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Executive Summary

In order to better understand the effect of tire carcass construction and pavement texture on tire/pavement noise generation, a measurement program was conducted on a group of four automobile tires on three pavement textures. The tires included all combinations of cap ply, no cap ply, sidewall filler height of 1.75 inches and sidewall filler height of 0.35 inches. The tires, General AmeriG4S, P205/65R15, were nominally identical in all other respects including tread pattern and rubber compound properties. During this investigation, other tire design variables such as tire pressure and rim size were held constant. The pavement samples were made of rigid Portland Cement Concrete (PCC) pavement sections with smooth, textured and porous surface textures. Tests were conducted at speeds of 10, 20 and 30 mph.

The Tire/Pavement Test Apparatus (TPTA) at the Ray W. Herrick Laboratories at Purdue University was used for the tests. Five microphones were used to measure the sound generated by the tire/pavement interaction. Three microphones were located according to the specifications of the Close Proximity Method (ISO/CD 11819-2). The other two microphones were located such that one was in front of the tire 5 cm from the leading edge of the contact patch and one was behind the tire 5 cm from the trailing edge of the contact patch, along the centerline of the tire.

The tires all produce similar overall sound pressure level and frequency spectra for a specific test surface. The three pavements produced significantly different spectra. The porous pavement produced higher levels below 1000 Hz but lower levels than the other two pavement types above 1000 Hz. The pavement surface textures investigated had a much more significant effect on sound generation and radiation of the tires than the variations investigated for cap ply and sidewall filler height.

Introduction

Measurements were taken to study the effect of two tire parameters and pavement texture on the generation of noise. This report discusses the measurement procedure and analyses performed to understand the effects of varying the construction of an automobile tire on the sound pressure level radiated from the tire when operated over various pavement textures.

The filler height and cap ply were varied within a test group of four tires. The filler height is either 1.75 inches or 0.35 inches. There is either a cap ply or no cap ply. The test surfaces used for this experiment include a smooth, ground Portland Cement Concrete (PCC), a textured PCC, and a porous PCC. The noise was measured for tire speeds of 10, 20 and 30 mph using the Tire/Pavement Test Apparatus (TPTA). All of these test variable changes are relatively significant within the design space of either the tire or pavement. The information obtained from this study provides insight about whether such changes are likely to have a significant effect on the noise radiated from the tire.

Test Methods

The Tire/Pavement Test Apparatus (TPTA) shown in Figure 1 at Purdue University's Ray W. Herrick Laboratories was used for these investigations.

Figure 1 The Tire/Pavement Test Apparatus (TPTA) at Purdue University's Ray W. Herrick Laboratories

Tire Specifications and Mounting

A tire was mounted to the TPTA arm and adjusted such that the normal force between the tire and pavement was 600 lbs. The tire was then run across the pavement at 30 mph for 15 minutes to allow it to reach a stable operating temperature. After warm-up, the tire inflation pressure was set to 30 psi. This procedure was repeated each time a new tire was mounted for testing or anytime there was a delay in testing of more than 1/2 hour. The characteristics and designations of the test tires are shown in table 1.

Table 1 Tire designations and specifications

Tire Designation	Cap Ply Status	Filler Height
A28	No Cap Ply	0.35 in.
B39	No Cap Ply	1.75 in.
C23	Cap Ply	0.35 in.
D27	Cap Ply	1.75 in.

The A28 tire is the reference tire for this set of tires and represents a more typical construction. Aside from the test parameters, the tires were nominally identical in construction, tread and rubber compound and were mounted on nominally identical 6 inch rims.

Testing was performed on each tire at speeds of 10, 20 and 30 mph.

Pavement Surface Textures

For the purposes of this investigation, the six pavement sections were rigid Portland Cement Concrete (PCC) samples. Three of these sections consisted of PCC with specific surface textures to be used in testing. These textures were smooth, textured and porous as shown in Figures 2 through 4. Additional photographs of the pavement sections in-situ are shown in Appendix A.

Figure 2 Portland Cement Concrete with smooth surface

Figure 3 Portland Cement Concrete with textured surface

Figure 4 Portland Cement Concrete with porous surface

The remaining three pavement sections consisted of PCC with smooth surfaces. No measurements were made for these surfaces.

Microphone Placement

The test tires were mounted to one of the TPTA arms and surrounded by an array of five microphones as shown in Figure 5. The remaining arm had a generic tire attached to balance the loads on the TPTA and was not equipped with microphones.

Figure 5 Microphone array surrounding a test tire

Three of the microphones, Bruel and Kjaer Type 4188-A-021, were placed according to the Close Proximity Method (CPX) draft standard (ISO/CD 11819-2). The locations are shown in Figure 6.

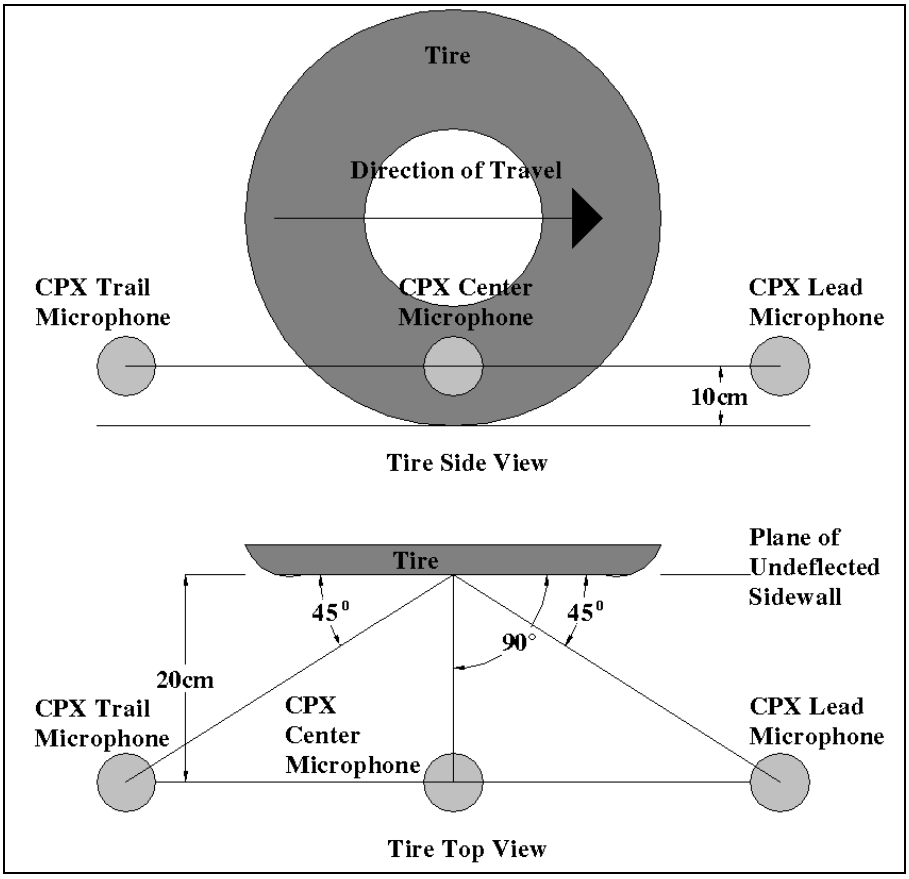


Figure 6 Close Proximity Method (CPX) microphone placements (ISO/CD 11819-2)

The CPX microphone locations are referred to throughout this report as CPX Lead microphone, CPX Center microphone and CPX Trail microphone to denote the CPX microphones traveling at the leading edge, center and trailing edge of the tire respectively.

Two additional microphones, Modal Shop Type 40AE, were located along the center-line of the tire at points horizontally 5 cm to the front and rear of the tire as measured on a plane 5 cm above the surface of the pavement as shown in Figure 7.

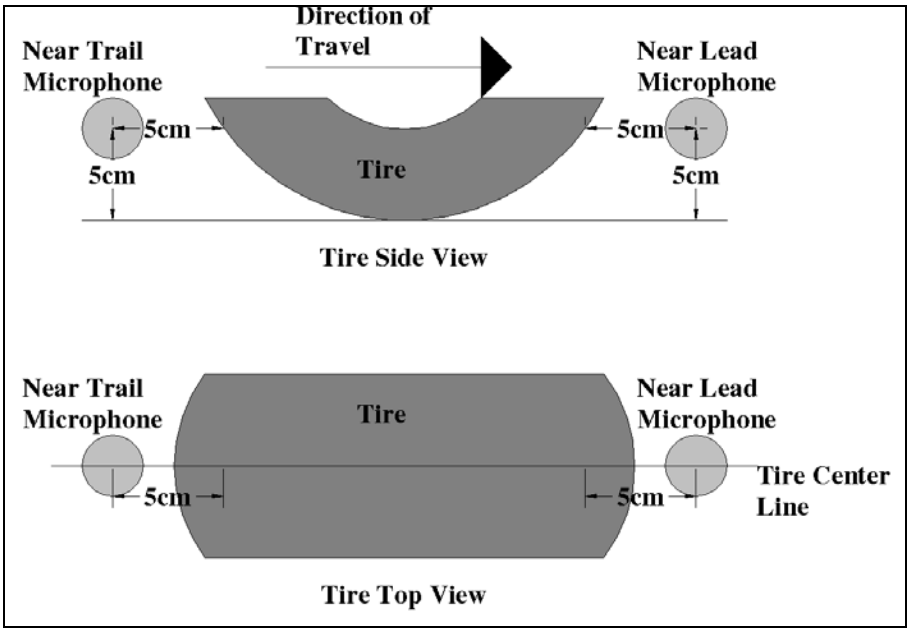


Figure 7 Near-field microphone placements

These microphone locations are referred to as Near Lead microphone and Near Trail microphone to denote the microphone traveling at the leading edge and trailing edge of the tire, respectively.

Data Acquisition

The microphone array was cabled to a Bruel & Kjaer type 3560-C Portable PULSE Acquisition Front-end that was mounted to the TPTA. This front-end was linked via Wi-Fi compatible wireless LAN hardware to a laptop computer running Bruel & Kjaer PULSE Noise and Vibration Analysis Type 7700 software. The microphone array used in this experiment was subjected to a standard field calibration routine on a weekly basis. Calibration values were not updated as long as no significant changes occurred. All the data shown in this report were acquired within a one week period during which no calibration values were altered. The microphones were equipped with windscreens, Bruel & Kjaer type UA 0237, in an attempt to mitigate the effects of wind-noise, which will be discussed in detail in a later section.

The PULSE system was configured as a narrow band Fourier analyzer for a frequency range of 0 to 5000 Hz with 400 lines of resolution. Linear averaging was used with 100 averages. Average updating was accomplished via a magnetic proximity probe mounted on the moving

arm. This probe sensed a stationary magnet mounted at the position at which acoustical measurements were to be initiated for a given pavement surface. Accordingly, the average was updated once per revolution of the TPTA arm such that the complete measurement encompassed 100 revolutions. The five microphone locations were measured simultaneously during testing.

Data Reduction

The Bruel & Kjaer Pulse was used to calculate the auto-spectra of the acoustical signals measured at each of the microphones in real time. The auto-spectra were calculated from 0 to 5000 Hz with a resolution of 400 lines. For some of the data, A-weighted, 1/3rd octave band spectra were calculated from the narrow band spectra using EXCEL. Narrow band spectral data was imported into EXCEL and A-weighted. This A-weighted narrow band data was then assigned to appropriate 1/3rd octave bands using a brick wall filter design. The data in these bands was summed to synthesize A-weighted, 1/3rd octave band spectra. This synthesized data was used throughout the main body of this document in the figures. The data in the appendices is shown in narrow band format.

Test Sequence

The test sequence follows:

1. One of the tires was mounted and warmed up for 15 minutes.
2. The trigger magnet was located at one of the test pavement sections.
3. Noise data was collected at 10, 20, and 30 mph.
4. The TPTA was stopped, the trigger was moved to another surface and step 3 was repeated.
5. After data were collected for three surfaces, the sequence was repeated with a new tire.

Background Noise

During operation of the TPTA, there are noise sources extraneous to the tire/pavement noise being studied. Collectively these sources are referred to as background noise. These sources include mechanical noise generated by the drive components of the TPTA, wind noise due to flow over the moving microphones and other sources. Due to noise control efforts, the majority of extraneous sources have been reduced to negligible levels leaving wind-noise as the dominant background noise source.

As an initial step in treating wind-noise, all microphones were equipped with Bruel & Kjaer type UA 0237 windscreens. These windscreens provide a significant reduction in measured wind-noise. To ensure that the remaining wind noise is sufficiently lower in level than the tire/pavement noise of concern, the following method of establishing a background noise floor was established.

The tire to be tested was mounted on the TPTA and adjusted such that the tire was approximately one inch above the surface of the TPTA pavement and would not make contact with the pavement at any point during the rotation of the TPTA. The TPTA was then operated at speeds of 10, 20 and 30mph. During this mode of operation all noise sources except the noise generated by the tire/pavement interface were present and were measured collectively. The results of these measurements were then compared to the corresponding noise measurements with the tire in contact with the pavement.

The noise floor was sufficiently below the phenomena of concern above 300-500 Hz. For frequencies below 300 Hz wind noise dominates the measurements and, as such, objective analysis of data below 300 Hz is not practical. As operating speed is increased, the noise floor increases. In the limiting case of 30 mph the noise floor is highest and closest to the tire/pavement noise level. A representative example for one of the near field microphones is shown in Figure 8 where the background noise measurement is plotted relative to the noise generated by tire A28 operating at 30 mph over the three pavement textures. Above 300 Hz the signal to noise ratio is sufficiently large.

For the CPX locations, the tire/pavement noise level is lower. However, the level remains high enough above the wind noise level except for the cases in which the tires were being run over the porous pavement. In this case the measured tire/pavement noise drops close to the level

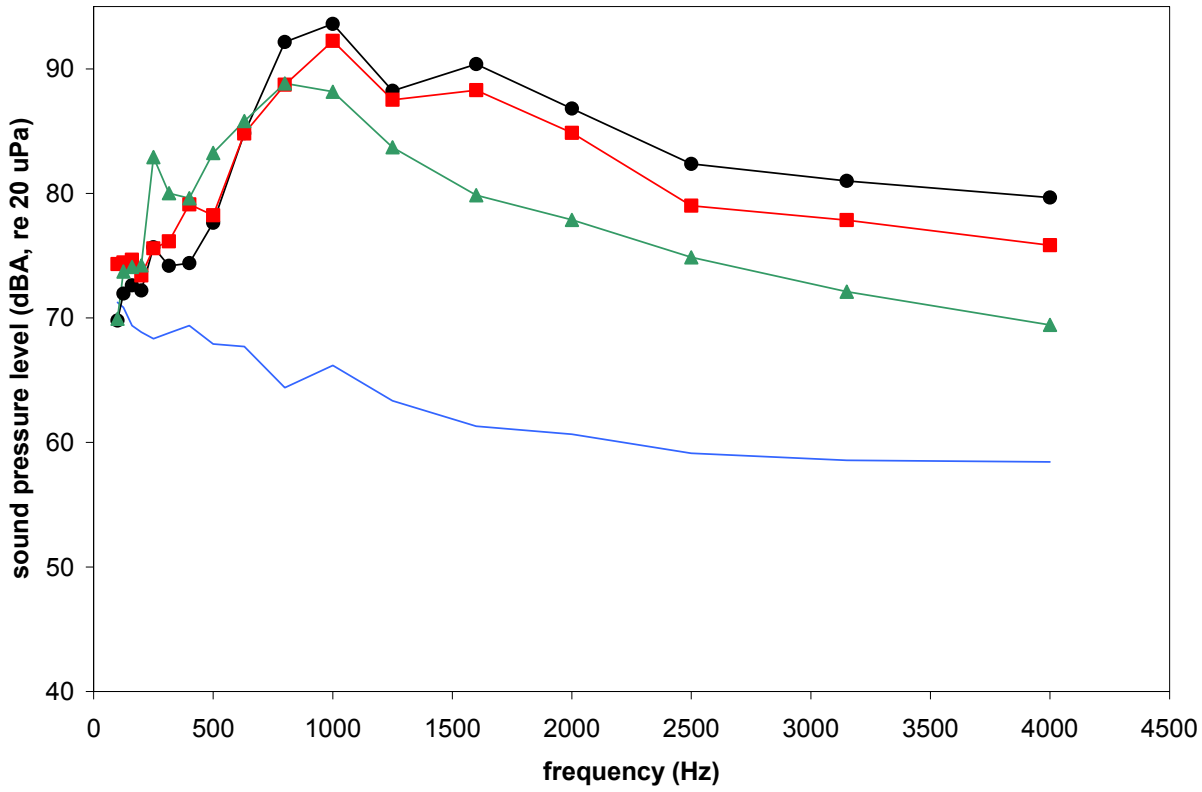


Figure 8 1/3rd octave, A-weighted spectra of background noise relative to noise generated by three pavement textures for reference tire (A28) operating at 30 mph as measured at the Near Trail microphone. (-●●- = smooth pavement, -■■- = textured pavement, -▲▲- = porous pavement, ——— = background noise)

of the noise floor above frequencies of approximately 2500 Hz. A typical example for the case of tire A28 at 30 mph over the porous surface is shown in Figure 9. Other wind noise data in narrow band format is shown in Appendix B. Throughout the remainder of this report, only data above 500 Hz where the wind noise is negligible will be shown.

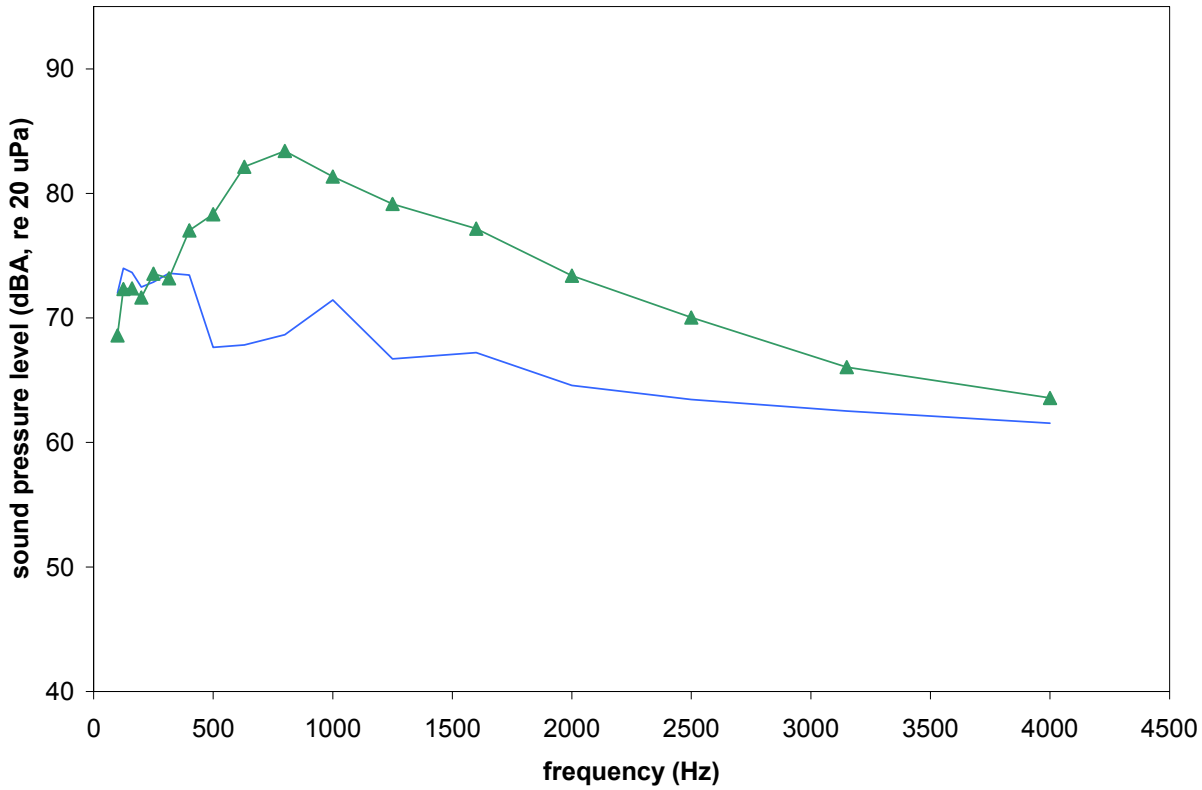


Figure 9 1/3rd octave, A-weighted spectra of background noise relative to noise generated by porous pavement texture for reference tire (A28) operating at 30 mph as measured at the CPX Lead microphone. (-▲▲- = porous pavement, ——— = background noise)

Results

Effect of Pavement Texture

Typical data for the three pavement surface texture conditions are shown in Figure 10. These data are for the case with the reference tire (A28) at 30 mph for the trailing microphone of the CPX configuration. The overall noise radiation is highest for the porous pavement. This is due to a spectral peak near 800 Hz. Above 1000 Hz the porous surface has the lowest sound radiation of the three pavement surface alternatives. The sound radiation of the other two pavement surfaces peaks in the 1000 Hz spectral band. Above 1000 Hz the smooth surface has the highest sound radiation of the three pavement surface alternatives. Other results in narrow band format for all tires and speeds are collected in Appendices E-H. In general, the porous surface has the highest sound radiation for all speeds due to the spectral peak in the 800 Hz frequency band. The spectra for the smooth surface and the textured surface are higher above 1000 Hz.

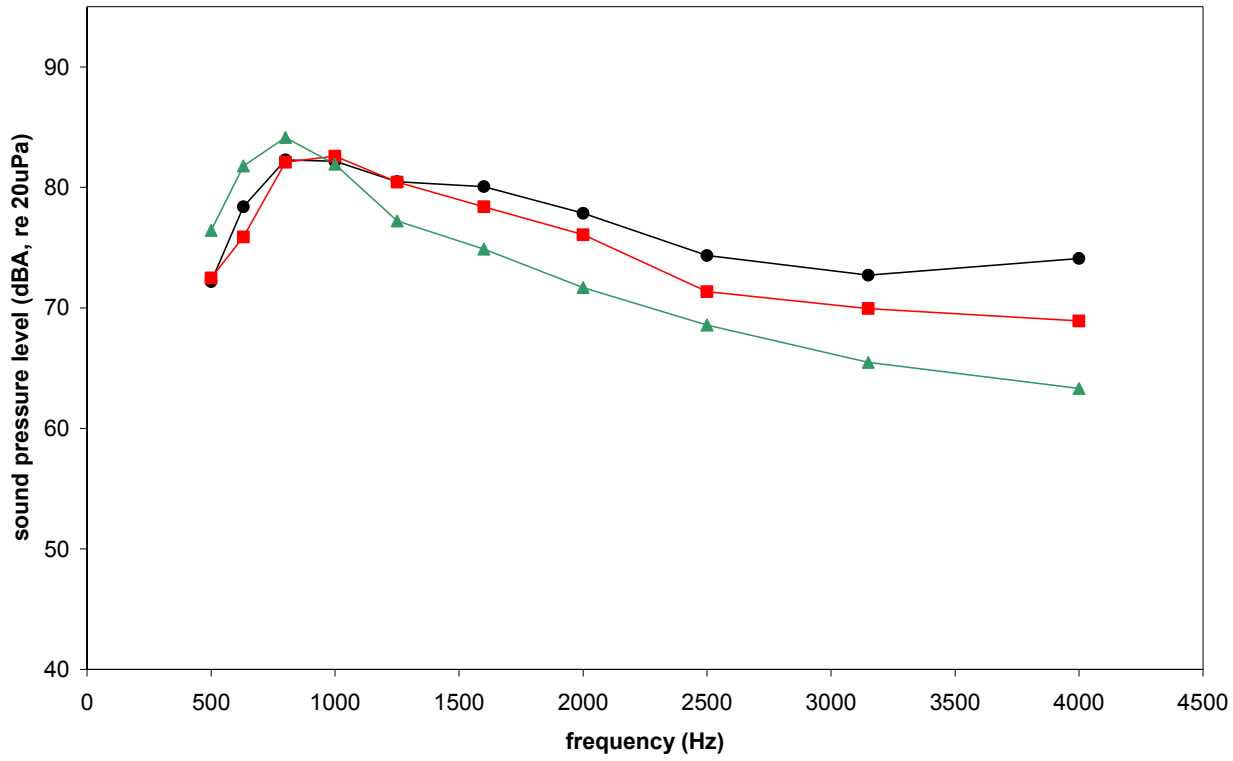


Figure 10 1/3rd octave, A-weighted spectra for reference tire (A28) operating over three pavements at 30 mph as measured at the CPX Trail microphone (-●●- = smooth pavement, -■■- = textured pavement, -▲▲- = porous pavement)

Typical data for one of near field microphones is shown in Figure 11. These data were measured for the microphone at the trailing edge of the contact patch at 30 mph. The spectra have the same shape as the spectra of the CPX microphones shown in Figure 10. However, sound radiation for the porous surface is significantly lower that the sound radiation for the other two pavement surface types. At this near field location, the smooth pavement surfaces has the highest sound radiation of the three surface pavement alternatives in all frequency bands above 500 Hz. The data for other speeds and microphone positions are shown in Appendices E-H in narrow band format. The results for these other cases are similar.

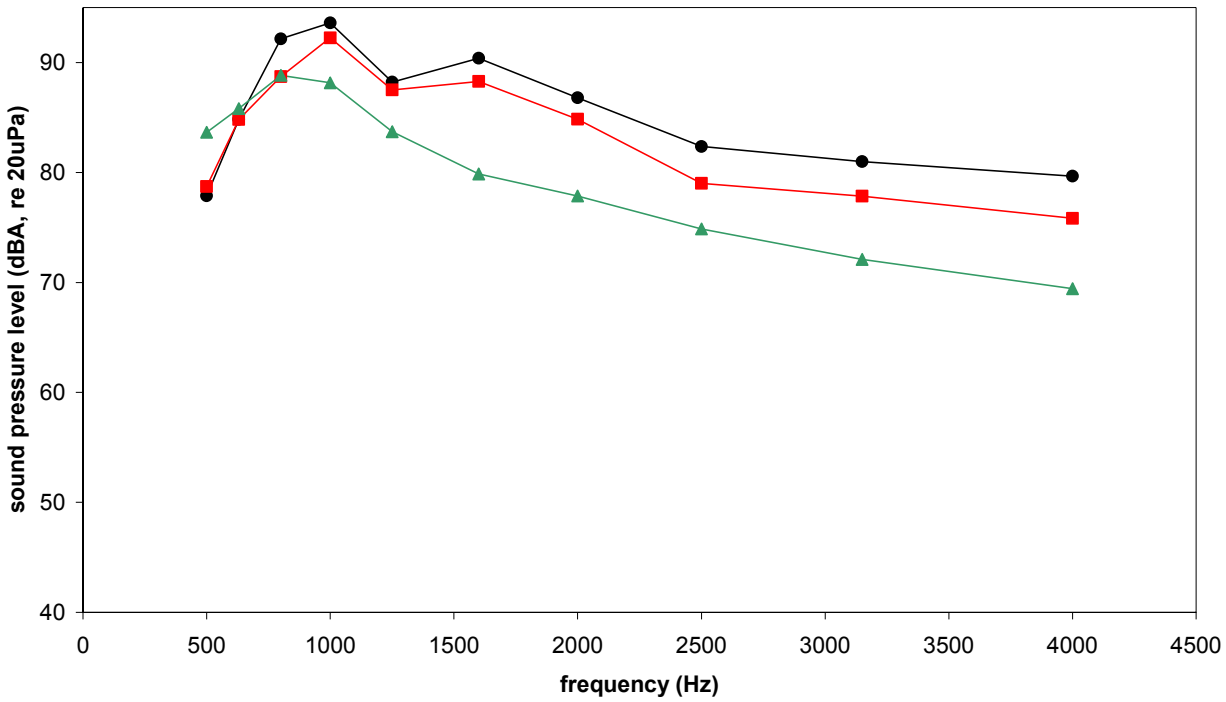


Figure 11 1/3rd octave, A-weighted spectra for reference tire (A28) operating over three pavements at 30 mph as measured at the Near Trail microphone (-●●- = smooth pavement, -■■- = textured pavement, -▲▲- = porous pavement)

The effect of pavement type is significant. The spectra of the three pavement type alternatives differ significantly. The increased texture height and high porosity of the porous concrete apparently cause increased sound at lower frequency in the 800 Hz range but decreased sound above 1000 Hz. The smooth pavement is quieter below 1000 Hz but noisier above 1000 Hz.

To investigate further, the relative difference between the near field and CPX microphones was calculated. The differences between the near field microphones and the CPX microphones locations for a typical example are shown in Figure 12. The spectral difference for the porous surface is much different than the spectral differences for the other two cases.

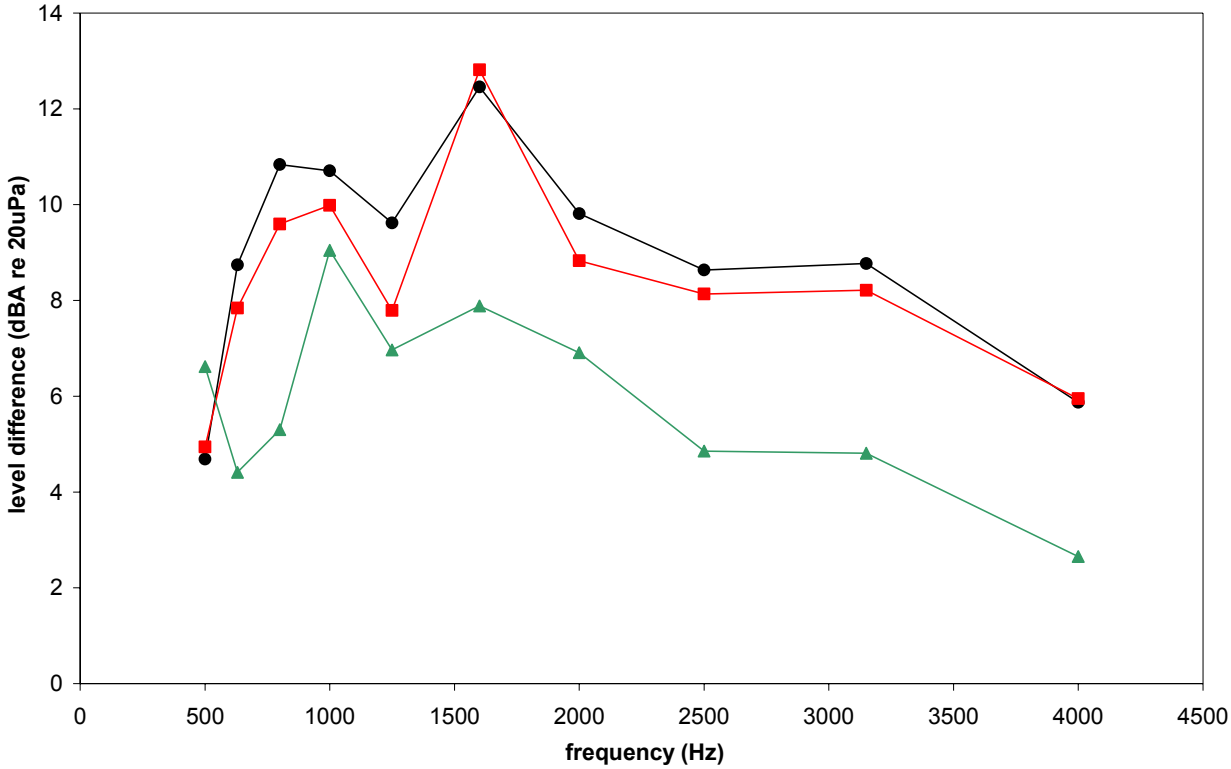


Figure 12 1/3rd octave, A-weighted spectra of Near Lead microphone minus CPX Lead microphone for reference tire (A28) operating over three pavements at 30 mph. (-●●- = smooth pavement, -■■- = textured pavement, -▲▲- = porous pavement)

Apparently, the noise generation mechanisms on the porous surface are different than the noise generation mechanisms for the smooth and textured surface. Texture causes certain of these mechanisms to increase and others to decrease.

Effect of Cap Ply and Filler Height Tire Design Parameters

Typical data for the four tires at one of the CPX locations are shown in Figure13. These data are for the case with textured surface at 30 mph for the trailing microphone of the CPX array. In general, all four tires radiate sound at similar levels with similar spectra. For the various tires, there are several minor differences in the spectra that do not affect the overall level. The results

are collected for all of the surfaces at the various speeds in Appendix C.

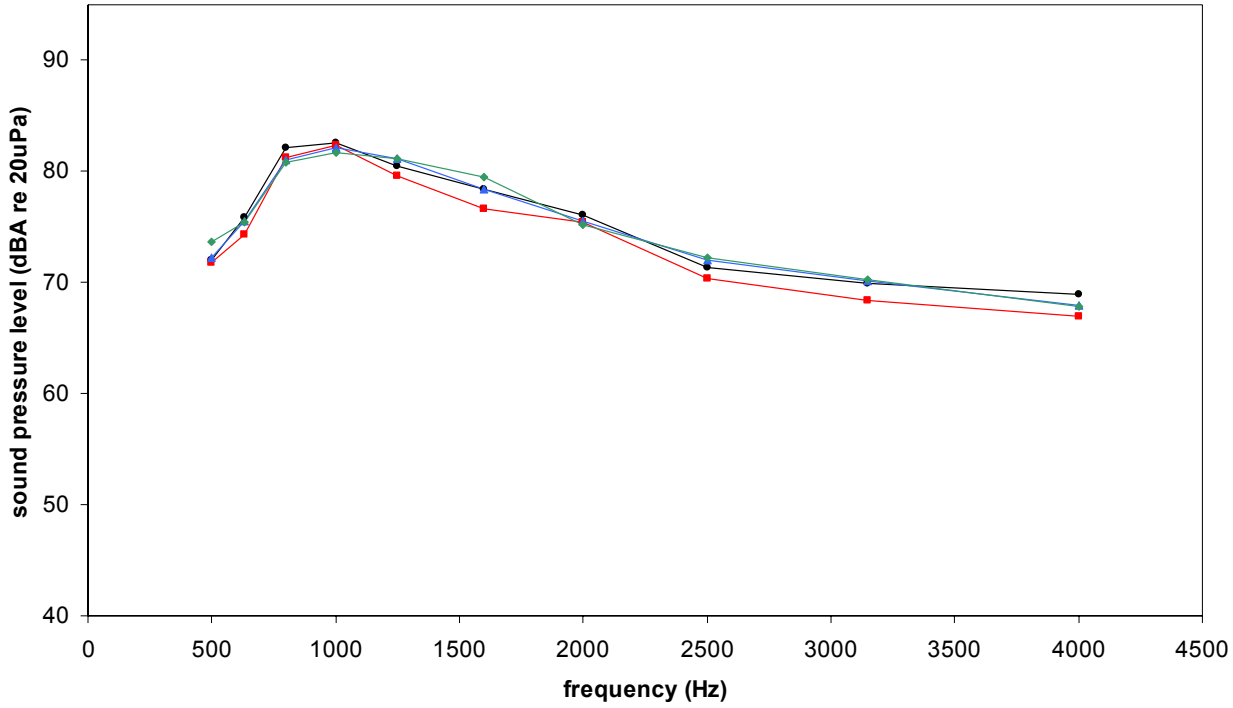


Figure 13 1/3rd octave, A-weighted spectra for all tires operating on textured pavement at 30 mph as measured at the CPX Trail microphone (-●- = tire A28, -■- = tire B39, -▲- = tire C23, -◊- = tire D27)

Typical data for the near field microphones for the different tire designs are shown in Figure 14. These data are for the case with textured pavement at 30 mph with the microphone at the Near Trail location. At the near field location, there are only minor differences in the overall level or the spectrum for the tires. Similar data in narrow band format are collected in Appendix D for the near field microphones for all speeds and surfaces.

