

New Windshield Improves Vehicle Interior Cabin Noise and Articulation Index

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Acoustics plays an ever-increasing role in the automotive industry, particularly in the quest for a quieter passenger cabin. Consumers equate quiet with quality, as shown in the J.D. Power and Associates 2002 Vehicle Acoustics Study, and the OEM that can provide a quieter passenger cabin will gain a competitive edge in the marketplace.

One new factor contributing to consumer demand for quieter vehicles is the increasing use of telematics within the vehicle including voice-activated technology and cell phones. It is now important that OEMs examine all possible ways to reduce road and wind noise as well as structure-borne noise penetrating the cabin to levels where the human ear can easily and comfortably hear speech.

The intelligibility of speech is defined as the accuracy with which a normal listener can understand a spoken word or phrase. Speech has a dynamic range of about 30 dB in each 1/3-octave band from 200 to 6000 Hz, and the long-term rms overall sound pressure level at the speaker's lips is about 65 dB. The Articulation Index (AI) is a measure of speech intelligibility in continuous noise. It ranges from 0 to 1, corresponding to 0% and 100% intelligibility, respectively. AI determines a ratio between the received speech signal and the level of interfering noise. Speech intelligibility is based on this signal-to-noise ratio, which is determined by calculations within 18 1/3-octave bands or other appropriate methods described in ANSI S3.5. A higher ratio indicates greater speech intelligibility. For example, AI of 0.3 or below is considered unsatisfactory; 0.5 to 0.6 is satisfactory; and greater than 0.8 is excellent.

Within every acoustic environment, there is always a certain degree of ambient background noise present that interferes with the speech signal. This reduces the signal-to-noise ratio and the receiver must significantly concentrate on the speech in order to hear it with any degree of accuracy. Therefore, reducing noise entering the cabin that is contributing to ambient noise would be beneficial in enhancing speech intelligibility.

While many vehicle manufacturers include noise-reducing structures and packages in the production phase of the vehicle, a pervasive weak link in Noise Vibration and Harshness (NVH) solutions for vehicles is the glass. In particular, the vehicle's windshield. Previous efforts of the automotive industry to improve cabin NVH have rarely focused on designing the windshield for improved interior acoustics.

Acoustic energy can be transmitted rather easily through the vehicle's windshield compared with other passenger compartment boundaries. At high operating speeds, strong aerodynamic pressure fluctuations around the windshield cause the glass surface to radiate noise to the vehicle's interior. In addition, impinging airflows on panel edges and bends in the vehicle's exterior can generate acoustic noise with subsequent transmission to the vehicle interior. The transmission of airborne noise generated by adjacent moving vehicles and structure-borne noise created by structural vibrations of the car body contribute to the noise transmission of windshields. Given this information, automotive glazing now becomes a primary focus as a transmission path to the vehicle interior for road and wind noise, external airborne noise and structure-borne noise.

The standard laminated glass windshield was first introduced for the safety benefit of providing occupant retention in the event of a crash. It also has proven vibration damping characteristics. Laminated glass consists of a 'sandwich' of a tough, polyvinyl butyral (PVB) interlayer bonded between two sheets of glass under heat and pressure. The PVB interlayer damps vibrations in the glass and, in automotive applications, produces a significant reduction in road and wind noise. Remarkably thin, the 'sandwich' ranges between 3.8 to 5.2 mm in thickness, depending upon its application, and weighs about 11% less than tempered glass of similar thickness. This weight reduction becomes important in overall vehicle design given OEMs' concern with vehicle weight.

The typical approach for an acoustics solution with glass is to increase the thickness of the glass. Yet, this approach provides limited benefits in terms of attenuating cabin noise and is not a viable solution based on the weight and fuel economy concerns of the automotive industry. With the increasing demand for even quieter automotive interiors without adding weight to the vehicle, there is a strong demand for improved control of NVH via the windshield through product design at equivalent or lesser weight than that of standard windshields.

