log_{10}(\text{Surface Area}) \qquad (1)$$

Modeling the cab interior as a small room, the sound power level from each surface is then propagated to each receiver location using equation 2. If a partition or other vehicle component blocks the line of sight between the source and the receiver, an empirically derived correction factor (K) is applied, otherwise this correction factor is zero.

$$\mathrm{Lp_i} = \mathrm{Lw_i} + 10\log_{10}\left[\frac{Q}{4r^2\pi} + \frac{4}{A}\right] + K \qquad (2)$$

where: r = the distance from the measurement area to the receiver position, usually the driver's ear
A = the total sound absorption in the cab
Q = the directivity factor (in this case $Q = 2$)
K = a correction factor based on line of site to the receiver

The contribution from each area is then logarithmically summed to determine the level at the driver's ear. The room constant, the total sound absorption in the cab, (A) from equation 2 is related to the absorption in the cab by equation 3.

$$A = S\overline{\alpha} \qquad (3)$$

where: S = *the interior surface area*
$\overline{\alpha}$ = *the average absorption coefficient*

The room constant is calculated based on the measured in-cab reverberation time. To do this, a small loudspeaker is placed at several locations while a microphone is placed at the receiver position. Random noise is then generated and played through the loudspeaker and abruptly turned off through software controls. The decay rate is then measured and the reverberation time is displayed based on the T_{20} or T_{30}. The room constant is then calculated from equation 4.

$$A = \frac{0.161 * V}{T_{60}} \tag{4}$$

where: V is the interior cab volume

Care must be taken to insure that the measured sound decay is from the cab interior sound field and not a function of the speaker response. With typical reverberation times ranging from about 0.2 to 0.5 seconds, it is easy to have the microphone in the direct field of the loudspeaker. Sometimes the total sound absorption in the cab is adjusted according to Norris Eyring equation or other accepted theories.

In developing these equations we are assuming, for engineering analysis, that the cab volume and typical dimensions are large enough to provide a diffuse enough field, and that the surfaces approximate point sources. We must also be concerned with the modal response in the cab. If for example, the receiver position is located at a node, our predicted sound level may be much higher than that actually measured. For this analysis, our low frequency limit is based on the modal response of the cab, the microphone spacing used with the sound intensity probe, and the measured pressure intensity index. Using the engineering criteria of requiring an overlap of three modes, the low frequency limit (f_l) can be calculated from equation 5.

$$f_l = 2100\sqrt{\frac{T_{60}}{V}} \tag{5}$$

For heavy trucks and motor homes, the interior volume ranges from about 10 m^3 to about 50 m^3 and the reverberation time ranges from about 0.2 to 0.5 seconds. This gives us a practical lower frequency limit of about 250 Hz, matching the practical lower frequency limits for a sound intensity probe with 12 mm microphones and a 12 mm spacer, and the performance limits for most conventional absorbers and decoupled barriers.

Once a model is developed based on summing the sound pressure level contributions from all of the measurement surfaces, the effects of adding noise control treatments or altering the construction materials of the cab can easily be determined and a treatment package optimized. By increasing the room constant, the effects of adding sound absorption can be modeled. This is critical in many medium and heavy duty truck studies since the interiors of these vehicles are not typically very sound absorptive.

3. CASE STUDY

In this case study, we present the results of our measurements and modeling in a large truck cab. The purpose of the study was to determine the sound level contributions from each of the interior surfaces to the sound level at the driver's ear with the vehicle operating on road at 55 mph. Using this information, a noise reduction treatment package was developed to achieve "best in class" sound levels and sound quality. Instrumentation used for the measurements included a B&K Portable Pulse analyzer, and a B&K 3584 sound intensity probe with a 4197 sound intensity microphone pair and 12mm spacer. The cab interior was divided into 16 sections and scanned using the procedures outlined in ANSI S12.12-1992. Sound pressure level measurements and in cab reverberation time measurements were made using a B&K 2260 Sound Level Meter with the BZ7210 Basic Sound Analysis and BZ7204 Building Acoustics Software.

The sound power levels and associated sound propagation parameters were input into our Source Identification Model. This model, based in Excel, then provides a rank ordering of the various sound paths according to the A-weighted sound level contribution at the driver's ear or various other metrics. Results of the baseline measurements are shown in Table 1.