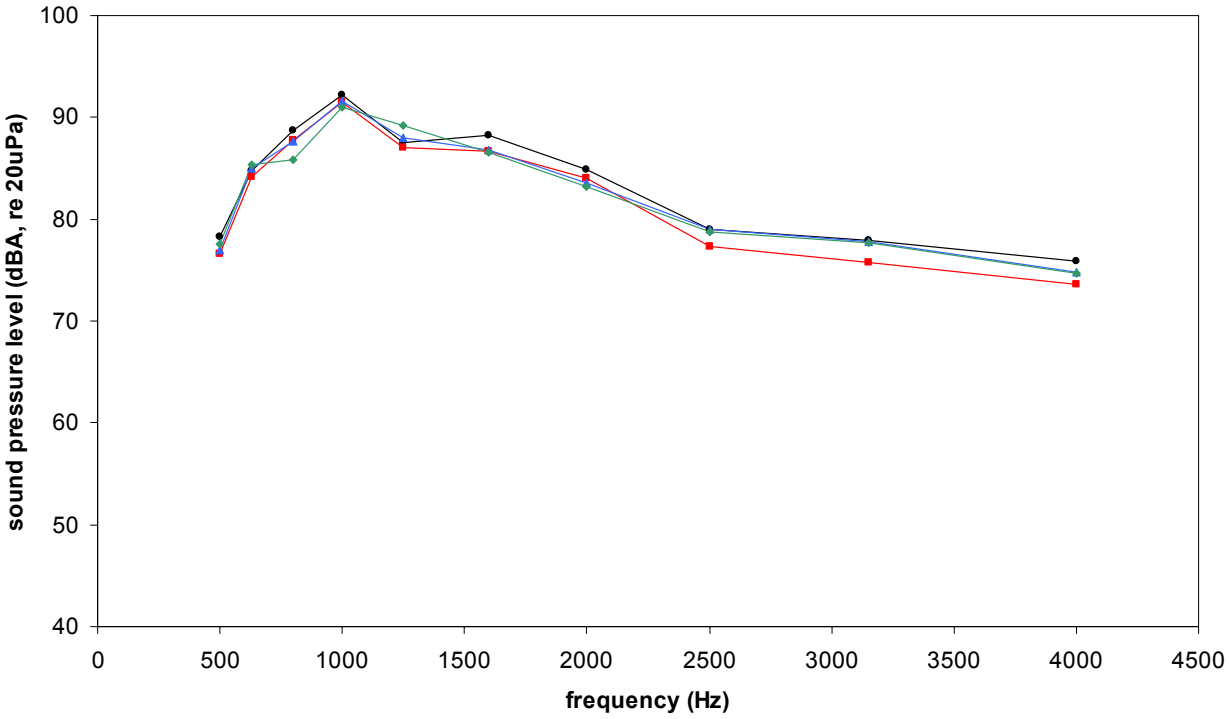


Figure 14 1/3rd octave, A-weighted spectra for all tires operating on textured pavement at 30 mph as measured at the Near Trail microphone (-●- = tire A28, -■- = tire B39, -▲- = tire C23, -◊- = tire D27)

Conclusions

The TPTA appears to be an effective tool for the evaluation of both pavement and tire alternatives. Measurements were accomplished quickly with excellent repeatability. A significant number of pavement or tire alternatives can be tested in a relatively short period of time.

The tire variations of cap ply and filler height produced minimal differences. There were no significant trends found above 500 Hz. The B39 (no cap ply, 1.75" filler height) was the only tire with a consistent trend, in this case a slightly lower noise radiation in the band between 1000 and 2000 Hz was measured. Other design variables such as the tread pattern and the rubber compound should be investigated to identify quiet tire alternatives.

The porous surface produced significantly different spectra than the other two surfaces. Consistently the noise generation between 500 Hz and 1000 Hz was higher than the other two surfaces and the noise above 1000 Hz was lower than the other two surfaces. These differences are significant and indicate different noise generation mechanisms are active for the porous surface than for the other pavement surfaces. These differences are consistent across all four tires. The role of texture depth, texture size, and porosity will be very important to understand.

References:

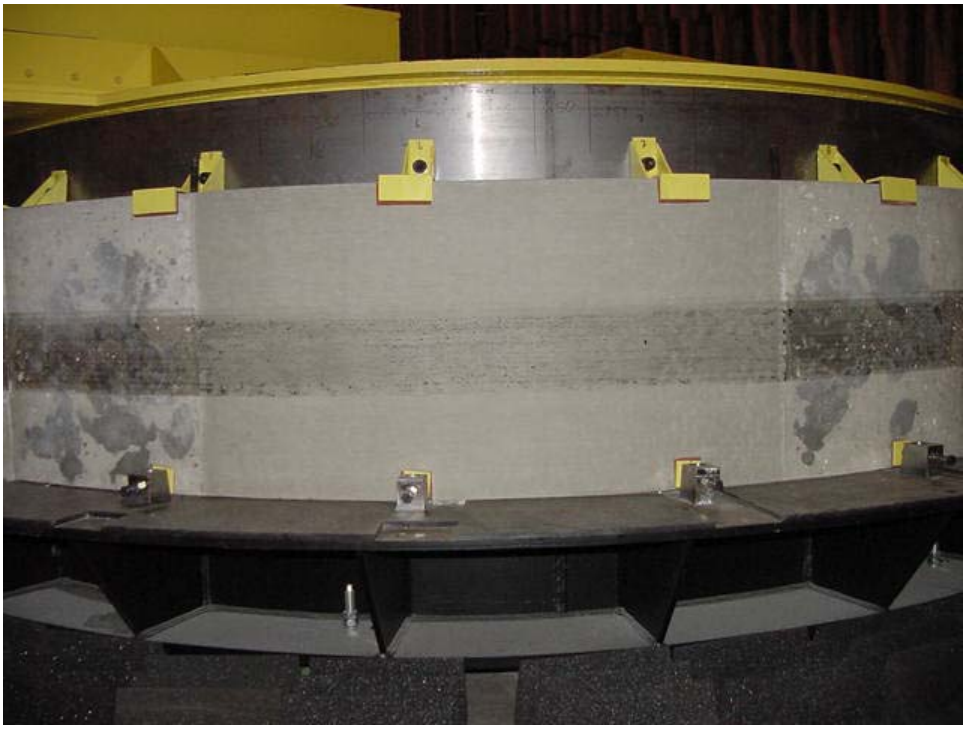
[1] International Organization for Standardization*, Acoustics—Measurement of the influence of road surfaces on traffic noise—Part 2:" The close-proximity method",* Draft Standard ISO/CD 11819-2, Geneva, Switzerland: ISO/TC 43/SC 1/WG 33, December 2000.

Appendices:

Appendix A: Pavement sample photographs

Smooth Portland Cement Concrete surface

Smooth Portland Cement Concrete close-up



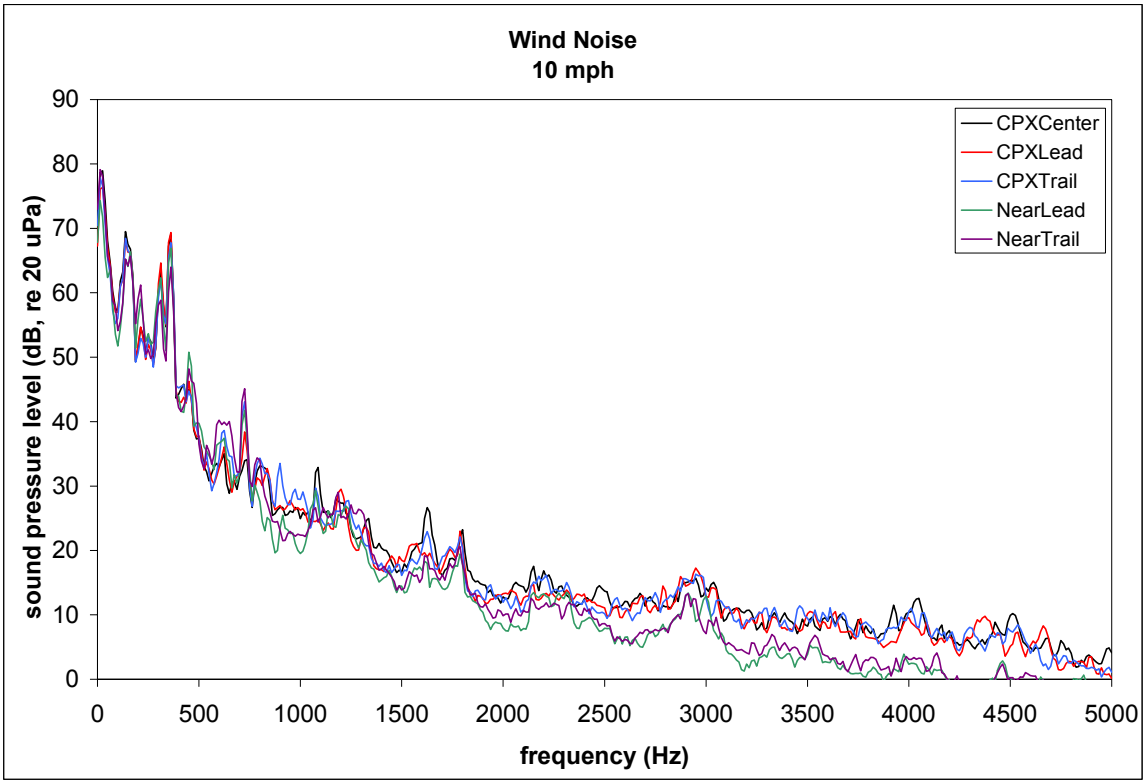
Textured Portland Cement Concrete surface

Textured Portland Cement Concrete close-up

Porous Portland Cement Concrete surface

Porous Portland Cement Concrete close-up

Appendix B: Wind noise narrow band spectra


Wind Noise
10 mph
sound pressure level (dB, re 20 uPa)
frequency (Hz)
CPXCenter
CPXLead
CPXTrail
NearLead
NearTrail
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4500
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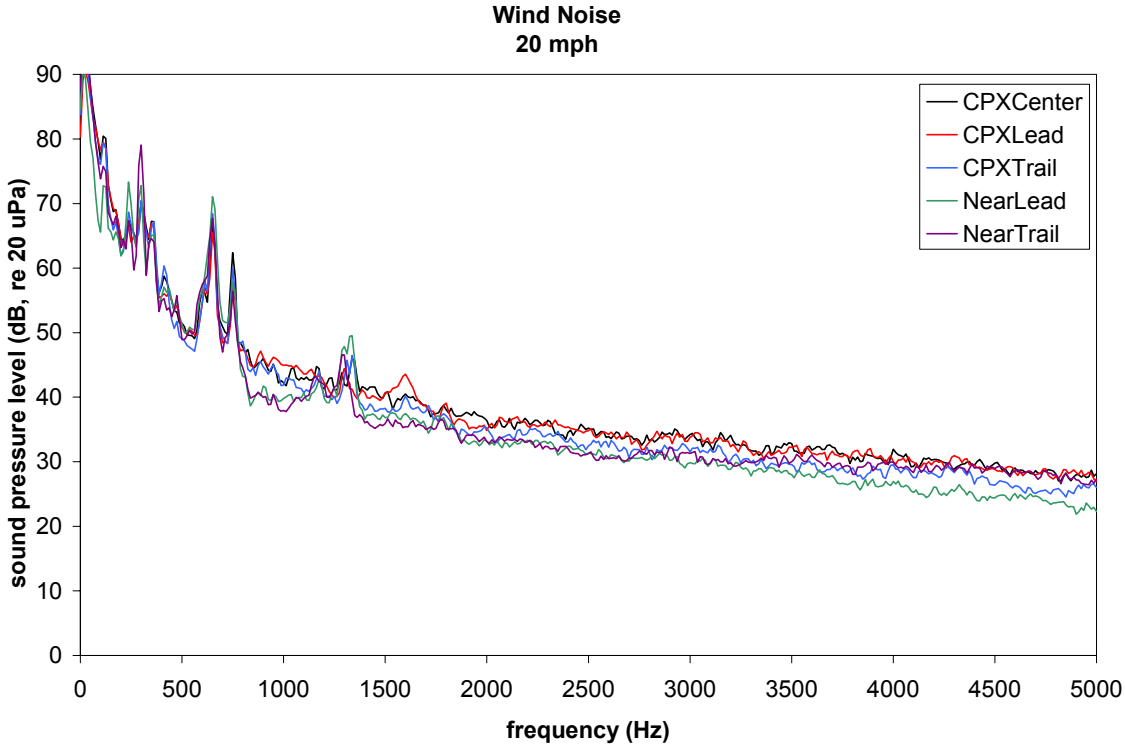
Wind Noise
20 mph
sound pressure level (dB, re 20 uPa)
frequency (Hz)
CPXCenter
CPXLead
CPXTrail
NearLead
NearTrail
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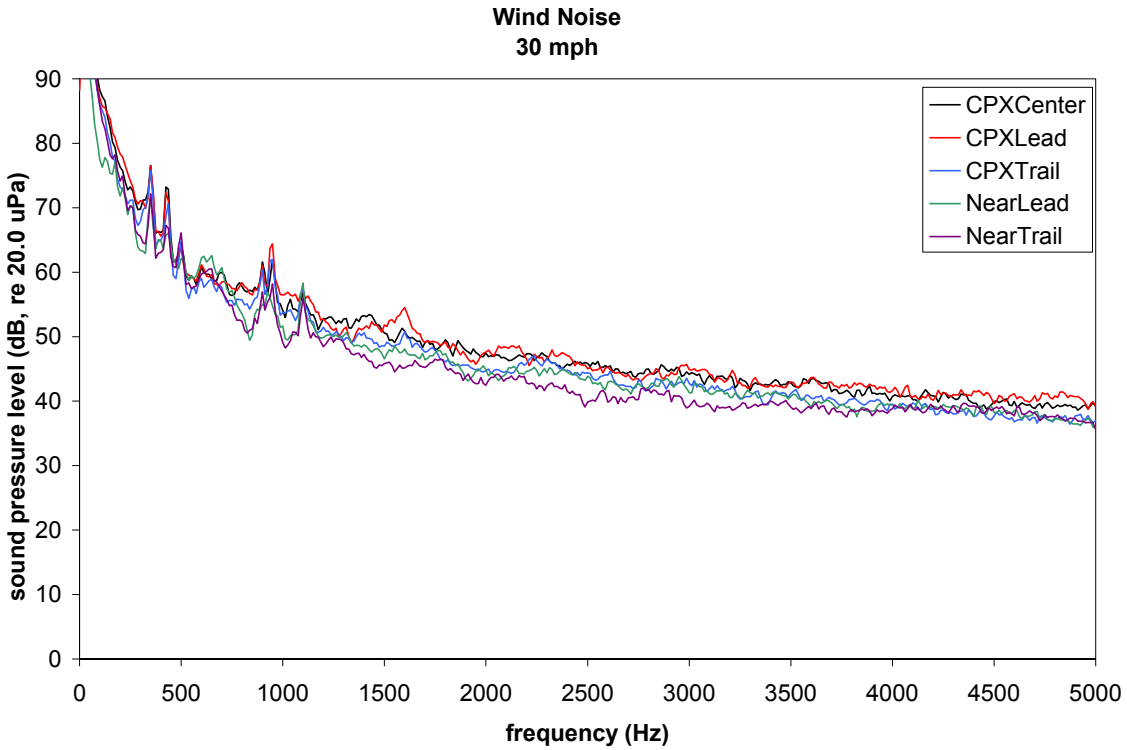
Wind Noise
30 mph
sound pressure level (dB, re 20.0 uPa)
frequency (Hz)
CPXCenter
CPXLead
CPXTrail
NearLead
NearTrail
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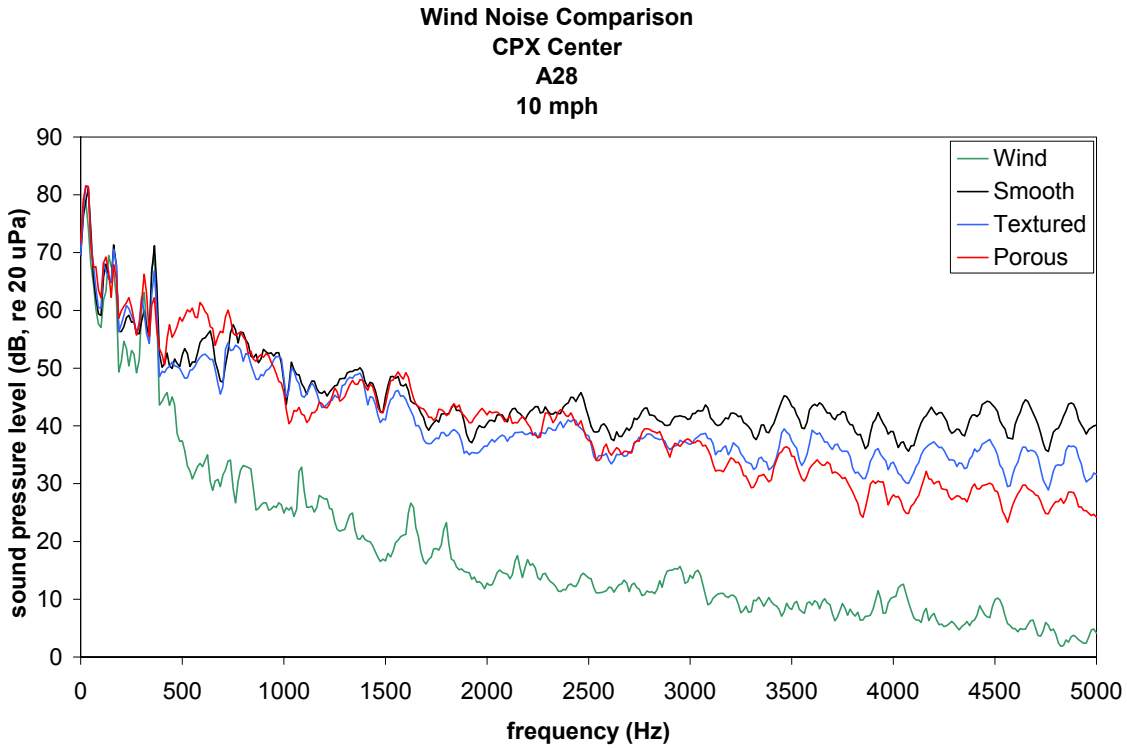
Wind Noise Comparison
CPX Center
A28
10 mph
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Wind
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Textured
Porous
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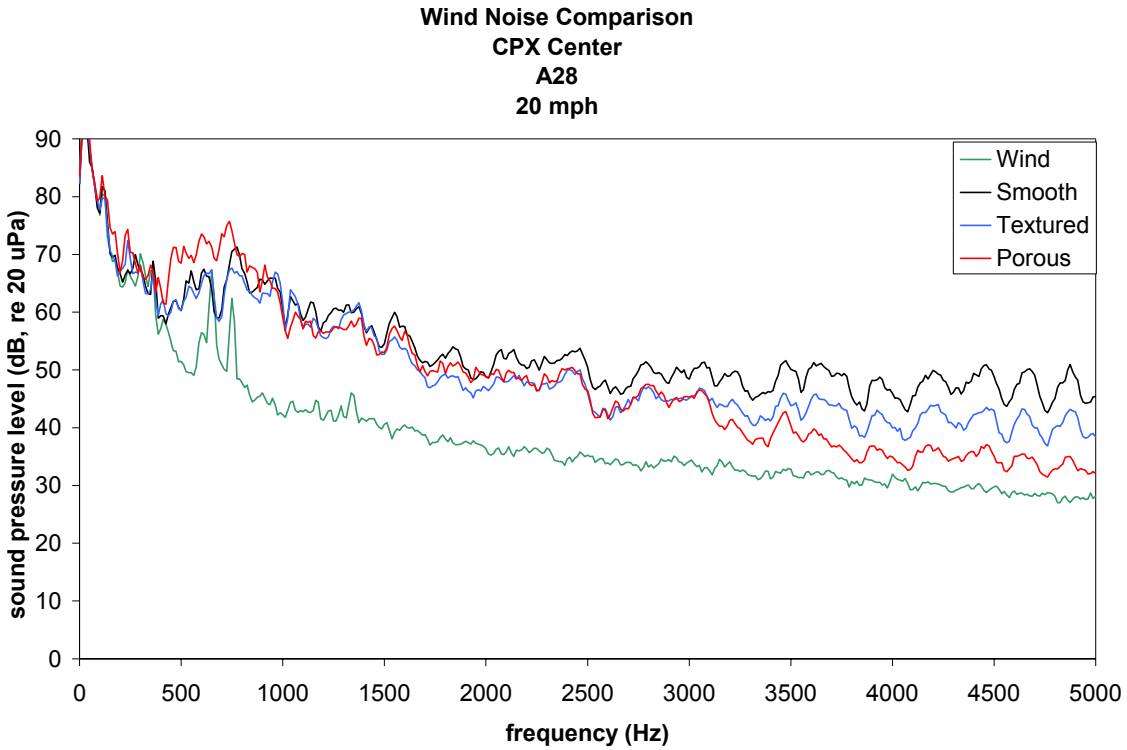
Wind Noise Comparison
CPX Center
A28
20 mph
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Wind
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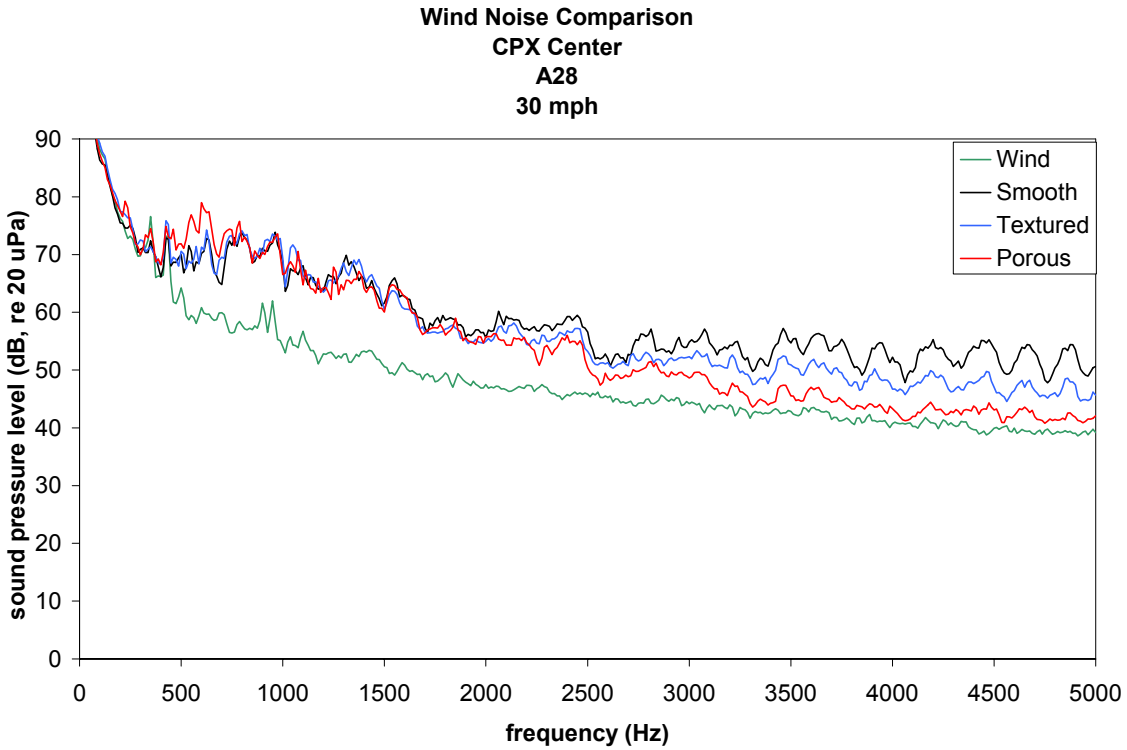
Wind Noise Comparison
CPX Center
A28
30 mph
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Wind
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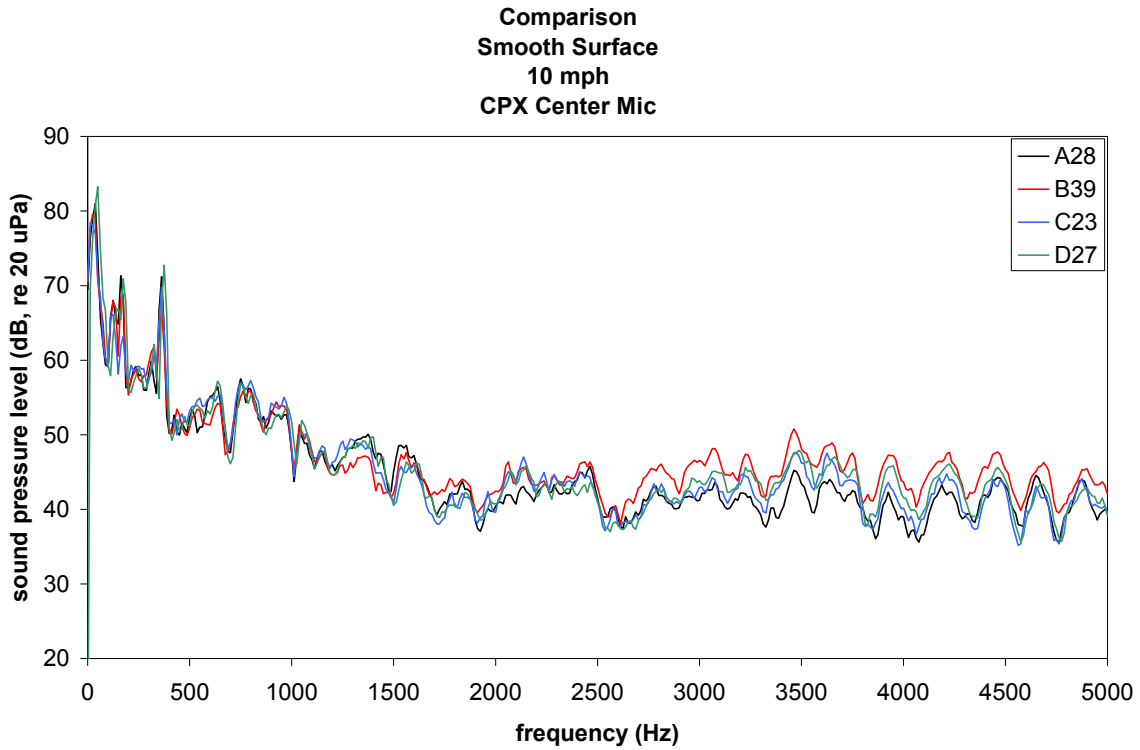
Appendix C: Narrow band spectra at CPX microphone locations; multiple tires at one speed and surface texture.


