The Effect of a Vehicle Cargo Rack Fairing on Sound Levels and Speech Intelligibility Within the Vehicle Cabin

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INTRODUCTION

The purpose of this study is to quantify the reduction of cabin noise inside a vehicle due the installation of a fairing to the cargo rack installed on the roof of the vehicle. The vehicle used for this study is a 2007 Saab 9-3 Turbo station wagon with a cargo rack comprised of two 1" diameter tubes, the forward tube is centered approximately 9" aft of the leading edge of the sunroof opening, and 3.5" above the opening. The vehicle, with cargo rack and fairing are shown in Figure 1.

Figure 1 – The vehicle used for this study shown from the driver's side (top) and from the vehicle front (bottom), without the fairing installed (left) and with the fairing installed (right)

Sound pressure level measurement results are reported in terms of A-weighted decibels (dBA) and one-third-octave-band sound pressure levels. The A-weighted decibel scale represents the sound pressure level as a single number in which the contribution from each measured frequency band is weighted to reflect the human perception of sound at low to moderate volume levels, with a de-emphasis of low and extremely high frequencies.

The sound level measurements were processed to determine Speech Intelligibility Index (SII) ratings for each operating condition. The SII rating ranges between 0.00 and 1.00, and indicates the intelligibility of human speech under adverse listening conditions, including high background noise. Higher SII ratings indicate better speech intelligibility; values below 0.3 indicate unsatisfactory intelligibility, up to 0.5 indicates acceptable intelligibility, up to 0.7 indicates good intelligibility, and values above 0.7 indicate excellent intelligibility. This rating system is formally defined in ANSI/ASA S3.5 – American National Standard Methods for Calculation of the Speech Intelligibility Index.

For reference, 0dBA is considered the threshold of human hearing, a typical conversation is held around 60dBA, and 120dBA is considered the threshold of pain; a human can barely perceive a change of ±3dB, and a change of ±10dB is perceived as a doubling or halving of loudness. All decibel level values reported herein are to be interpreted as A-weighted L_{eq} sound pressure level values referenced to 20µPa, unless noted otherwise.

The results stated in this report represent only the specific acoustical conditions present at the time of the tests. Measurements performed in accordance with this test method on nominally identical vehicles and acoustical conditions may produce different results.

BACKGROUND

Sound pressure level within the vehicle cabin was measured according to the procedures in ISO Standard 5128, with minor deviations as detailed in this report. Measurements were taken at vehicle speeds of 20, 30, 40, 50, 60, 70 and 80 miles per hour under the following four conditions:

- SOFU – Sunroof Open, Fairing Uninstalled
- SOFI – Sunroof Open, Fairing Installed

- SCFU – Sunroof Closed, Fairing Uninstalled
- SCFI – Sunroof Closed, Fairing Installed

Note that in the Sunroof Closed conditions, both the glass sunroof and the interior sunscreen were closed to most closely approximate a vehicle without a sunroof, and to most completely and practically isolate the aerodynamic noise caused by turbulence at the cargo rack from other cabin noise sources.

Measurements were taken using a Norsonic model NOR145 sound level meter (SLM) with a 1/2” random incidence microphone element and windscreen attached, a type I device. The SLM calibration was verified before and after measurements were taken to a precision of 0.1dB. The SLM was installed at vehicle operator ear height, centered between the driver and passenger seats, oriented forward. Measurements were taken at each operating condition until three measurements were recorded within 3dBA of each other; these three measurements were then averaged together, and this average is reported herein. Note that ISO 5128 calls for at least two microphone positions, one at ear height adjacent to the vehicle operator’s head and one at the same height at the center of the passenger seating area, and furthermore calls for only a single operator in the vehicle; due to the complexity of operating the vehicle on public roadways while taking and cataloging the measurements, an assistant operator occupied the passenger seat to handle the measurements, and only a single microphone position was used. The SLM is shown at the measurement location within the vehicle in Figure 2.