The acoustic performance of tempered glass and standard windshields made with PVB can be characterized by the Sound Transmission Loss (STL). The STL of tempered glass alone of varying thickness corresponds to the basic sound transmission behavior of a sound barrier with the response at low frequencies be-

ing determined by the panel's static stiffness. Since glass reacts best to excitation frequencies that match its natural frequencies, the low internal damping of tempered glass produces resonances that dramatically decrease STL. Sound transmission follows the mass law of acoustics above the resonant frequencies and is dictated by the mass or surface density of glass. In this mass-controlled region, the transmission loss increases approximately 6 dB by doubling its surface density or frequency.

However, glass has a specific coincidence frequency at which the speed of airborne incident acoustical waves match that of the glass bending wave. At the coincidence frequency, the acoustic wave is especially effective at causing glass to vibrate, which makes the vibrating glass an effective sound radiator at that specific frequency and above. As a result, glass becomes less of a barrier to sound and exhibits a transmission loss dip, or so-called coincidence dip. This phenomenon shows significant deviation from the mass law because increasing the thickness of the glass does not effectively address the coincidence dip.

Standard windshields made with a PVB plastic interlayer exhibit sound transmission behavior similar to that of tempered glass. While the presence of a standard PVB interlayer reduces the coincidence dip of glass, the coincidence dip remains present and considerable deviations from the mass law exist. As the coincidence dip occurs in the frequency range of 1500 to 5000 Hz, where wind noise is typically heard and speech intelligibility is greatly affected, standard windshields have less than desirable acoustic performance, especially in terms of speech intelligibility.

When the sound transmission behaviors of two windshield constructions were compared – a thicker and heavier laminate with a thinner and lighter laminate – the thicker laminate, while better at low- to mid-frequencies, was not significantly different from the thinner laminate at frequencies of 1500 Hz and above. The coincidence dip affects the transmission of wind noise, airborne noise and road noise. Therefore, increasing the thickness of the interlayer provides little acoustic improvement.

A further assessment of vehicle interior noise was gained by evaluating the interior sound spectra of a class E passenger sedan at the front passenger headspace, which was recorded at ambient temperatures at various vehicle-operating speeds. Of particular interest is the increase of wind noise in the frequency range from 1000 to 6000 Hz at higher speeds (Figure 1). The transmission of high-frequency wind noise correlates well with the low STL performance of standard windshields resulting from the coincidence effect. This further points to the windshield as one of the critical paths for

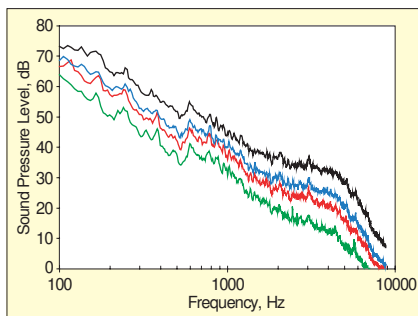


Figure 1. Front passenger seat headspace noise spectra at vehicle operating speed of 72 (green), 105 (red), 121 (blue) and 161 kmph (black). The vehicle was equipped with a standard windshield.

transmitting wind noise and external airborne noise.

In summary, standard windshields have two fundamental problems with regard to sound transmission – vibration at resonance frequencies in the low frequency region where glass transmits structure-borne noise and the coincidence effect which affects the ability of the windshield to attenuate high frequency noise. Increasing the thickness of either the glass or the interlayer does not address these problems effectively. Therefore, in order to create an appropriate NVH solution for the windshield, the underlying principles governing sound transmission through windshields must be examined.

The sound transmission and dynamic response characteristics of structures are essentially determined by mass, stiffness and damping. Mass and stiffness are associated with the storage of kinetic and strain energy, respectively, and damping relates to the dissipation of energy and to the conversion of mechanical energy associated with vibration to heat. For standard windshield constructions, mass is primarily determined by the thickness of the glass and stiffness by the thickness of the glass and the properties of the interlayer. Damping is based on the interlayer dynamic mechanical properties such as loss factor and shear storage modulus, separately.