Comparison
Smooth Surface
10 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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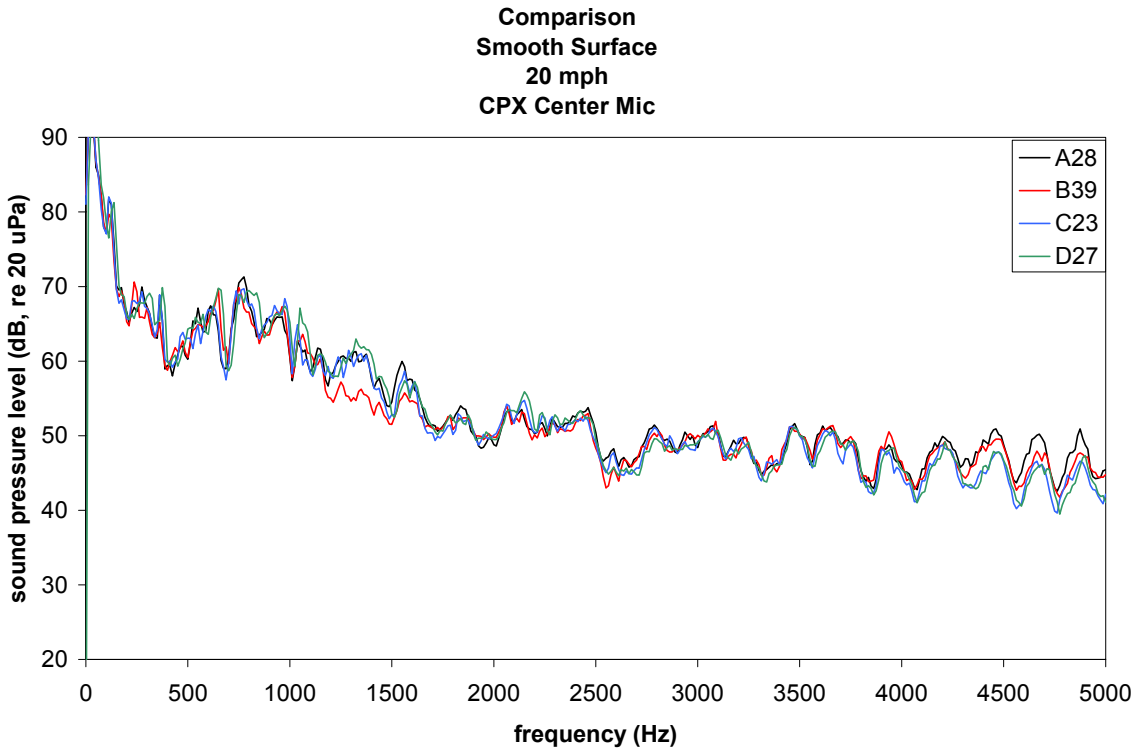
Comparison
Smooth Surface
20 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
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B39
C23
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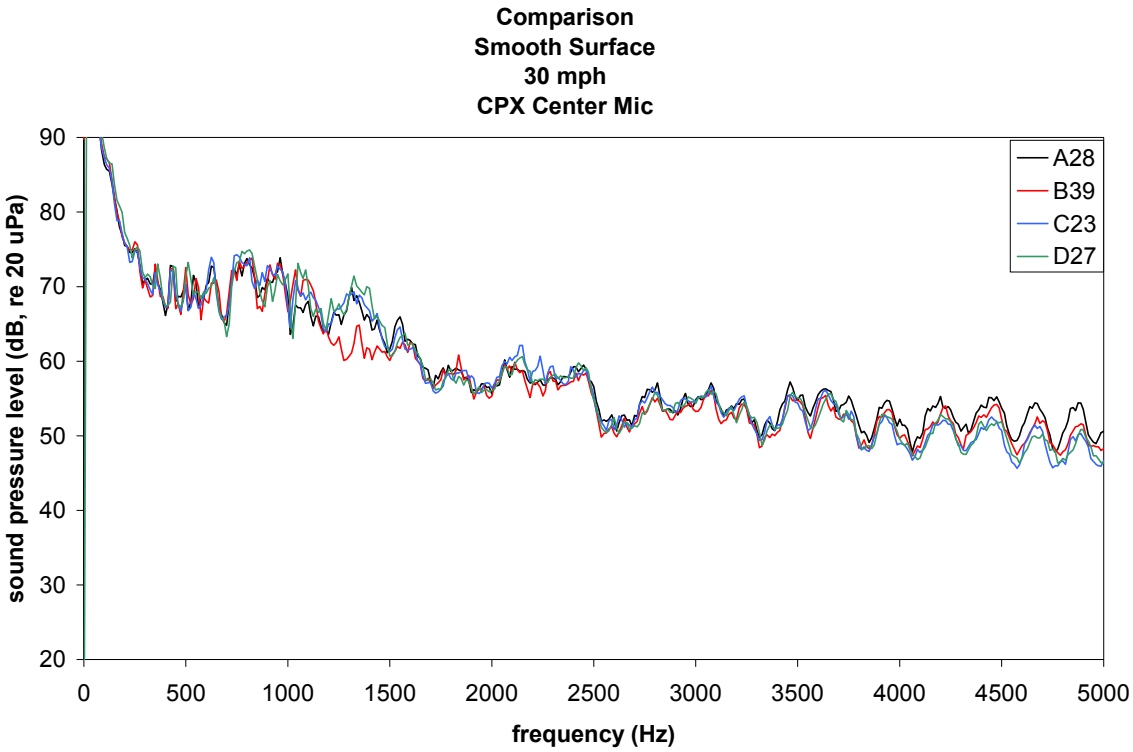
Comparison
Smooth Surface
30 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
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B39
C23
D27
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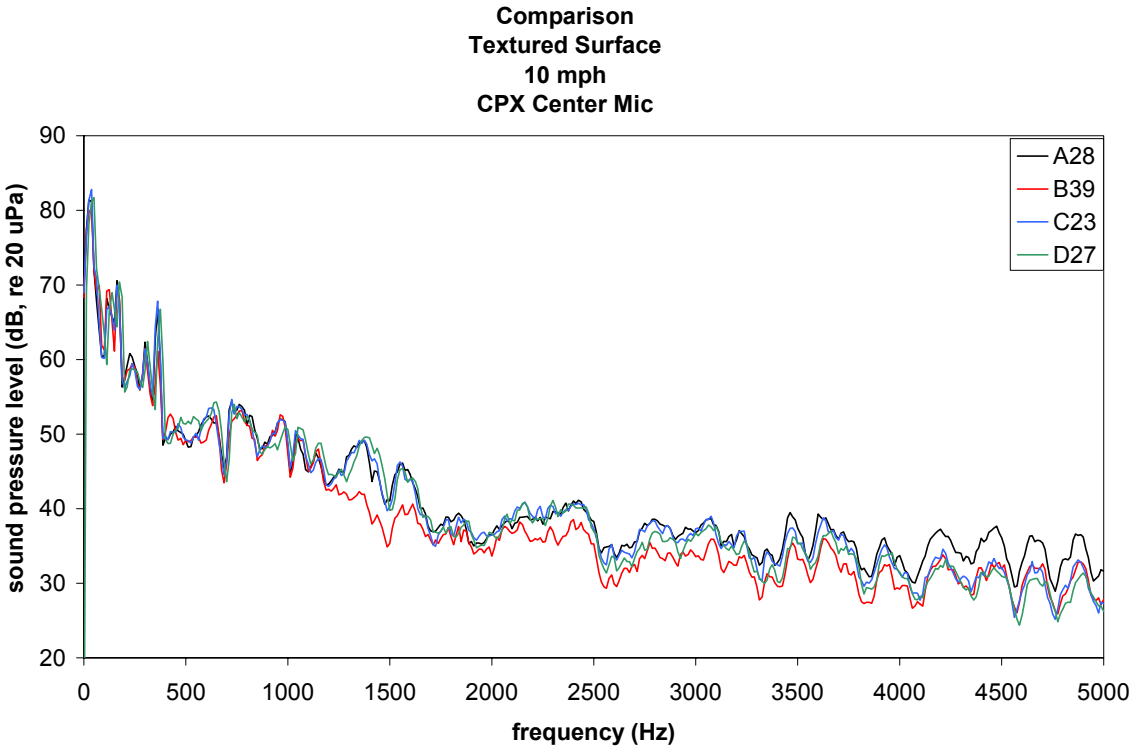
Comparison
Textured Surface
10 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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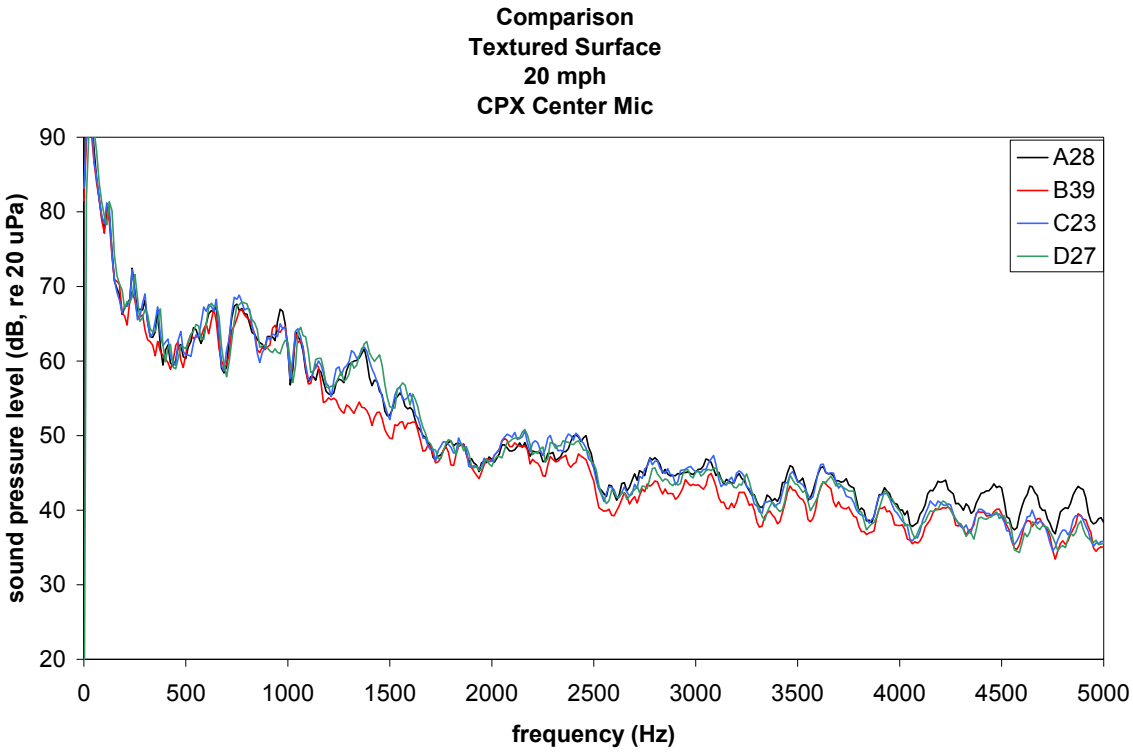
Comparison
Textured Surface
20 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
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50
40
30
20
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500
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1500
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3000
3500
4000
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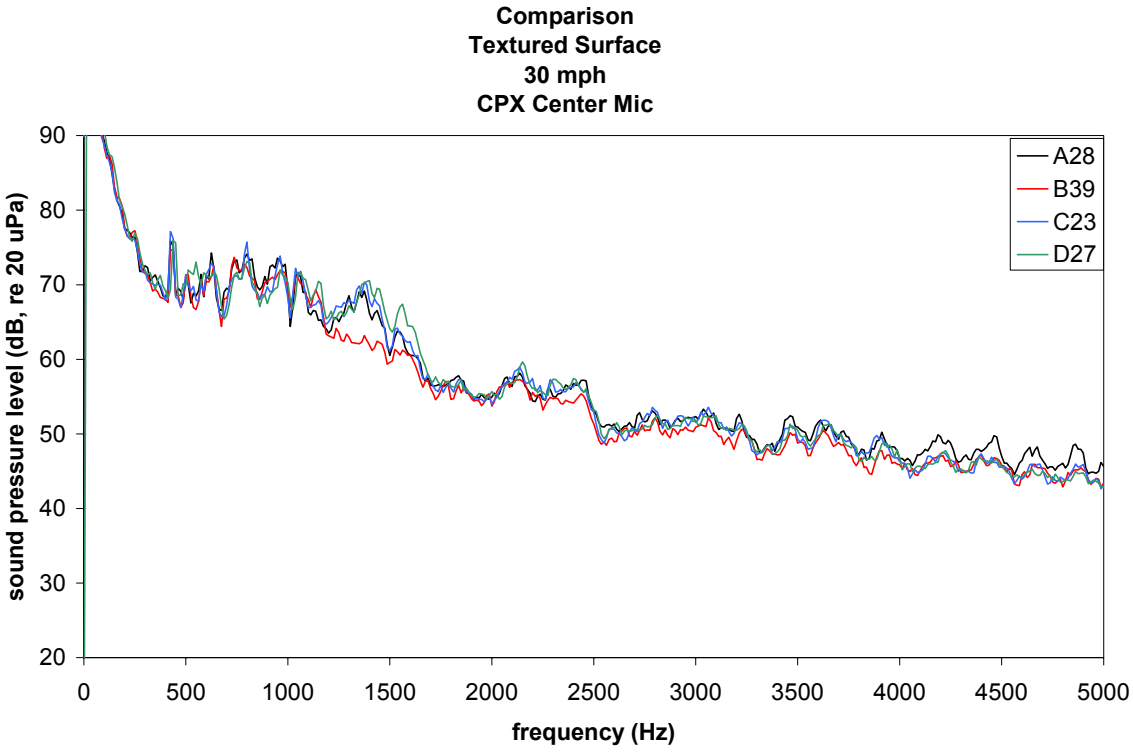
Comparison
Textured Surface
30 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
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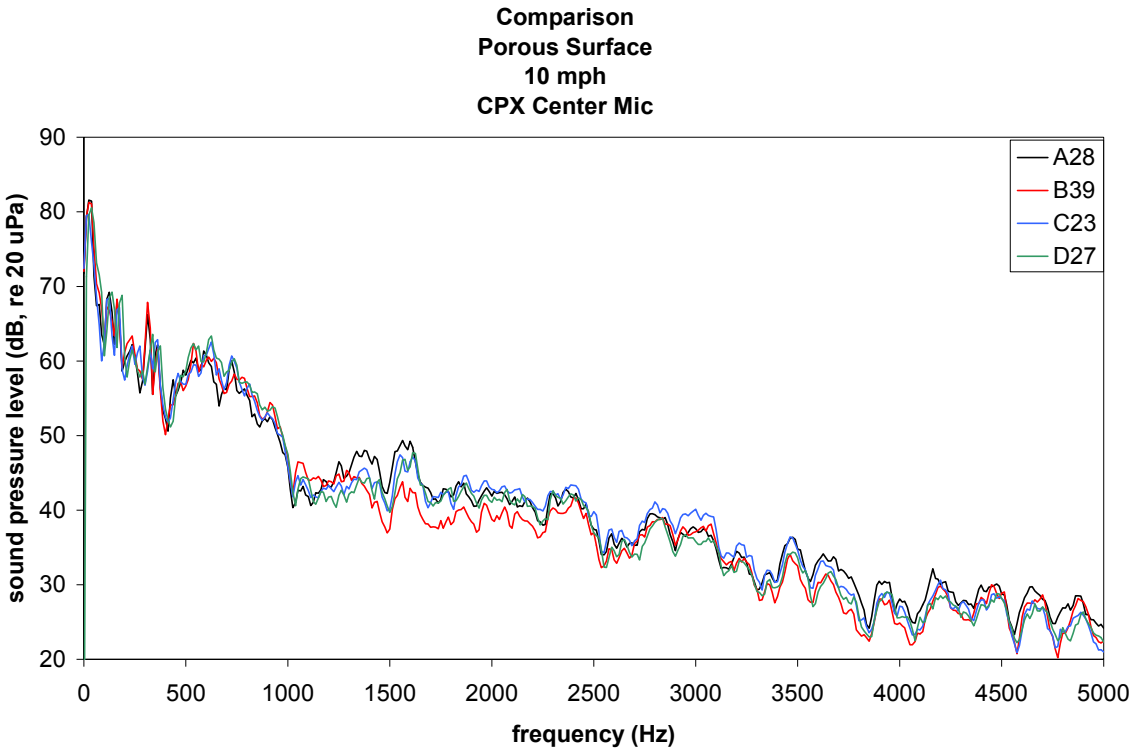
Comparison
Porous Surface
10 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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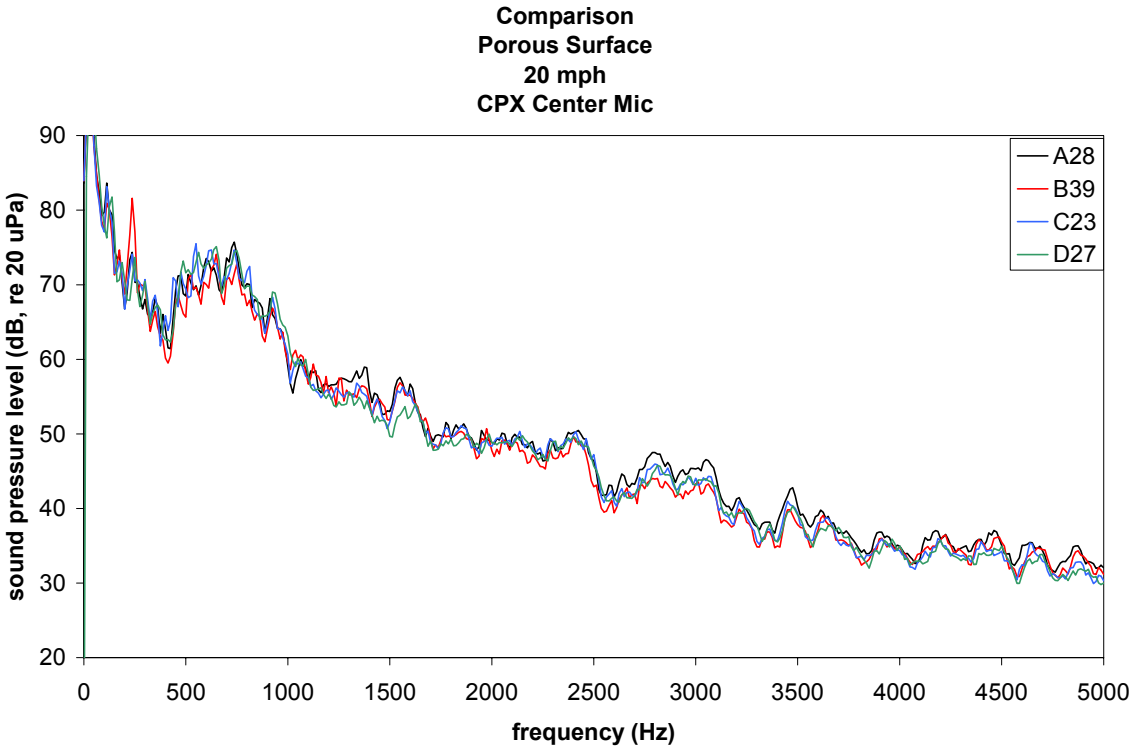
Comparison
Porous Surface
20 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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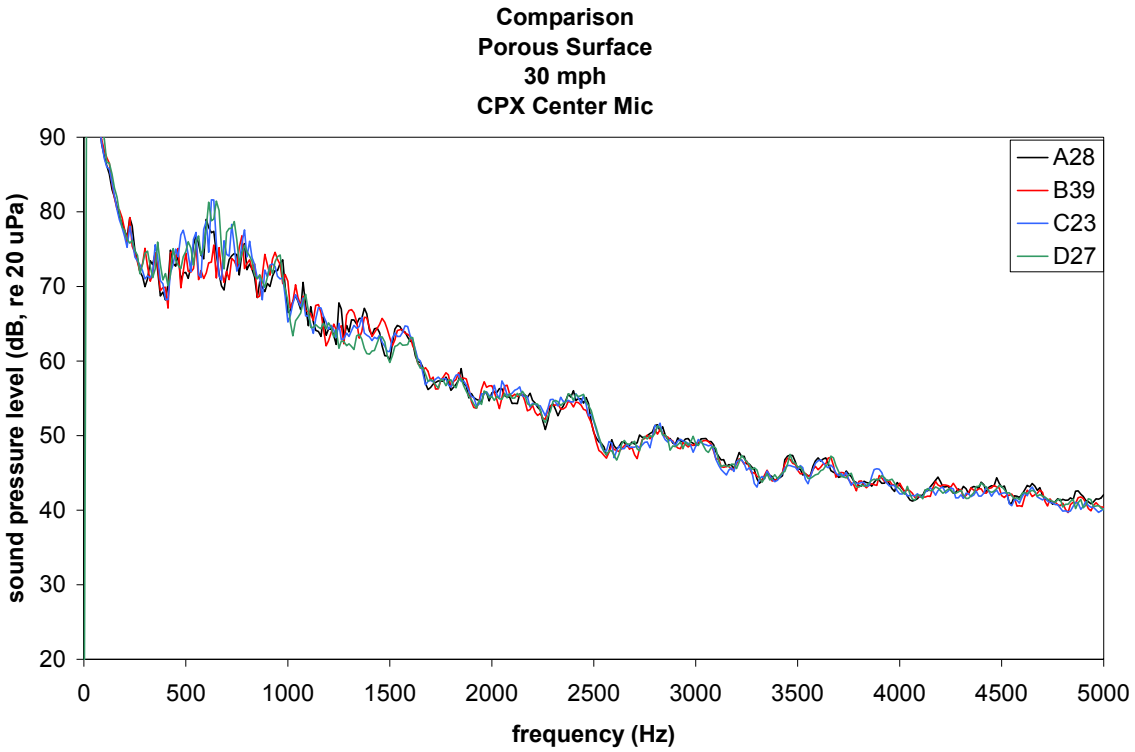
Comparison
Porous Surface
30 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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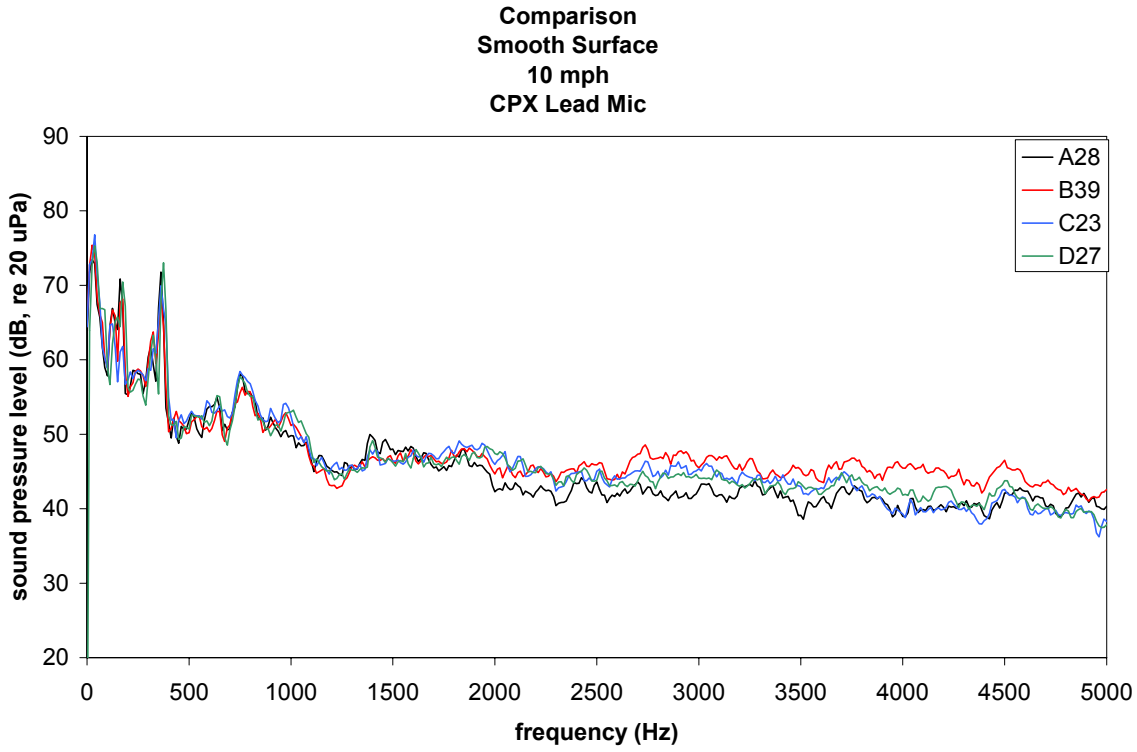
Comparison
Smooth Surface
10 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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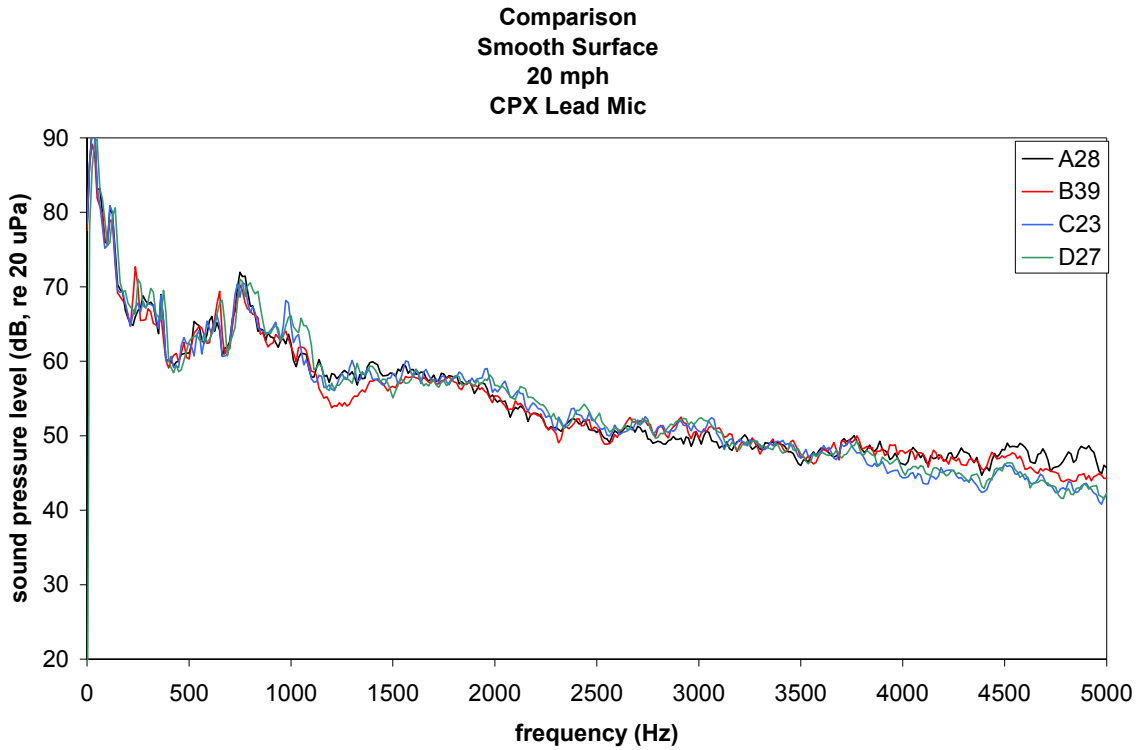
Comparison
Smooth Surface
20 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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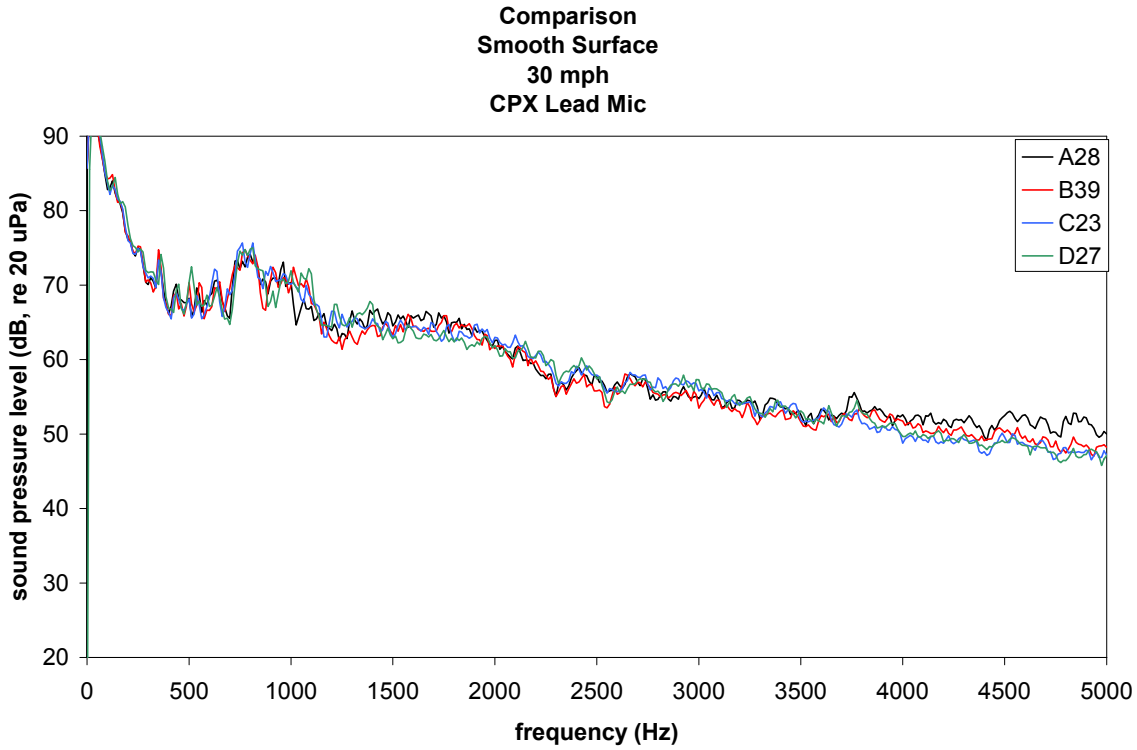
Comparison
Smooth Surface
30 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
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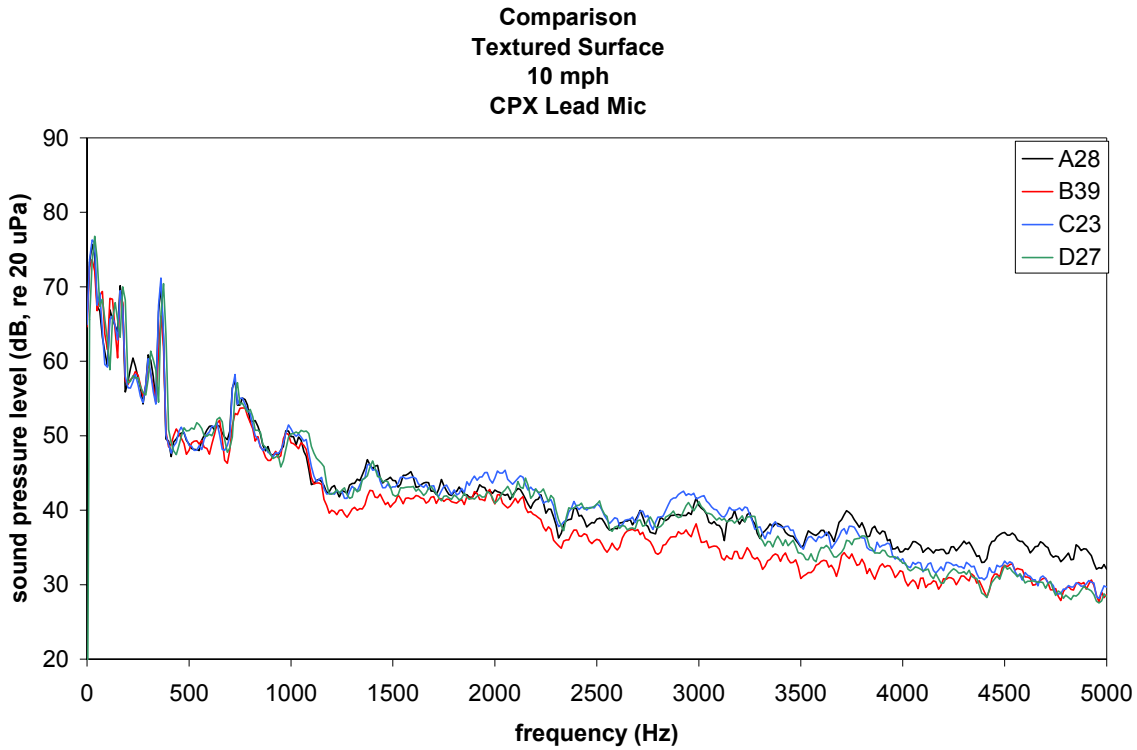
Comparison
Textured Surface
