

# Evaluation of Ground Vehicle Wind Noise Transmission through Glasses Using Statistical Energy Analysis

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## ABSTRACT

The contribution of wind noise through the glasses into the vehicle cabin is a large source of customer concern. The wind noise sources generated by turbulent flow incident on the vehicle surfaces and the transmission mechanisms by which the noise is transmitted to the interior of the vehicle are complex and difficult to predict using conventional analysis techniques including Computational Fluid Dynamics (CFD) and acoustic analyses are complicated by the large differences between turbulent pressures and acoustic pressures. Testing in dedicated acoustic wind tunnel (AWT) facilities is often performed to evaluate the contribution of wind noise to the vehicle interior noise in the absence of any other noise sources. However, this testing is time-consuming and expensive and test hardware for the vehicle being developed is often not yet available at early stages of vehicle design. In addition, modifications of the vehicle exterior geometry that may be beneficial to interior noise are often difficult to implement during the testing or to evaluate properly via test. This paper describes a test-based approach to measuring and understanding the contribution of exterior wind noise to the interior cabin noise through the individual glasses and the development of a correlated Statistical Energy Analysis (SEA) model capable of predicting the effect of a design change to any combination of thickness or material changes to the glasses. AWT testing was performed with interior microphones, accelerometers on the glasses, and arrays of flat exterior pressure transducers to establish the acoustic and structural-acoustic transfer functions to the interior. An underbody skirt, extensive taping of exterior gaps, and "blocker" parts on the interior of the glasses were used in order to isolate the noise contribution through individual glasses. Two versions of the front side glass -monolithic and laminated - were tested to compare the effect of the glass material and damping on transmitted wind noise and to provide a reference from which the wind noise load at this important location could be inferred. The data set from this testing was processed and used to correlate an SEA model of the test vehicle capable of being used for design studies of the effect of the glasses on the interior wind noise.

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## INTRODUCTION

Vehicle NVH testing and development have shown that vehicle glasses are often the dominant wind noise transmission paths to the interior due to the lack of sound package on the glasses and the locally high wind noise sources due to reattachment of mirror wakes, pillar wakes, and other flow reattachments. As a result, many vehicle manufacturers have adopted acoustic laminated glasses as a replacement for monolithic glasses at locations where wind noise transmission is dominant, especially windshield and front side glasses, in order to reduce interior levels to meet wind noise attribute targets. Acoustic wind tunnel testing allows the opportunity to evaluate vehicle interior noise due

solely to wind noise sources, but it is expensive to run all the test configurations needed to fully understand the effects of various design changes. A simulation model is needed that accounts for both structural and acoustic inputs from wind noise turbulence through each of the vehicle glasses. As part of an overall model of the vehicle, the turbulent input model provides the ability to study vehicle glass design changes along with structural design changes. A statistical energy analysis (SEA) model is well suited to this application because it is accurate and efficient in the frequency range of interest and it inherently handles the statistical nature of turbulence.



**Fig. 1. Standard Test Setup for Vehicle in Acoustic Wind Tunnel with all Seals and Edges Taped and Underbody “Skirt” In Use**

The turbulent input SEA model must be validated with wind tunnel testing to ensure proper handling of the noise generation mechanisms, both structural and acoustic. Acoustic wind tunnel testing always evaluates the interior noise levels at critical locations such as front passenger or rear passenger ear positions for one or more operating speeds and yaw angles. However, more detail is needed to validate the SEA model. The two types of transmission through vehicle glasses can be categorized as structural and acoustic. Structural transmission involves excitation of the resonant modes in the glass by the exterior turbulent pressure field, and then subsequent acoustic radiation into the vehicle interior. Acoustic transmission is so-named because the structural vibration modes of the glass are not excited. The energy from the exterior turbulent pressures is transmitted directly through the mass of the glass to the interior through ‘mass-law’ transmission. Separation of these two paths of transmission in acoustic wind tunnel (AWT) testing requires more information than is normally collected.

Three measurement types are required during wind tunnel testing in order to fully validate the SEA turbulent input model: exterior pressure, interior pressure, and glass vibration. The exterior pressure measurements are used to define the input load to the exterior acoustic spaces in the SEA model. The interior pressure measurements are used to validate the overall prediction of interior noise by the full vehicle SEA model. Vibration measurements on the vehicle glasses are compared to the predicted glass vibration in the SEA model in order to validate the structural excitation path. Because the SEA model uses spatial averages to define the vibration and pressure fields, a relatively small number of measurements are taken in the interior of the vehicle and on the vehicle glasses. A significantly larger number of pressure measurements are taken on the exterior of the glasses to define the turbulent input since turbulent input loads are still not well understood.