Table 1. Source Rank Order

Baseline		
Location	**Level (dBA)**	**Rank**
Left Side Floor	70.0	1
Right Side Floor	67.9	2
Middle Floor	67.7	3
Drivers Side Step Well	65.0	4
Engine Cover	65.0	5
Passenger Side Step Well	64.6	6
Drivers Door	61.4	7
Backwall	60.1	8
Passengers Door	59.8	9
Drivers Dash	57.1	10
Passengers Dash	56.3	11
Drivers Side Backwall	56.1	12
Passengers Side Backwall	55.6	13
Roof Middle	55.1	14
Roof Back	54.3	15
Roof Front	45.4	16
A-Weigthed Level (dBA)	**75.7**	
Articulation Index (%)	**29.5**	
SIL (dB)	**65.3**	

The model also provides the one-third octave band sound pressure levels from each surface. This is necessary for the selection of appropriate noise control treatments. The spectrum from each of the sources presented in Table 1 is shown in Figure 1. For this particular cab the predicted A-weighted sound level was 0.2 dBA lower than the measured level. The predicted $1/3^{rd}$ octave band sound pressure levels differed from the measured levels by up to 2.5 dBA; but are generally within about 1.0 dB. This data, however; was acquired on road with many uncontrollable elements. Such variation is well within acceptable limits for engineering studies.

Based on the source path ranking, one can see that the cab floor, step wells, and the engine cover were the dominant noise paths. It is important to note that this rank ordering is based only on the A-weighted sound level. From Figure 1, we can determine the dominant sources for each one-third octave band. By reducing the radiated sound power level of a surface based on the increase in sound transmission loss provided by a new material, the resulting sound pressure level at the driver's ear can be predicted. In addition, an increase in sound absorption is easily modeled by increasing the total sound absorption in the cab by a fixed amount. Based on customer input, a treatment package was developed. The predicted results are presented in Figure 2. Actual measured results correlated well with the predicted results.

Except for the ease in modeling the effects of increased or decreased sound absorption, much of the same results could have been determined through windowing. However, with windowing, the preparation would have been much more difficult and data acquistion time would have been much greater. This type of study typically takes two people only one day to prepare the test vehicle and obtain all of the measurment data. With a windowing study, the preparation and data acquistion takes about 1 week.

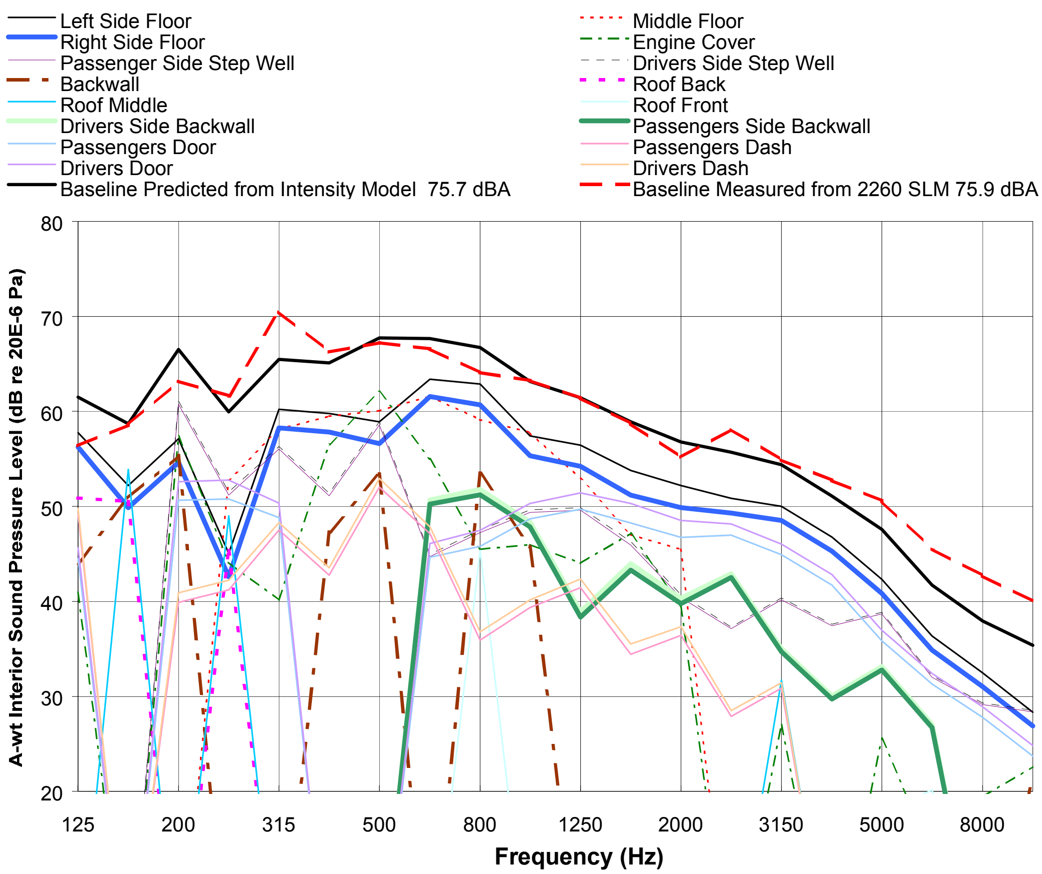

Figure 1. Baseline Driver's Ear Analysis Airborne Path of Correlation for the Sound Intensity Model vs. Measured Sound Pressure