10 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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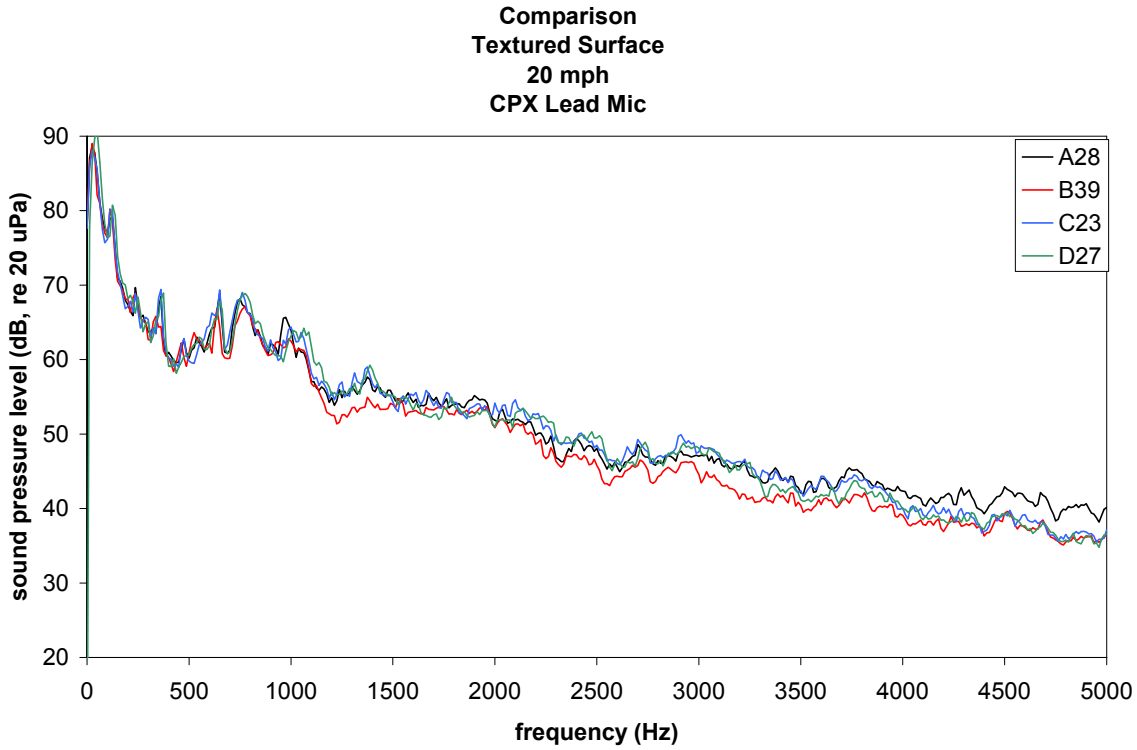
Comparison
Textured Surface
20 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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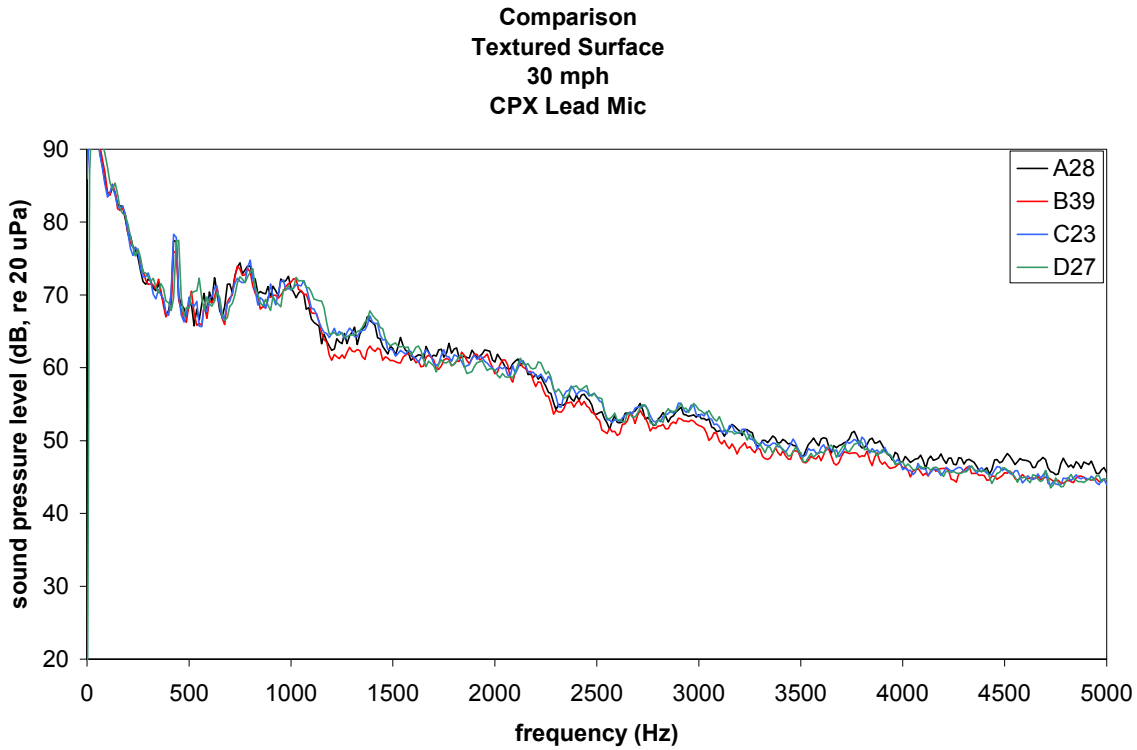
Comparison
Textured Surface
30 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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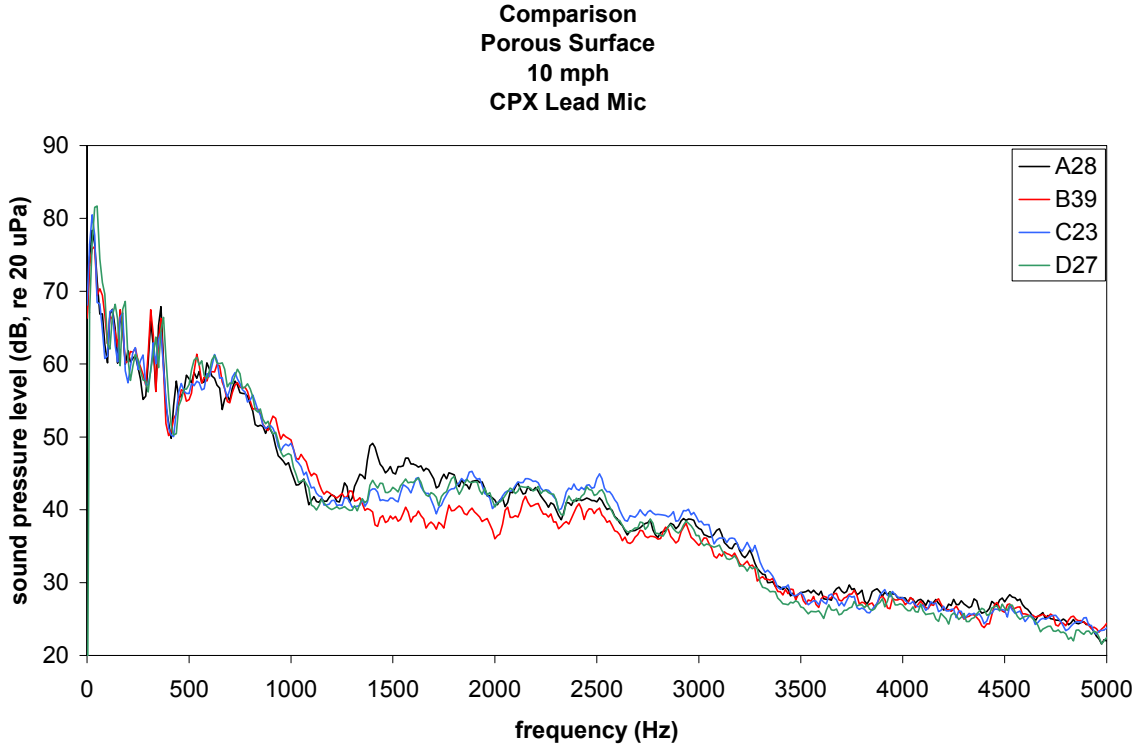
Comparison
Porous Surface
10 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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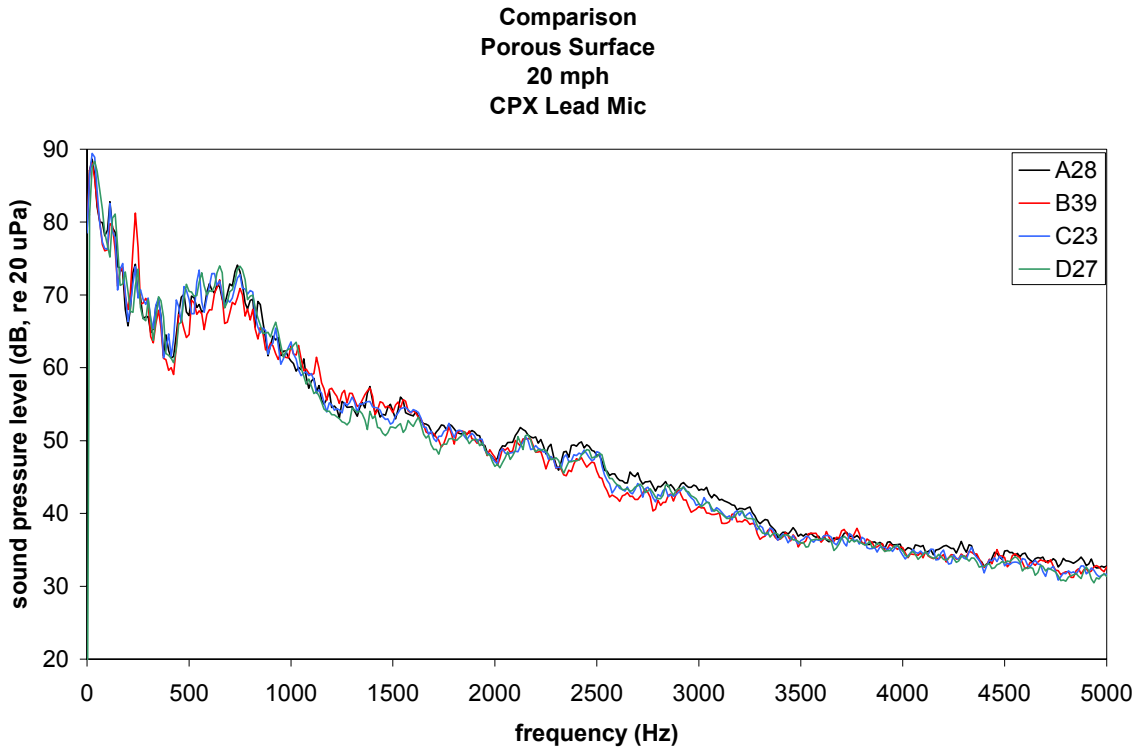
Comparison
Porous Surface
20 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
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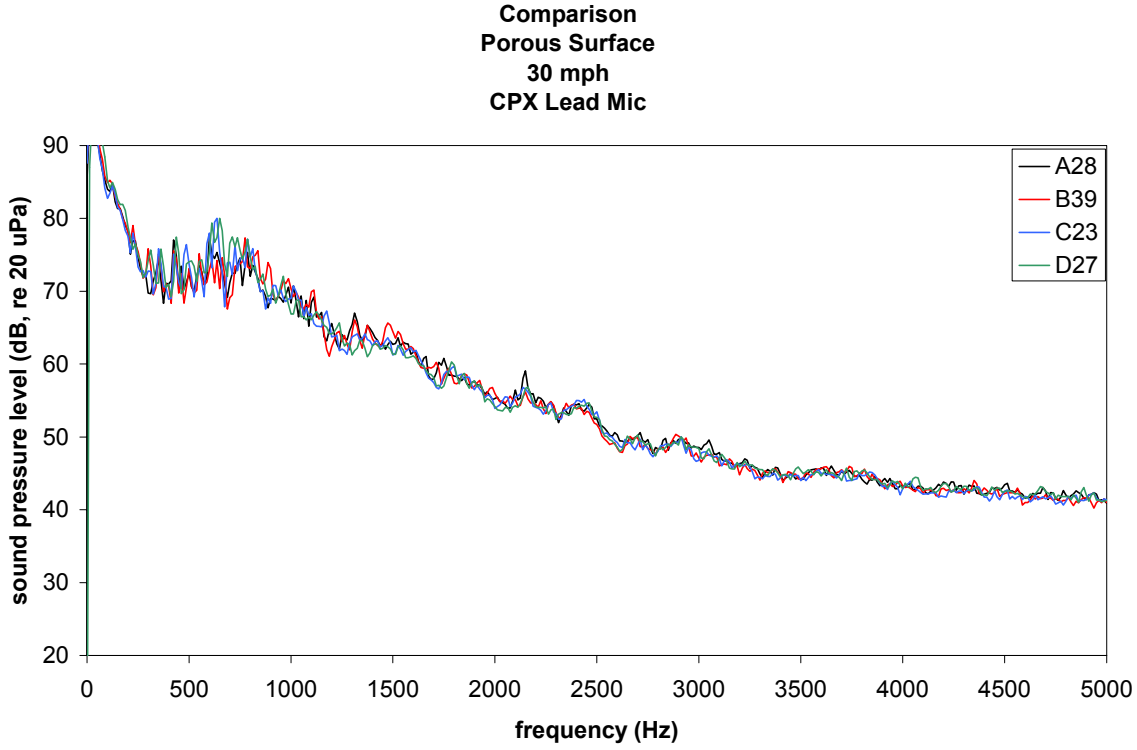
Comparison
Porous Surface
30 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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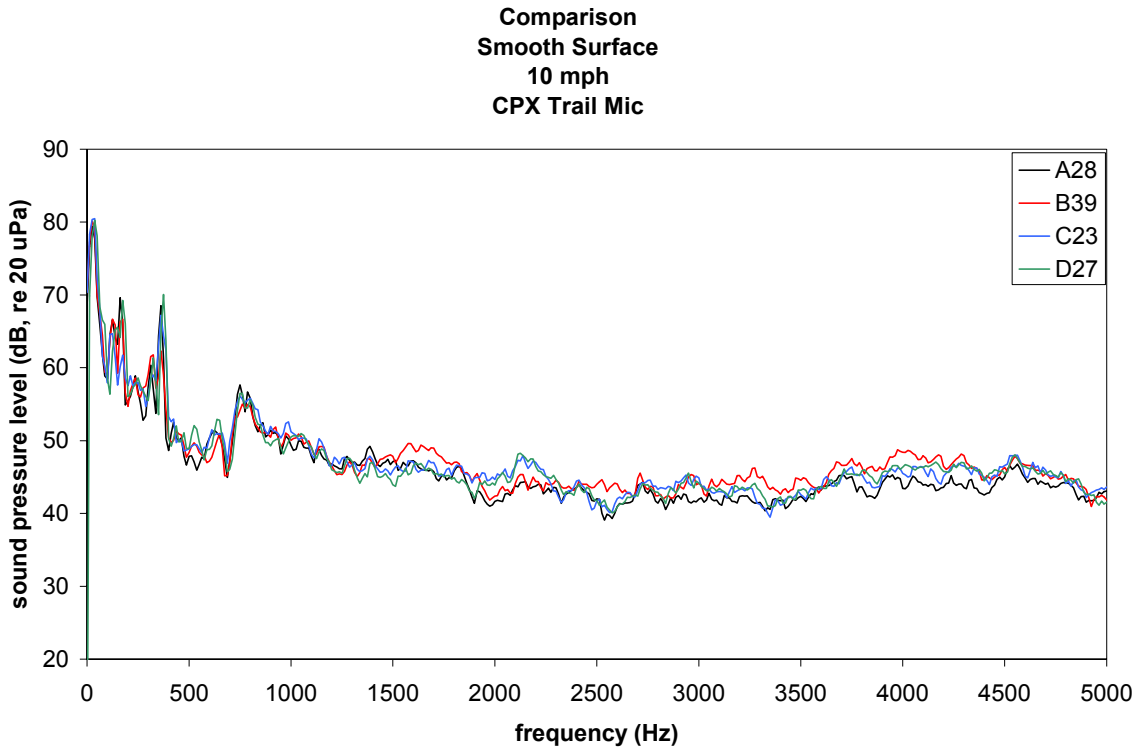
Comparison
Smooth Surface
10 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
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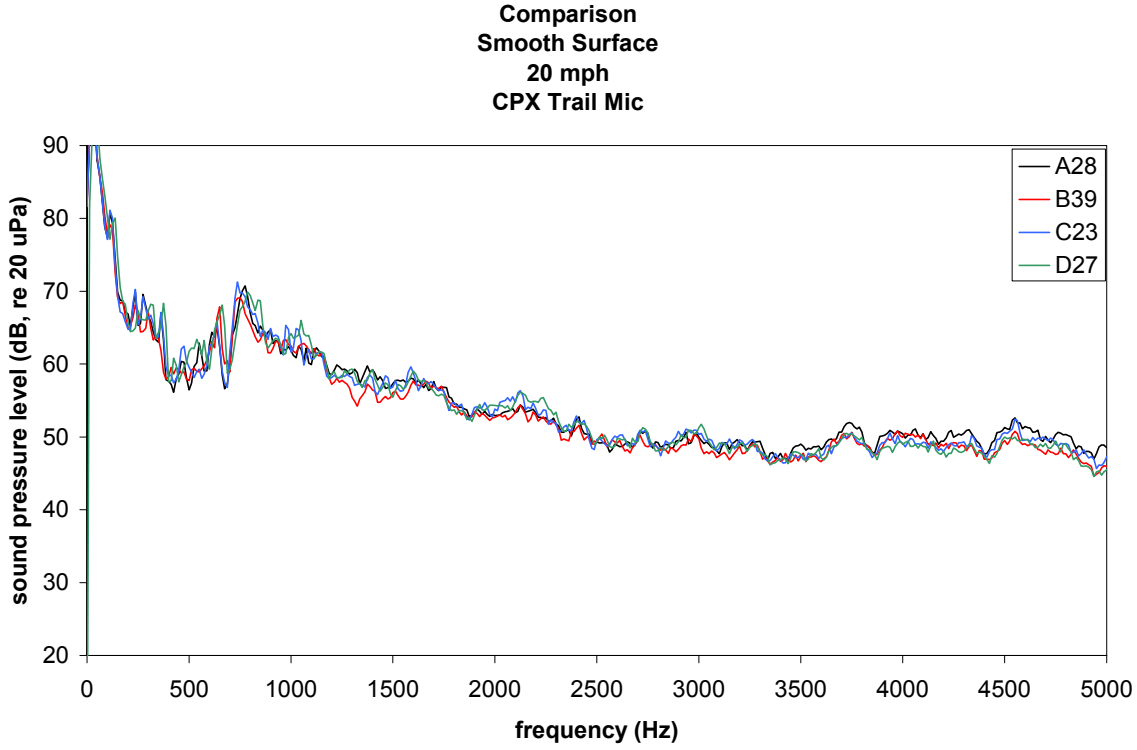
Comparison
Smooth Surface
20 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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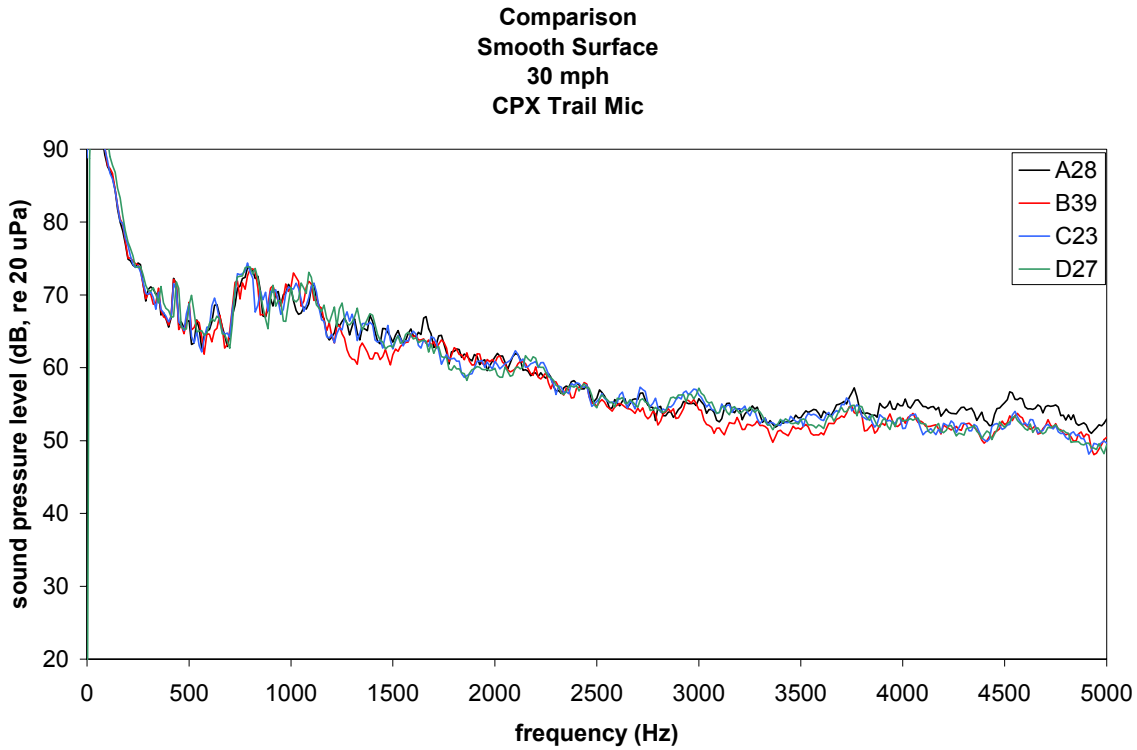
Comparison
Smooth Surface
30 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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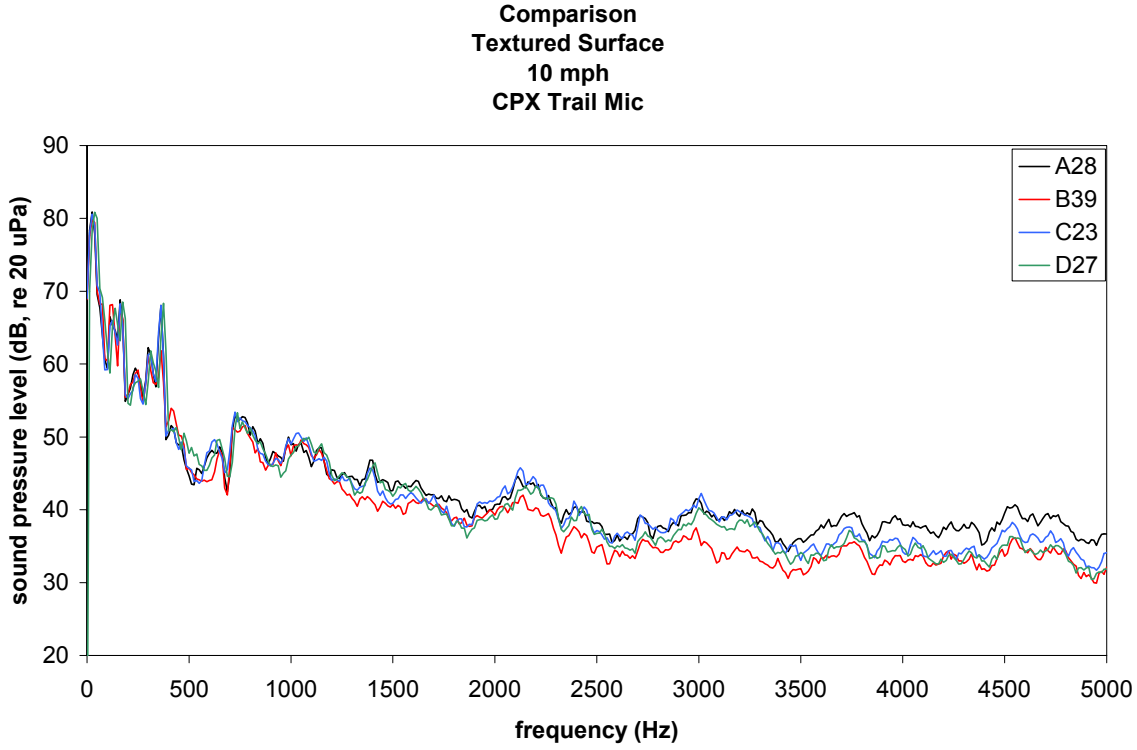
Comparison
Textured Surface
10 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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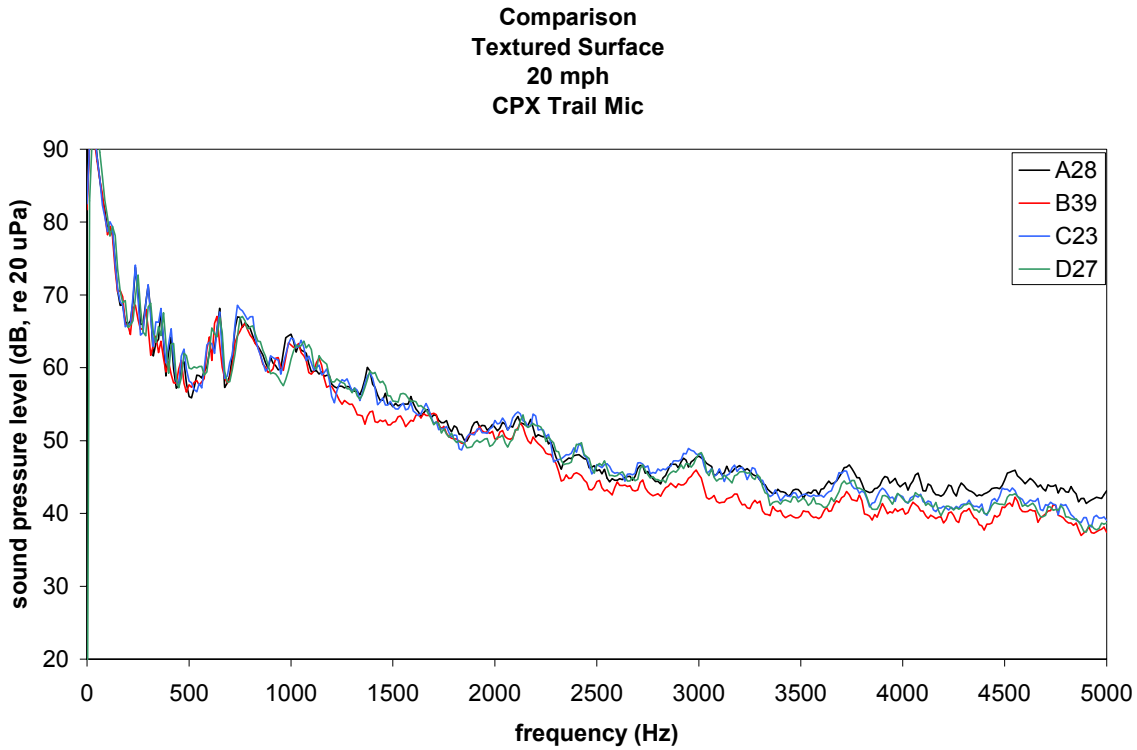
Comparison
Textured Surface
20 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
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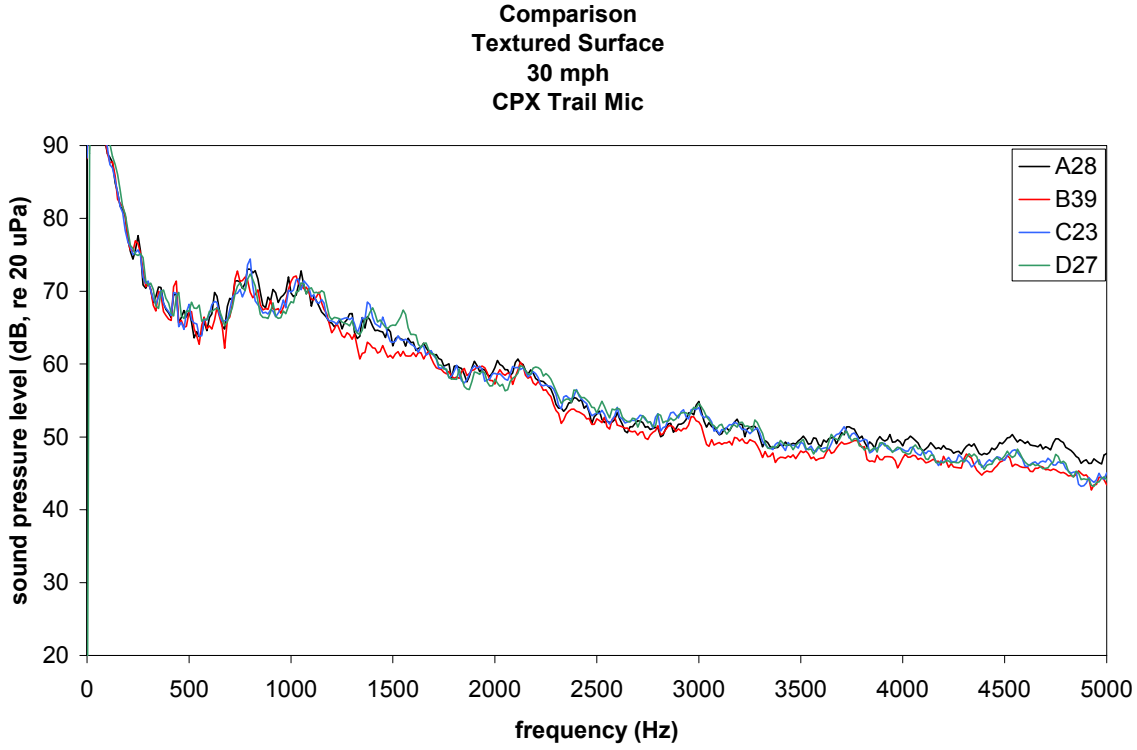
Comparison
Textured Surface
30 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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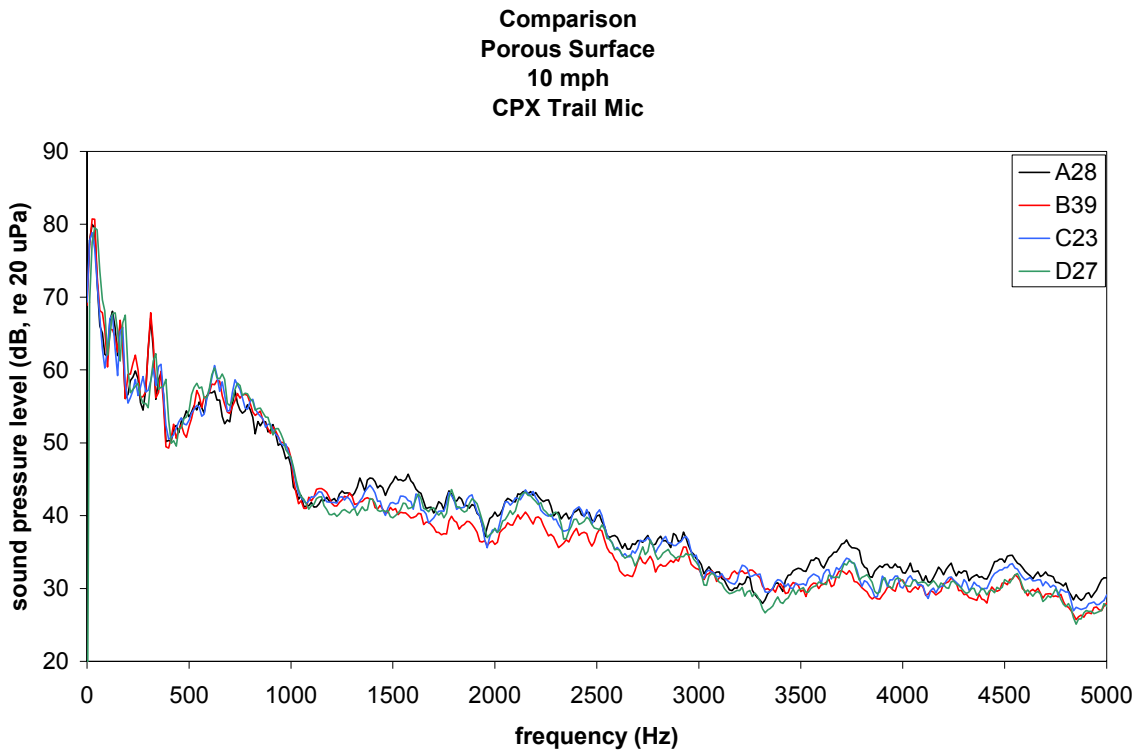
Comparison
Porous Surface
10 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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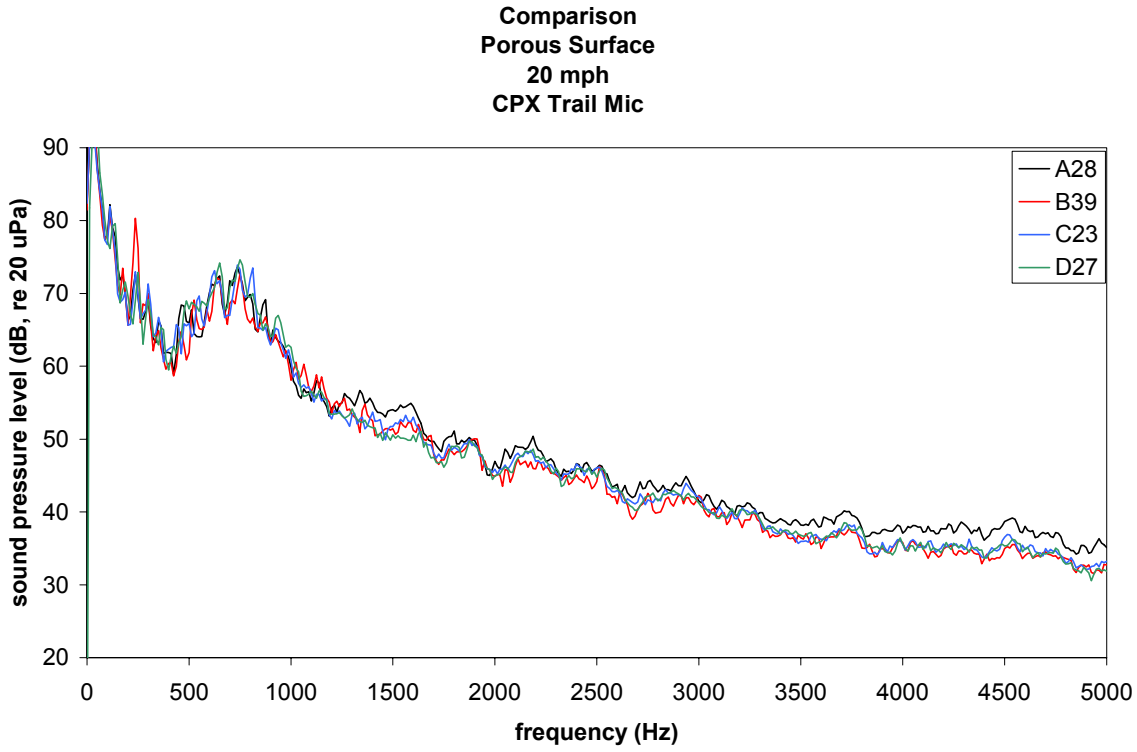
Comparison
Porous Surface
20 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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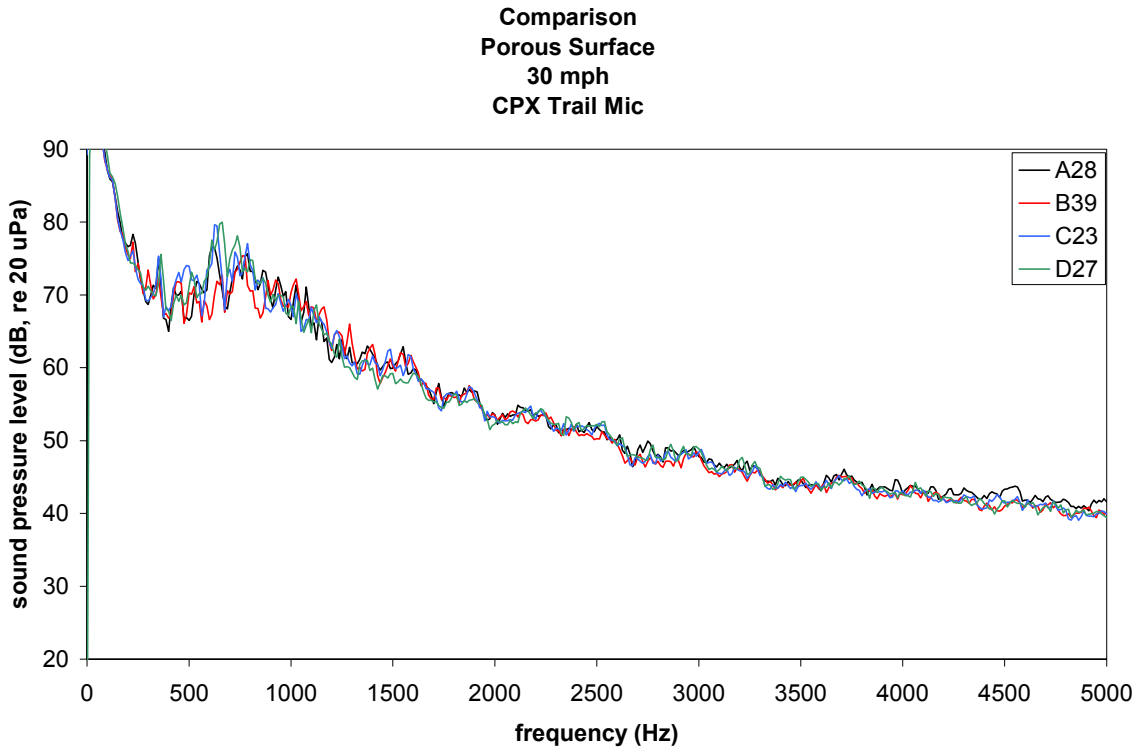
Comparison
Porous Surface
30 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
90
80
70
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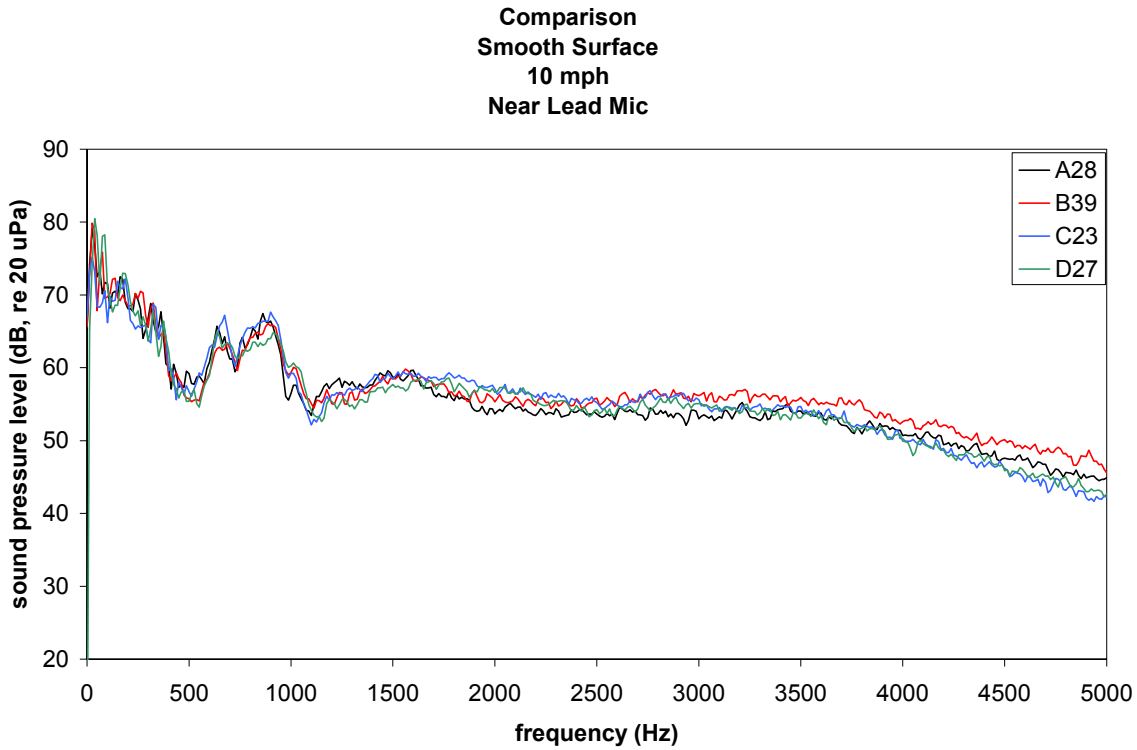
A28
B39
C23
D27