Figure 2 – Position of the sound level meter within the vehicle cabin shown from the side (left) and the top (right)

The fairing reduces the aerodynamic drag on the vehicle, which correspondingly reduces aerodynamic noise, but does not significantly affect other contributors to cabin noise, including (but not limited to) tire noise, engine noise, and noise generated by other vehicles or systems within the operator’s vehicle (stereo, HVAC, etc.). Tire and engine noise were controlled for by taking measurements at a variety of vehicle speeds, without varying other major contributors to these noise sources (tire pressure was verified at 37psi, cold, per vehicle manufacturer recommendation, engine speed was maintained as close to 2,500rpm as possible, vehicle speed was as constant as possible, extraneous cargo was unloaded from vehicle, road surfaces were dry, wind was negligible – below 5mph, etc.). Road noise and noise from other vehicles was controlled for by using roadways with relatively smooth pavement, which were not being used by many other vehicles at the time the measurements were taken. Noise from systems within the vehicle were controlled for by turning off all nonessential systems. Averaging the three measurements within 3dB of each other for each operating condition, as discussed previously, further reduces the effect of extraneous noise sources.

RESULTS & DISCUSSION

The A-weighted sound pressure level measurement results are tabulated in Table 1, and shown graphically in Figure 3.

Table 1 – Sound Level Measurement Results, in dBA

Operating Condition	Vehicle Speed [mph]						
	20	30	40	50	60	70	80
SOFU	61	68	75	80	86	90	93
SOFI	59	63	66	69	72	73	74
SCFU	57	60	62	65	69	72	75
SCFI	57	59	61	63	65	67	68

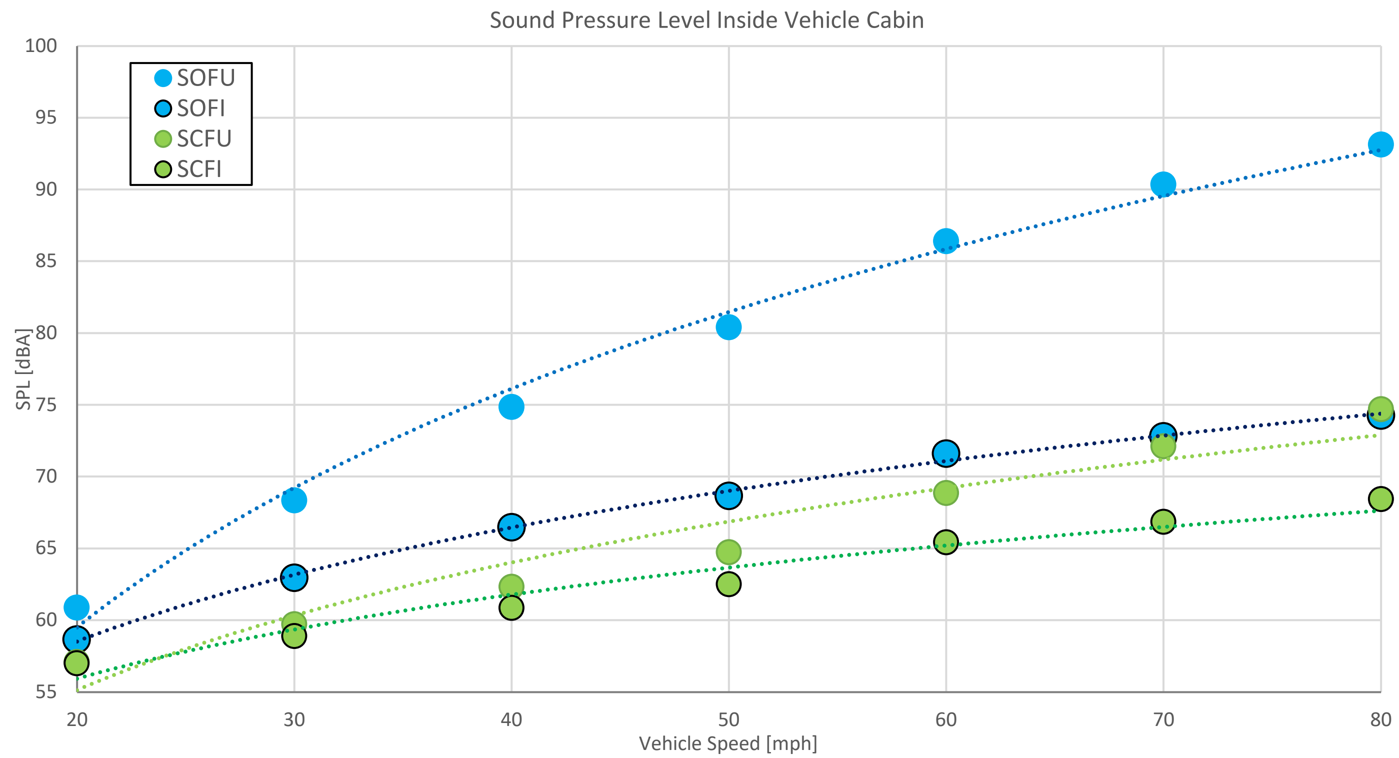


Figure 3 – Sound level measurement results in dBA, with logarithmic curves of best fit