A full vehicle SEA model previously correlated from laboratory measurements with a known and controlled acoustic source [1] was used in conjunction with the turbulent input SEA model and the acoustic wind tunnel test data in order to understand the wind noise transmission mechanisms, which may have both structureborne (direct glass excitation) and airborne (acoustic sources in the turbulent flow) components. The SEA model also allows the correlated contribution through each of the dominant glasses from the test data to be modeled and for design studies to be performed to evaluate the impact of a change to one or more glasses or to one or more glass wind noise loads (due to a form change). The SEA model supports understanding and interpretation of the test data, allows the performance of useful analytical studies, [2,3] and reduces the overall acoustic wind tunnel testing needed for vehicle NVH development.

## ACOUSTIC WIND TUNNEL TESTING

A test vehicle was prepared for the acoustic wind tunnel testing with a standardized preparation technique involving taping all seals and edges of the doors, glasses, hood, and tailgate. For the majority of the testing, the wheels and underbody were also blocked through the use of an underbody “skirt” taped flush to the vehicle and floor so that flow underneath the vehicle was minimized. This standard testing configuration is shown below in [Figure 1](#).

To remove a main source of flanking path noise transmission and allow the testing of wind noise contribution through individual glasses, heavy “blocker” parts were applied to all of the vehicle glasses [4]. These custom-designed parts were of a surface density approximately equal to the glasses being blocked and were taped around the edges to the inside of the window frames with a 50mm thick decoupler foam layer between barrier and glass to provide additional noise attenuation and minimize the noise leakage.

An interior view of the test vehicle with these window “blocker” parts installed can be seen in [Figure 2](#).



**Fig. 2. Front Side Glass Interior View of “Blocker” Parts**

## Transducer Positioning

Acoustic wind tunnel test results may be comprised of just interior SPL data for benchmark vehicle wind noise evaluation. However, since one of the main goals of this study was to improve understanding of the noise transmission mechanisms of turbulent flow to vehicle interior, measurement of the fluctuating exterior pressures was important. An array of thin, flat pressure microphones was mounted on the vehicle glasses and shifted to different locations to measure the fluctuating pressure at a large number of spatial locations on the glasses. The microphones were mounted in rubber skirts which were taped to the window glass to minimize flow disruptions. The location of all exterior pressures measured on the front side glass and those tested during one representative test run are shown in [Figure 3](#).

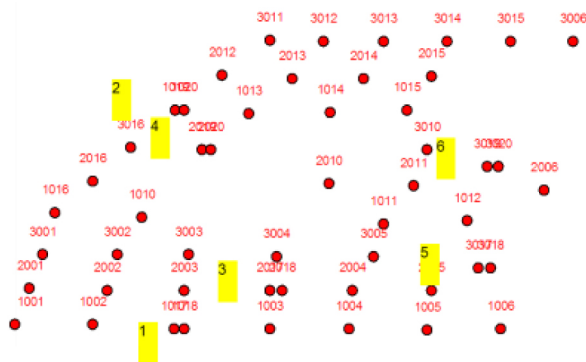


**Fig. 3. Exterior Pressure Transducers on Front Side Glass: Highlighted Yellow Numbers Indicate Microphone Pairs**

Measurement of glass vibration is generally not of primary concern compared to the interior noise. However, wind noise sources consist of both structureborne and airborne components and at many frequencies the direct

structural excitation of the glass from the turbulent flow is important, since the glass then radiates into the interior. In order to validate both the structural and acoustic turbulent input mechanisms in the SEA model, vibration measurements were crucial to this study. To measure the vibration, lightweight accelerometers were mounted at several points on the windshield, front and rear side glasses, and sunroof glass. The accelerometer positions on the front side glass are shown in [Figure 4](#).



**Fig. 4. Lightweight Accelerometer Mounting Positions on Front Side Glass**

Lastly and most obviously the interior acoustic response was measured at the different operating speeds and yaw angles. In addition to the standard ear positions for the four seat positions, extra microphone positions such as passenger foot area and passenger knee area were used in order to better understand the interior SPL distribution within the cabin and determine the contribution strength of non-glass paths in the lower part of the vehicle.

## Exterior Pressure Test Results

The exterior fluctuating pressures varied widely even across the same glass surface, particularly for the front side glass. [Figure 5](#) shows a selection of measurements from the front side glass that vary over a range of 20 dB. The lowest measurement is in the reattached boundary layer region (point 3019 in pair 6) and the highest measurements are in the A-pillar reattachment region (high frequency peak, point 2016) and the mirror reattachment region (low frequency peak, point 1003).

The measurements can be grouped into categories based on their location within the expected turbulence regions. The three regions shown in [Figure 6](#) have different levels and frequency characteristics. In the two wake regions, the frequency of the peak corresponds to the scale of the impingement structure. The peak in the A-pillar wake spectrum is at a higher frequency due to the smaller scale of the A-pillar turbulence as compared to the mirror turbulence. The overall levels for the two wake regions are similar. The