Appendix D: Narrow band spectra at Near-field microphone locations; multiple tires at one speed and surface texture.


Comparison
Smooth Surface
10 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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80
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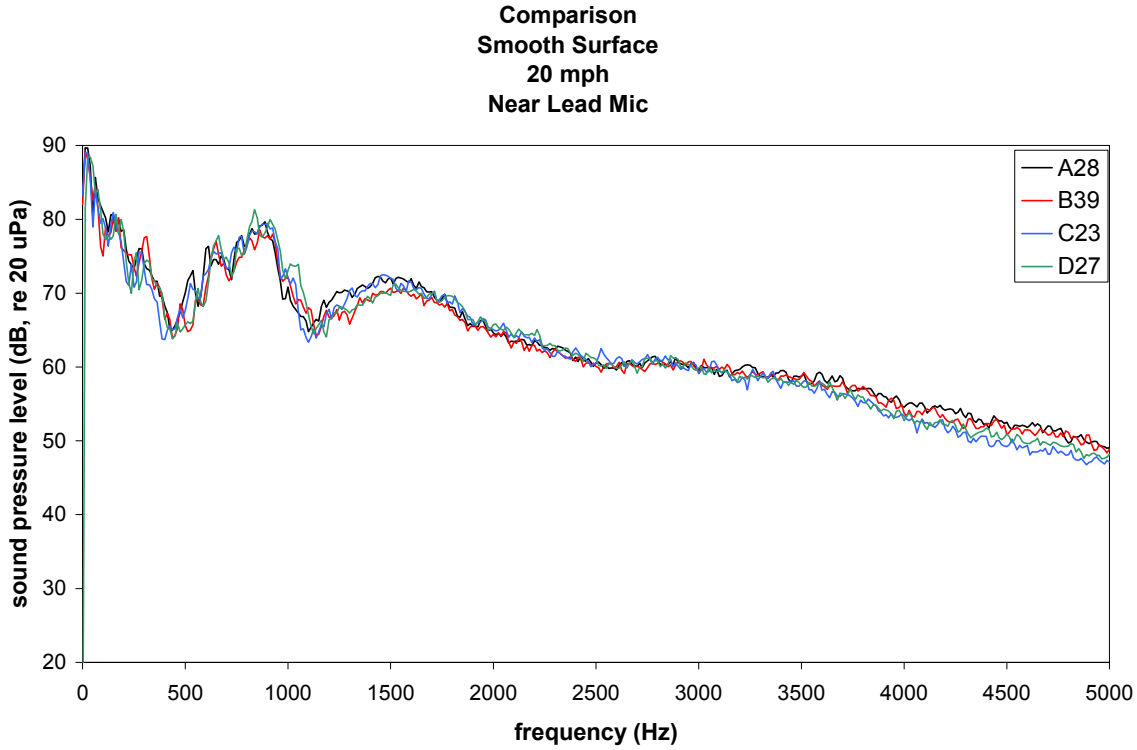
Comparison
Smooth Surface
20 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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80
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4500
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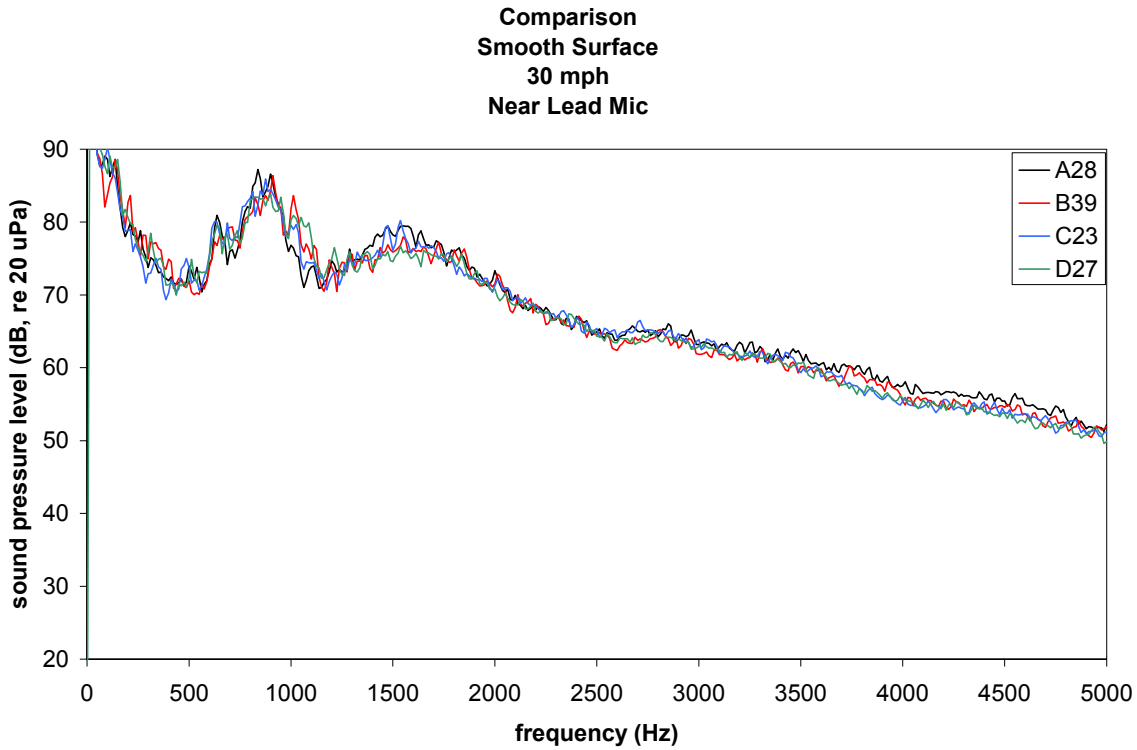
Comparison
Smooth Surface
30 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
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0
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4500
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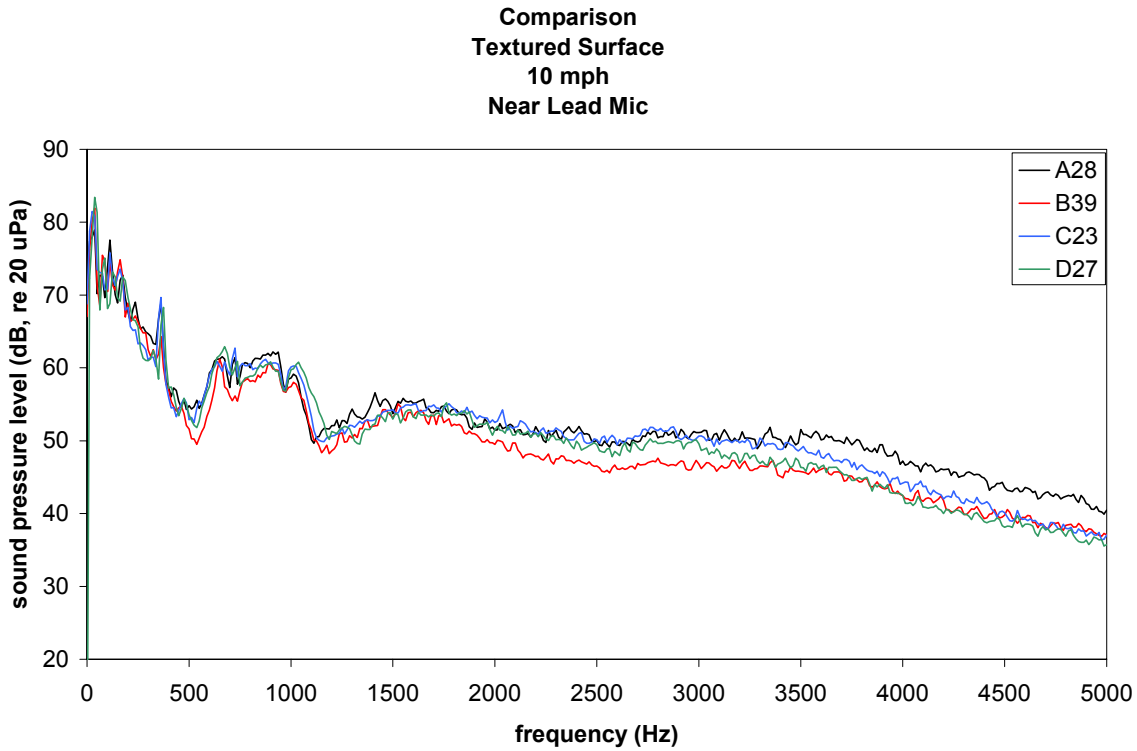
Comparison
Textured Surface
10 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
30
20
0
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3500
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4500
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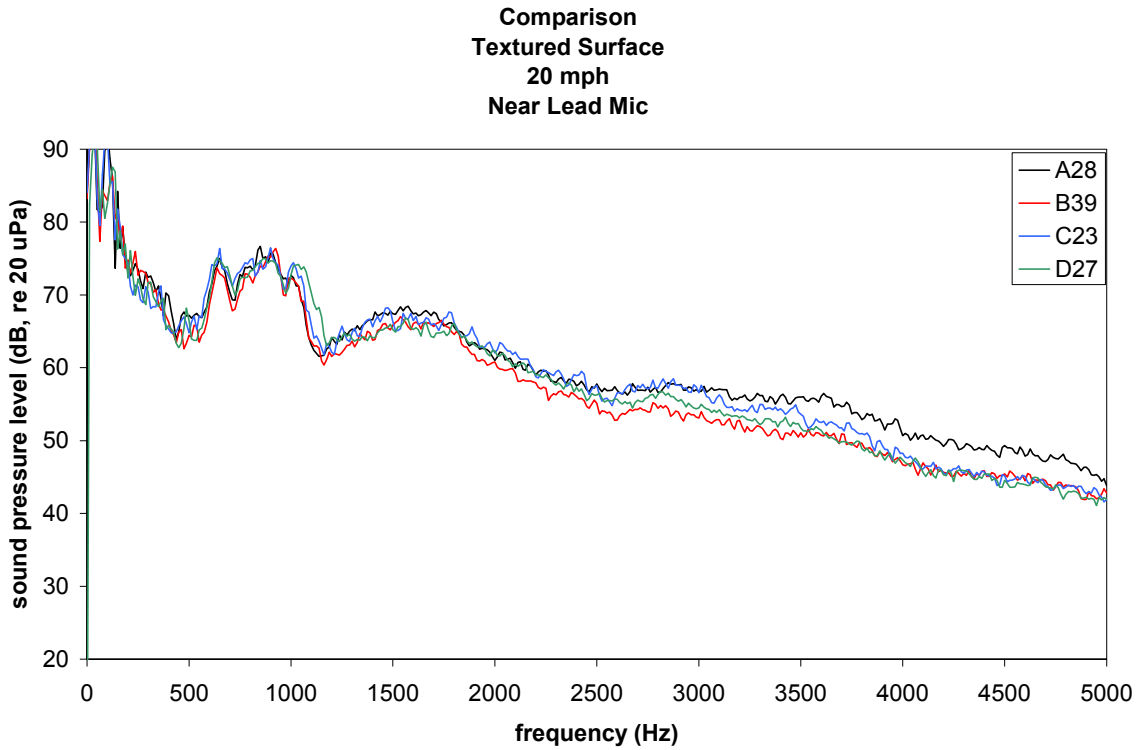
Comparison
Textured Surface
20 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
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60
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0
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4500
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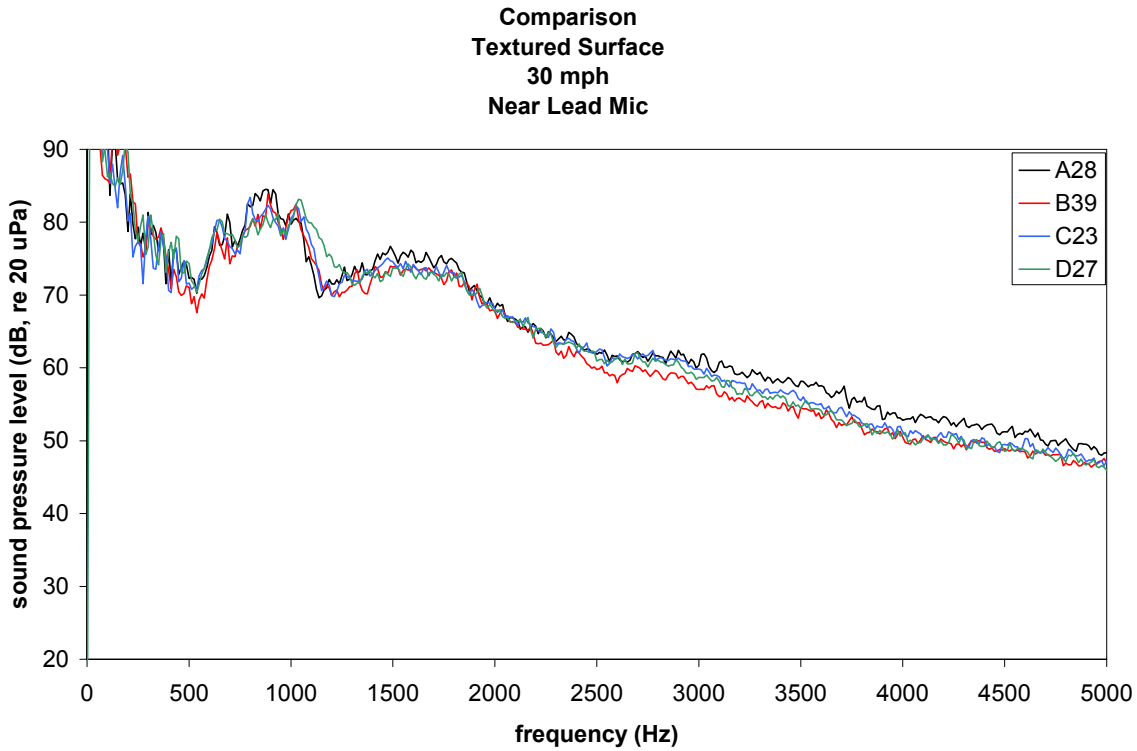
Comparison
Textured Surface
30 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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80
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60
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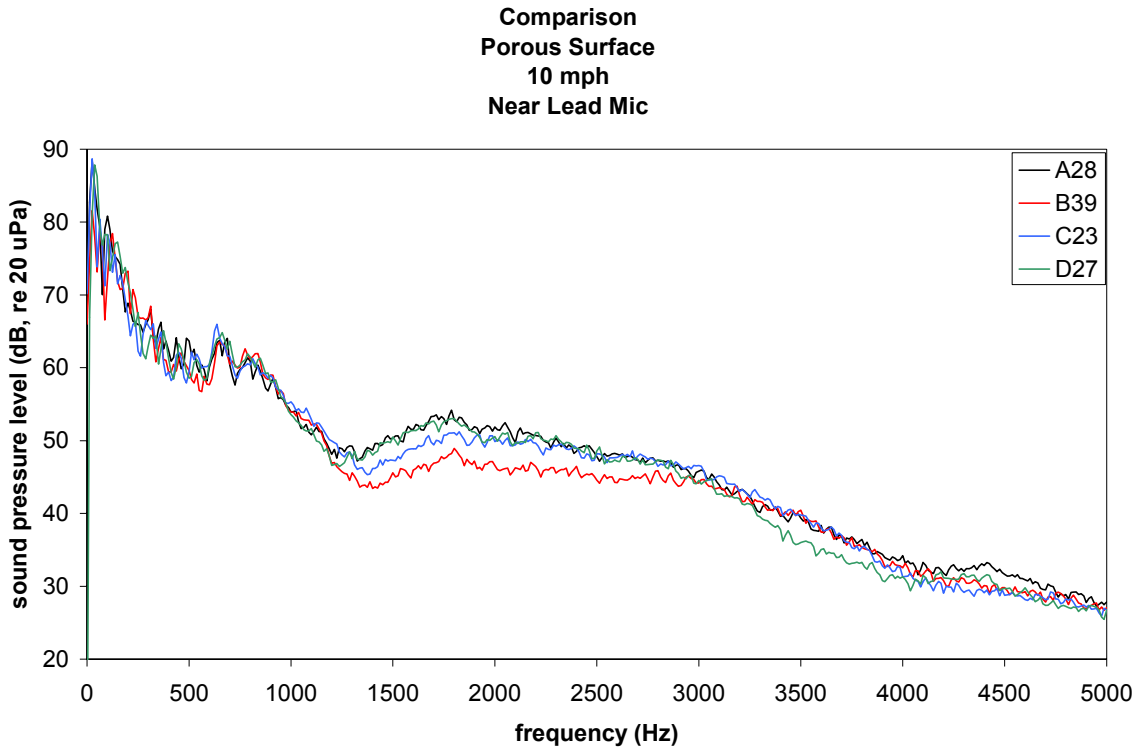
Comparison
Porous Surface
10 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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80
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60
50
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3500
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4500
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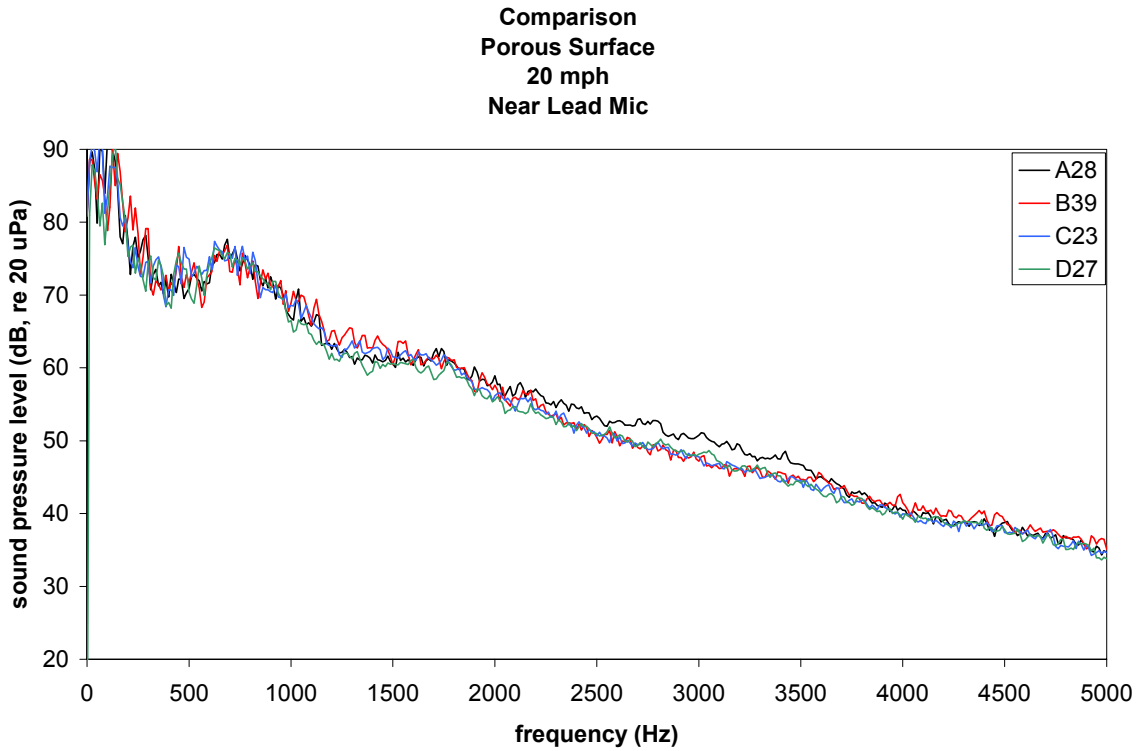
Comparison
Porous Surface
20 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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80
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4500
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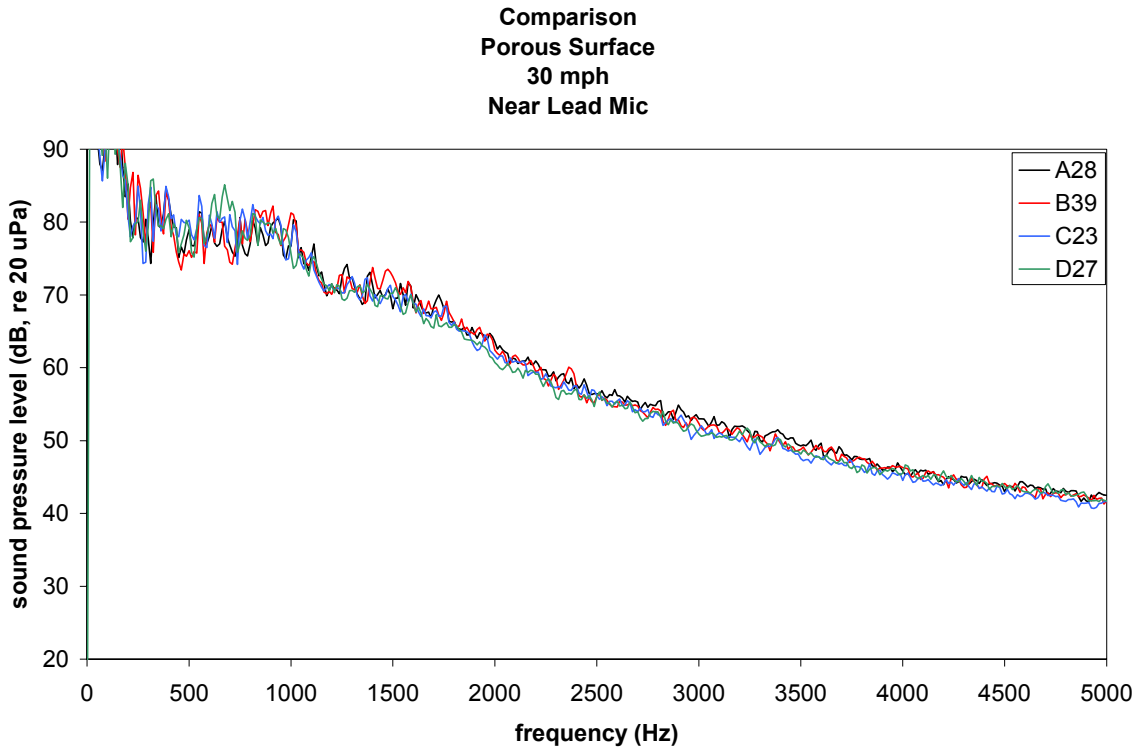
Comparison
Porous Surface
30 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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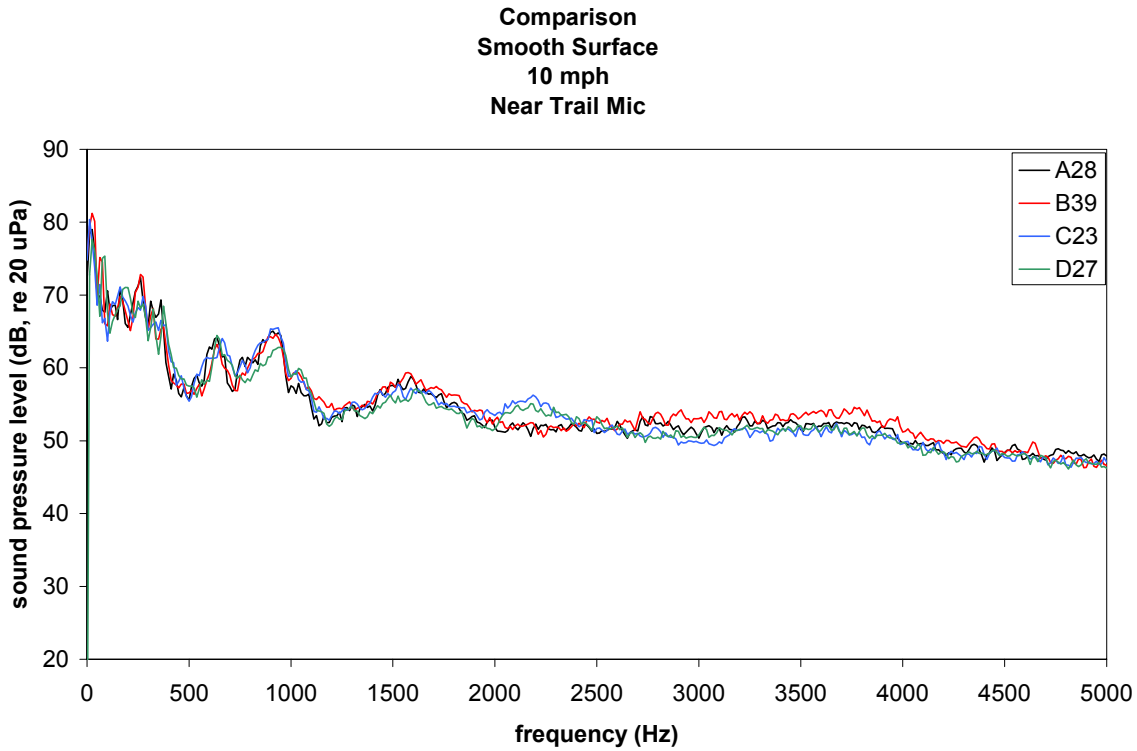
Comparison
Smooth Surface
10 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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80
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60
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40
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3500
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4500
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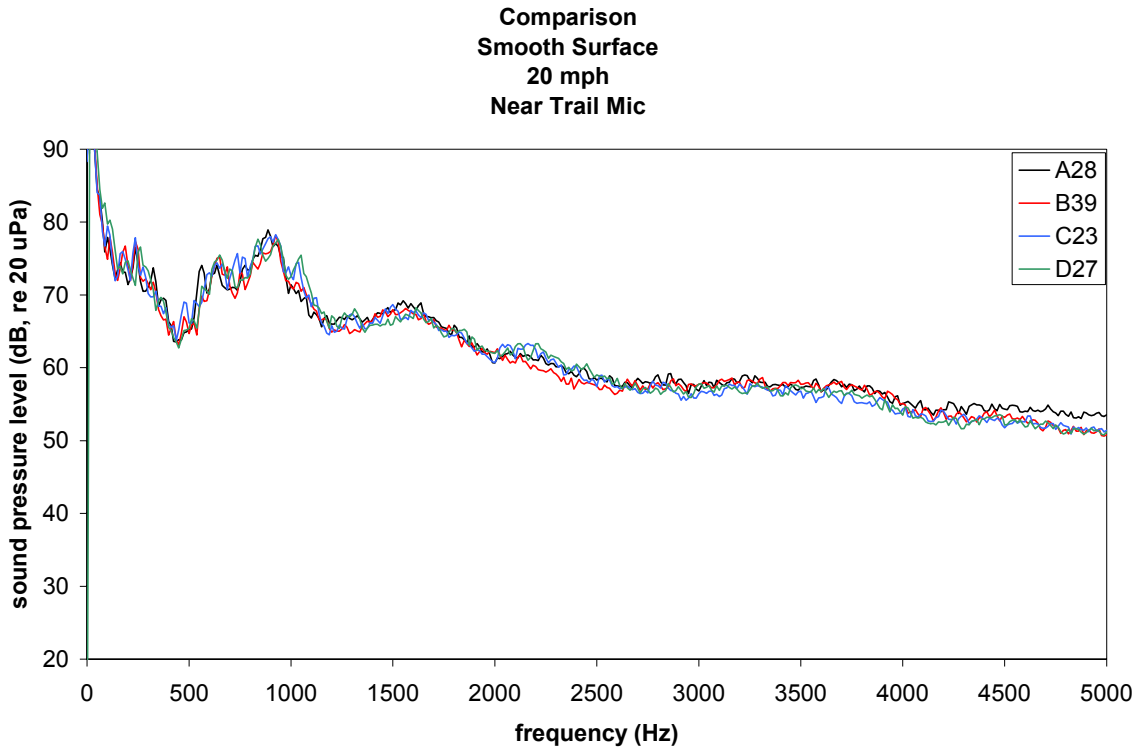
Comparison
Smooth Surface
20 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
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80
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60
50
40
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3500
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4500
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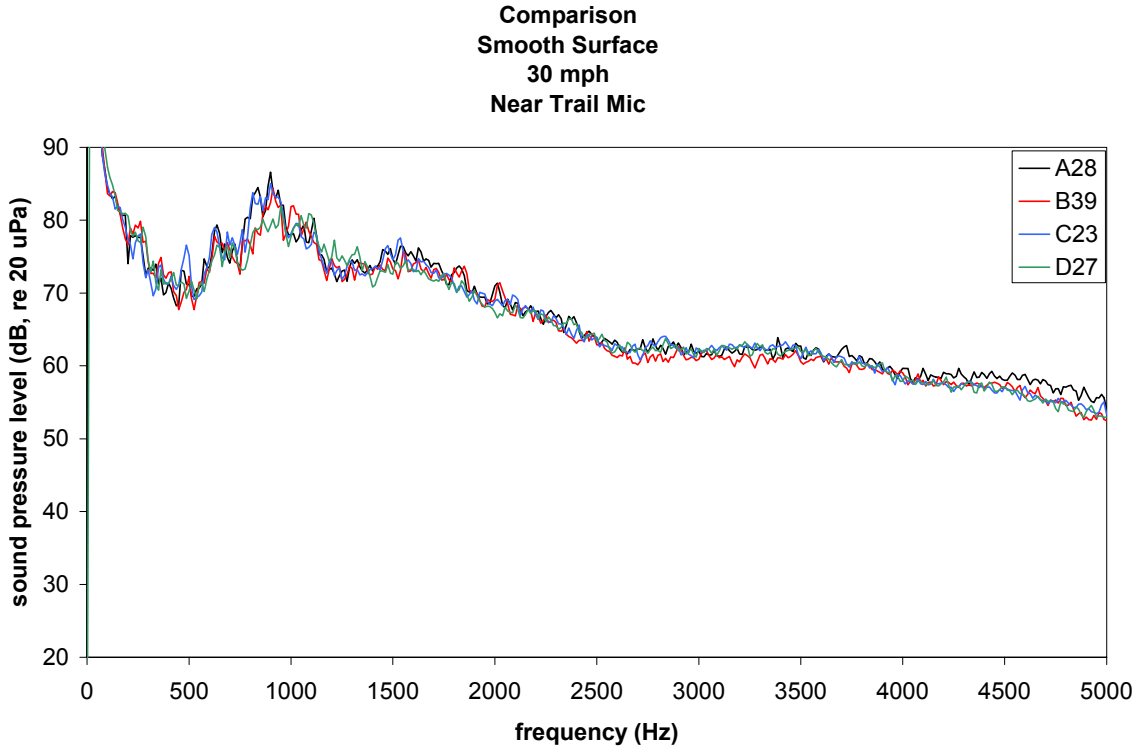
Comparison
Smooth Surface
30 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
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50
40
30
20
0
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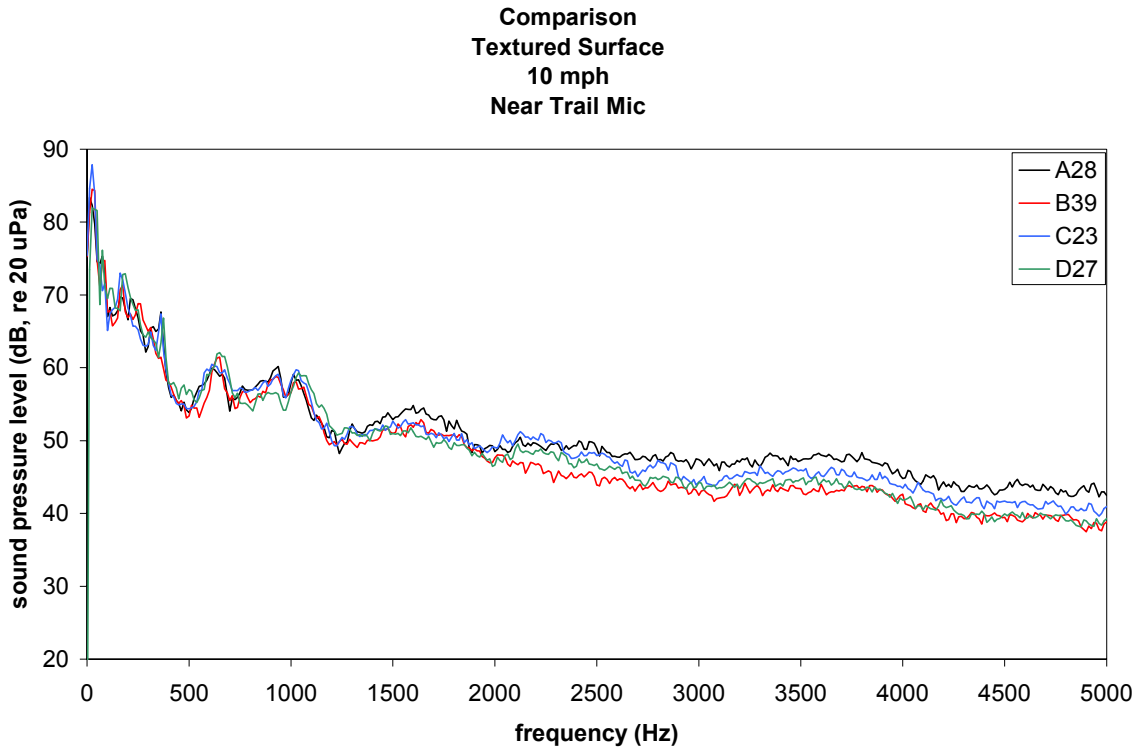
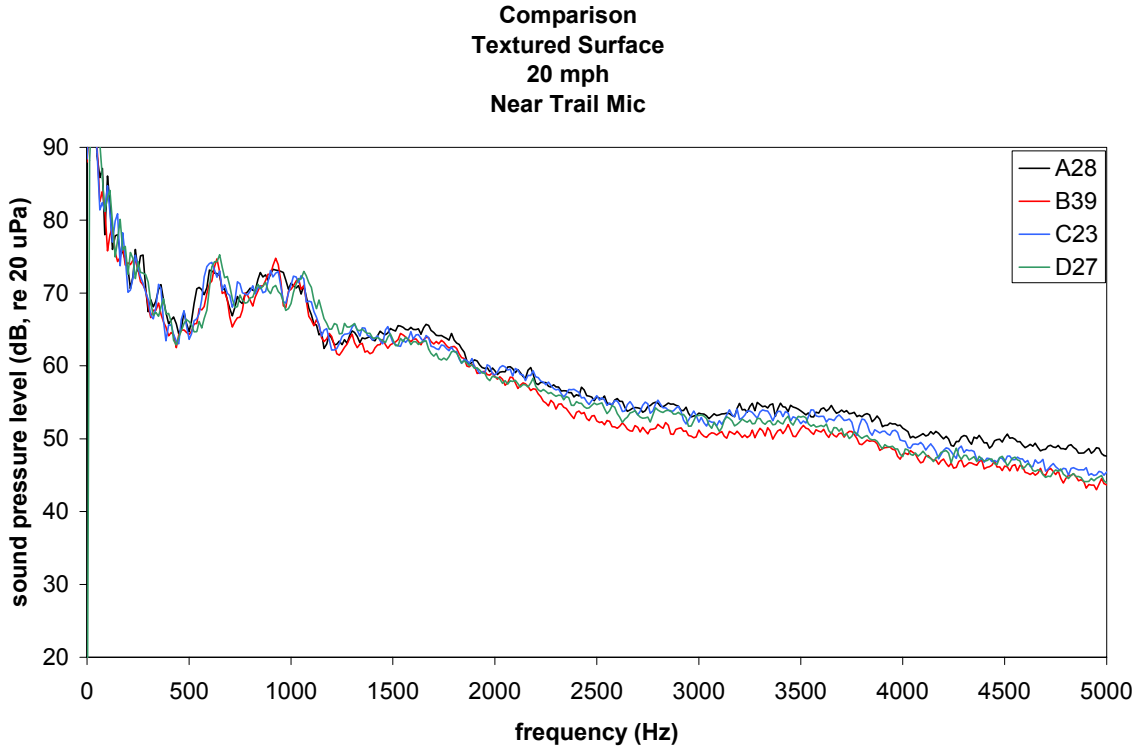
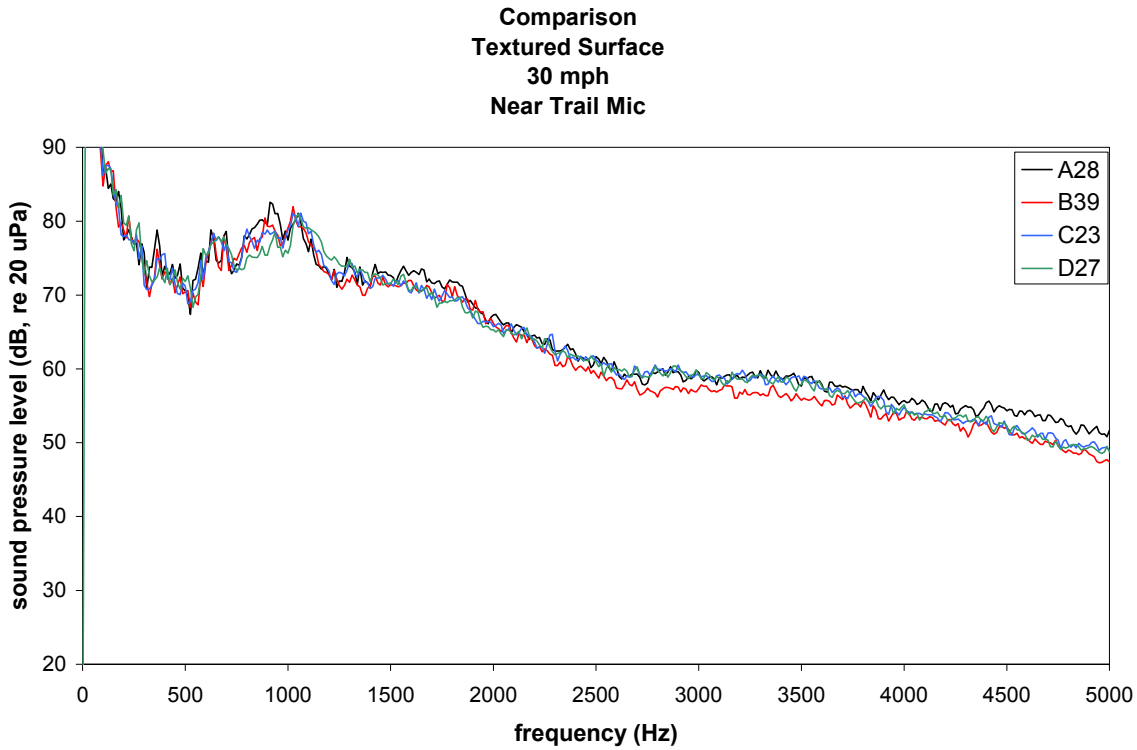
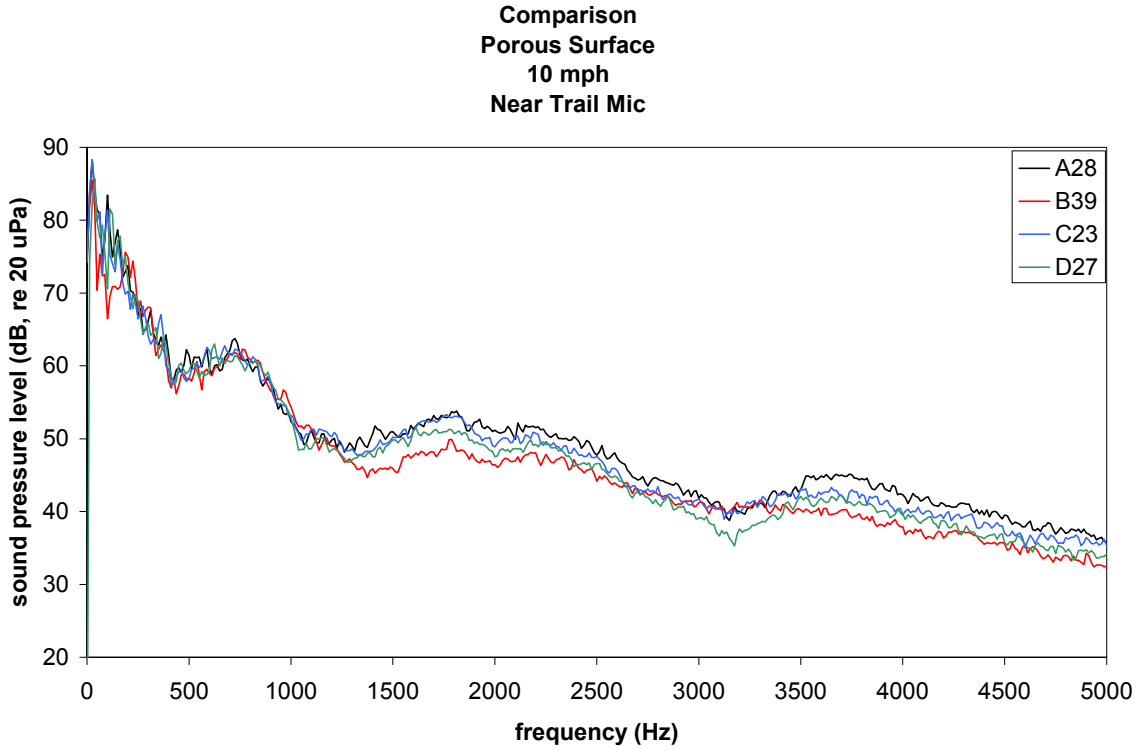
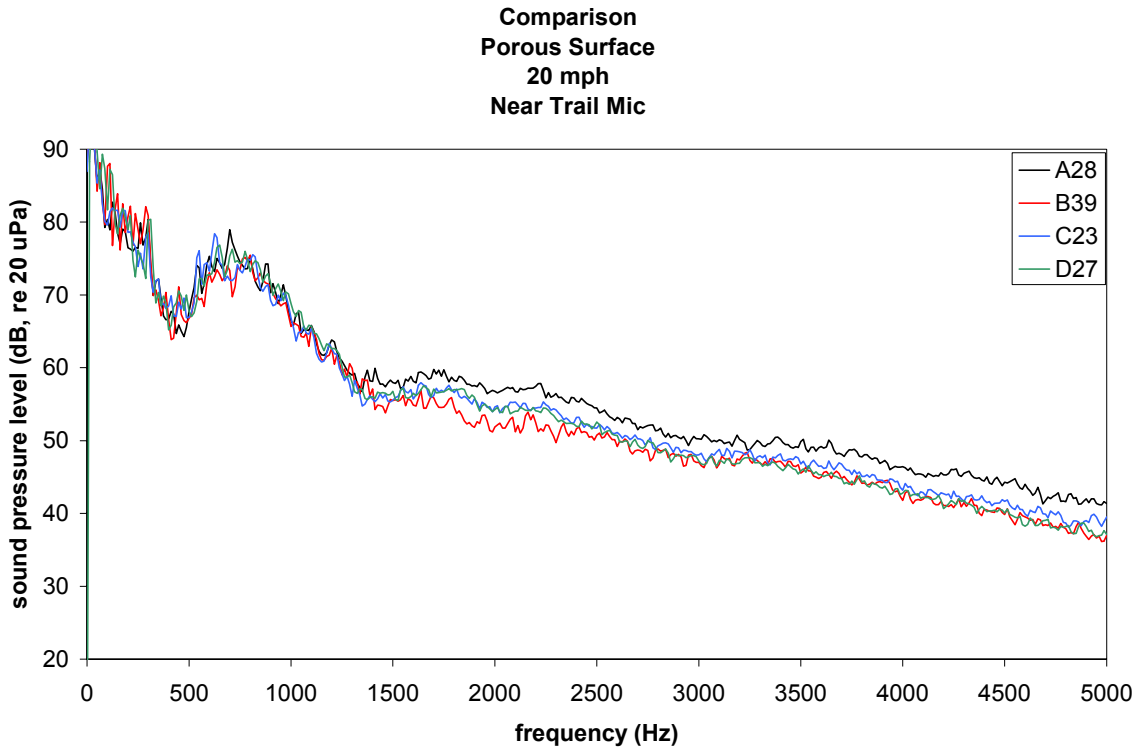
1000
1500
2000
2500
3000
3500
4000
4500
5000