Sound level within the cabin trends upward with increasing vehicle speed. It is notable that at highway speeds (60mph and above) without the fairing installed and with the sunroof open, cabin sound levels exceed 85dBA, which is the recommended exposure limit (REL), and threshold for hearing protection to be recommended, as defined by the National Institute for Occupational Safety and Health (NIOSH). Furthermore, even with the sunroof closed cabin sound levels exceed 70dBA at highway speeds, approximately 10 decibels above a typical conversation, making conversation within the cabin difficult, and reducing intelligibility of speech or music played through the stereo system.

The reduction in cabin sound levels achieved with the installation of the fairing is shown in Figure 4. The fairing is shown to have reduced cabin sound levels by up to almost 19 decibels, as experienced with the sunroof open, and by up to 6 decibels with the sunroof closed. Linear trend lines are shown for these conditions, and the trend lines track the measurements well.

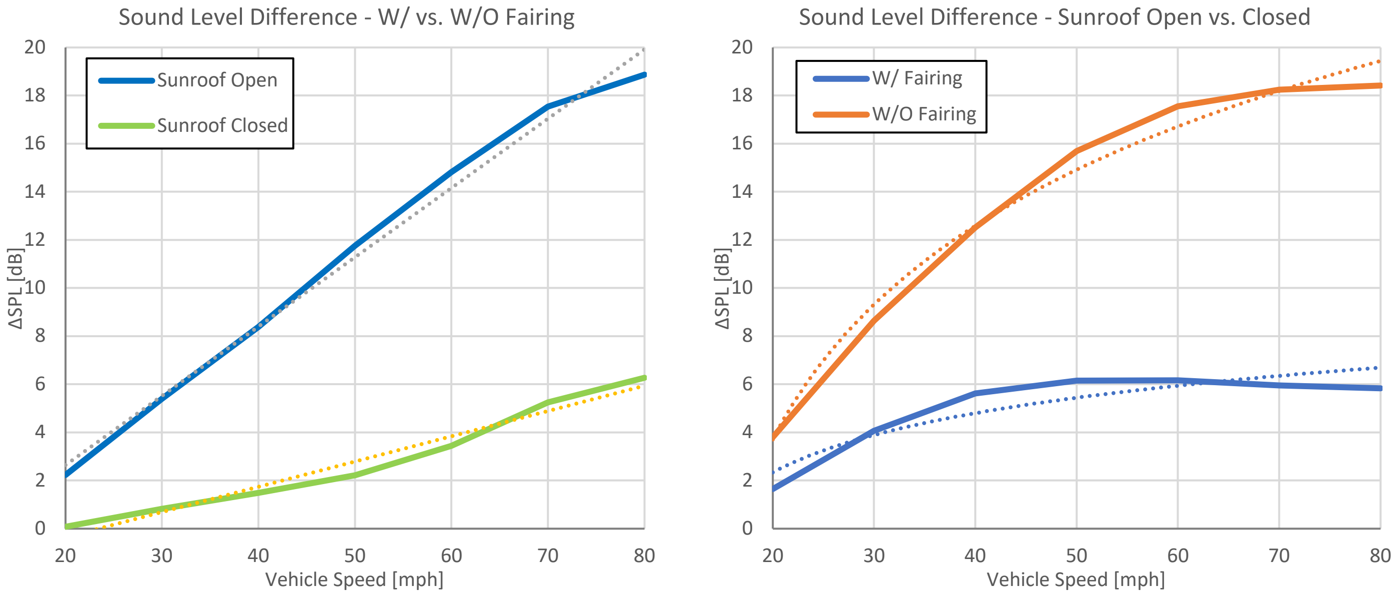


Figure 4 – Difference in cabin sound level with the sunroof open vs. closed at left, and with vs. without the fairing installed at right

The increase in cabin sound levels effected by opening the sunroof is also shown in Figure 4. Note that without the fairing installed, cabin sound levels are shown to increase by approximately 18dB when the sunroof is opened at highway speeds. This increase would be perceived as nearly a quadrupling of sound level. Conversely, with the fairing installed, the increase in cabin sound level when opening the sunroof at highway speeds (and indeed down to approximately 40mph) is limited to approximately 6dB.