Studies have shown that damping is a good mechanism for noise attenuation. Damping in the windshield depends on the properties of the interlayer, which are temperature and frequency dependent. Thus, in order to increase windshield acoustics performance, it is necessary to design a new interlayer that meets certain performance criteria.

To design a new interlayer, the primary parameters considered by researchers at Solutia Inc. include interlayer dynamic mechanical properties, damping properties of PVB glass laminates, interactions of acoustic waves on windshields, and frequency and service temperature range of interest. It is therefore important to design the new interlayer with a large loss factor and proper modulus, given the frequency and service temperature range of

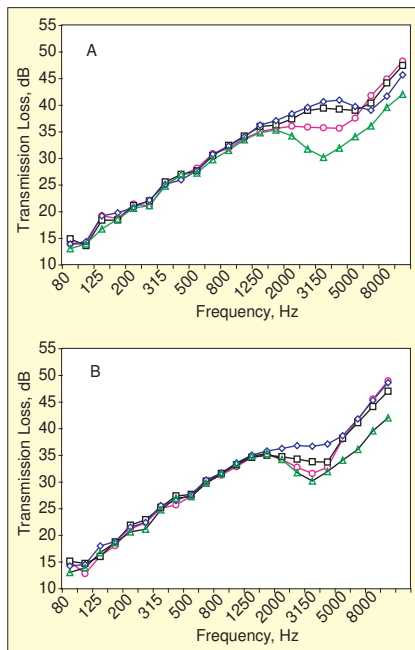


Figure 2. Sound transmission loss performance of laminated glass per ASTM E90 at 10°C (red), 20°C (black) and 30°C (blue): (A) Vanceva™ Quiet PVB, (B) standard PVB, laminate configuration is 2.1 mm glass/0.76 mm interlayer/2.1 mm glass. A 4.8 mm monolithic glass (green) is used for reference. Test panel size is 47 × 74 cm.

interest. Additionally, windshields made with the new interlayer need to meet the automotive industry's impact-resistance safety requirements. This limits the freedom to choose proper viscoelastic polymer materials and thereby increases the difficulty in designing the interlayer.

In addition, the new windshield must be optimized and aligned with human perception of automotive interior noise and acoustical comfort. The most sensitive frequency range for human hearing is about 100 to 4000 Hz, which is also the frequency range humans mainly use for verbal communication. The voice recognition range is from 100 to 8000 Hz, with 95% intelligibility at 500 to 8000 Hz, and 60% intelligibility at 1000 to 6000 Hz.

Vanceva™ Quiet, Solutia's new acoustical grade interlayer, meets the primary objective of a new interlayer for windshields. It dramatically improves the acoustical performance over standard windshields, especially coincidence effects and resonant vibrations.

When the sound transmission behavior of the Vanceva™ Quiet acoustical and standard windshields are compared, the interlayer has a pronounced effect on the coincidence effects of glass. While the standard interlayer improves glass STL by as much as 4 dB over tempered glass, the acoustical interlayer adds an additional 5 to 6 dB improvement. Suppression of the coincidence effect is beneficial to wind noise reduction and external airborne noise reduction.

The Vanceva™ Quiet interlayer's high damping characteristics improve glass performance with respect to sound trans-