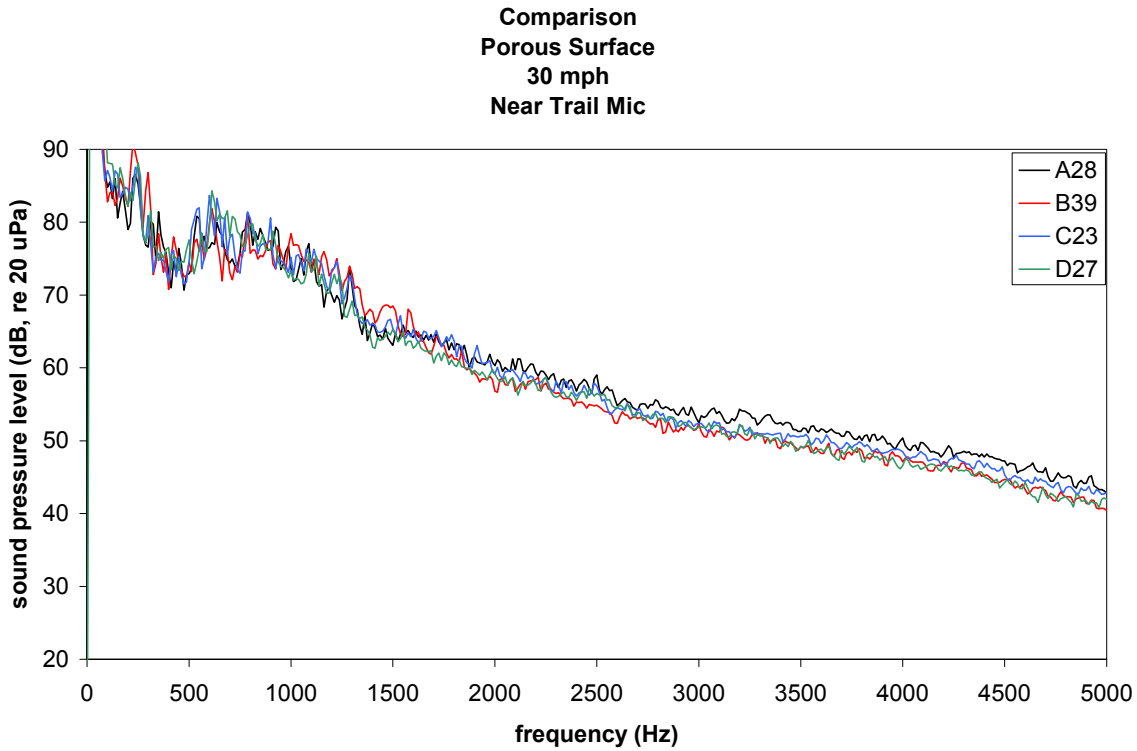

Comparison
Textured Surface
10 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


Comparison
Textured Surface
20 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

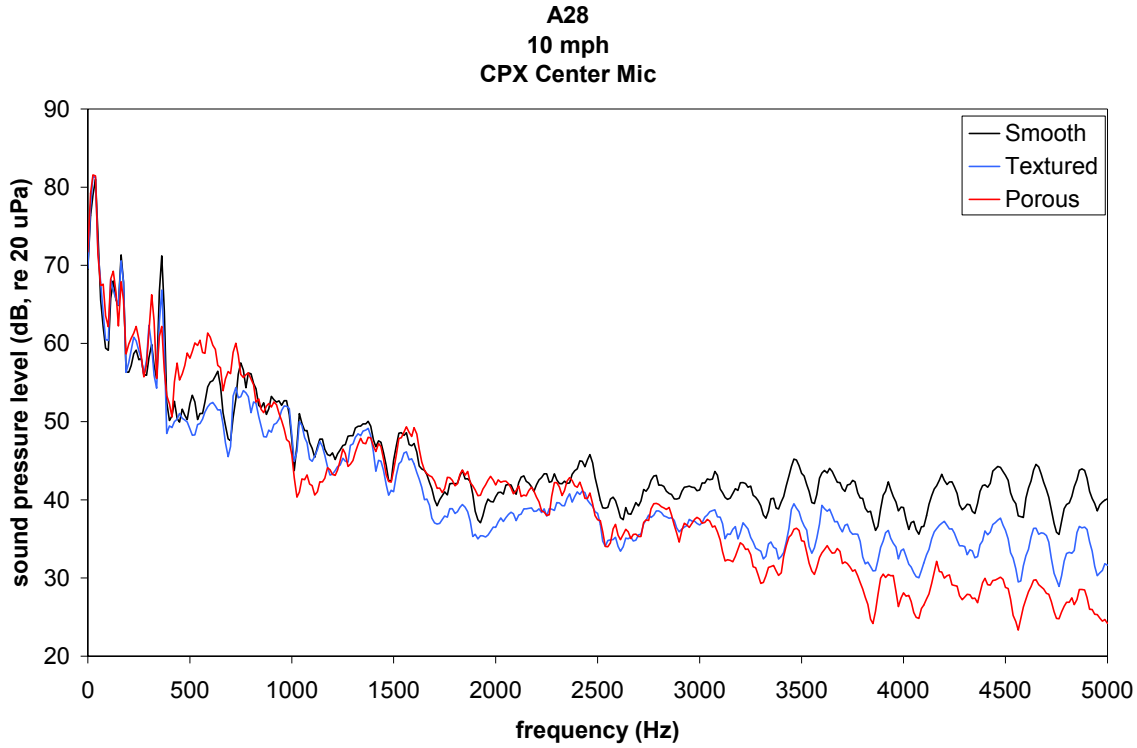

Comparison
Textured Surface
30 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

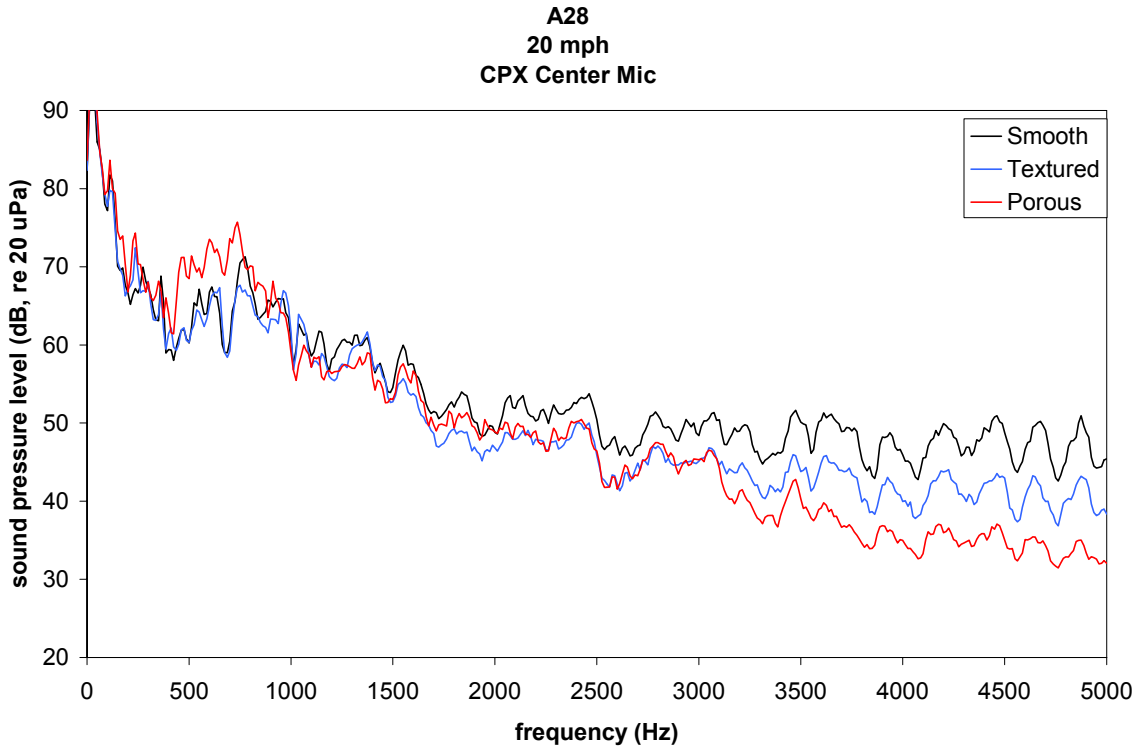

Comparison
Porous Surface
10 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

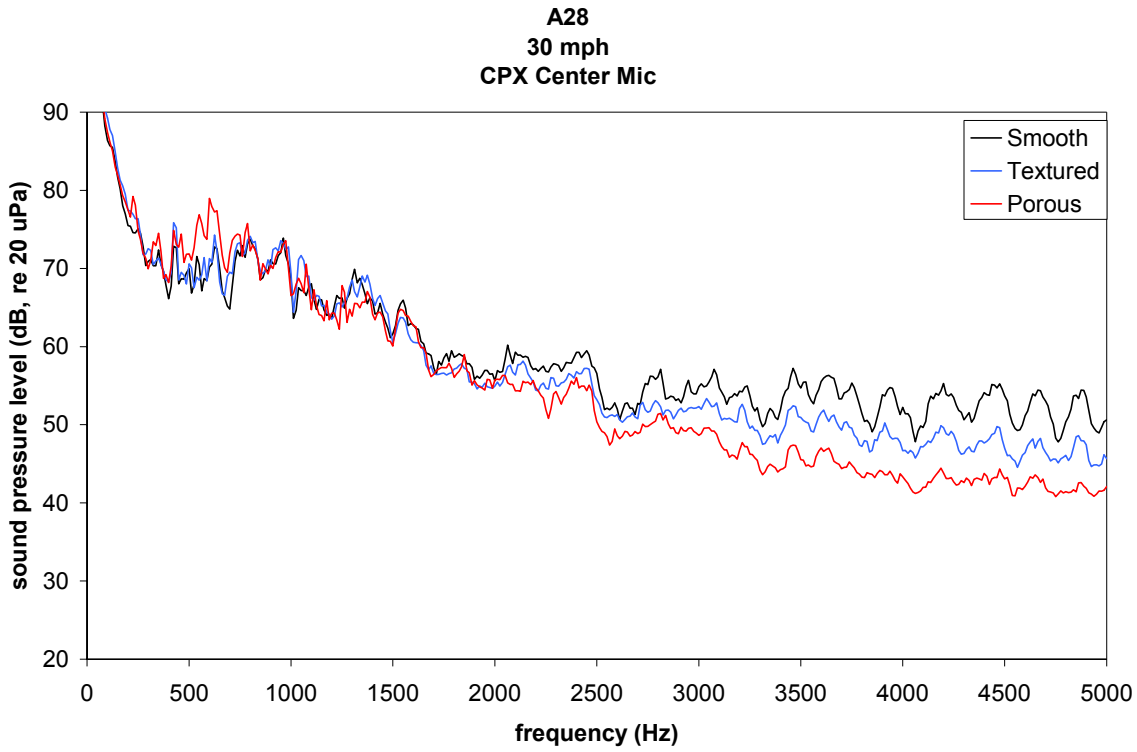

Comparison
Porous Surface
20 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

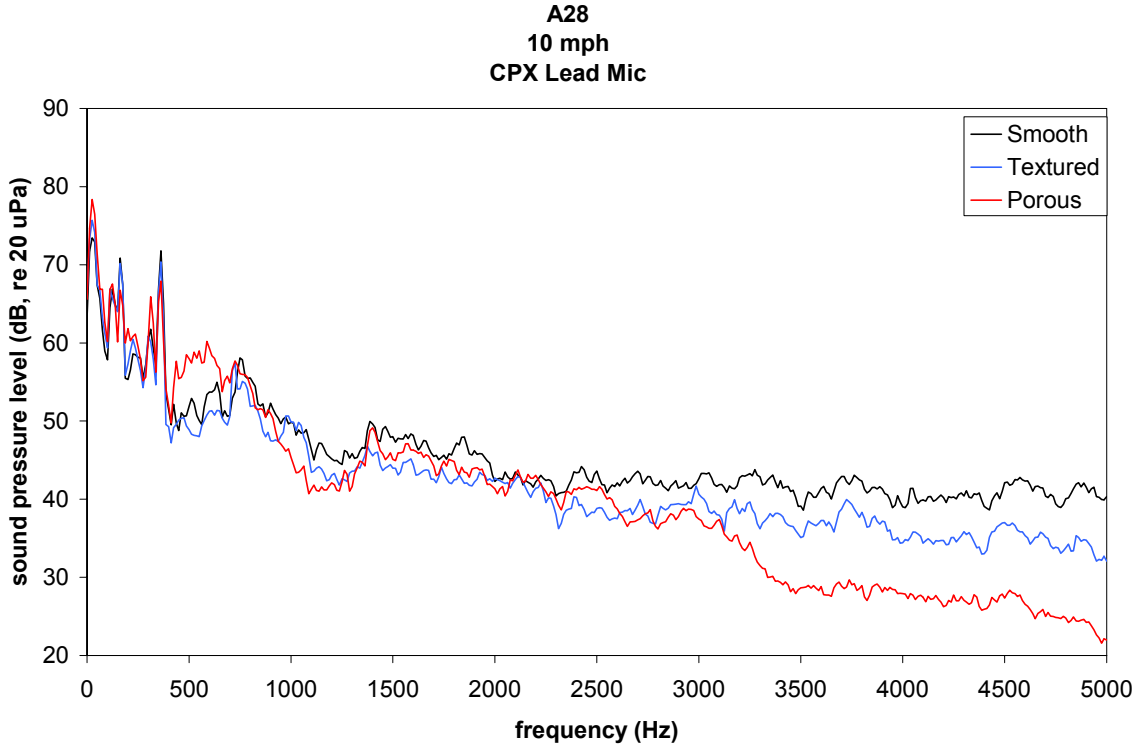

Comparison
Porous Surface
30 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
A28
B39
C23
D27
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

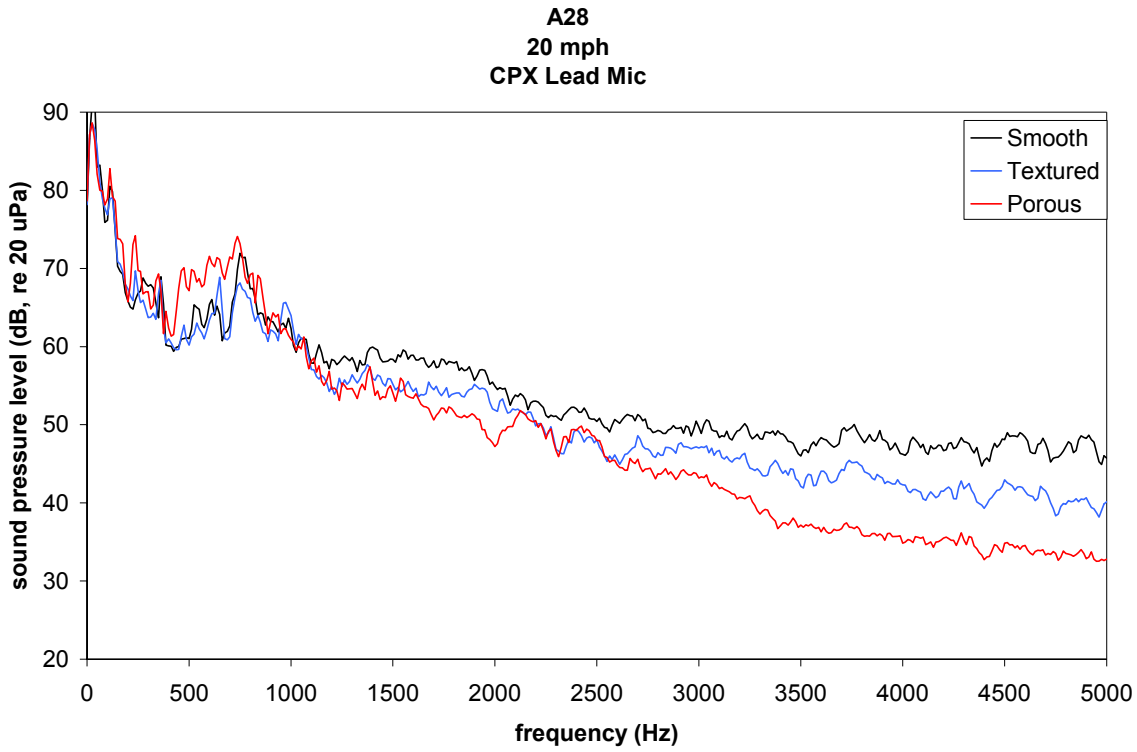
Appendix E: Narrow band spectra for tire A28; multiple surface textures at one speed and microphone location.

