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Noise reduction and sound quality improvement with acoustic windshield in diesel-powered vehicles

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1. ABSTRACT

Windshields, with their low internal damping, are an acoustical weak link in automotive glazing. This has been especially true in diesel-powered vehicles. In the past, acoustically-enhanced glass products were typically achieved by utilizing solid and mass product design elements to increase the glass thickness. This is no longer acceptable as automakers are interested in weight savings, especially as they develop vehicles that are more fuel-efficient. Laminated safety glass, with a standard polyvinyl butyral (PVB) interlayer, is used extensively for automotive windshields, and offers improved acoustical performance over tempered glass. The standard PVB interlayer is not designed specifically for acoustical and Noise, Vibration and Harshness (NVH) purposes. Studies of the parameters affecting acoustical properties and actual noise reduction capability of standard laminated glass led to the development of an acoustical grade PVB interlayer.

Dynamic responses for windshields made with acoustical grade PVB, Saflex® Q series, were studied in the lab with considerably high damping of resonant vibrations and a significant reduction of structure-borne noise noted. It also exhibited improved acoustics in the 1500 Hz to 6000 Hz frequency region, which is a key region for wind noise and airborne noise transmission, and a weight savings of up to 15%. Further studies on the acoustic windshields to measure for enhanced wind and road noise reduction were conducted on high-speed test tracks. Test results show the acoustic windshields reduce cabin interior noise in the high frequency range by up to 6 dB. Subjective and objective results indicate windshields made with acoustical grade PVB can greatly improve vehicle wind and road noise performance, and overall in-cabin noise quality, resulting in a significantly quieter passenger cabin with a significant overall vehicle weight savings.

With the effectiveness shown by the acoustic windshield in significantly reducing road and wind noise, researchers were curious as to whether the acoustic windshield would show similar levels of sound improvement when used on a diesel-powered vehicle.

2. INTRODUCTION

Acoustics now play an important role in the automotive industry. Quieter passenger cabins are no longer solely the province of luxury vehicles. As people tend to spend more time in their vehicles as participants in an increasingly mobile society, quiet is no longer a luxury but a “must-have” for vehicle owners at all price points. This trend is being driven by several factors including the ever-increasing use of telematics in the vehicle and consumers’ perception of vehicle quality. According to the J.D. Power and Associates 2002 Vehicle Acoustics Study, consumers equate quiet with quality. As a result, astute OEMs are now integrating acoustic
solutions to ease vehicle Noise, Vibration and Harshness (NVH) throughout their product lines, which will help them gain a competitive advantage in the market place.

Diesel vehicles have long been popular in Europe, especially in terms of fuel economy. With the seemingly continuous escalation of gas prices in the U.S., diesel-powered vehicles are gaining popularity in the U.S. because of their fuel efficiency. However, there exists a perception that diesel engines, in general, are noisier than gas-powered engines. Researchers wanted to test the acoustic windshield on a diesel-powered vehicle to see if it could achieve wind- and road-noise reduction similar to the results shown with the acoustic windshield on vehicles with gas-powered engines.

While many vehicle manufacturers include noise-reducing structures and packages in the production phase of the vehicle, a pervasive weak link in NVH solutions is the vehicle’s glass; in particular, the windshield, making it the “big hole up front” in terms of acoustics. 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 into 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’s interior. The transmission of airborne noise generated by adjacent moving vehicles, and structure-borne noise created by structural vibration of the vehicle’s 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 of road and wind noise, external airborne noise, and structure-borne noise. 1-4

The sound transmission and dynamic response characteristics of structures such as glass are 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; to the conversion of mechanical energy associated with heat.

Glass has little internal damping. It is well known that sound transmission through glass exhibits coincident and resonance effects. Glass has a specific coincident frequency at which the speed of airborne incident acoustical waves matches that of the glass bending wave. At the coincident frequency, the acoustic wave is especially effective at causing the glass to vibrate, which makes the vibrating glass an effective sound radiator at that specific frequency and above. As a result, glass becomes transparent 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 coincident dip (Figure 1).

