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Tire Noise Reduction with Fiber Exterior Wheel Arch Liners

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ABSTRACT

Tire noise reduction was evaluated with acoustically designed exterior wheel arch liners. The wheel liners were made with a fiber blend selected to meet acoustical requirements, process demands, and durability challenges. Fiber liners were installed in a vehicle and noise level measurements were made under a range of operating conditions. The results show the reduction in tire noise that can be achieved at the source and in the vehicle. A critical part of this evaluation was a rapid analysis technique to select metrics that correlated with subjective assessments. The analysis techniques also helped quantify the improvements over a baseline condition.

INTRODUCTION

Tire and road noise can be a significant part of the noise from a vehicle depending on speed, road surface, and frequency. Their contribution to interior noise depends on the source levels and the noise reduction from the exterior to the interior. Airborne tire noise is generated by noise radiated from the tire. Mechanisms include phenomenon such as the pumping of air in and out of the tread pattern and the vibrations of the side wall and tread band resulting from the tire's interaction with the road surface (1). Road noise comes from a non uniform road surface that generates structural excitation through the tire and suspension system into the vehicle body. This excitation of the vehicle body can generate noise throughout the vehicle rather than only in the vicinity of the tire. This is structure borne noise.

The purpose of this paper is to describe an approach to reduce airborne tire noise using fiber exterior wheel arch liners. This paper will also explain the analysis technique used to quantify improvements over a baseline condition.

SOURCES AND PATHS OF TIRE NOISE

The source of tire noise and its paths to both interior and exterior spaces are shown in Figure 1. Tire noise is generated at the interface between the tire tread and the road surface while the tire is rotating (tire patch) (2). The local interactions at the tire patch and the vibrations of the tire side wall generate noise that propagates to the exterior space and into the vehicle through the underbody, doors, and windows. These interactions also create structure borne noise that is transmitted into the vehicle through the suspension and the body.

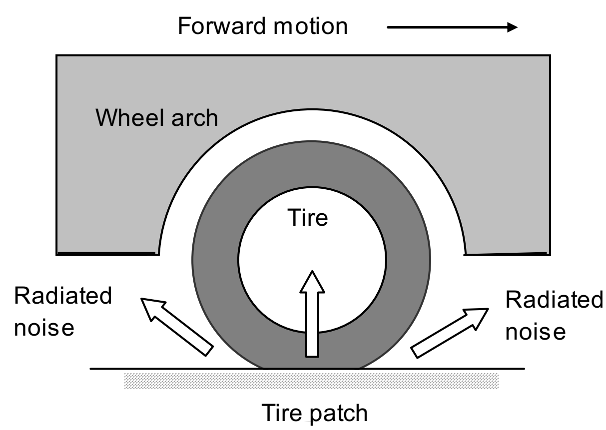

Figure 1 Tire noise and radiated paths

REDUCTION OF TIRE NOISE

Reduction of tire and road noise is accomplished by either reducing noise at its source or reducing noise along the path between source and receiver. NVH engineers acknowledge that reduction of noise at the source is the most efficient and most economical means for treating a noise problem. In cases when the noise source cannot be further redesigned, as is the case with a tire tread and tire material, then the noise must be reduced in the vicinity of the source before it propagates to other parts of the vehicle. Alternative approaches to reduce noise along the path to a receiver often lead to more complex and more expensive problem solutions. Therefore, a sound absorbing wheel liner was developed for use in the exterior of the wheel arch and in close proximity to the tire. This design will reduce air borne noise and reduce the source strength of the tire noise.

Another feature of a fiber wheel liner is its ability to reduce the noise from the impact of stone, gravel, and rain in the wheel arch. The high frequency “ping” of gravel against sheet metal is replaced by the low frequency “thud” of gravel against fiber. Controlling impact noise with a fiber wheel liner will also reduce structural excitation before it travels to other parts of the vehicle. A fiber wheel arch liner that deals with these two noise sources might also allow other passive NVH treatments to be minimized while maintaining or reducing interior noise levels.