Sound level measurements taken within the vehicle cabin for each of the four operating conditions are shown as a function of frequency in Figure 5. The SOFU condition is shown at the top of the figure, followed by the SOFI, SCFU, and SCFI conditions. Tabulated measurement results are available upon request.

Sound level measurements taken within the vehicle cabin for each of the seven vehicle speeds are shown as a function of frequency in Figure 6. The 80mph condition is shown at the top-left of the figure, followed by the other conditions in descending order.

Aerodynamic noise seems to be the dominate noise source above approximately 400Hz in this set of measurements, likely with road noise dominating at lower frequencies; note that the aerodynamic noise is in direct competition with the range of human speech (approximately 150Hz and above). The noise reduction due to the fairing is most pronounced at middle- and high-frequencies, above approximately 400Hz, but there is also a low-frequency effect – in the 40Hz one-third-octave band in this set of measurements.

Conditions with the fairing installed and sunroof open (SOFI) were remarkably similar across the frequency spectrum to conditions without the fairing and with the sunroof closed (SCFU).

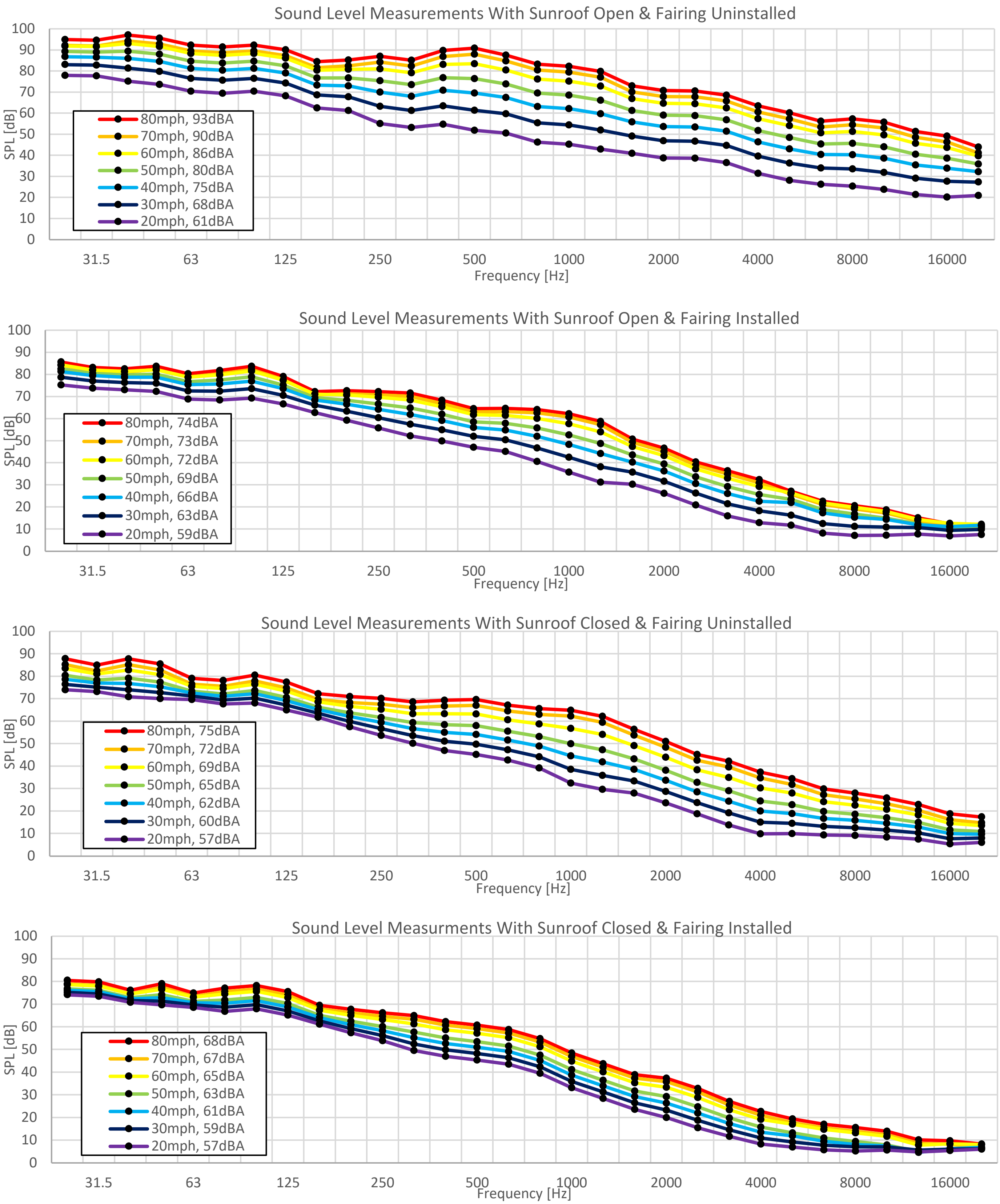
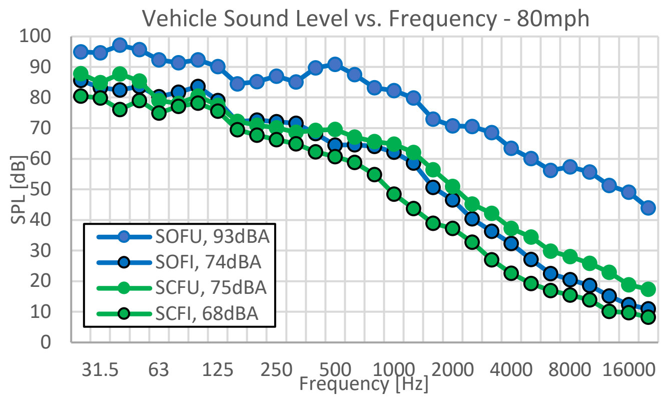
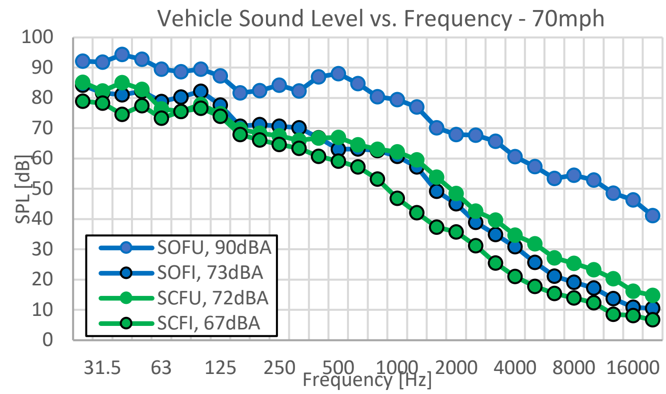
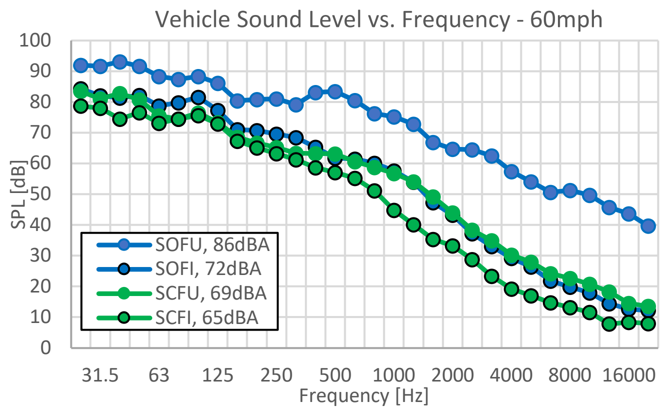
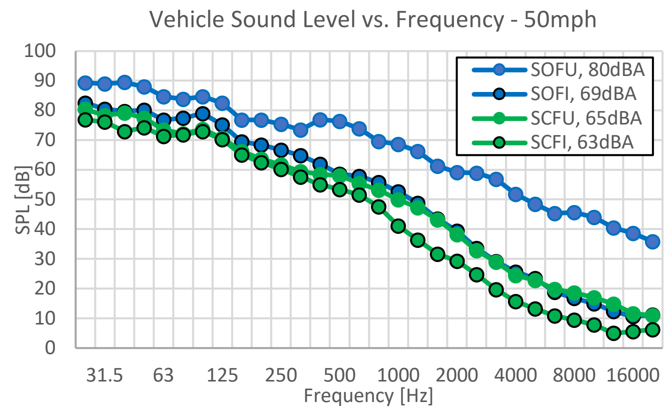