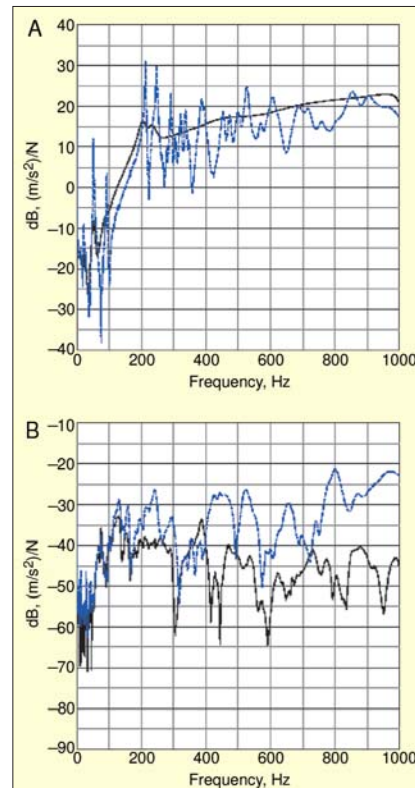


Figure 3. Comparative FRFs of VQ PVB windshield (black) vs. standard PVB windshield (blue): (A) in free-free conditions, windshields were excited by direct impact; and (B) installed on car, windshields were excited via engine vibration.

mission in two important areas. First, the acoustical interlayer reduces overall bending stiffness of the laminate and affects the acoustic impedance of each glass layer. The equivalent coincidence frequency of the laminated glass is shifted to a higher and less important frequency range. When the outer glass layer is driven by bending waves, the viscous interlayer creates shear strains within itself, and the interlayer transforms the bending wave energy of glass into heat energy. This results in a reduction of sound transmission at the coincidence region, which significantly reduces this effect. Second, resonant vibrations of glass at low frequencies are greatly influenced by the interlayer and are characterized by much broader and lower amplitude vibrations when compared to glass (Figure 2).

A simple modal analysis of a windshield made with the Vanceva™ Quiet acoustical interlayer vs. the standard windshield was performed in a semi-anechoic room by impact tests in free-free conditions in which windshields were suspended. Vibration frequency response function (FRF) measurements of the two windshields installed on vehicles were also performed. The installed windshields show a difference in damping above 100 Hz (Figure 3).

The vibration damping of the two windshields was further studied in an engine run-up experiment in which the

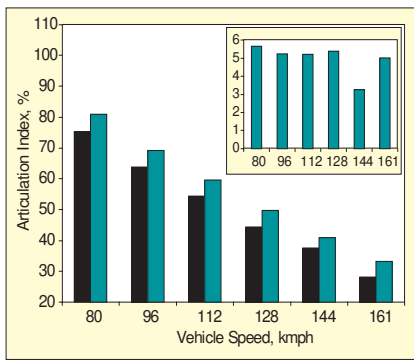


Figure 4. Articulation Index of front passenger headspace of a 2002 model year minivan. Dark columns – standard windshield; blue columns – acoustical windshield. Inset: Improvement in AI in % versus speed by the acoustical windshield. Windshield construction: 2.2 mm glass/interlayer/2.3 mm glass.

engine speed was increased from 1000 to 6000 rpm in 2-minute intervals. The results are similar to the FRF measurements of the installed windshields. An analysis of the 500 Hz octave band shows an improvement in vibration level of 5 to 10 dB. For frequencies below 150 Hz the differences between both materials are not obvious.

To conduct a noise reduction comparison, windshields with Vanceva™ Quiet were made of the same production glass as standard windshields. Cabin sound pressure levels at the front passenger seat headspace were recorded for a 4-door sedan passenger car, an SUV and a minivan with a standard production windshield and acoustical windshields at 112 kmph (70 mph). The tests were performed on high-speed tracks with favorable weather conditions. The baseline of the vehicle (standard windshield) was recorded first. The standard windshield was then replaced with the acoustical windshield and allowed to cure for 24 hours prior to testing. Finally, the standard windshield was installed and the vehicle baseline was measured again. The vehicle operating speed was from 80 kmph (50 mph) to 161 kmph (100 mph) at an increment of 16 kmph (10 mph).

The Vanceva™ Quiet acoustical windshield provides the most significant noise reduction in the frequency range of 1500 to 6000 Hz where wind noise is typically heard and human speech intelligibility is greatly affected. It can reduce wind and road noise by as much as 6 dB, a change significant enough to be noticed by occupants. In addition, the reduction in noise at low- to mid-frequencies is noticeable, where vibrations of the standard windshield at its resonance frequencies are likely present. There is up to a 2 to 3 dB reduction at some frequencies, indicating that the acoustic windshield is also effective at reducing structure-borne noise.

