Passenger Vehicle Interior Noise Reduction by Laminated Side Glass

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Abstract
The transmission of aerodynamically generated noise, in particularly wind noise, and road noise through vehicle glazing has become of increasing importance and is a major problem in automotive NVH today. Conventional tempered side glass has inherent noise transmission problems and radiates noise more easily at around 1-6 KHz at high vehicle operating speeds for highway driving. Laminated side glass was applied to address this problem. Experimental investigation was carried out to study the effectiveness of laminated glass for overall vehicle interior noise reduction, and in particularly wind noise. Two types of laminate glass, one with a conventional polyvinyl butyral (PVB) and the other with an acoustically enhanced PVB were used in the study. Test results show that replacing monolithic tempered glass with conventional PVB laminated glass results in a 1-4 dB interior noise reduction in the frequency range of interest and an additional 1-5 dB reduction with acoustically enhanced PVB laminated glass. The result is a significant reduction of wind noise and consequently quieter vehicle interior. The study shows that laminated side glass provides a convenient and effective method to reduce the transmission of aerodynamically generated noise. The acoustically enhanced PVB can replace conventional PVB in windshields to further achieve quieter vehicle interior.

1. Introduction
Automobile aerodynamic or wind noise has received more attention in recent years [1-3] as a result of design improvements that reduce other sources of noise (e.g., engines, transmissions, and tires) significantly and of increased operating speed for highway driving. As automobile manufacturers have increased their efforts to design and build quieter cars, and reduce vehicle interior noise through addition of extra door seals and use of acoustic insulation packages, automotive glazing has become the primary transmission path of wind noise, external airborne noise and structure-borne noise, and is a major contributor to the customer’s perception of vehicle interior noise level. The side windows of an automobile are especially important for the interior noise level of the automobile and one of the major radiators of wind noise into the
passenger compartment. Conventional tempered monolithic glass has been used as side windows for many years. Because the thickness of the side glass is generally less than five millimeters, and in most cases less than four millimeters, acoustic energy can be transmitted rather easily through side windows compared to other areas of the passenger compartment boundaries. At high operating speed, aerodynamic pressure fluctuations resulting from exterior airflow in the vicinity of the side window are very strong, causing the glass surface to radiate noise to the vehicle interior. Impinging airflows on panel edges and bends can generate acoustic noise with subsequent airborne transmission to the vehicle interior.

Glass is an area difficult to treat for NVH improvement. Because of weight and fuel economy concerns, simply increasing the thickness of side glass to improve interior noise level is no longer preferable today.

Laminated glass, made of a polyvinyl butyral (PVB) plastic interlayer sandwiched by two panes of glass sheet, has long served for safety purpose. Less known is the advantage in noise attenuation properties. Over the past 15 years, architectural use of PVB laminated glass in buildings near airports and railways has served to reduce the noise levels inside the buildings, making it more comfortable for the occupants. Likewise this technology is now being used in buildings where street and highway traffic noise is a problem. Recent advances in PVB technology [4] have made it possible for direct application of laminated glass as vehicle side glazing to deliver NVH improvements.

In this paper, results of experimental study on the effectiveness of laminated glass for overall vehicle interior noise reduction, and in particularly wind noise, are reported. Two types of the laminate side glass, one with a conventional PVB (standard PVB in the discussion below) and the other with an acoustically enhanced PVB are used in the study.

### 2. Test Protocol

Laminated side glass used for testing was made with conventional PVB interlayer (referred as standard PVB laminated glass) and with Solutia’s Vanceva™ Quiet, an acoustically enhanced PVB interlayer (referred as acoustic enhanced PVB laminated glass).

Laboratory sound transmission loss (STL) Measurements were conducted per ASTM E90-98 at Architectural Testing Inc. in York, Pennsylvania. Annealed flat glass and laminated flat glass were used for the testing.

Measurements of vehicle interior noise reduction by laminated side glass were conducted on a S80 passenger vehicle from Volvo. Tested front side windows were tempered glass, standard PVB laminated glass, and acoustically enhanced PVB laminated glass. The S80 was equipped with standard laminated side glass on all four doors as received. The front windows were replaced with the test glass of interest, and the rear windows remained to be the standard PVB laminated glass throughout the test program unless otherwise noted. The tempered and standard PVB laminated glass were as supplied. The acoustically enhanced PVB laminated glass was made with production heat strengthened glass. The laminated glass, 2.1-mm glass/interlayer/2.1-mm glass, was 4.96-mm thick, while the tempered glass was 4.85-mm thick. Testing was
conducted at high-speed tracks at Transportation Research Center (12-km oval) in East Liberty, Ohio and Continental Tires Uvalde Proving Ground (14-km oval), in Uvalde, Texas. Data were gathered on three sections of the test track, and data recording was over a 30-s duration at each section of the test track. The average of data from three sections was reported in this paper. Test temperature (air) was around 20 °C.