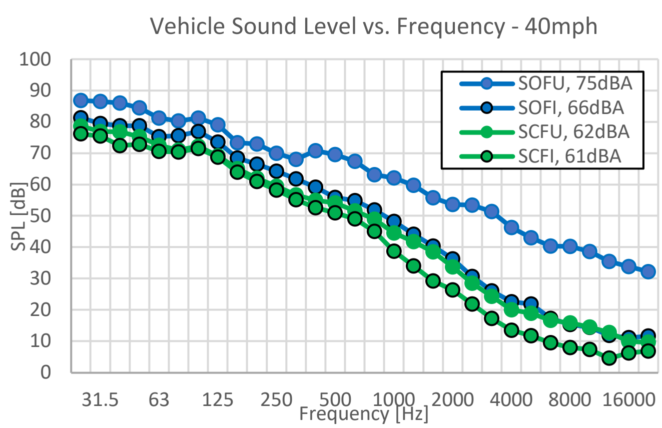
Figure 5 – One-third-octave-band sound level measurement results for each operating condition

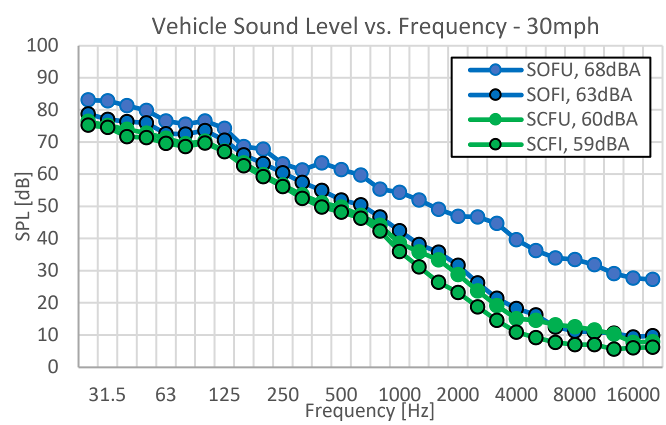












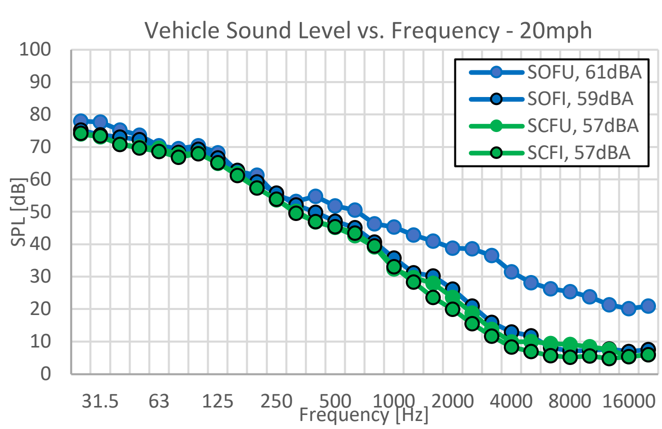


Figure 6 – One-third-octave-band sound level measurement results for each vehicle speed

The Speech Intelligibility Index was calculated for each operating condition, assuming raised speech level with the speaker and receiver at a distance of two feet. Results are tabulated in Table 2, and shown graphically in Figure 7.

Table 2 – Speech Intelligibility Index

Operating Condition	Vehicle Speed [mph]						
	20	30	40	50	60	70	80
SOFU	0.84	0.56	0.31	0.13	0.07	0.01	0.00
SOFI	0.94	0.90	0.76	0.67	0.64	0.57	0.52
SCFU	0.95	0.92	0.88	0.81	0.63	0.48	0.39
SCFI	0.95	0.93	0.91	0.89	0.85	0.82	0.80