Figure 1: Sound transmission of monolithic glass of different thickness:
Black curve – 4.0-mm; Green curve – 5-mm.
The typical approach for an acoustic solution with glass is to increase its thickness. Yet, this approach provides limited benefit in terms of attenuating cabin noise and is not a viable solution given 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 NVH control via the windshield through product design at equivalent, or lesser, weight than that of standard windshields.

3. WINDSHIELDS WITH STANDARD PVB INTERLAYER AND SOUND TRANSMISSION

Standard windshields are made with laminated glass to protect occupants in the event of a crash. Figure 2 illustrates the configuration of a typical windshield, which consists of a standard 0.76-mm thick polyvinyl butyral (PVB) interlayer sandwiched between two sheets of glass under heat and pressure. The thickness of each glass sheet is typically 2.3-mm. The standard PVB interlayer, which has been used in windshields for more than 60 years, has not been optimized for improved acoustics until recently.

![Figure 2: Illustration of a typical windshield sandwich configuration.](image)

Windshields of varying glass thickness are not uncommon. They are made to meet certain design objectives such as acoustics, lighter weight, impact resistance with respect to safety, and structural rigidity for overall mechanical strength.

The acoustic properties of tempered glass and standard windshields made with PVB may be characterized by 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 being 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 reduce 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.

Windshields made with standard PVB exhibit sound transmission behavior similar to that of tempered glass, as shown in Figure 3. 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 1500 – 5000 Hz, where wind noise is typically heard and speech intelligibility is greatly interfered, standard windshields have less than desirable acoustic performance, especially in terms of speech intelligibility.
To further evaluate the potential of weight savings and the consequent impact on acoustic performance, standard windshields of different thickness and/or weight were constructed to examine the potentials of weight savings and consequently the impact on their acoustic performances. The results are summarized in Table 1.

Table 1: Standard windshield constructions, weight, and acoustics.

<table>
<thead>
<tr>
<th>Windshield</th>
<th>kg/m²</th>
<th>Weight Savinga (%)</th>
<th>STLb 100–1000 Hz</th>
<th>STLb 1600–6000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3-mm G/PVB /2.3-mm G</td>
<td>12.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.1-mm G/PVB /2.1-mm G</td>
<td>11.3</td>
<td>8.8</td>
<td>-0.25 dB</td>
<td>-0.69 dB</td>
</tr>
<tr>
<td>2.0-mm G/PVB /2.0-mm G</td>
<td>10.8</td>
<td>13.9</td>
<td>-1.05 dB</td>
<td>-0.80 dB</td>
</tr>
<tr>
<td>2.3-mm G/PVB /1.6-mm G</td>
<td>10.6</td>
<td>16.0</td>
<td>-1.05 dB</td>
<td>-0.80 dB</td>
</tr>
</tbody>
</table>

a. Relative to the windshield construction 2.3-mm glass/PVB /2.3-mm glass.
b. Average STL increase (+)/decrease (-) in the frequency range of interest relative to the windshield construction 2.3-mm glass/PVB /2.3-mm glass.

The typical approach to improving the acoustic performance of a standard windshield is to use thicker glass. 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, is not significantly different from the thinner laminate at frequencies of 1500 Hz and above. Additionally, the presence of the coincidence dip, which is important for the transmission of wind noise, airborne noise and road noise, makes improvement by using a thicker and heavier laminate insufficient to noticeably enhance the acoustic environment inside the vehicle.

On the other hand, thinner glass windshields are designed with the objective of achieving weight savings that can result in improved fuel economy. One of the design approaches is the use of an asymmetric glass configuration to achieve light-weight windshields. In this configuration, the outboard glass is typically 2.1 to 2.3 mm thick to maintain impact strength with respect to sand and gravel impact, while the thickness of the inboard glass is reduced significantly to lower the overall windshield weight. The overall mechanical strength of this type of windshield is satisfactory and the thinner glass windshields provide significant weight savings. However, these results are achieved at the expense of windshield acoustics, or vehicle interior quietness.
They also point to the many challenges faced by vehicle NVH design engineers in designing standard windshields to balance weight savings and improved windshield acoustics.