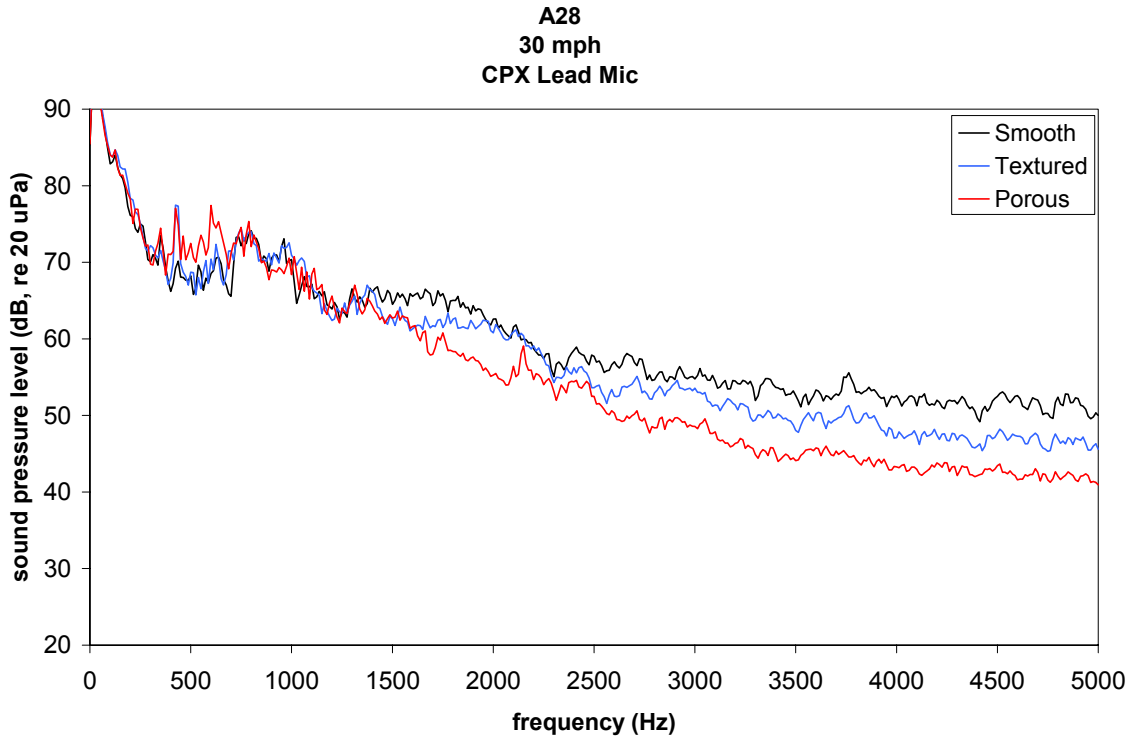

A28
10 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

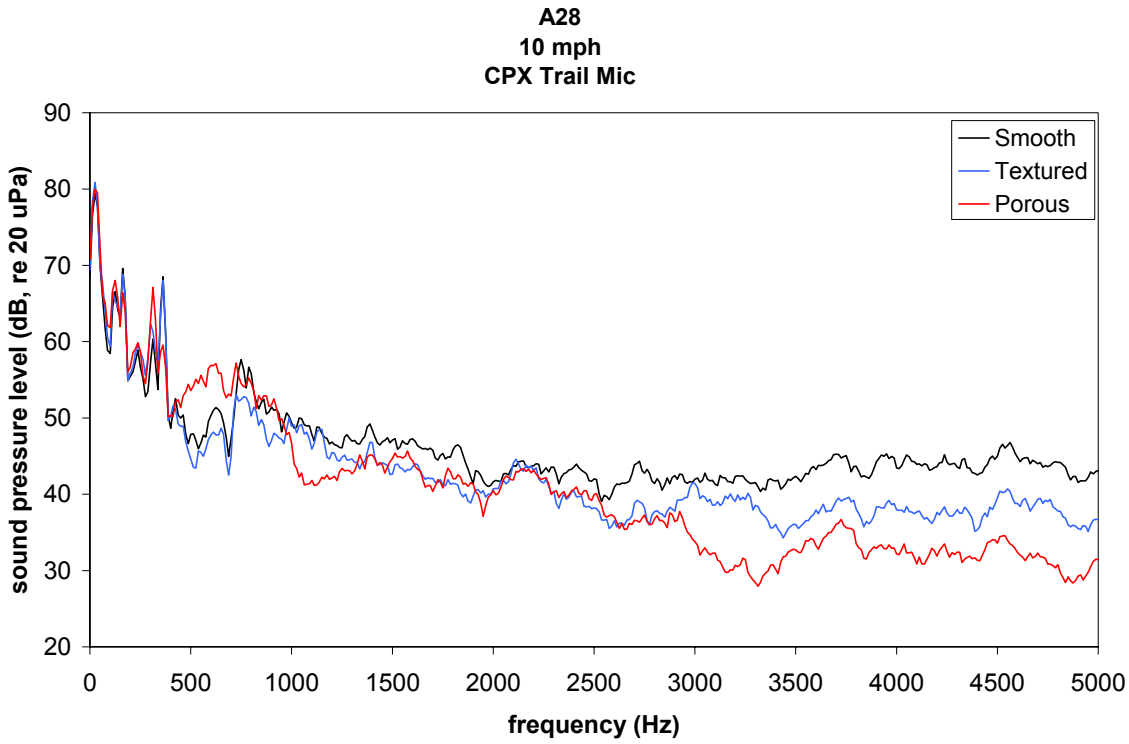

A28
20 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

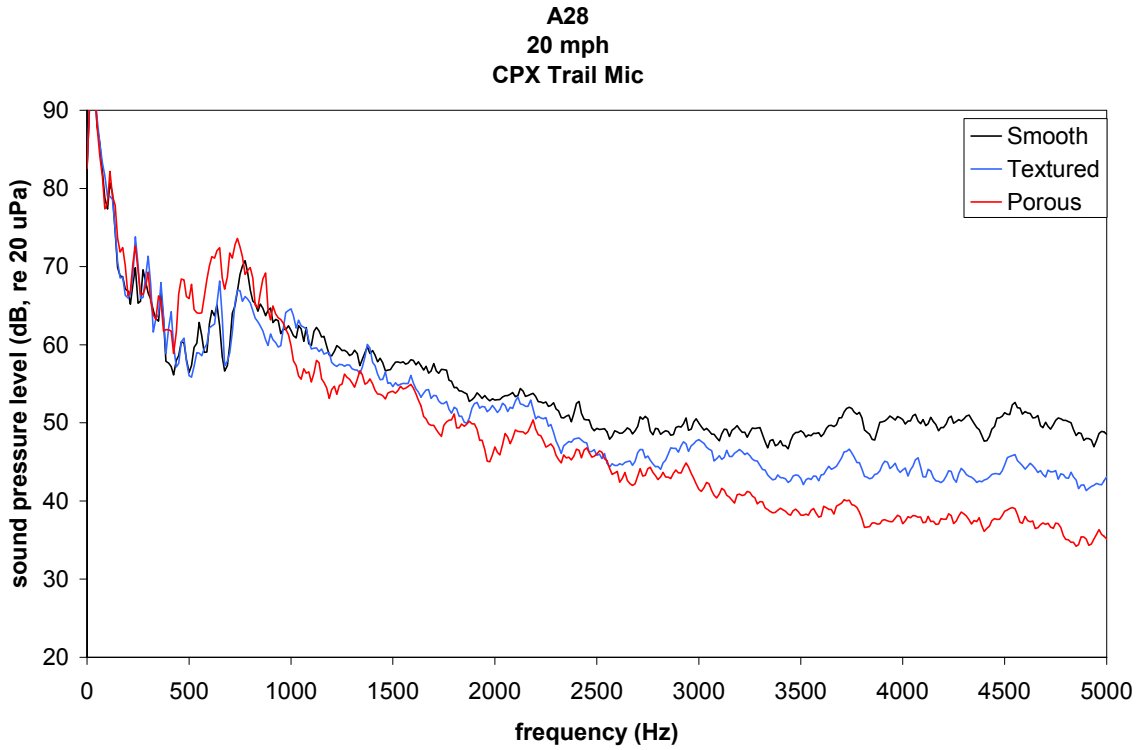

A28
30 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

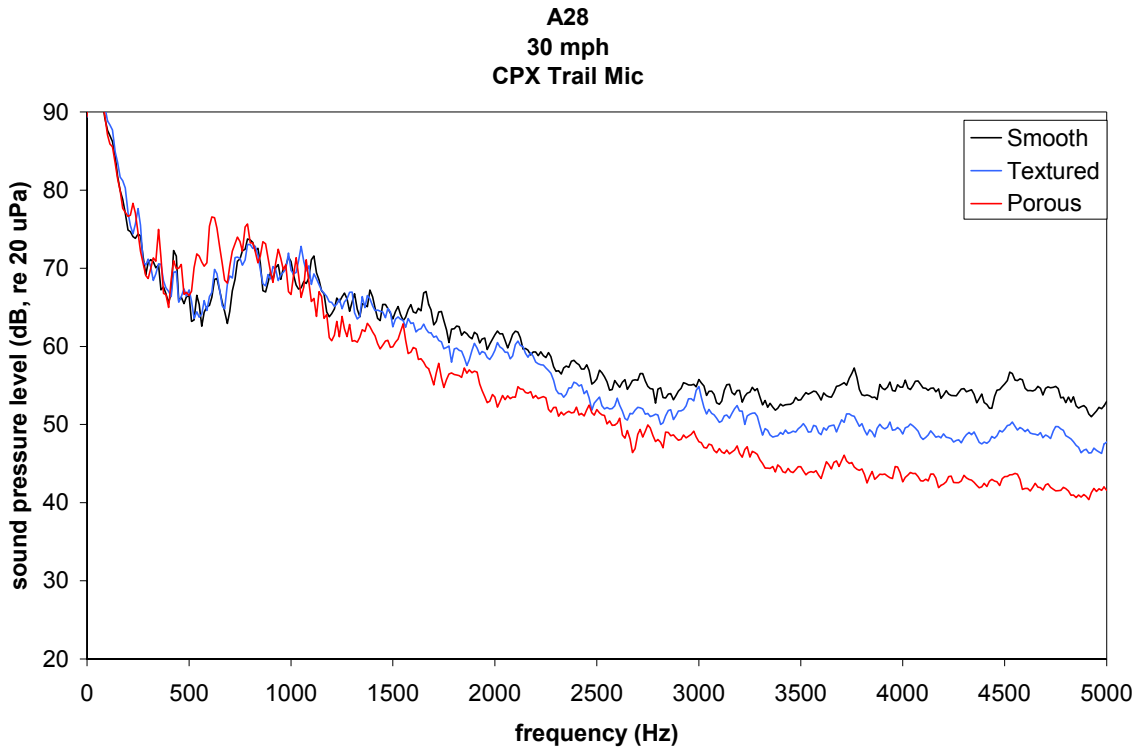

A28
10 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

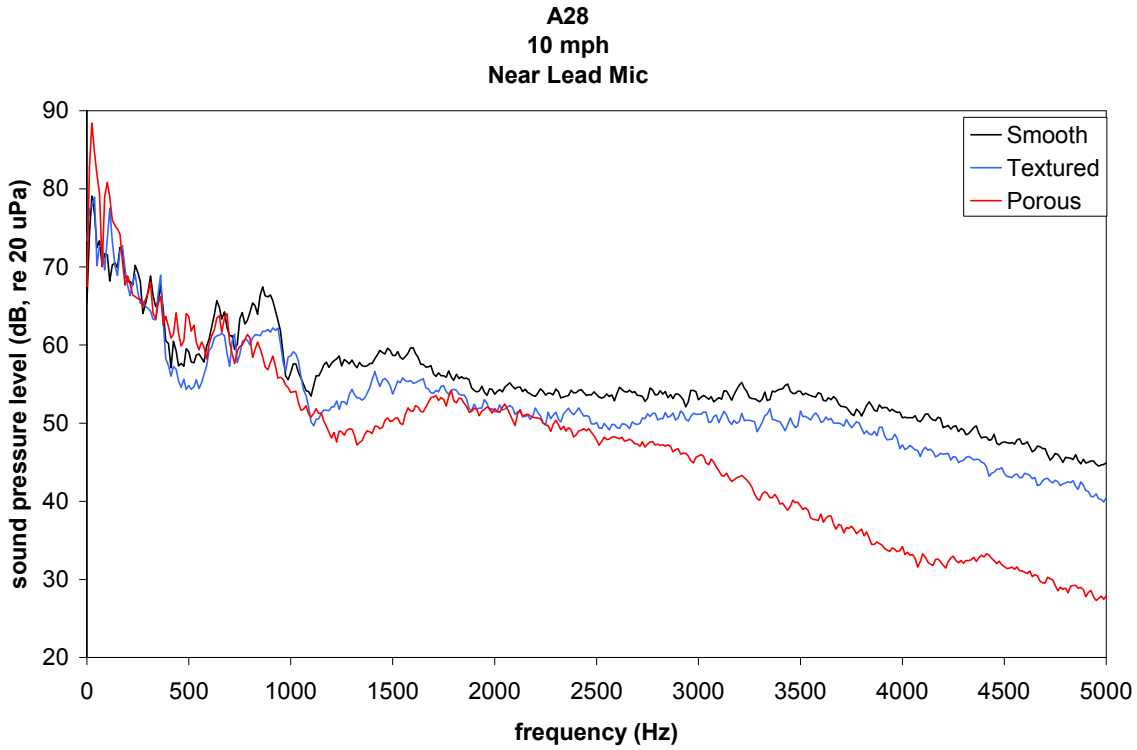

A28
20 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

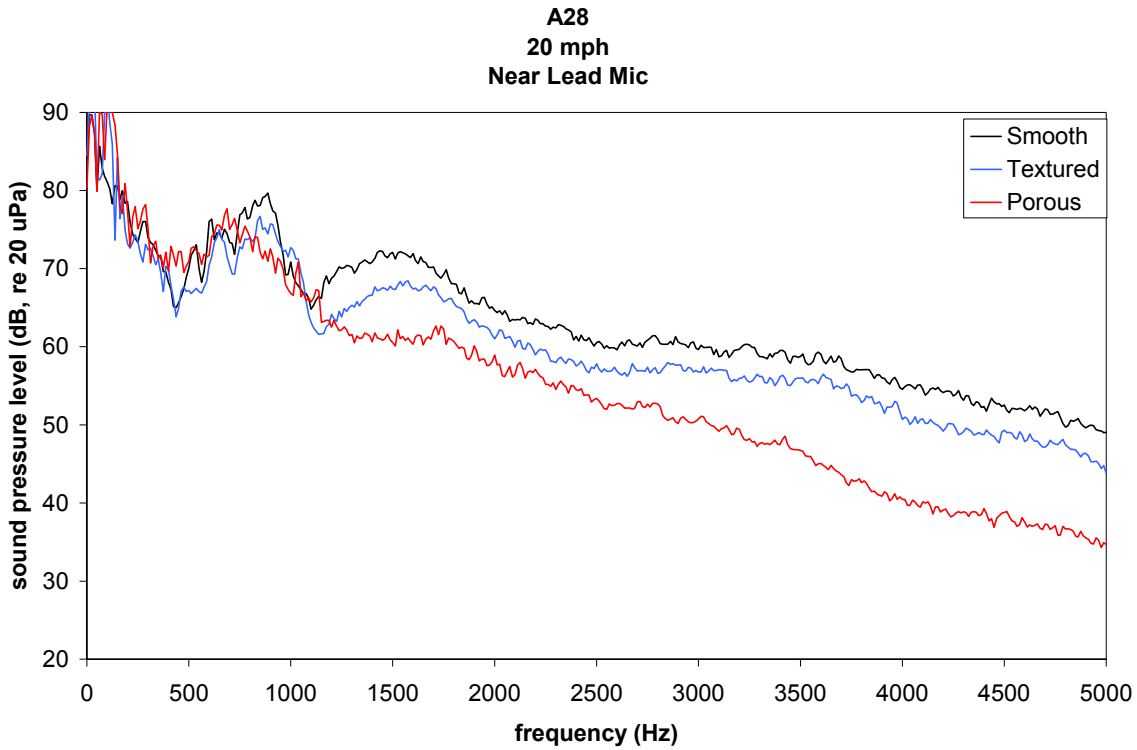

A28
30 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

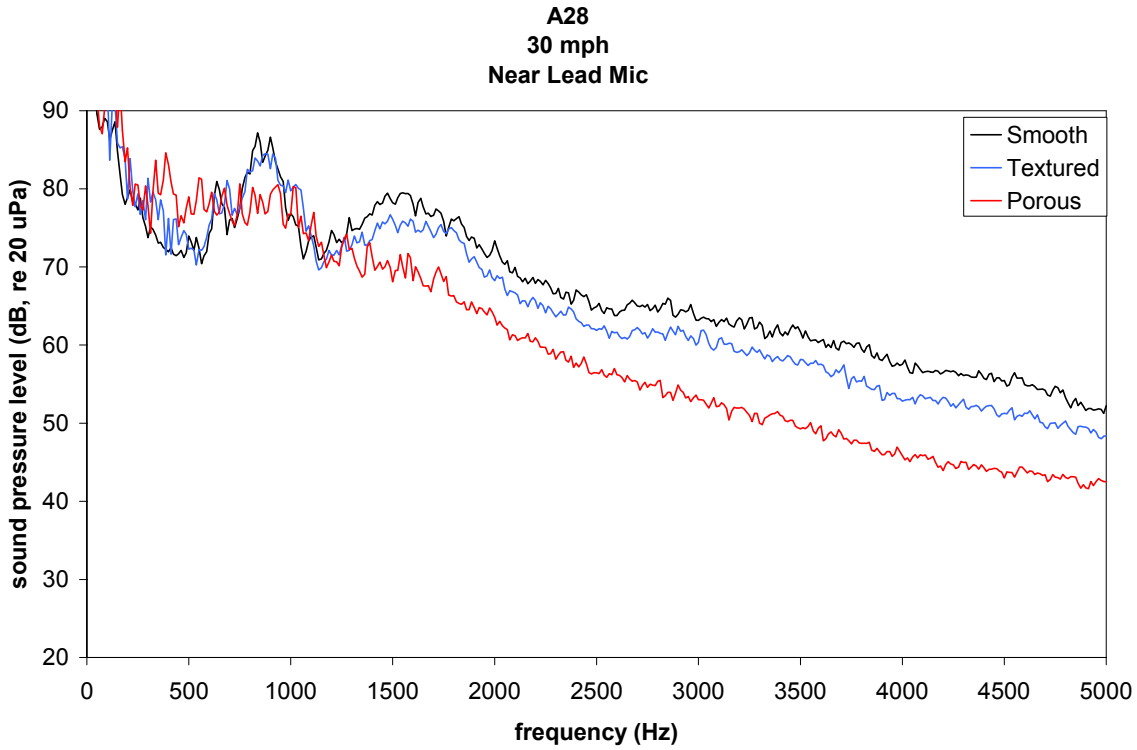

A28
10 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

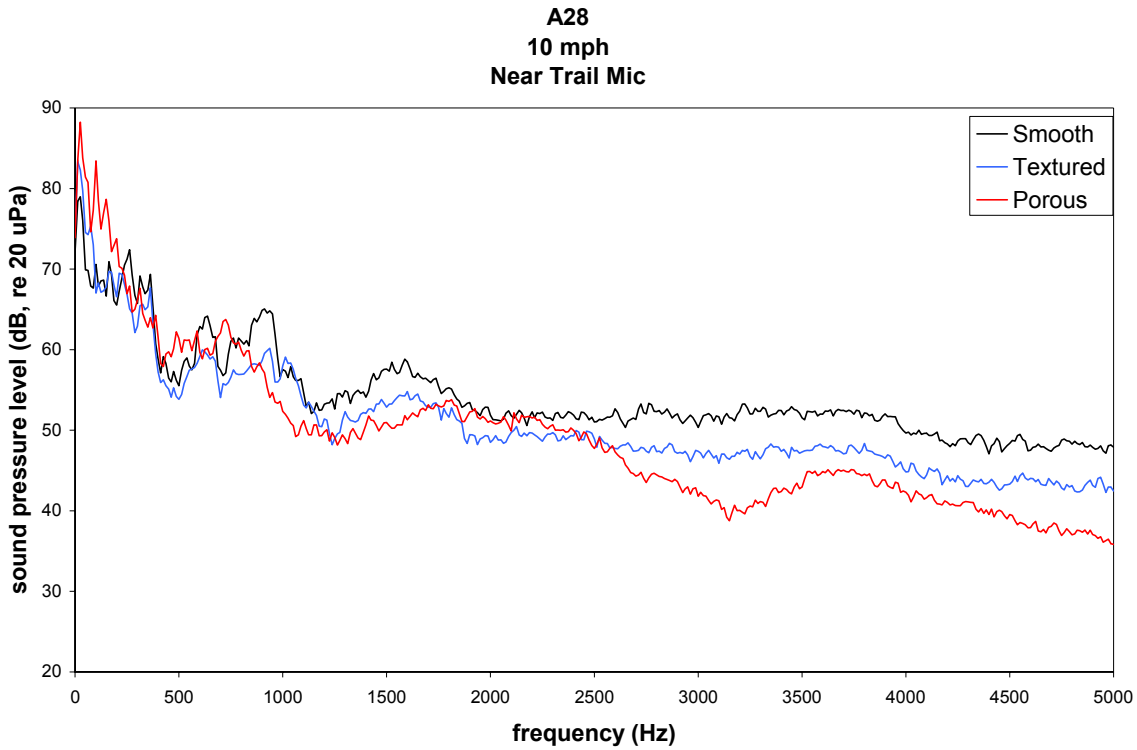

A28
20 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

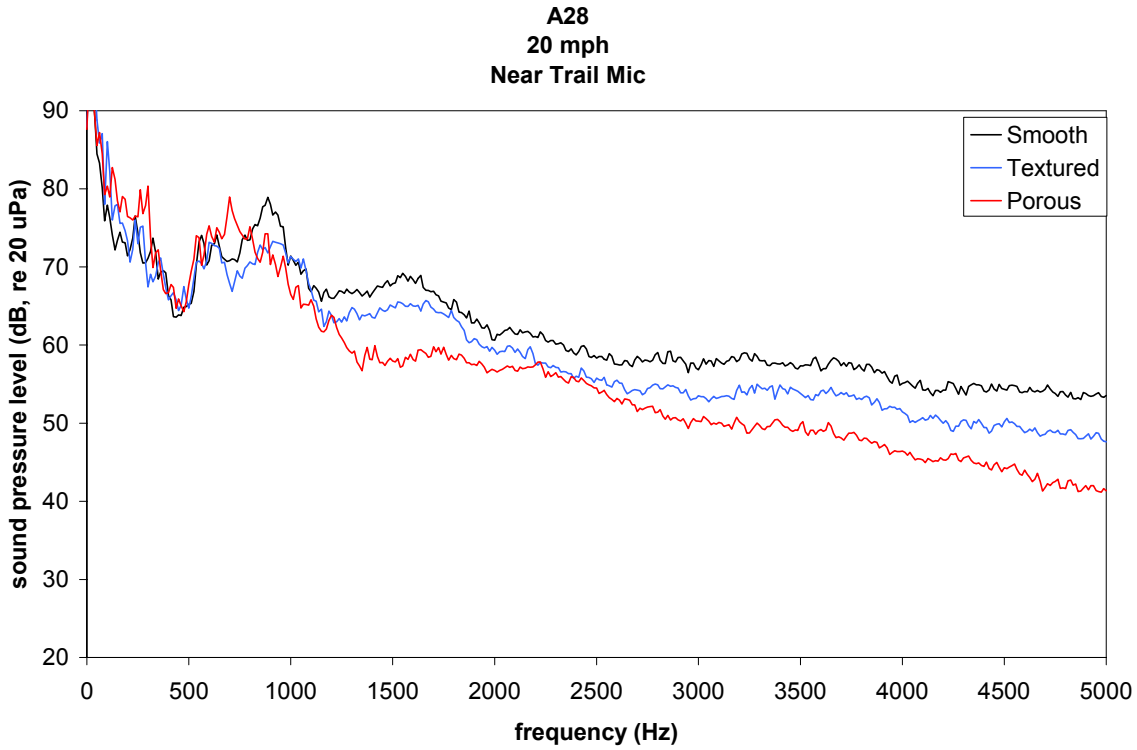

A28
30 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

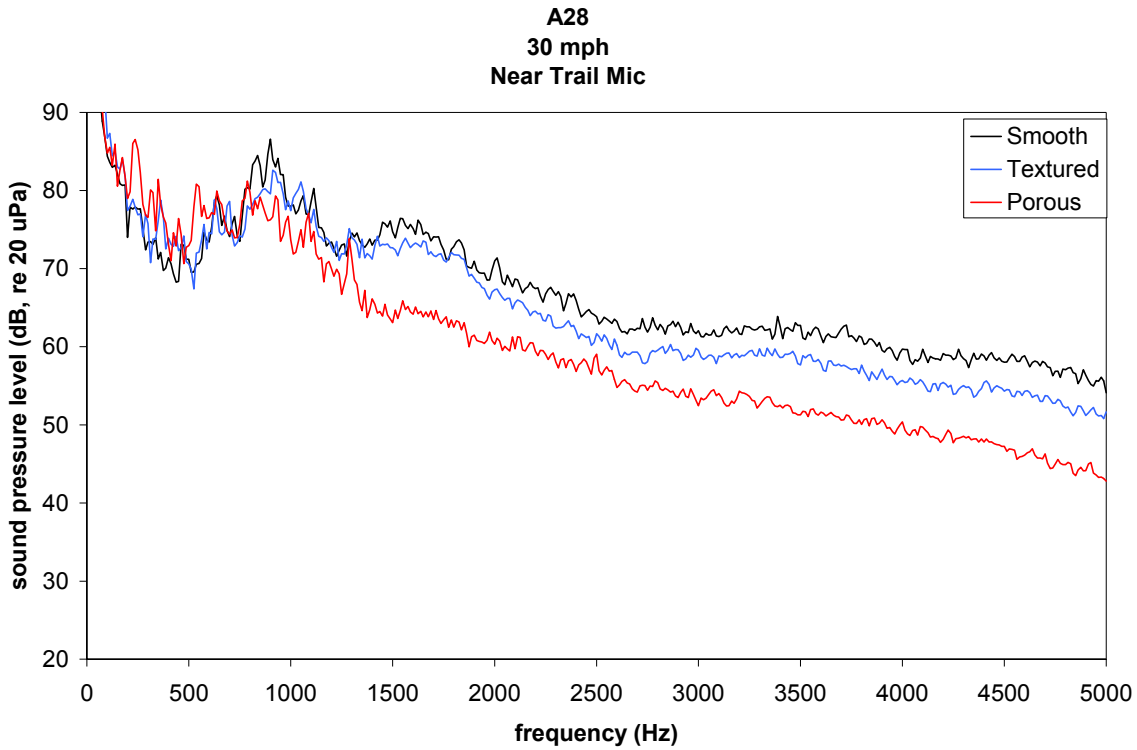

A28
10 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


A28
20 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

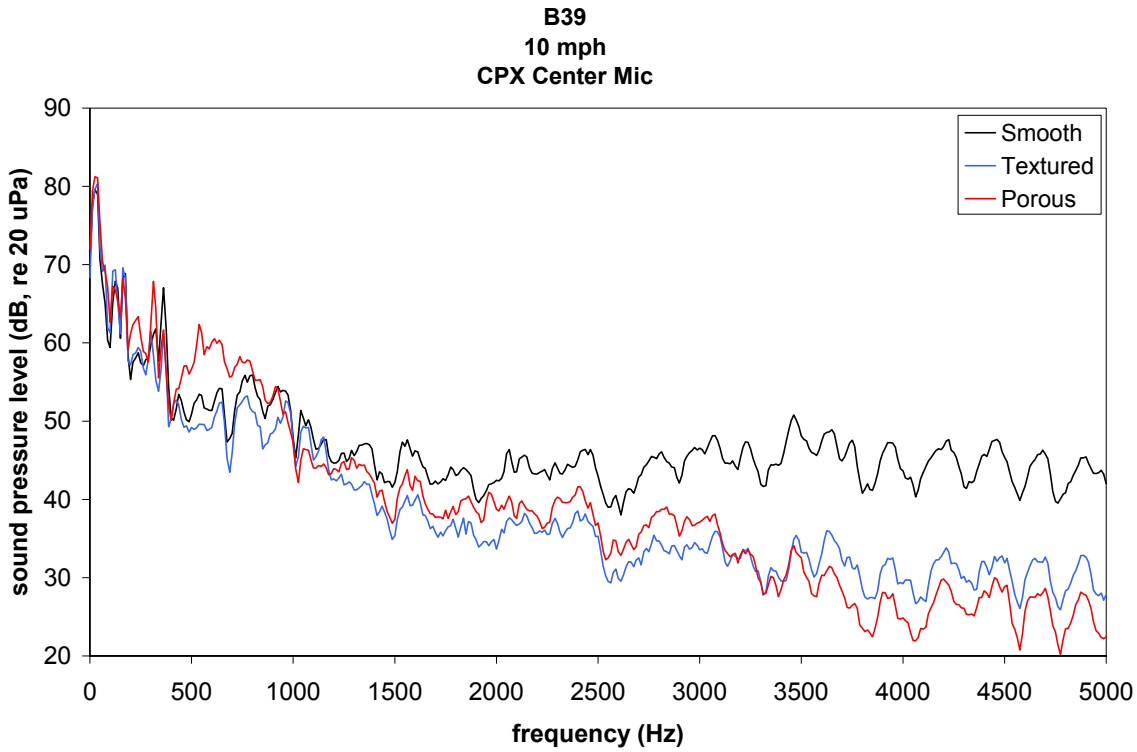

A28
30 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

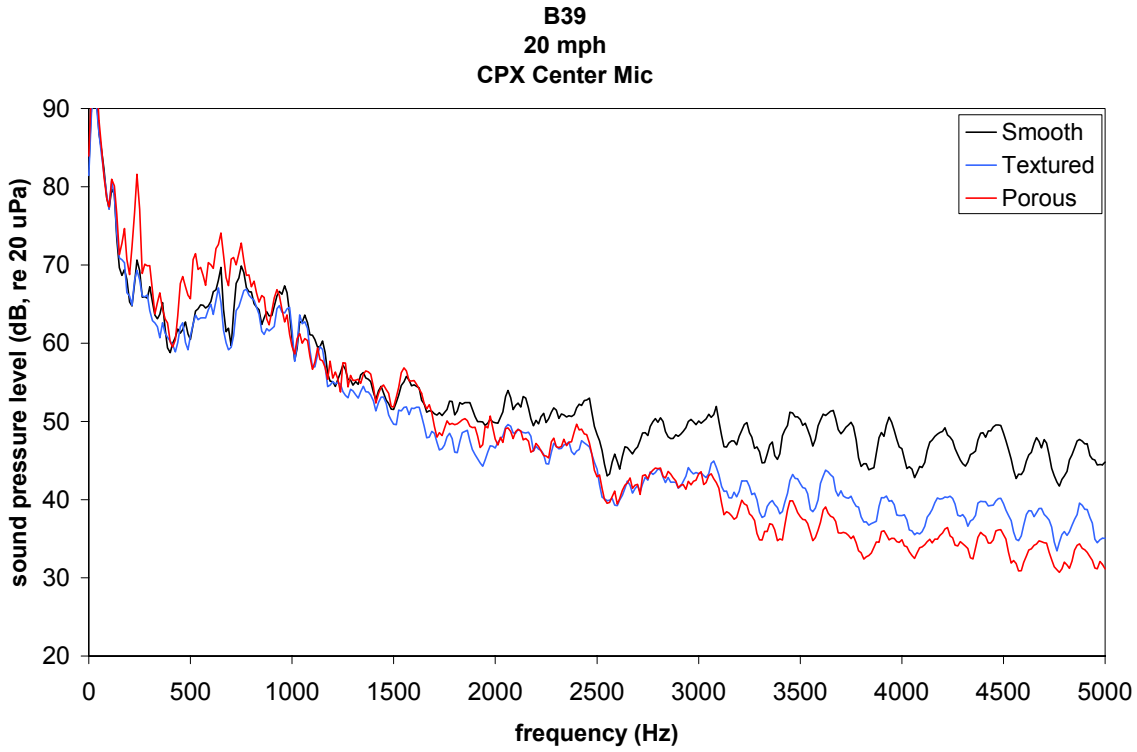

A28
10 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

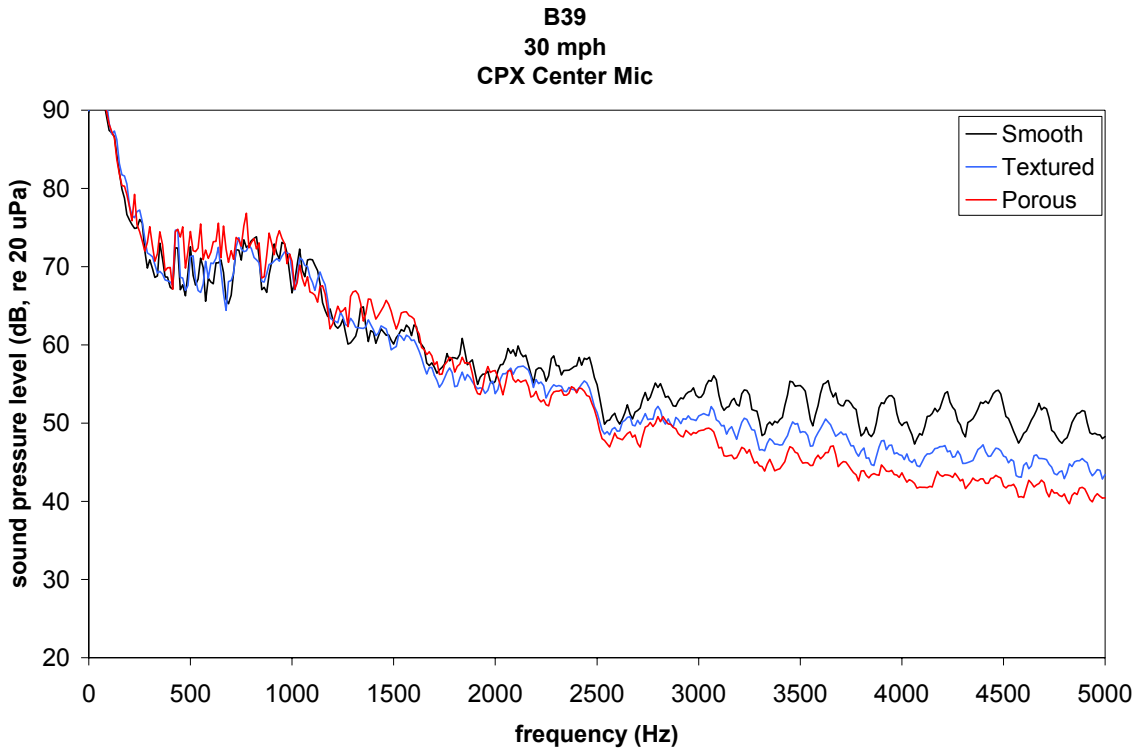

A28
20 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

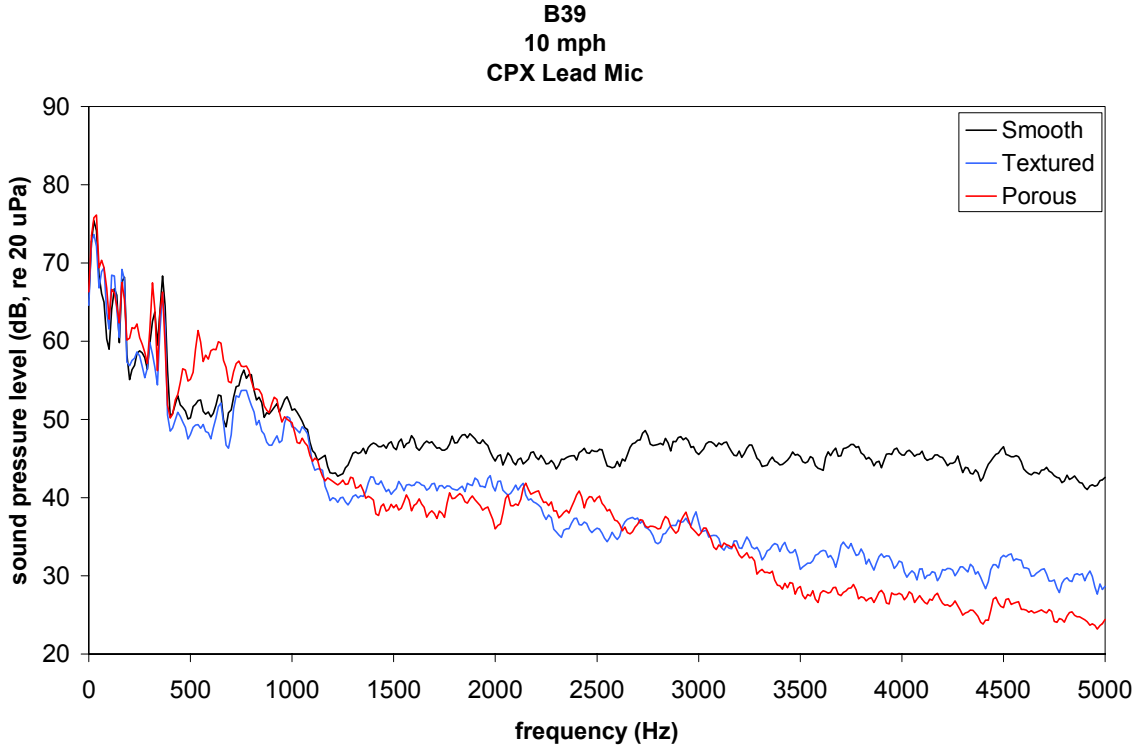

A28
30 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

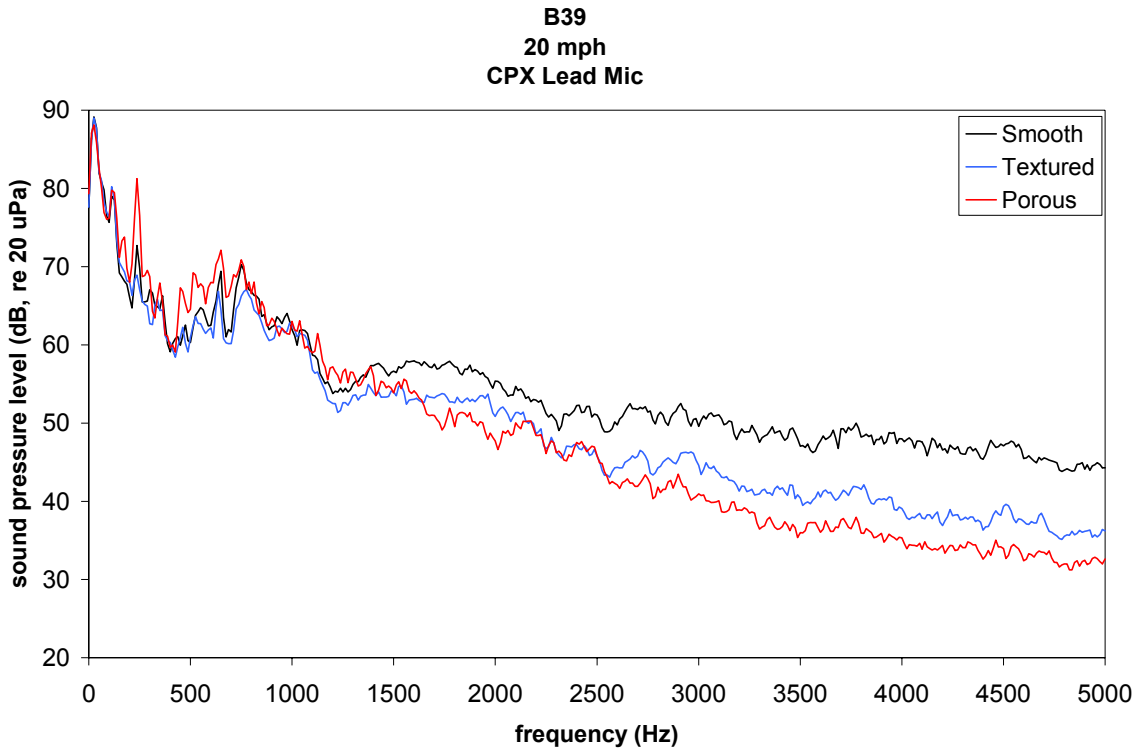
Appendix F: Narrow band spectra for tire B39; multiple surface textures at one speed and microphone location.