The interior noise reduction from an acoustical wheel liner will depend on the amount of tire noise and its attenuation along a path to the vehicle occupants. The noise level will vary depending on vehicle speed and road surface. If tire noise is a dominant part of the interior noise, then reduction of tire noise near its source could produce a quieter vehicle. While the acoustical liner provides sound absorption under all conditions, its influence may be overcome by other more dominant noise sources. When tire noise is masked by engine, wind, or exhaust noise, the reduction in tire noise will be a smaller part of the overall noise signature.

A final aspect of tire noise is the far field noise, often referred to as pass-by noise. Pass-by noise was not measured in this study. However, measurements representing source strength were made near the tire and offer insight on pass-by noise reduction.

DESIGN OF A FIBER WHEEL LINER

The material selected for the wheel liner was a non woven material made from polyester fibers. While acoustical performance was a primary consideration, the exterior location of this material placed an equally important emphasis on durability and resistance to weathering. Also, the material needed to be processed and molded to match the shape and contour of the wheel arch.

Physical tests and sound absorption tests were conducted on a range of non woven materials to select an acceptable fiber formulation for the liner. Figure 2 shows the random incidence sound absorption coefficient for the material with a 10 mm air space. In reality, air spaces of varying depths are present behind the wheel liner. For the vehicle selected for this study, the liner covered the entire wheel well. It extended from the edge of the body to a depth of about 300 mm into the wheel cavity over a span of 180 degrees around the wheel from the lowest levels of the body sheet metal. The space between the face of the wheel liner and the inner sheet metal ranged from 25 mm to 150 mm, with the largest part of the liner having a space of about 50 mm.

A greater air space behind the material will add further sound absorption at low frequencies and can actually be used to tune the fiber liner. Figure 3 shows calculated sound absorption at normal incidence with various air spaces. The overall sound absorbing properties of the fiber liner will be a weighted average of the results at each air space. The weighting would be based on percent area for each air space as installed. This average was not calculated for this paper as the focus was on the experimental results.

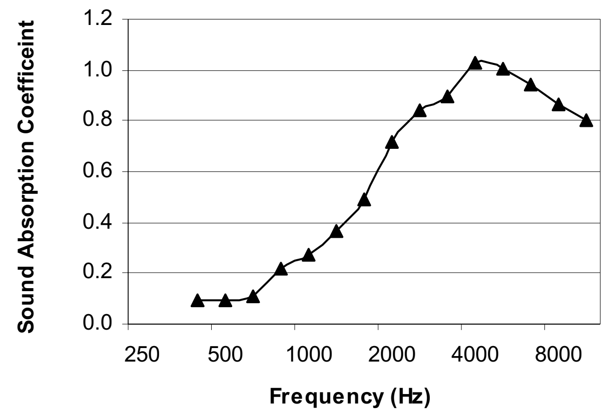

Figure 2 – Random incidence sound absorption coefficient for fiber wheel liner with 10 mm air space

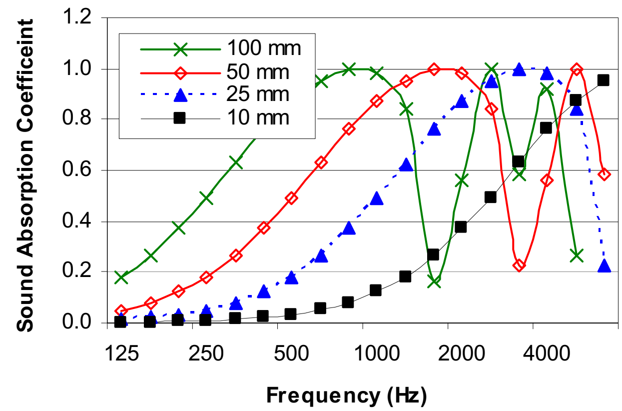

Figure 3 – Normal incidence sound absorption coefficient for fiber wheel liner with varying air spaces (calculated)

Even with the previous sound absorption data, it is difficult to estimate the impact of an acoustical wheel liner on exterior or interior noise levels without further information on the levels of tire noise and other sources in the vehicle. Therefore a robust test plan was established to make prototype parts and evaluate their performance on a production vehicle.