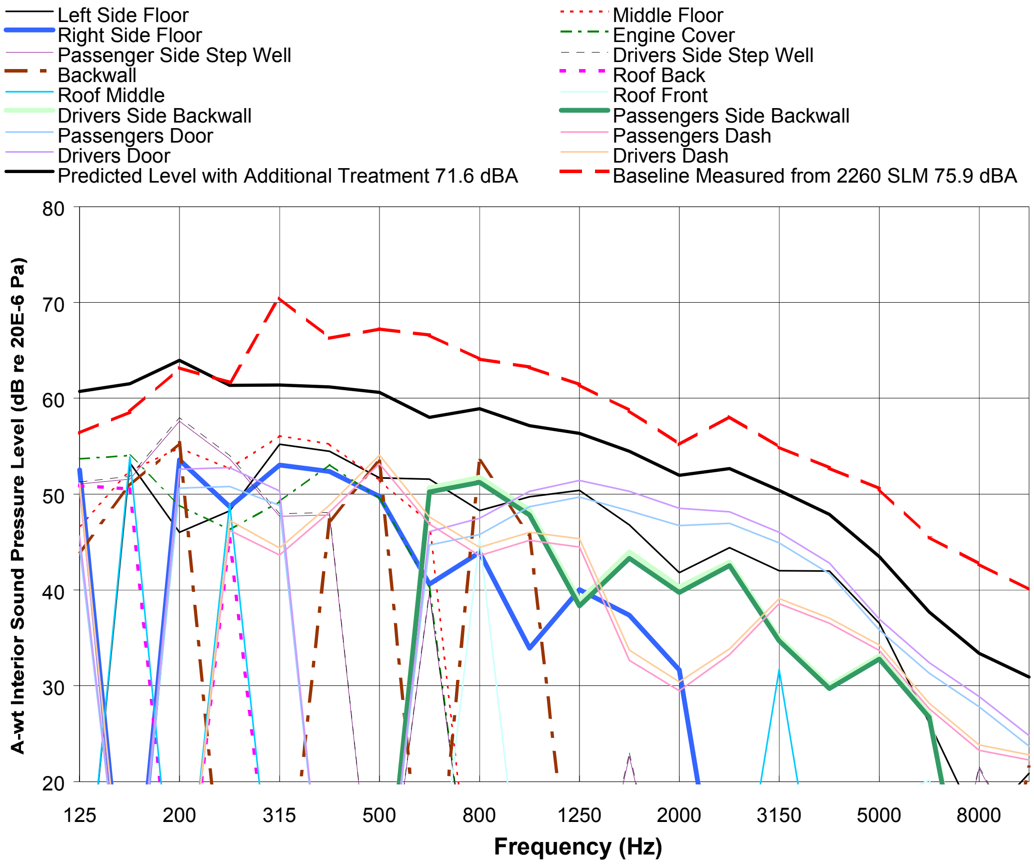

Figure 2. Recommended Acoustic Package Driver's Ear Analysis of Airborne Path Correlation for the Sound Intensity Model vs. Measured Sound Pressure

References

1. Charles T. Moritz, Acoustical Selection of Class 8 Truck Floormats, SAE Paper 1999-01-1688.
2. Charles T. Moritz, Jeff A. Kleckner and Pranab Saha, Development of Quiet Sound Package Treatments for Class 8 Trucks, SAE Paper 2001-01-1541.
3. Shuji Hata, Mutsumi Takahashi, Naomasa Utsunomiya and Hideaki Sakata Application of Acoustic Intensity Measurement to High Frequency Interior Noise, SAE Paper 830342.
4. Shaobo Yang, Jian Pan, Prakash Sabnis, and Ashok Khubchandani, Determination of Vehicle Interior Sound Power Contribution Using Sound Intensity Measurement, SAE Paper 971907.
5. Robert Hickling, Peng Lee, Alexei Goumievski, and Wei Wei, Determining Sound Power for Automotive Applications, SAE Paper 972037.
6. L. E. Schroeder, Feasibility of Using Acoustic Room Models and Measured Sound Power to Estimate Vehicle Interior Noise, SAE Paper 2001-01-1533.
7. L. E. Schroeder, Visualization of Truck Interior Noise, SAE Paper 2001-01-2808