Acoustic data were recorded using a binaural head – “kunstkopf” or sonic artificial head.[2] Recorded data were fed into a digital-audio-tape-(DAT)-recorder at 48 kHz sampling frequency. DAT data were then downloaded to a computer workstation, calibrated with a 1 kHz, 94.5 dB calibration tone to ensure sound reference to Pa units of pressure. Results were gathered for both the right and left ear of the binaural head, seated in the front passenger seat.

Two B&K ½” microphones were also used to collect the acoustic data, one located in the front passenger side 10-cm away from the center of the side glass and the other in the rear passenger side also 10-cm away from the rear side glass. The front microphone served to closely monitor noise transmitted through the glass, while the rear microphone was used as a control. This paper reports only on the data from the binaural head; the data from microphones will be reported elsewhere.

Measurements were carried out with the door seals and glass edges of the front windows of the vehicle untaped and taped. Because results were identical, this paper reports only on the data from the untaped vehicles.

3. Sound Transmission Loss And Damping of Glass

Figure 1 shows the sound transmission loss (STL) comparison of monolithic glass, laminated glass with standard PVB interlayer, and laminated glass with Solutia’s acoustically enhanced PVB interlayer, an interlayer formulated specially for enhanced vibration damping and sound attenuation. Glass has its inherent problem with noise transmission due to very low internal damping. Significant deviations from mass law of acoustics are observed with glass, as shown in Figure 1, where wave coincident phenomena reduces its sound transmission loss performance. At the coincident frequency, the speed of incident sound in air matches that of the glass bending wave, resulting in glass to become transparent to sound.

Standard laminated glass uses a viscoelastic PVB polymer layer to separate two layers of glass. The PVB layer reduces overall bending stiffness of the laminate, and discontinues the acoustic impedance of each glass layer. The equivalent coincident frequency of a laminated glass is, therefore, pushed to a higher and less important frequency range. The addition of a small damping to glass by PVB makes it less excitable by incident sound and minimizes the coincident effect. When the outer glass layers are driven to bending waves, the viscous inner layer creates shear strains within itself, and the bending wave energy of the glass is transformed into heat energy by the interlayer. This results in a dramatic reduction of the amplitude of vibration and sound transmission.

The acoustically enhanced PVB interlayer with high damping characteristics further reduces coincident effect and improves STL performance. This can clearly be seen in the STL results.
shown in Figure 1. Standard PVB interlayer improves glass STL by as much as 4 dB at the coincident frequency range and the acoustically enhanced PVB interlayer adds an additional 5 dB improvement. Both interlayers improve STL over a wide frequency range from 1KHz to 10KHz.

Figure 1. Sound transmission loss data comparison. Panel dimension is 47cm x 74cm, and temperature is 20 °C.

4. Vehicle Interior Noise

Interior sound spectra were recorded at various speeds for vehicle with tempered side glass on all four doors. The results are shown in Figure 2. The frequency scale is in logarithmic to better illustrate the wave coincident effect of glass and wind noise transmitted through the window. Of particular interest is the increase of noise, or wind noise, in the frequency range from 1KHz to up to 8 KHz, transmitted through glass at higher vehicle speed. This transmission of high frequency

Figure 2. Interior sound spectrum vs. vehicle speed. The vehicle is with tempered side glass. Passenger side right ear response. Logarithmic frequency scale is used for better illustration.

Figure 3. Interior sound spectrum (right ear) at 105 kph (65 mph). Dark trace (red) is the solo (without truck); light trace (blue) is next to truck running at the same speed. Front side glass is tempered glass.

Figure 4. Interior sound spectrum (right ear) at 105 kph (65 mph). Dark trace (red) is vehicle with standard PVB laminated glass and next to truck running at the same speed; light trace (blue) is vehicle with tempered side glass and next to the truck.
wind noise correlates well with the poor STL performance of glass at high frequency range resulting from the wave coincident effect, as indicated by laboratory sound transmission loss results.

Figure 3 compares the interior sound spectra at 105 kph (65 mph) for vehicle tested solo and next to a moving, over-the-road, Class 8 diesel tractor-trailer. The vehicle side glass was tempered on all four doors. The truck generated a broad band of noise at high levels, including wind, wheel, and tire noise, engine noise, and low-frequency rumble. Transmitting of external airborne noise generated by the truck into the interior is apparent, as shown by the increase in sound pressure level from 1KHz up to 8KHz. This data corroborates with the laboratory STL testing results and wind noise test results shown in Figure 2, demonstrating the poor sound transmission loss performance of glass, which is vulnerable to transmitting wind noise and external airborne noise. In addition, there is a significant increase in sound pressure level at around 500 Hz, likely due to the “booming” effect the side glass generated by the running truck at a close distance.

5. Interior Noise Reduction by Laminated Glass

5.1 Standard PVB Laminated Side Glass

Figure 4 shows the effectiveness of the laminated glass to airborne noise and other type of noise generated by a Class 8 diesel truck trailer moving next to the vehicle. A 2 to 6 dB noise reduction is observed over the frequency 2KHz to 8KHz, indicating that side glass is a critical path to the noise transmission.