ROAD TESTING

A North American luxury sedan that had 4 plastic wheel arch liners was chosen for tests. Four fiber wheel liners, 2 front and 2 rear liners, were fabricated to the exact shape and mounting details of the plastic liners. The 4 fiber liners weighed 2.6 kg compared to 5.0 kg for the plastic liners. This represents a 48% weight savings. Prototype fiber liners were installed in the test vehicle and a test plan was outlined.

The test plan included 4 conditions:

- No wheel liners
- 4 Plastic wheel liners
- 2 Fiber liners in rear
- 4 Fiber liners

These conditions represent extremes between no treatment for the wheel arch, a plastic wheel liner with no sound absorption but some sound transmission loss, and a fiber wheel liner with high absorption but low transmission loss.

Road tests were conducted at three different speeds, 48, 72, and 97 kilometers per hour (kph), over both rough and smooth road surfaces. The roads for the tests were chosen based on their surface roughness, uniform condition (both had been recently paved), limited traffic, and proximity to the development lab. Additional tests were conducted in a coast down mode from 97 to 48 kph with no load on the engine. A final test was conducted at 48 kph with 2 wheels in the gravel on the side of the road.

For all of the tests, a microphone, protected with an unobtrusive windscreen, was positioned in the rear left wheel well. This was located in the space next to the shock absorber. In addition, interior noise levels were measured with a binaural head at the front right passenger and with a second binaural head at the left rear passenger. An optical tachometer provided driveshaft RPM information.

For each vehicle configuration, the vehicle was driven for about 10 minutes to the test location as a standard warm-up period. The data from all channels were then acquired simultaneously for 30-40 seconds. The sampling frequency was set at 32 kHz, to provide a maximum analysis frequency of 12 kHz. All data were stored in time domain to allow for both frequency and time domain post-processing.

DATA ANALYSIS

The recorded data were analyzed in the frequency domain to produce narrow-band and third octave band auto spectra and in time domain to generate psychoacoustic metric functions versus time.

Engineers who were experienced in sound quality studies listened to the recordings. They noticed significant differences at the wheel well microphone between all configurations, but noticed only a subtle yet perceivable difference between "no liners" and "4 fiber liners" conditions for interior recordings. The recorded data were next examined to identify parameters and/or functions that correlated with the subjective assessment.

EXTERIOR NOISE

The frequency spectrum measured at the wheel well microphone in the baseline configuration with plastic liners is shown in Figure 4. This shows the broad band nature of the noise with a reduction in level beginning above 2000 Hz.

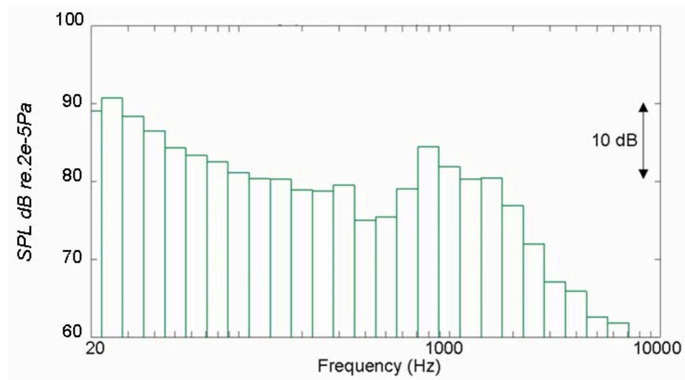

Figure 4 - Third-octave auto spectrum of wheel well microphone at 72 kph on a smooth road, plastic liners

A-weighted sound pressure levels were also determined for each of the test conditions. Figure 5 shows the A-weighted sound pressure levels at the wheel well microphone based on vehicle speed and road surface. The noise level increases with speed and with roughness of the road surface [3]. Reductions of 2 to 3 dBA were measured with fiber liners for the smooth road and 1 to 2 dB for the rough road. These measurements are also listed in Table 1.