Therefore, to create an appropriate NVH solution for the windshield and equally appropriate design choices for NVH engineers, it is necessary to design a new interlayer that meets certain performance criteria in terms of the fundamental performance problems of the standard windshield with respect to resonant vibrations and coincidence dip.

4. WINDSHIELDS WITH ENHANCED ACOUSTICS FOR IN-VEHICLE NOISE CONTROL

To design a new acoustic interlayer, the primary parameters considered by researchers at Solutia Inc., included interlayer dynamic mechanical properties; damping properties of PVB glass laminate; interactions of acoustic waves in windshields; and frequency and service temperature range of interest. Additionally, windshields made with the new acoustic interlayer needed to meet the impact-resistance safety requirements established by the automotive industry. This requirement limits the freedom to choose a proper viscoelastic polymer material and thereby increases the difficulty in designing the acoustic interlayer.

In addition, the new acoustic windshield must be optimized and aligned with human perception of automotive interior noise and acoustical comfort. Although the stated range for human hearing is 20 – 20000 Hz, the most sensitive frequency range is about 100 – 4000 Hz, which is also the frequency range humans mainly use for verbal communication. The voice recognition range is from 100 – 8000 Hz, with 95% intelligibility at 500 – 8000 Hz, and 60% intelligibility at 1000 – 6000 Hz.

Saflex Q series, Solutia’s new acoustic grade interlayer, meets the primary objective in designing a new interlayer for windshields: It improves upon the acoustical performance deficiencies of standard windshields, especially coincident effect and resonant vibrations, which reduces noise levels within the vehicle cabin and improves overall noise quality. The viscoelastic PVB interlayer in the acoustical windshield improves the damping property of the glass and makes it less excitable by incident sound and minimizes the coincident effect.

When the sound transmission behaviors of the acoustic and standard windshields are compared (Figure 4) the acoustic interlayer has a pronounced effect on the coincident effect of glass. While the standard interlayer improves glass STL by as much as 3-4 dB over tempered glass, the acoustic interlayer adds an additional 7-8 dB improvement. Therefore, the suppression of the coincident effect is beneficial to wind-noise reduction and external airborne-noise reduction.

Figure 4: Sound transmission loss of acoustical laminate (blue curve) and standard PVB laminate (black curve) at 20°C. Laminate configuration: 2.1-mm glass/0.76-mm acoustic interlayer or 0.76-mm standard PVB/2.1-mm glass. A 5-mm monolithic glass (green curve) is used as reference.
To conduct an accurate nose reduction comparison, acoustic windshields were made of the same production glass as the standard windshields. Cabin sound pressure levels at front passenger seat head space were recorded for 4-door sedan passenger cars, SUVs, and a minivan first with standard production windshields, and then with acoustic windshields. All vehicles in this test had gas-powered engines. The testing was performed on high-speed tracks with favorable weather conditions. The baseline of the vehicle (standard windshield) was recorded first. The windshield was then replaced with the acoustic windshield, allowing curing 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). Typical noise reduction achieved by the acoustic windshield at the front passenger head space is shown in Figure 5. There is up to a 6 dB wind-and-road noise reduction at 96 kmph vehicle operating speed. In addition, there are noticeable reductions in noise levels in the low to mid frequency region. With the acoustical windshield, the improvement in articulation index (AI) is 7 and the reduction in Zwicker loudness is 2 sones. Similar noise reduction and sound quality improvement are also noted at other operating speeds.