The effect of standard PVB laminated side glass on wind noise transmission is shown in Figures 5 and 6. Reduction in wind noise (by as much as 3 dB) and consequently reduction in interior noise level is obtained by replacing tempered side glass with the laminated glass.

5.2 Acoustically Enhanced PVB Laminated Side Glass

The effectiveness of the acoustically enhanced PVB laminated side glass on wind noise, as compared with standard PVB interlayer, is shown in Figures 7, 8, and 9. Interior noise reduction
with acoustic interlayer is significant, a 2 to 5 dB reduction is observed in frequency between 1KHz to 6KHz. In addition, the effect on low to mid frequency noise, typically due to panel vibration at its resonant frequencies, is noticeable, indicating high damping performance characteristics of the acoustic interlayer. The overall result is a reduction of wind noise by as much as 8 dB over tempered glass. This is in agreement with the laboratory sound transmission loss measurement results.

A stack plot of interior sound spectrum vs. vehicle speed is shown in Figure 10. The frequency is plotted in logarithmic scale. When compared with similar plots for tempered glass (Figure 2) and standard PVB laminated glass (Figure 6), the benefit of replacing tempered glass or standard PVB laminated glass by acoustic enhanced laminated glass to deliver improvement NVH performance for side windows is obvious.

Figure 7. Interior sound spectrum at 96 kph (60 mph) solo, passenger side right ear response. Dark trace (red) is vehicle with acoustic enhanced PVB in front laminated side glass; light trace (blue) is vehicle with standard PVB laminated side glass.

Figure 8. Interior sound spectrum at 128 kph (80 mph) solo, passenger side right ear response. Dark trace (red) is vehicle with acoustic enhanced PVB in front laminated side glass; light trace (blue) is vehicle with standard PVB laminated side glass.

Table 1 tabulates the sound quality matrices, Zwicker loudness (ISO 532B in diffuse field), Articulation Index (%), and dBA, of vehicle interior sound for both standard and acoustically enhanced laminated side glasses. Test results from both passenger outboard and inboard ear responses are included. The acoustically enhanced PVB laminated side glass shows better sound quality over the standard laminated glass for both outboard and inboard ears, indicating its effectiveness in improving the overall vehicle interior sound quality. Binaural sound playback was conducted and is consistent with the improvement in sound quality matrices.

Figure 11 shows overall loudness improvement, or interior noise reduction, for acoustically enhanced PVB over the standard PVB laminated side glass. The improvement on the sound hearing is very noticeable, as high frequency noise is much suppressed and sound quality is more preferable. Figure 12 shows overall Articulation Index (AI) improvement ($\Delta AI = AI_{A-PVB} - AI_{PVB}$). AI is a measure of how well humans communicate in the presence of noise. Because AI is closely related to human communication and preference to a sound, it is used to evaluate the effectiveness of laminated side glass.
The human ear responds to sound in a non-linear fashion, and is less sensitive to low frequency and more sensitive to high frequency sound. The most sensitive frequency range to human is about 1,000 Hz to 4,000 Hz, which is also the frequency range humans mainly use for communication to each other. Thus, humans object more to noise in this frequency range because it interferes with human speech intelligibility. The use of laminated side glass provides a convenient and effective way to reduce vehicle interior noise that interferes with human communication and improve sound quality.

The use of the acoustic enhanced PVB interlayer for windshields delivers similar benefits as observed with the side glass. Test results will be reported elsewhere.

![Figure 9. Interior sound spectrum at 161 kph (100 mph) solo, passenger side right ear response. Dark trace (red) is vehicle with acoustic enhanced PVB in front laminated glass; light trace (blue) is vehicle with standard PVB in front laminated glass.](image)

![Figure 10. Interior sound spectrum vs. vehicle speed. Front side glass is acoustic enhanced PVB laminate. Logarithmic scale plot for frequency is used for better illustration purpose.](image)

![Figure 11. Interior noise reduction (sones, ISO532B) for acoustic enhanced PVB laminated glass vs. standard PVB laminated glass. Front passenger right ear response.](image)

![Figure 12. Improvement in Intelligibility/Articulation Index (ΔAI) for acoustic enhanced PVB laminated glass vs. standard PVB laminated glass. Passenger right ear response](image)
6. Conclusion

Tempered side glass is major acoustic weak link that permits the transmission of wind noise and external airborne noise to the vehicle interior. Standard PVB laminated side glass reduces wind noise by as much as 3 dB and road (traffic) noise by 6 dB. Laminated glass with specially formulated, acoustically enhanced PVB interlayer further reduces wind noise by as much as 5 dB. The overall wind noise reduction over tempered glass is about 8 dB, consistent with the laboratory STL results. Thus, laminated side glass provides a convenient and effective method for the reduction of the transmission of wind noise and road noise. The result is a quieter vehicle interior and greater passenger comfort.

References