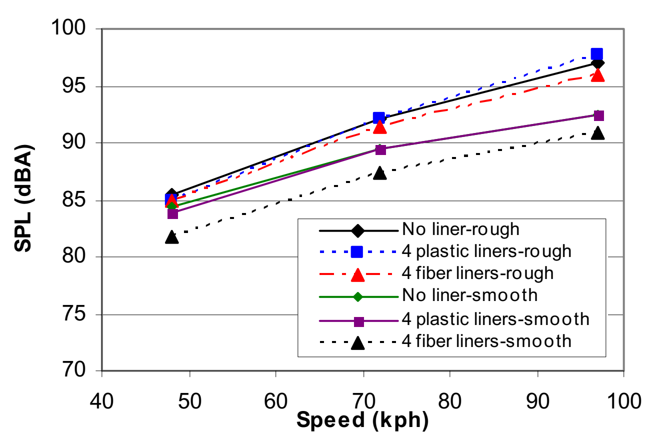

Figure 5 – SPL at wheel well versus speed for different road surfaces and test conditions

Table 1 - A-weighted SPL (dB) at wheel well microphone for different vehicle speeds and road surfaces

	SMOOTH			ROUGH		
	48 kph	72 kph	97 kph	48 kph	72 kph	97 kph
NO LINERS	84.4	89.5	92.5	85.4	92.1	97.0
4 PLASTIC LINERS	83.9	89.4	92.4	85.0	92.1	97.7
4 FIBER LINERS	81.8	87.4	90.9	84.9	91.4	95.9

Subjective assessments indicated a greater difference in these levels than measured with the dBA levels so the loudness in sones was examined. Figure 6 shows the loudness for the same conditions. These measurements correlate more closely with human response and begin to show even greater differences between test conditions. The maximum source strength is represented by the condition with no liners and the minimum by the condition with all fiber liners. Reductions of 4 to 15 sones were identified with fiber liners. These measurements are also listed in Table 2.

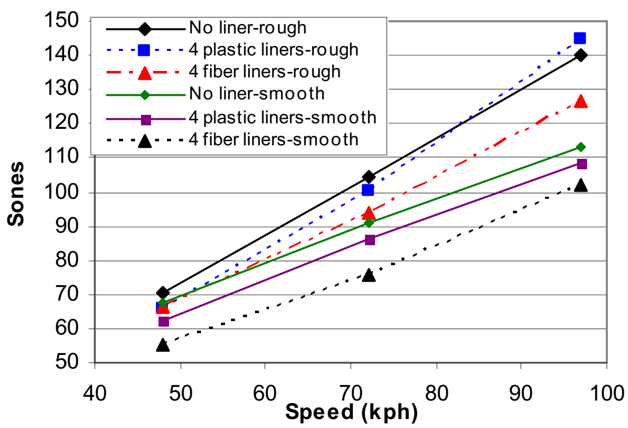

Figure 6 – Loudness at wheel well versus speed for different road surfaces and test conditions

Table 2 - Loudness at wheel well microphone for different vehicle speeds and road surfaces

	SMOOTH			ROUGH		
	48 kph	72 kph	97 kph	48 kph	72 kph	97 kph
NO LINERS	67.6	90.8	113.3	70.2	104.1	139.9
4 PLASTIC LINERS	62.4	86.0	108.5	65.8	100.3	144.8
4 FIBER LINERS	55.1	75.6	102.0	66.4	93.6	126.8

The measurements show 3 important points. First the interior noise increases with speed regardless of road surface. Second, at any speed, the noise increases with surface roughness. Third, the fiber liners are effective in reducing this noise on rough roads and smooth roads.