Additional testing was done on a Jeep® Grand Cherokee with a gas-powered engine and a Jeep® Grand Cherokee with a diesel-powered engine. Tests were conducted to establish a gas-powered vehicle baseline with a standard PVB windshield; a diesel-powered vehicle baseline with a standard PVB windshield; and the same diesel-powered vehicle with the acoustical windshield. It was discovered that gas-and diesel-powered vehicles have a similar wind-noise and road-noise problem and that the acoustical windshield is effective for reducing wind and road noise in the critical frequency range of 2500 – 4500 Hz. Figure 6 shows test results for acoustical performance at 96 kmph (60 mph). Similar results were observed at other vehicle operating speeds (Figure 7 and Figure 8). The acoustical windshield shows significant reduction in the vehicle interior noises across a broad range in the frequency 1000 – 6000 Hz. This is the range in which wind noise is typically heard and human speech intelligibility is greatly interfered.
Figure 6: Interior sound pressure level at the front passenger right ear in a 2008 Jeep® Grand Cherokee limited 3.0L V6 common rail turbo diesel at 96 kmph (60 mph). Windshield construction: 2.1-mm glass/interlayer/2.1-mm glass. Darker trace is vehicle with standard windshield; lighter trace is vehicle with the acoustical windshield.

Figure 7: Interior sound pressure level at the front passenger right ear in a 2008 Jeep® Grand Cherokee limited 3.0L V6 common rail turbo diesel at 128 kmph (80 mph). Windshield construction: 2.1-mm glass/interlayer/2.1-mm glass. Darker trace is vehicle with standard windshield; lighter trace is vehicle with the acoustical windshield.

Figure 8: Interior sound pressure level at the front passenger right ear in a 2008 Jeep® Grand Cherokee limited 3.0L V6 common rail turbo diesel at 160 kmph (100 mph). Windshield construction: 2.1-mm glass/interlayer/2.1-mm glass. Darker trace is vehicle with standard windshield; lighter trace is vehicle with the acoustical windshield.
5. DIESEL SOUND QUALITY IMPROVEMENT

Figure 9 shows the overall Articulation Index (AI) at the front passenger right ear for the Jeep® Grand Cherokee with acoustical windshield and with standard windshield. Articulation Index is a measure of how well humans communicate in the presence of noise and the preference to a sound. An improvement in AI reflects a reduction in the cabin noise, typically in the 1,000 – 5,000 Hz frequency. Figure 10 shows the overall comparison of Sharpness at the front passenger right ear. Sharpness is a measure of the ratio of the high frequency noise level to overall noise level. In general, sharpness is increased by adding higher frequency content, and decreased by adding lower frequency content. Thus, the reduction in Sharpness with the acoustical windshield indicates a more pleasant noise environment inside the vehicle.

![Figure 9: Articulation Index (AI) at the front passenger right ear in a 2008 Jeep® Grand Cherokee limited 3.0L V6 common rail turbo diesel between 80 kmph (50 mph) and 160 kmph (100 mph). Windshield construction: 2.1-mm glass/interlayer/2.1-mm glass. Darker column - standard windshield; Lighter column - acoustical windshield.](image)

![Figure 10: Sharpness at the front passenger right ear in a 2008 Jeep® Grand Cherokee limited 3.0L V6 common rail turbo diesel between 80 kmph (50 mph) and 160 kmph (100 mph). Windshield construction: 2.1-mm glass/interlayer/2.1-mm glass. Darker column - standard windshield; Lighter column - acoustical windshield.](image)

6. DESIGNING WINDSHIELDS FOR IMPROVED ACOUSTICS AND WEIGHT REDUCTION

A comparison of standard windshield construction and acoustic windshield construction shows that the thinner acoustic windshield has better STL than the thicker standard windshield (Figure 11). The standard laminate has a surface density of 12.3 kg/m², while the acoustic laminate has a
lower surface density, 11.3 kg/m². Despite its lighter weight and thickness, the acoustic laminate shows STL in the mass controlled frequency region comparable to the heavier standard laminate, as well as reduced coincidence dip and less sound transmission at high frequency range, which largely is due to the high damping characteristics of the acoustic interlayer. 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.