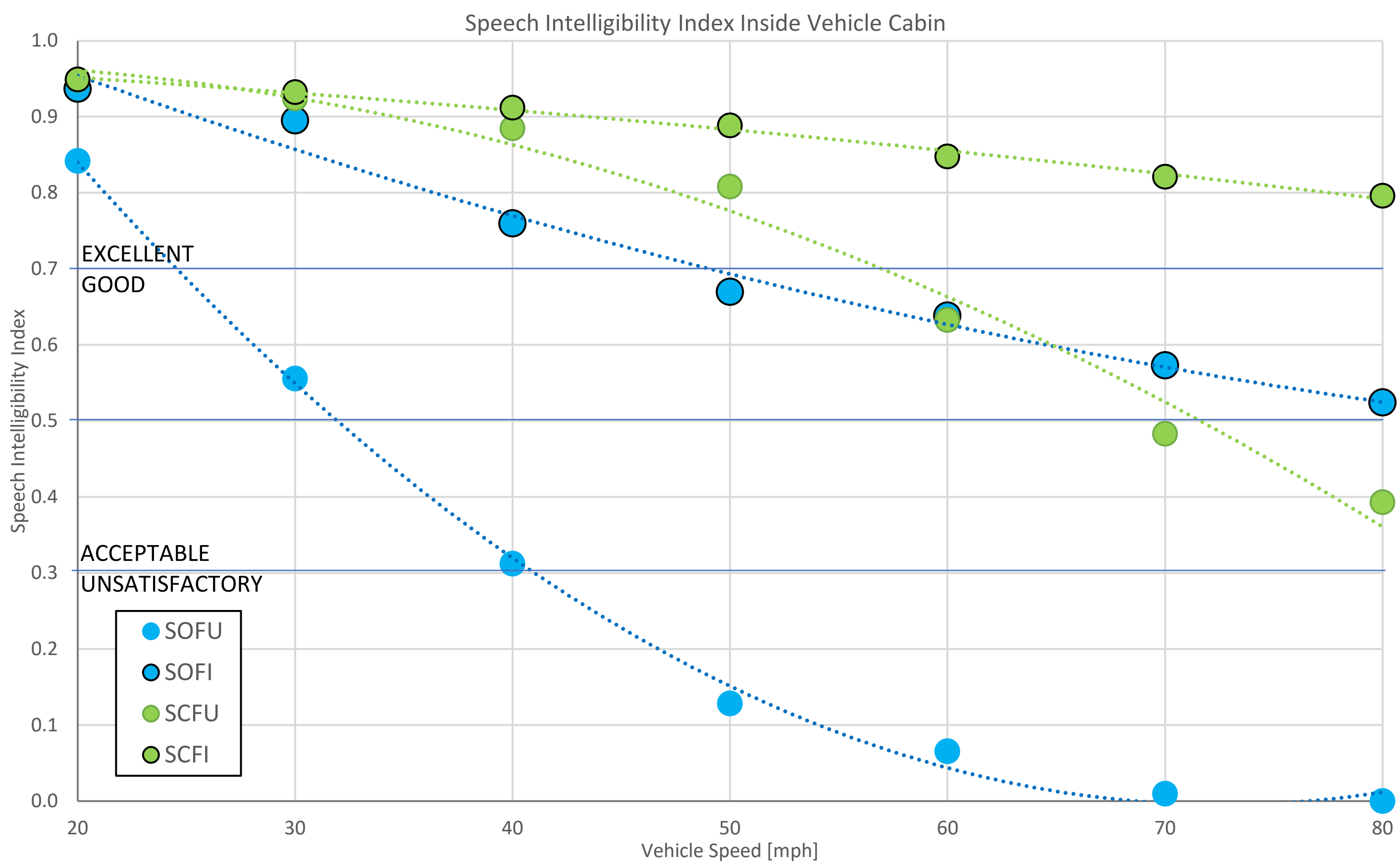


Figure 7 – Speech Intelligibility Index results with 2nd order polynomial curves of best fit

SII values trend downward with increasing vehicle speed. In the SOFU operating condition, the SII within the cabin was barely in the Acceptable range at 40mph, and in the Unsatisfactory range at higher speeds (indeed, down to the very bottom of the SII scale at the highest vehicle speeds). With the fairing installed, intelligibility is in the Good and Excellent ranges for all vehicle speeds. Note that the second-order polynomial trend lines for both conditions with the sunroof open are concave-upward, indicating a more rapid decline in intelligibility with increasing speed, while trend lines for both conditions with the sunroof closed are concave-downward. It is also notable that intelligibility conditions in the SOFI and SCFU operating conditions at 60mph are nearly identical, and above this speed intelligibility is better with the sunroof open and fairing installed.

The difference in speech intelligibility conditions in the vehicle cabin with and without the fairing installed is shown in Figure 8. This difference is shown to generally increase with increasing vehicle speed, although this increase is relatively gradual at lower vehicle speeds with the sunroof closed, and there is a slight decrease at the highest vehicle speeds with the sunroof open due to the fact that the SII ratings at the highest vehicle speeds in the SOFU operating condition are at the extreme low-end of the scale.