Figure 7 shows the third-octave auto spectra for 72 kph on a smooth road. All conditions exhibit a maximum at 800 Hz. The reduction in noise with fiber liners at frequencies above 1000 Hz is due to the sound absorbing properties of the fiber liner, shown in Figure 3. This effect is consistent across all vehicle speeds and road surfaces and shows that the sound absorption from the fiber wheel liners is truly reducing the noise generated in the vicinity of the tire. When the noise radiated from the wheel liner is an important contribution to pass-by noise, the reduction offered by fiber liners could be an effective countermeasure.

An interesting result is derived from the tests performed on gravel. The fiber liners offer more damping to impulsive excitation from stones and gravel than the plastic liners. Figure 8 shows the Transient Loudness function versus time of the wheel well microphone when the vehicle is driven at a constant speed of 48 kph over the same stretch of gravel. The peak excitations with no liners are partially reduced with plastic liners and are greatly reduced with fiber liners. These results show that fiber liners reduce both reverberant noise and impact noise.

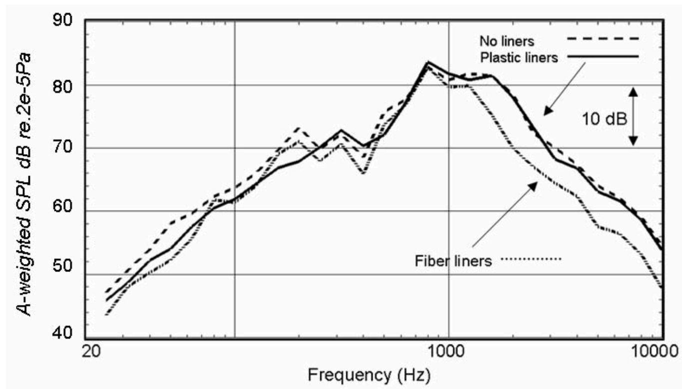

Figure 7 - A-weighted third-octave auto spectra of wheel well microphone at 72 kph on smooth road.

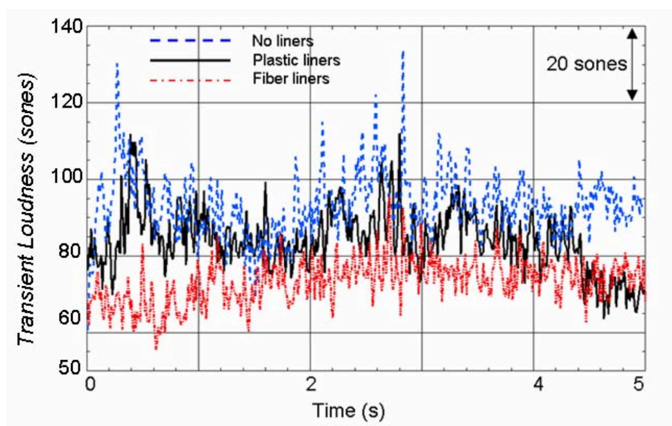

Figure 8 -Transient Loudness versus time at wheel well microphone with vehicle at 48kph over gravel.

INTERIOR NOISE

If airborne tire noise can be identified as part of the interior noise spectrum, then the reduction in source levels with a fiber liner could lower the interior noise levels or minimize the vehicle's noise reduction requirements.

A subjective evaluation of interior noise revealed no perceivable difference between plastic and fiber liners. However, without any liners, the interior noise was judged as being sharper and in general more annoying.

Figure 9 shows narrow band spectra from 20 to 3000 Hz at the right ear of the front passenger binaural head without liners and with fiber liners. The narrow band spectrum with plastic liners is indistinguishable from the spectrum with fiber liners and was not included in the plot. These comparable spectra indicate that the measured differences in the wheel arch are not transferred to the interior. Possible explanations for this are masking from wind noise or engine noise or significant attenuation of the airborne noise before it reaches the vehicle occupants. Detailed tests would be needed to separate these effects.