Therefore, it is possible to design windshields to achieve both improved acoustics and overall vehicle weight reduction. Table 2 lists constructions of several acoustic windshields and shows weight saving potentials and STL performance.

The validation of improved acoustics with the acoustic windshields at significant weight savings was performed on an SUV on a high-speed test track. Test results for the standard and acoustic windshields (Table 3) on the SUV show that the 15% lighter acoustic windshield reduces wind and road noise by as much as 3-4 dB. At 112 kmph, the average noise reduction at the front passenger head space is 0.85 dB in the 20 – 1000 Hz range and 1.4 dB in the 1000 – 6000 Hz range (Figure 12).

**Table 2:** Acoustic windshield constructions, weight, and acoustics.

<table>
<thead>
<tr>
<th>Windshield</th>
<th>kg/m²</th>
<th>Weight Saving%</th>
<th>STL(^b) 100–1000 Hz</th>
<th>STL(^b) 1600–6000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3-mm G/PVB /2.3-mm G</td>
<td>12.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.1-mm G/APVB(^c) /2.1-mm G</td>
<td>11.3</td>
<td>7.7</td>
<td>0.24 dB</td>
<td>+ 3.72 dB</td>
</tr>
<tr>
<td>2.3-mm G/APVB(^c) /1.6-mm G</td>
<td>10.6</td>
<td>13.8</td>
<td>0.10 dB</td>
<td>+ 3.76 dB</td>
</tr>
<tr>
<td>2.1-mm G/APVB(^c) /1.6-mm G</td>
<td>10.1</td>
<td>17.8</td>
<td>- 0.10 dB</td>
<td>+ 3.71 dB</td>
</tr>
</tbody>
</table>

**Figure 11:** Sound transmission loss of laminates at 20°C: standard laminate of 4.6-mm total glass thickness and surface density 12.3 kg/m² (black curve); Acoustical laminate of 4.2-mm total glass thickness and surface density 11.3 kg/m² (darker curve, circle). A 5-mm monolithic glass (green curve) is used as reference.
**Table 3**: Weight parameters of standard and acoustic windshields tested on a SUV.

*Based on windshield surface area of 1.4 m².*

<table>
<thead>
<tr>
<th>Windshield</th>
<th>kg/m²</th>
<th>Weight, kg*</th>
<th>Weight reduction, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thicker Glass Std windshield</td>
<td>14.06</td>
<td>19.7</td>
<td>0</td>
</tr>
<tr>
<td>Lighter acoustical windshield</td>
<td>12.31</td>
<td>17.2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Figure 12**: Sound transmission loss of laminates at 20°C: standard laminate of 4.6-mm total glass thickness and surface density 12.3 kg/m² (lighter curve, square); Acoustic laminate of 4.2-mm total glass thickness and surface density 10.3 kg/m² (darker curve, circle). A 4.8-mm monolithic glass (lighter curve, triangle) is used as reference.

7. **CONCLUSIONS**

While a thinner and lighter windshield has been the trend in automotive glazing for significant weight savings, its standard PVB interlayer has been the NVH limitation to designing quieter car interiors. This is proven to be true on diesel-powered vehicles with windshields made with standard PVB.

Windshields can be designed to fit any automaker’s specifications and can be made quieter with the acoustically enhanced PVB interlayer, Saflex Q series. Thinner windshields for greater weight savings and improved fuel economy are possible with the acoustic interlayer. Because the acoustic windshield can easily be made by replacing the standard PVB interlayer with the acoustic PVB interlayer in the standard windshield configuration, the acoustic windshield provides a convenient and effective means for reducing wind and road noise on both gas- and diesel-powered vehicles.
REFERENCES


8. Acoustic data were recorded using a binaural head. Results were gathered for both the right and left ear of the binaural head, seated in the front passenger seat. In this paper, the headspace sound pressure level was the average of both the right and the left ear responses.