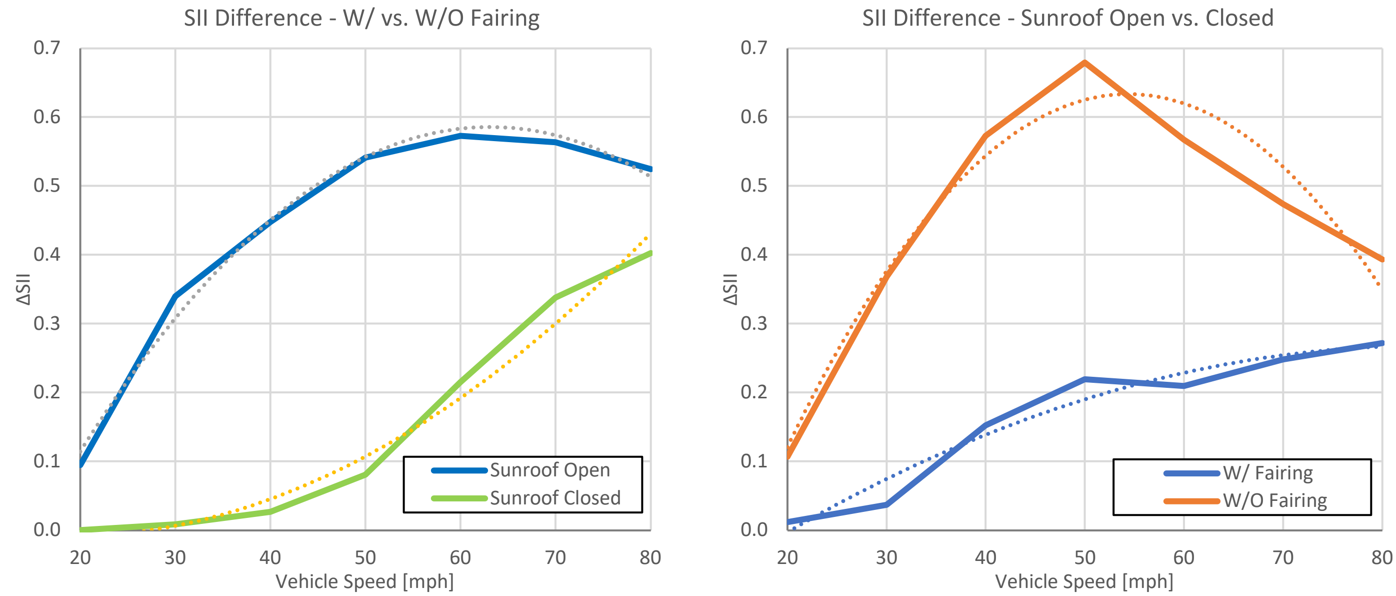


Figure 8 – Difference in cabin speech intelligibility with the sunroof open vs. closed at left, and with vs. without the fairing installed at right

The change in speech intelligibility conditions in the vehicle cabin caused by opening the sunroof is also shown in Figure 8. Again, the difference is shown to generally increase with increasing vehicle speed. It is notable that the second-order polynomial trend line for the conditions with the fairing installed is nearly linear, while the trend line for the conditions without the fairing shows a remarkable inflection point, with a decrease in the SII difference above 50mph vehicle speed. Essentially, without the fairing installed, opening the sunroof with the vehicle traveling at highway speeds had less of an effect on speech intelligibility conditions within the cabin than opening the sunroof at more moderate speeds.

CONCLUSION

Sound levels were measured inside the cabin of a vehicle traveling at a variety of speeds under four operating conditions: with and without a fairing installed and with and without the sunroof open. The fairing was found to reduce sound levels by more than 15dBA at highway speeds, and was found to limit the increase in cabin sound level when opening the sunroof while driving on the freeway to 6dBA. The effect of the fairing was found to be most pronounced at middle- and high-frequencies, above approximately 400Hz.

With the fairing installed, speech intelligibility conditions are in the Good and Excellent SII ranges for all operating conditions. This is a significant improvement over conditions without the fairing installed, which vary from the Acceptable range down to the bottom of the Unsatisfactory range at highway speeds.

The reduced cabin sound levels make conversation easier, both between occupants of the vehicle and especially over the telephone, and generally provide for a more pleasant driving experience, particularly during longer drives on faster roads.

ACKNOWLEDGEMENTS

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