Sound quality improvement was measured in a 2002 model year minivan. The plot of overall Articulation Index (AI) for the minivan is shown in Figure 4. AI is a measure of how well humans communi-

cate in the presence of noise. Because AI closely relates human verbal communication and preference to sound, it is used as one of the indices in the sound quality matrix. An improvement in AI reflects a reduction in cabin noise, typically in the 1000 to 5000 Hz frequency range.

The acoustical windshield exhibits significantly better sound quality over the standard windshield for the passenger seat headspace, indicating its effectiveness in improving overall vehicle interior noise quality. To further establish this point, the same test repeated on an SUV at 80 to 161 kmph shows a loudness reduction in cabin noise of 1.6 to 4.2 sones and a 1.2 to 2.1 dBA reduction in overall sound level (20 to 20,000 Hz). At 96 kmph and below, the increase in AI is about 2 to 5% where the articulation indices at these speeds are high to begin with. At and above 112 kmph, the increase in AI is about 7%, indicating a significant improvement in speech intelligibility.

The proven success of the Vanceva™ Quiet acoustical interlayer in the aforementioned tests indicates that the windshield is a major noise transmission path. With the acoustical interlayer, the overall improvement in AI was 5.3%, loudness reduction of 2.2 sones, and sound level reduction of 1.28 dBA over the vehicle operating speed of 80 to 161 kmph.

Sound transmission studies show that the combination of thinner glass and the new interlayer results in the acoustical laminate having equivalent or better transmission loss than the combination with thicker glass and standard PVB interlayer largely due to the high damping characteristics of the acoustical interlayer. Increasing glass thickness of a windshield made with a standard PVB interlayer does not effectively increase its internal damping. Instead, resonances of the windshield are shifted to slightly lower frequencies. In contrast, the acoustical interlayer effectively damps resonant vibrations of the windshield and significantly reduces its sound radiation. Thus, the less massive acoustical windshield performs better than a more massive, thicker, standard windshield in the low- to mid-frequency range.

A comparison of the sound transmission of a standard laminate and two acoustical laminates of different thickness shows the thinner acoustical laminate provides significant STL benefits. The standard laminate has a surface density of 12.31 kg/m², while the acoustical laminates have lower surface density, 11.56 kg/m². Despite their lighter weight and thickness, the acoustical laminates show STL in the mass controlled frequency region comparable to the standard laminate, as well as reduced coincidence dip and less sound transmission in the high frequency range. This is of particular significance since automotive windshield glazing is trending toward

thinner glass and, as a result, the transmission of wind noise is of increasing concern.

Conclusions. The windshield has been proven to be a major acoustics weak link that permits the transmission of wind noise, external airborne noise and structure-borne noise to the vehicle interior. A standard windshield exhibits coincidence dip and resonance effects, and its performance is also temperature sensitive. Increasing the thickness or weight of either the windshield or the laminate does not noticeably reduce the noise transmission.

The new Vanceva™ Quiet acoustical windshield reduces vehicle interior noise by as much as 6 dB – a change that is significant enough to be noticed by occupants – and significantly improves the noise quality at both ambient and sub-ambient temperatures. The Vanceva™ Quiet windshield's performance is well aligned with humans' perception of automotive interior noise, acoustical comfort and voice recognition. Also, the intelligibility of speech is greatly enhanced. The result with the Vanceva™ Quiet acoustical interlayer is a quieter vehicle interior, improved Articulation Index and greater passenger comfort. Additionally, the acoustical interlayer makes it possible to produce thinner windshields for greater weight savings.

Because the Vanceva™ Quiet acoustical windshield can be easily made by replacing the standard PVB interlayer in the standard windshield with the acoustical interlayer, the windshield provides a convenient and effective means for reducing the transmission of wind and road noise. OEMs can adopt the new acoustical interlayer as a means of further reducing noise within the passenger cabin and thereby raise the overall quality perception of, and consumer satisfaction with, their vehicles.

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