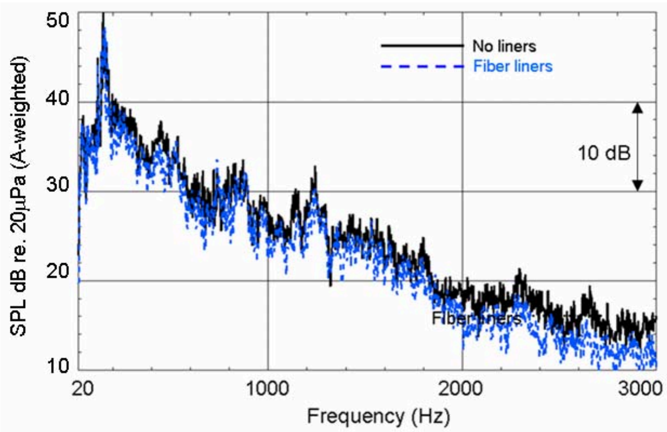

Figure 9 - Narrow band A-weighted spectra of right ear of front binaural head with fiber liners and without liners - 72 kph on smooth road

Next, the spectra at the rear seat location were examined to see if a location closer to the source would indicate a more pronounced effect with fiber liners. Figure 10 shows the corresponding data at the left ear of the binaural head at the rear left passenger position. Here, the differences are indistinguishable. Since the fiber liners reduce noise in the wheel well, other factors are preventing these reductions from being more prominent inside the vehicle.

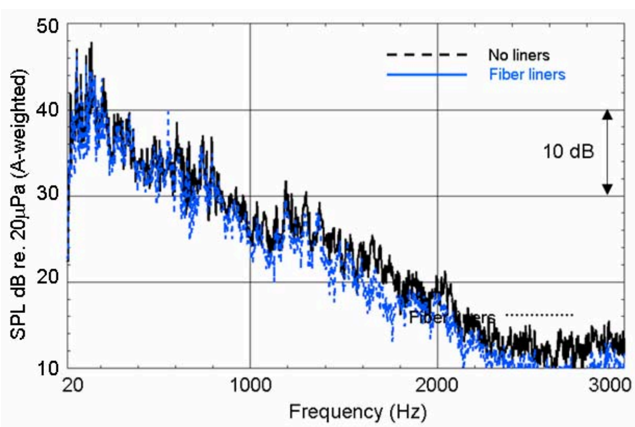

Figure 10 - Narrow band A-weighted spectra of left ear of rear binaural head with fiber liners and without liners - 72 kph on smooth road

Figure 11 and Figure 12 show the third-octave spectra at the front and rear binaural head for all wheel liner configurations. A noise reduction above 500 Hz of 1 to 2 dB with either plastic or fiber liners was observed compared to the condition with no liners. The differences between a fiber liner and a plastic liner for these measurement positions are indistinguishable.

The lack of effect of fiber liners at frequencies below 800 Hz is most likely due to the fact that the airborne tire noise is masked by other contributions, such as engine, wind, and structure borne noise.

The 3 to 4 dB noise reduction in the wheel well that was measured with a fiber liner at frequencies above 1 kHz does not result in equal noise reduction inside the vehicle. For this vehicle then, one can conclude that

- The interior component of tire noise experiences comparable noise reduction via the sound absorption of the fiber liner or the transmission loss of the plastic liner as it propagates to the interior; OR
- The other components of the NVH package, such as the floor system or trim insulation, provide sufficient attenuation of tire noise within the interior; OR
- The tire noise transmitted to the cabin is masked by higher level noise sources in the cabin such as wind, road, or engine noise.

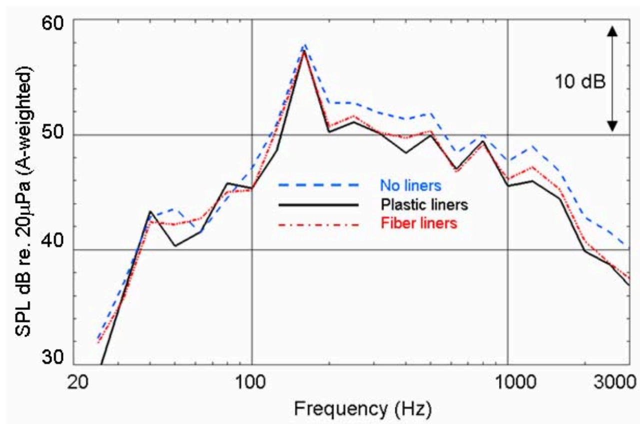

Figure 11 - Third-octave A-weighted spectra of right ear of front binaural head with no liners, with plastic liners, and with fiber liners - 72 kph on smooth road

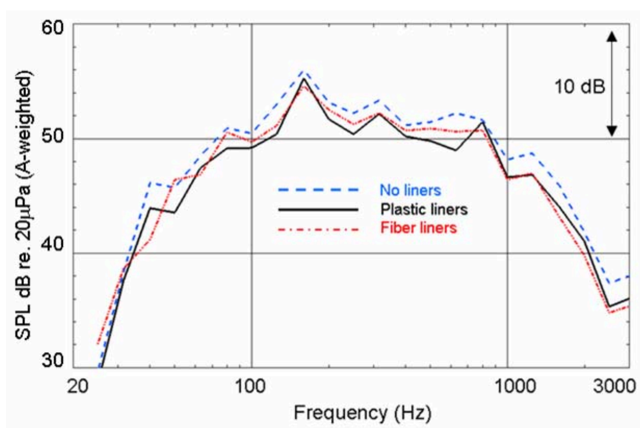

Figure 12 - Third-octave A-weighted spectra of left ear of rear binaural head with no liners, with plastic liners, and with fiber liners - 72 kph on smooth road

All of the previous data represent steady speeds with the engine powering the vehicle. Coast-down measurements were made as the speed decreased from

97 kph to 48 kph. No differences were seen between the powered runs and coast-down runs for measurements at the wheel liner or in the vehicle. Additional measurements on a dynamometer would be needed to separate the contribution from wind noise and turbulence around the vehicle. Measurements on a rotating tire could further separate tire noise from road induced noise and structural excitation.

An in-depth investigation of noise sources and paths was outside the scope of this quick experimental study which was performed mainly to assess in-situ acoustic performance of fiber liners on a North American vehicle.

CONCLUSIONS

These results show that fiber wheel arch liners are an effective means to reduce tire noise in the wheel well area. When tire noise is a dominant part of pass–by noise, the fiber liners may also reduce pass-by noise levels. When tire noise becomes a significant part of the interior noise in a quiet vehicle, this approach could potentially reduce interior noise levels or maintain equivalent noise levels while reducing the content of the NVH package. The analysis techniques described here deliver high confidence that the measured results and metrics will be in line with subjective responses by both the engineering team and consumers. This will allow comparisons of multiple design options for optimized performance and cost.

Conclusions from this study are:

1. Fiber wheel liners add sound absorption at the source of tire nose.
2. Tire noise is speed and frequency dependent and becomes most noticeable on rough roads and at high speeds.
3. Fiber wheel liners can reduce source strength from the tire from 4 to 5 dB above 1000 Hz.
4. Fiber wheel liners can reduce the loudness level at the tire from 4 to 15 sones, depending on speed and road surface.
5. When tire noise is the major component of pass-by noise, the pass-by noise may be reduced with fiber wheel liners.
6. When tire noise becomes a dominant part of the interior noise, lower interior noise levels may be achieved with fiber liners.
7. When tire noise is masked by wind noise, engine noise, or exhaust noise, then little impact will be measured inside the vehicle with a fiber wheel liner.
8. Fiber wheel liners reduce the exterior measured airborne noise and structure borne noise from stone and rain impact over plastic liners.
9. Sound Quality metrics such as sones and time varying loudness provide a better understanding of the subjective response to the interior noises measured here with fiber wheel liners.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Sone: a measurement of loudness that correlates with human response