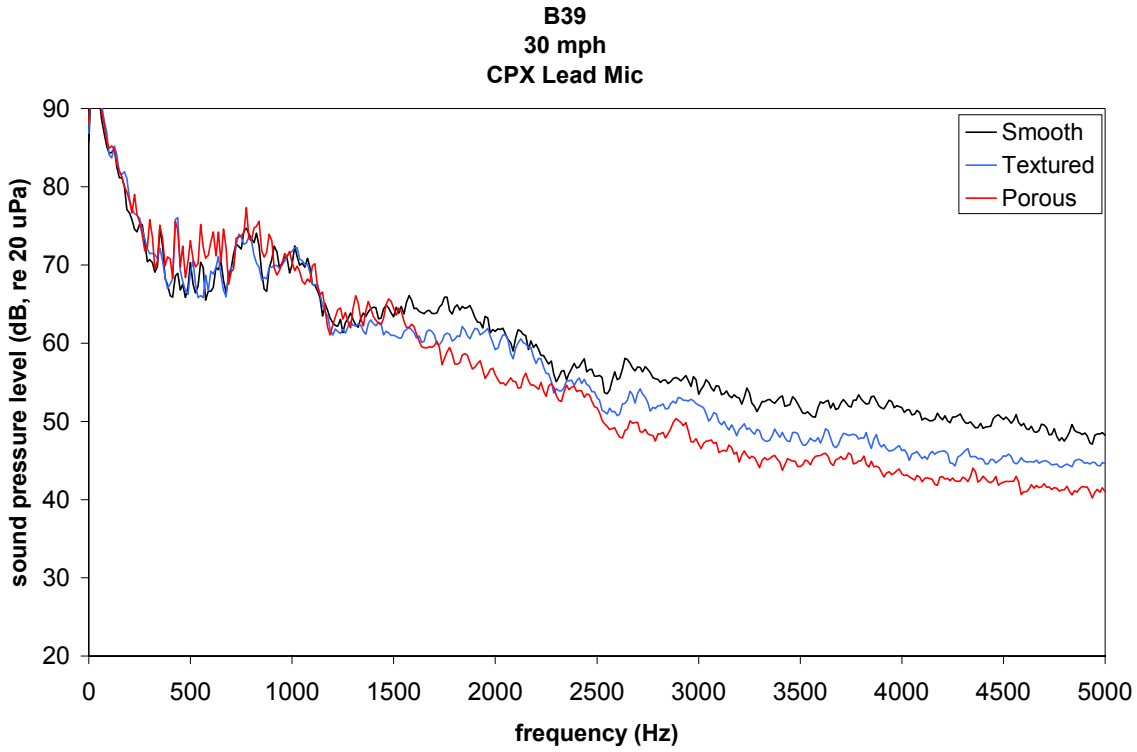

B39
10 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

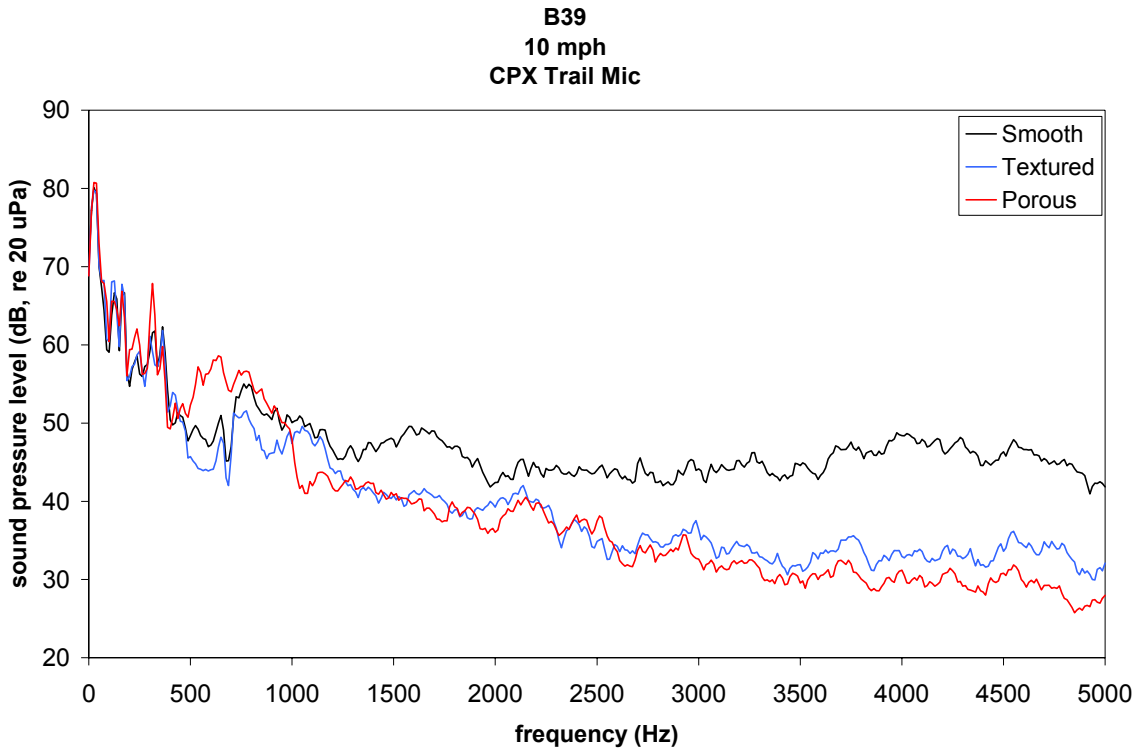

B39
20 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

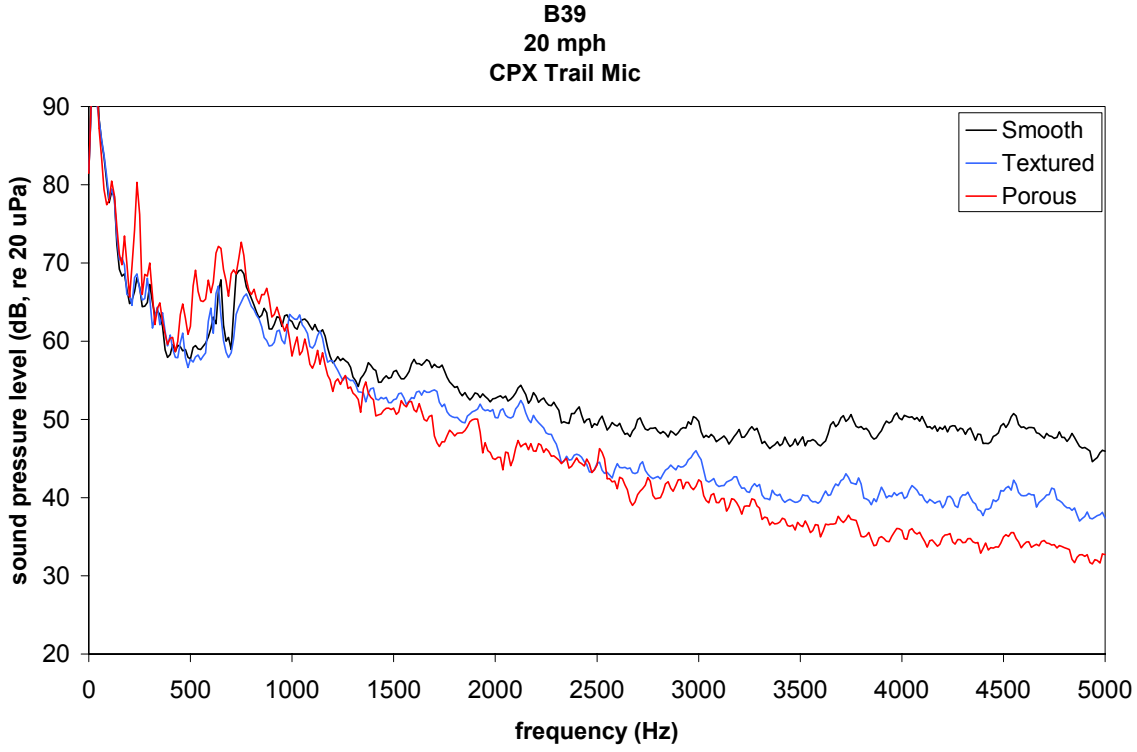

B39
30 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

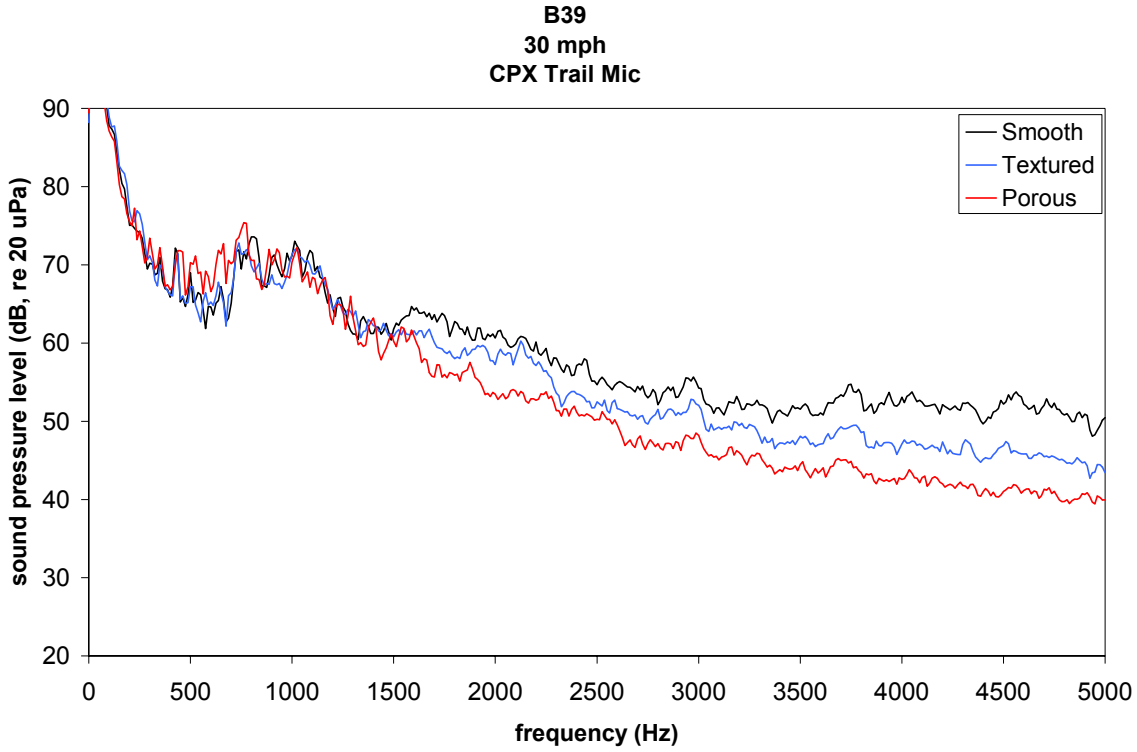

B39
10 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

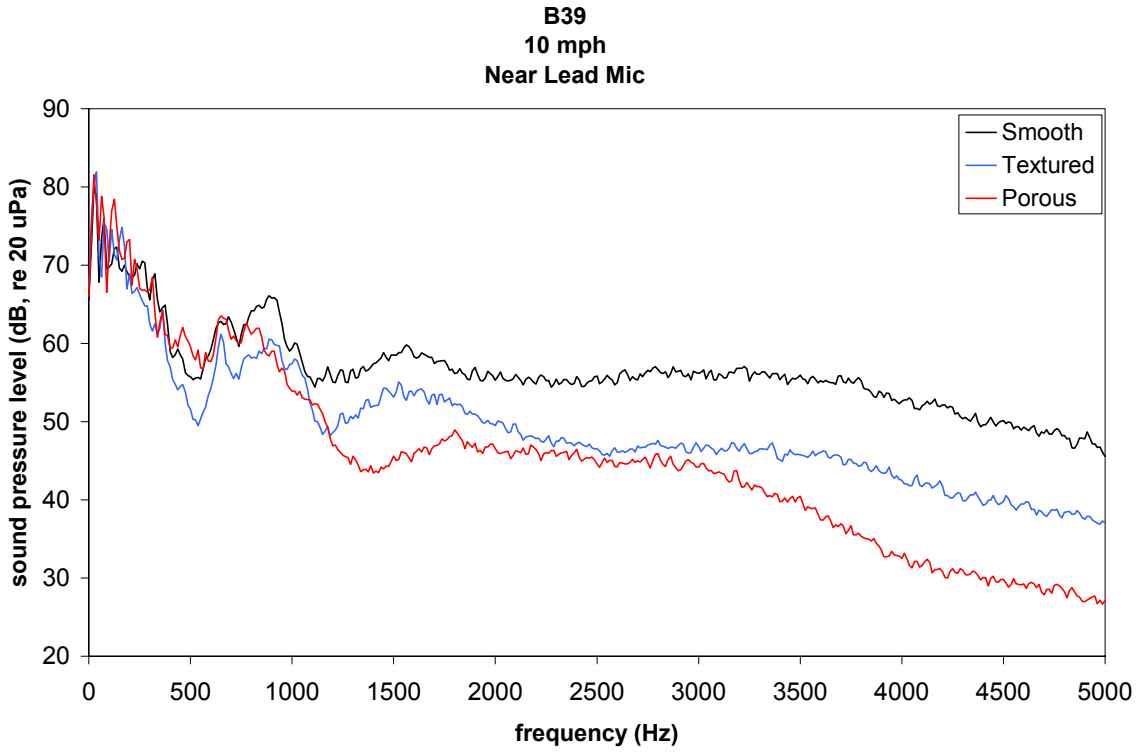

B39
20 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

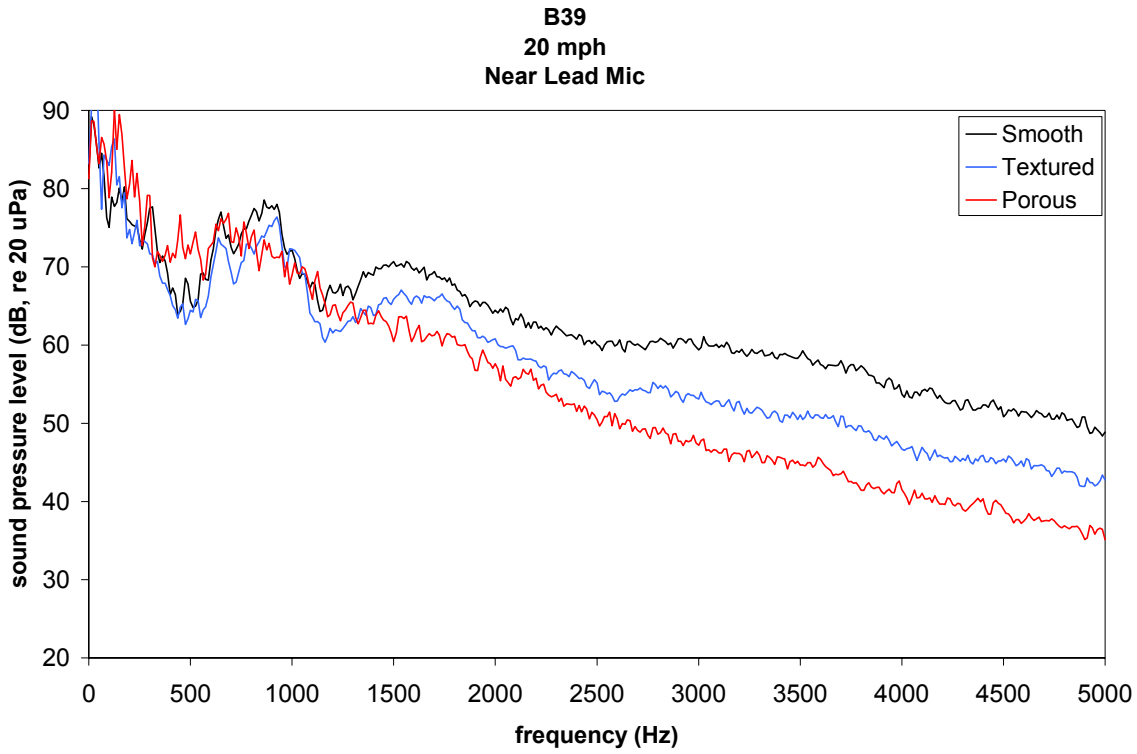

B39
30 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

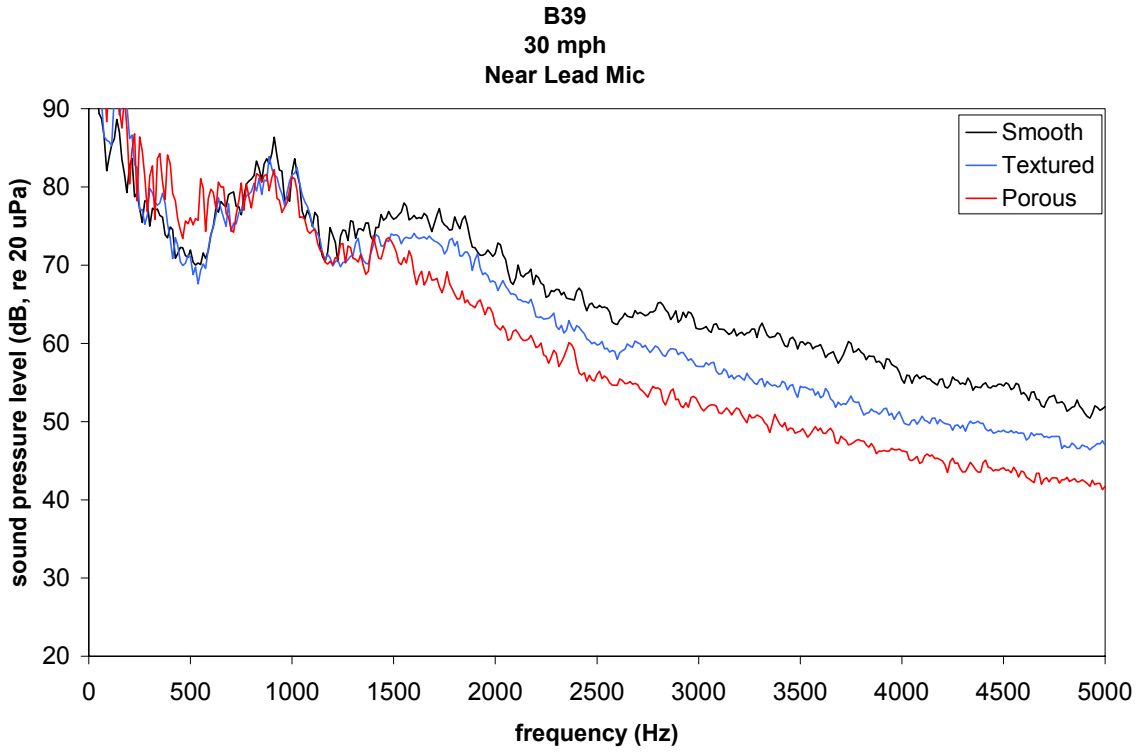

B39
10 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

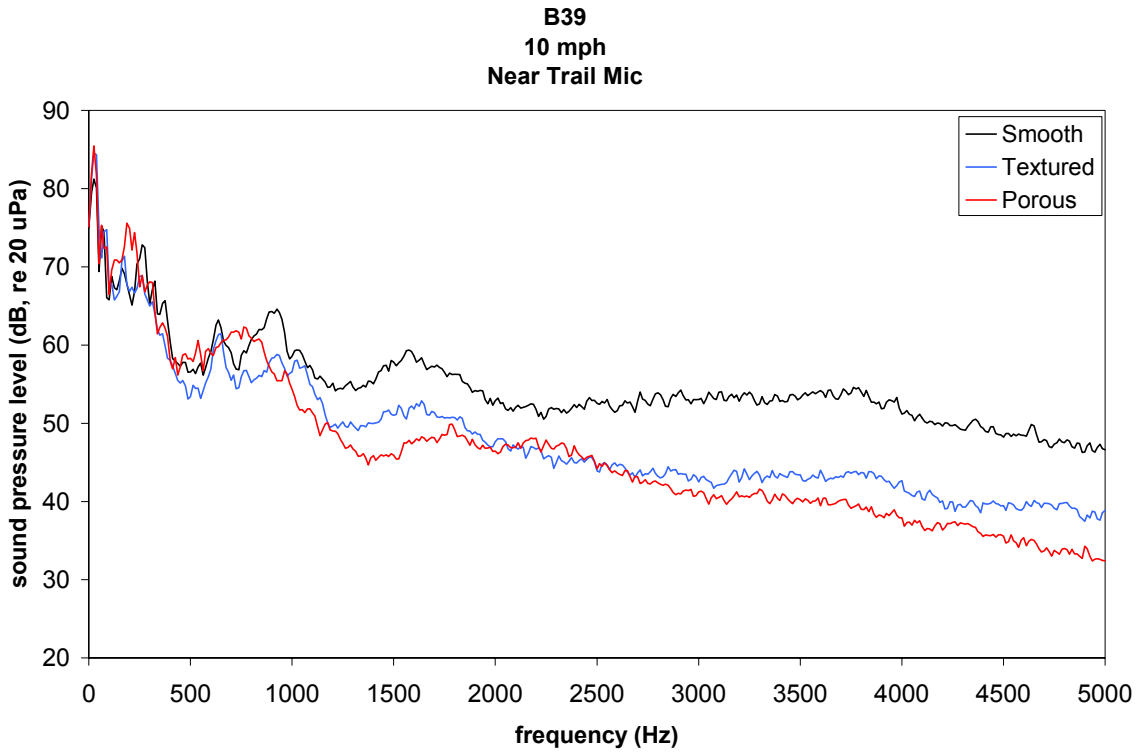

B39
20 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

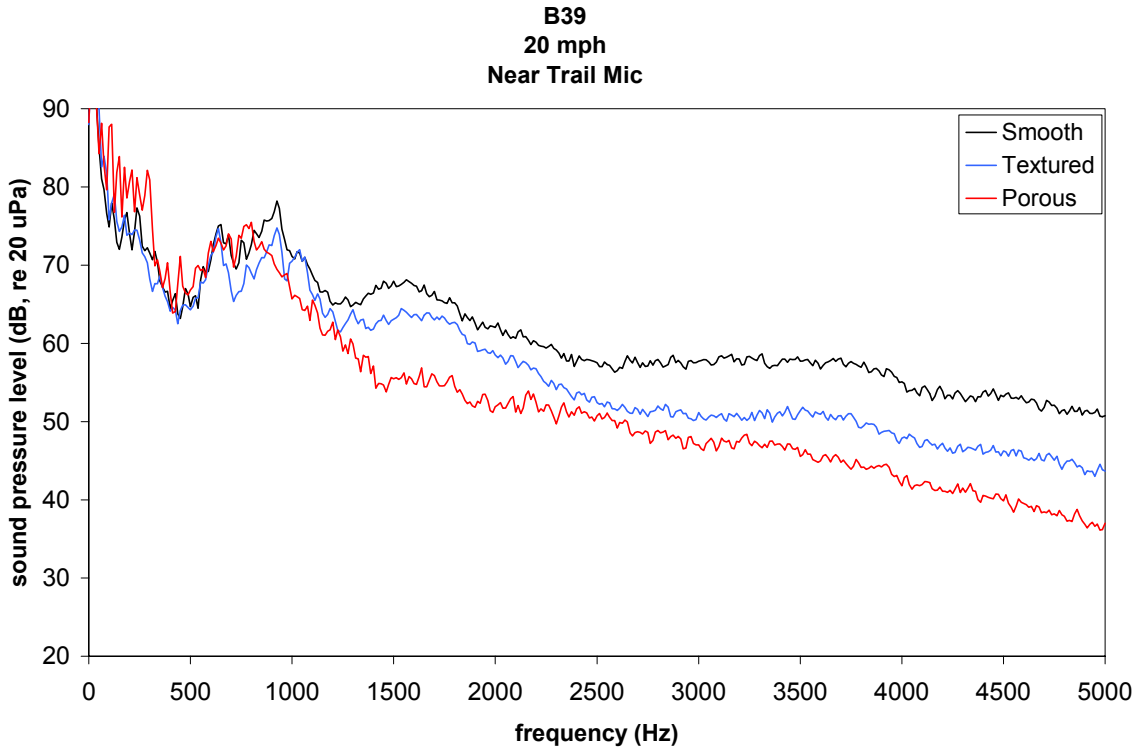

B39
30 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

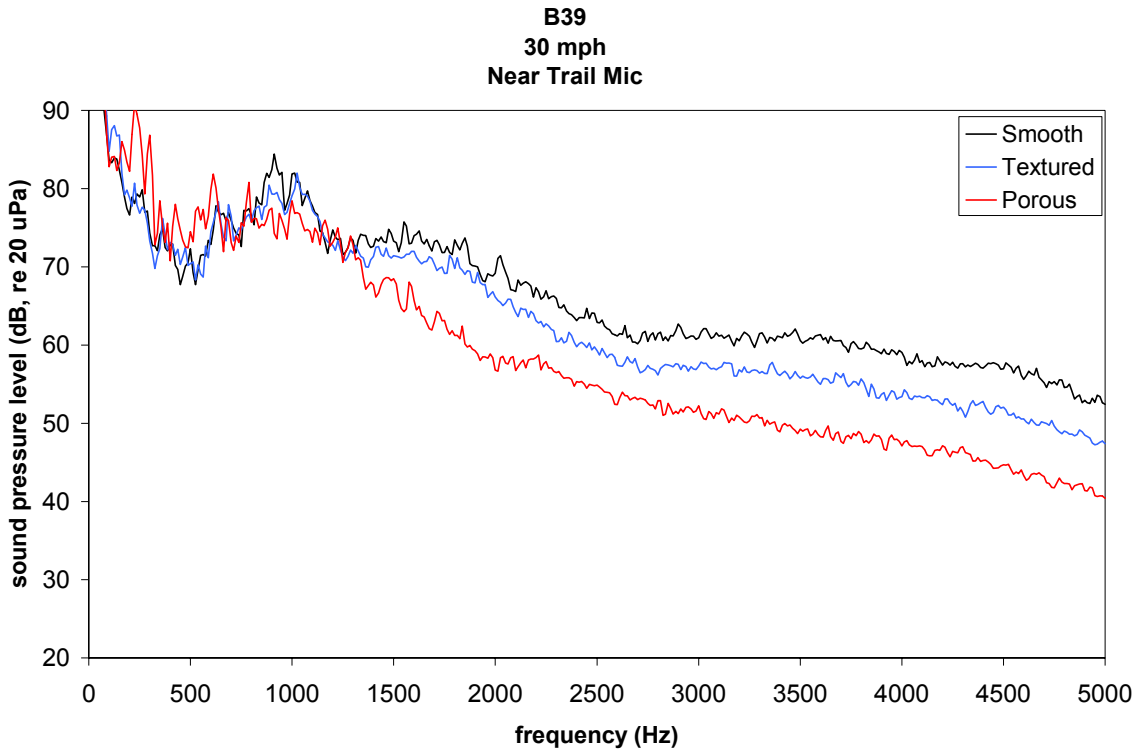

B39
10 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


B39
20 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

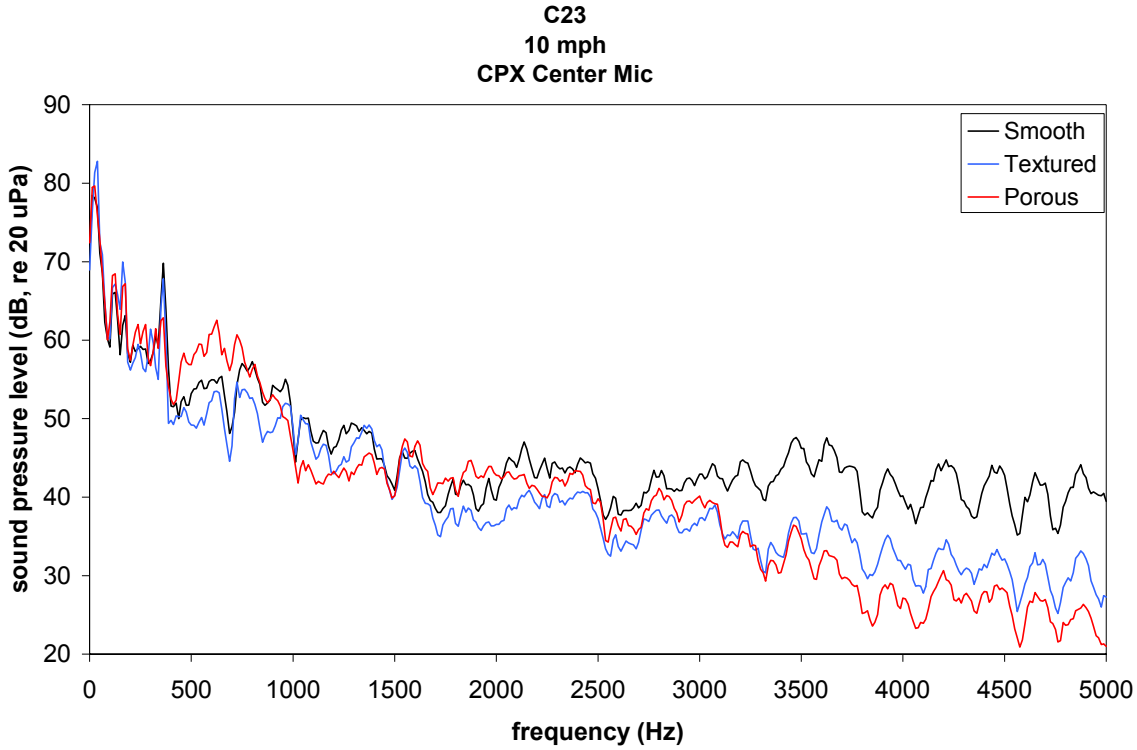

B39
30 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

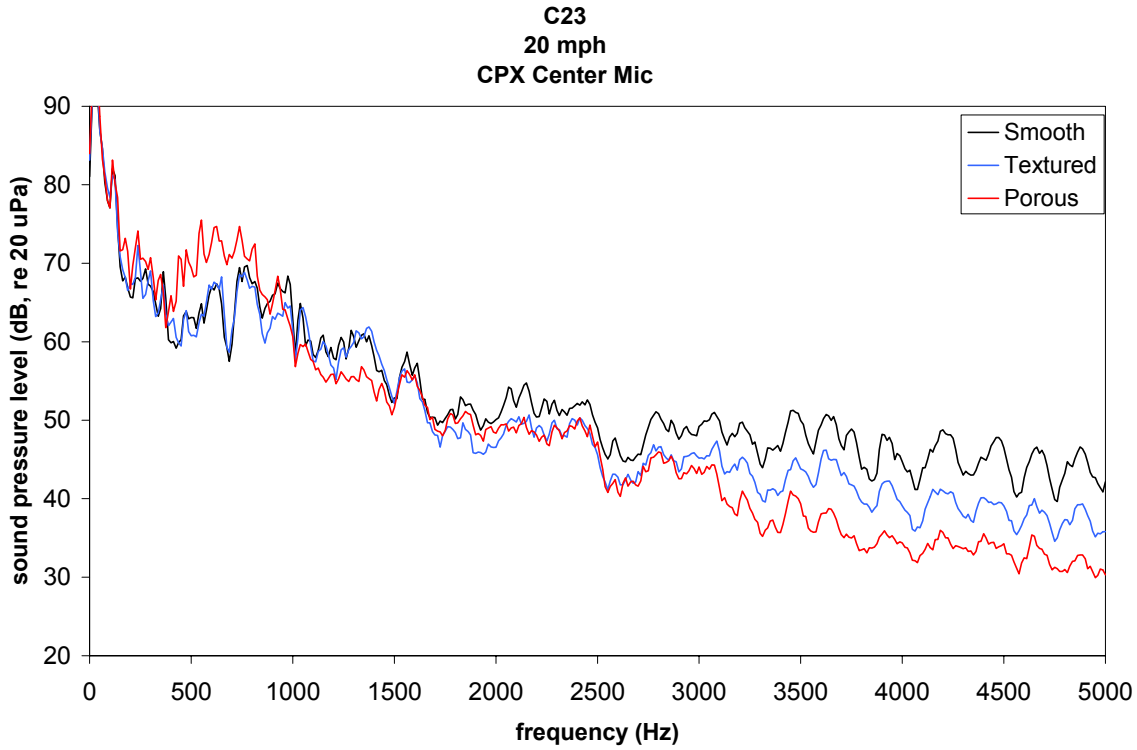

B39
10 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


B39
20 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


B39
30 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

Appendix G: Narrow band spectra for tire C23; multiple surface textures at one speed and microphone location.


C23
10 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


C23
20 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
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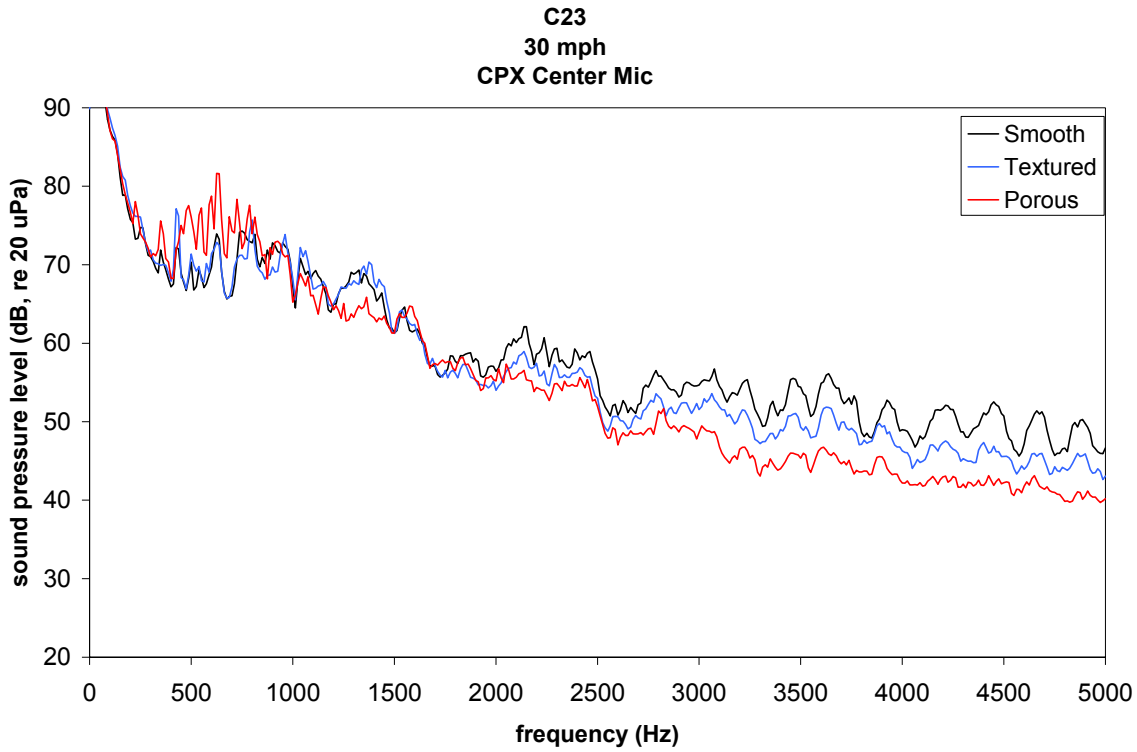
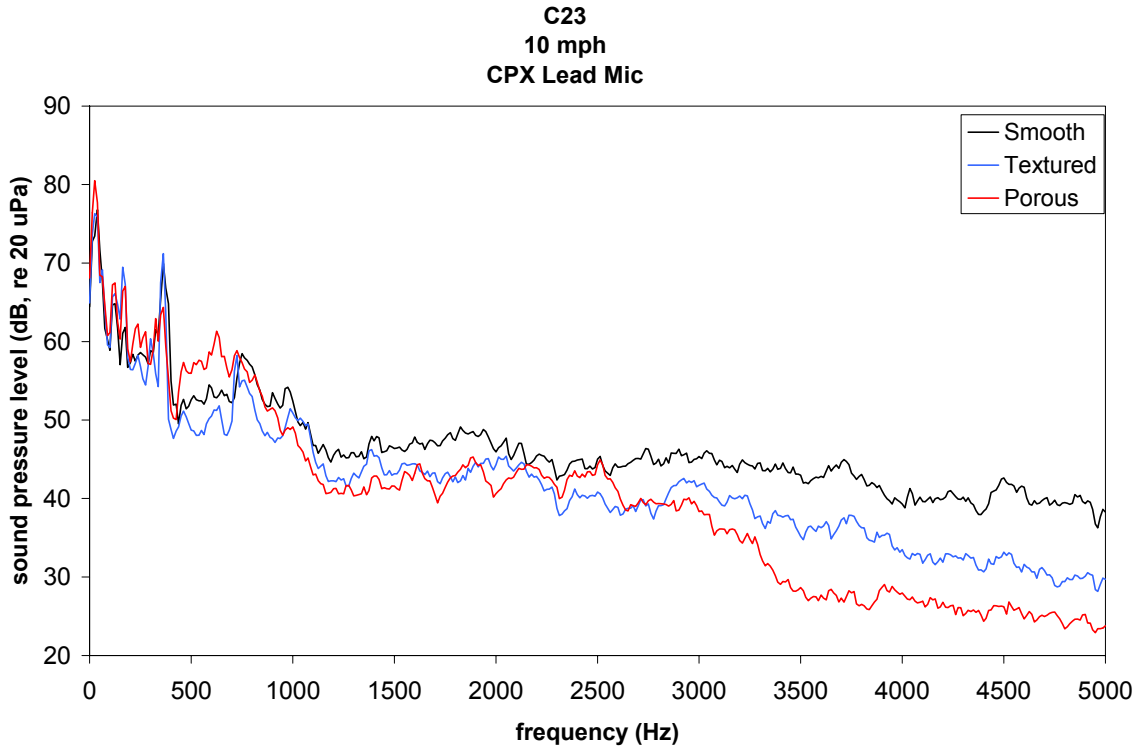
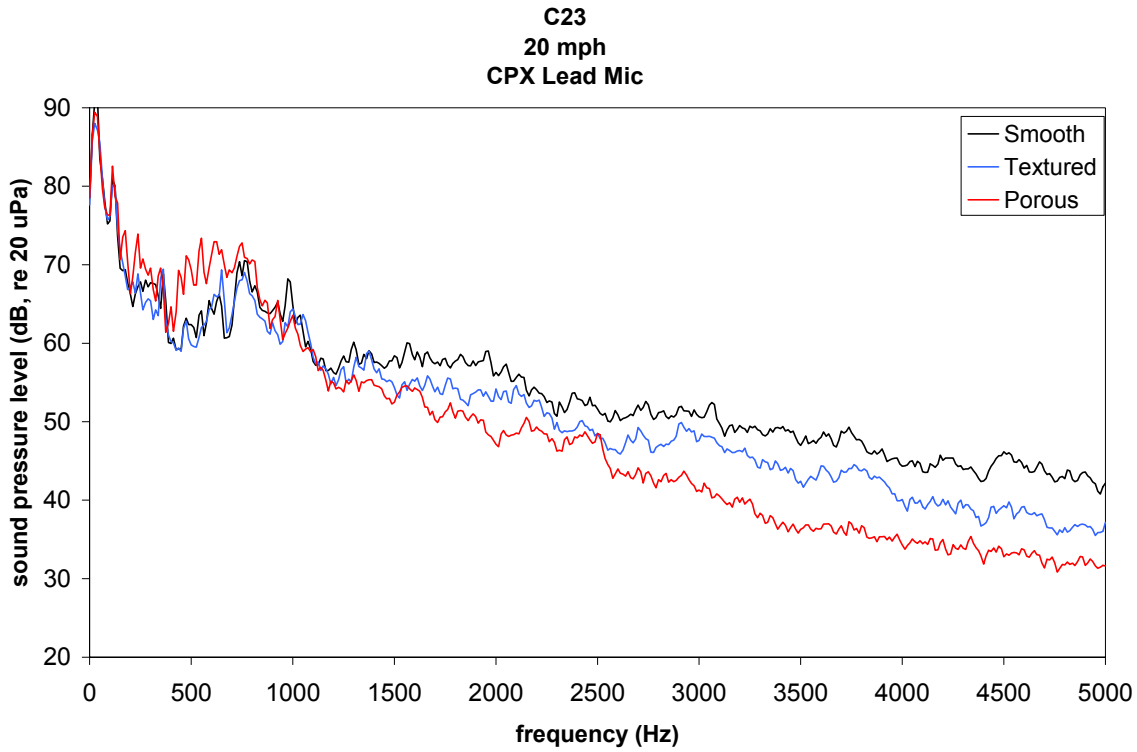
3500
4000
4500
5000


C23
30 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


C23
10 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


C23
20 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
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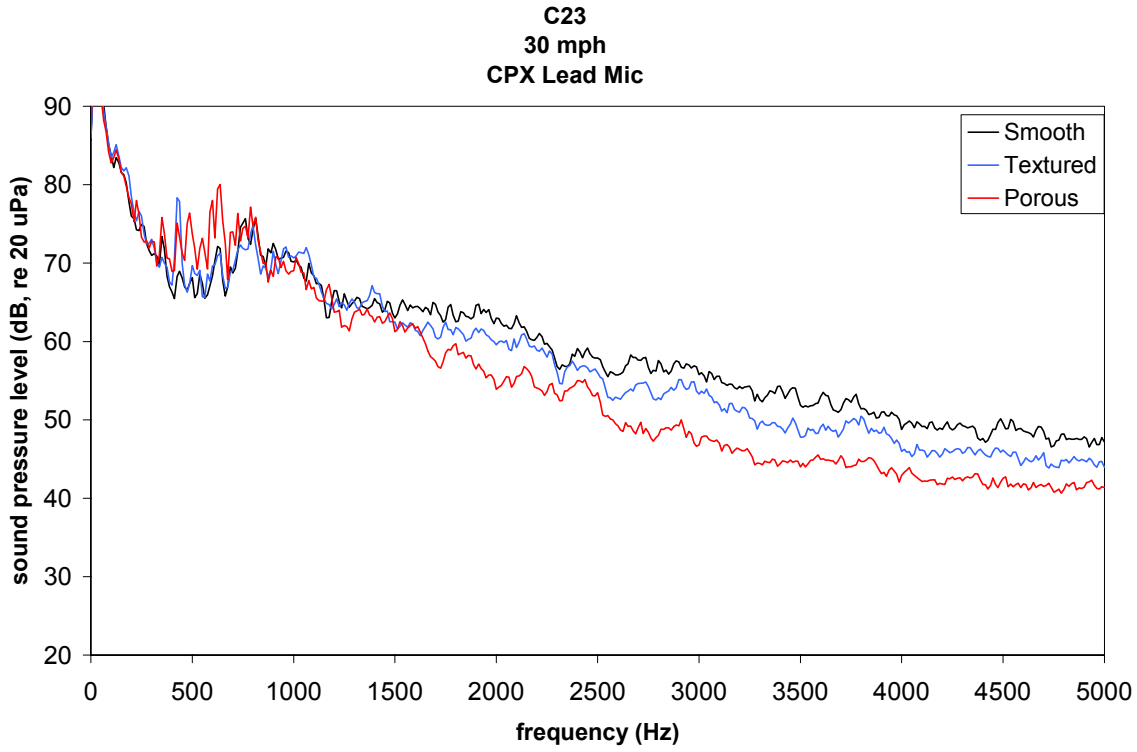
5000


C23
30 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
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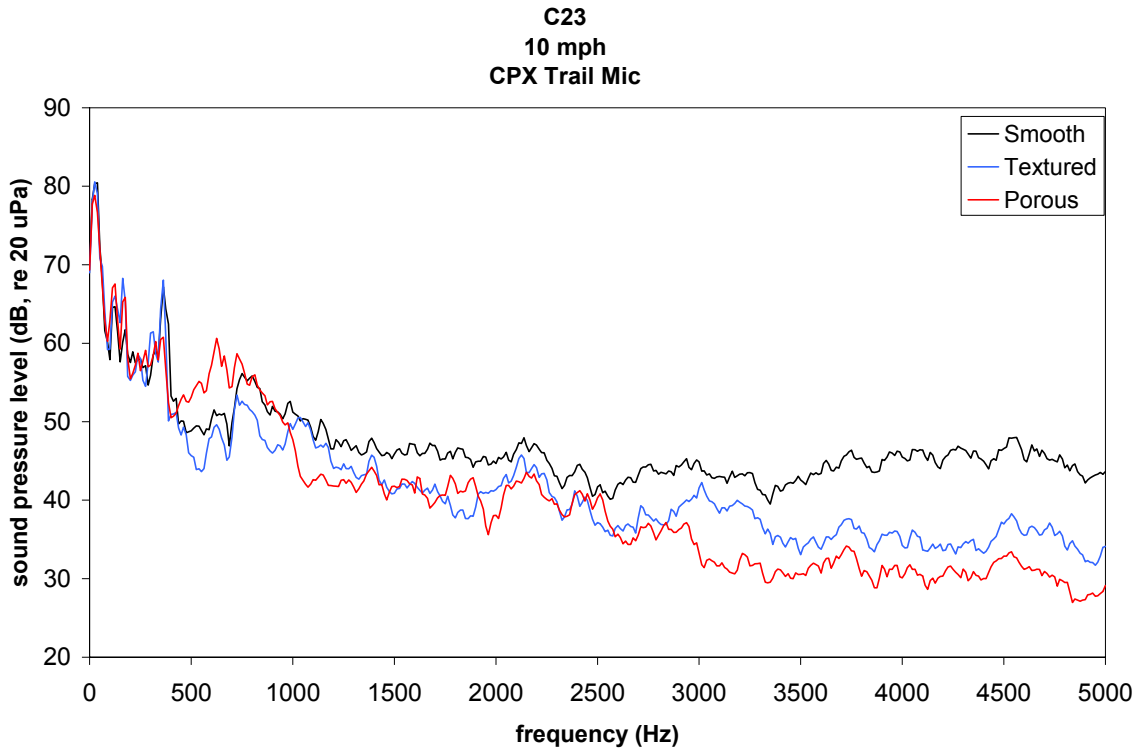
4500
5000


C23
10 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
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2500
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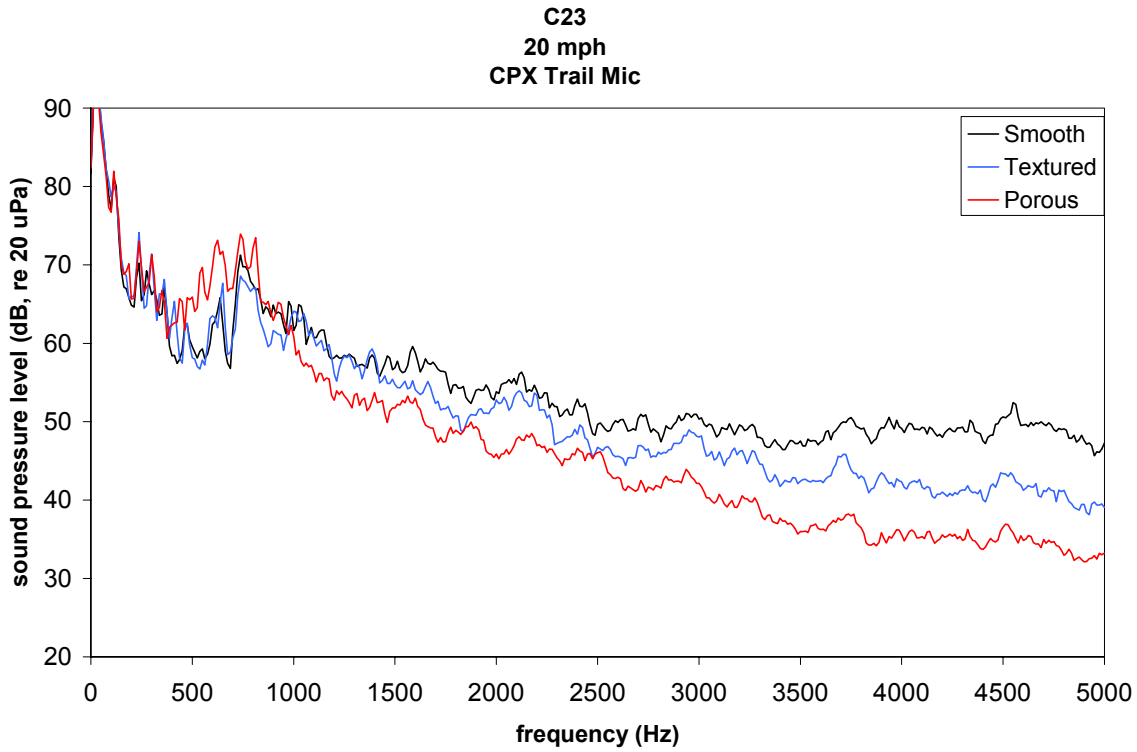
3500
4000
4500
5000


C23
20 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
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0
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3500
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4500
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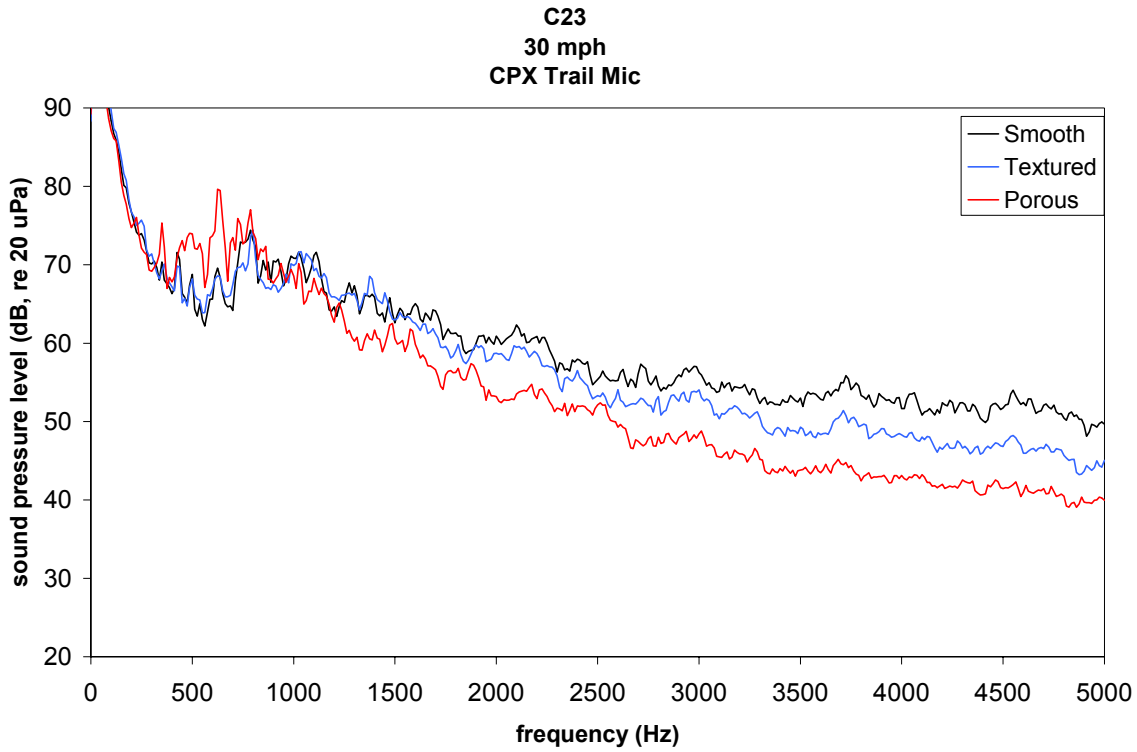
C23
30 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
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2500
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3500
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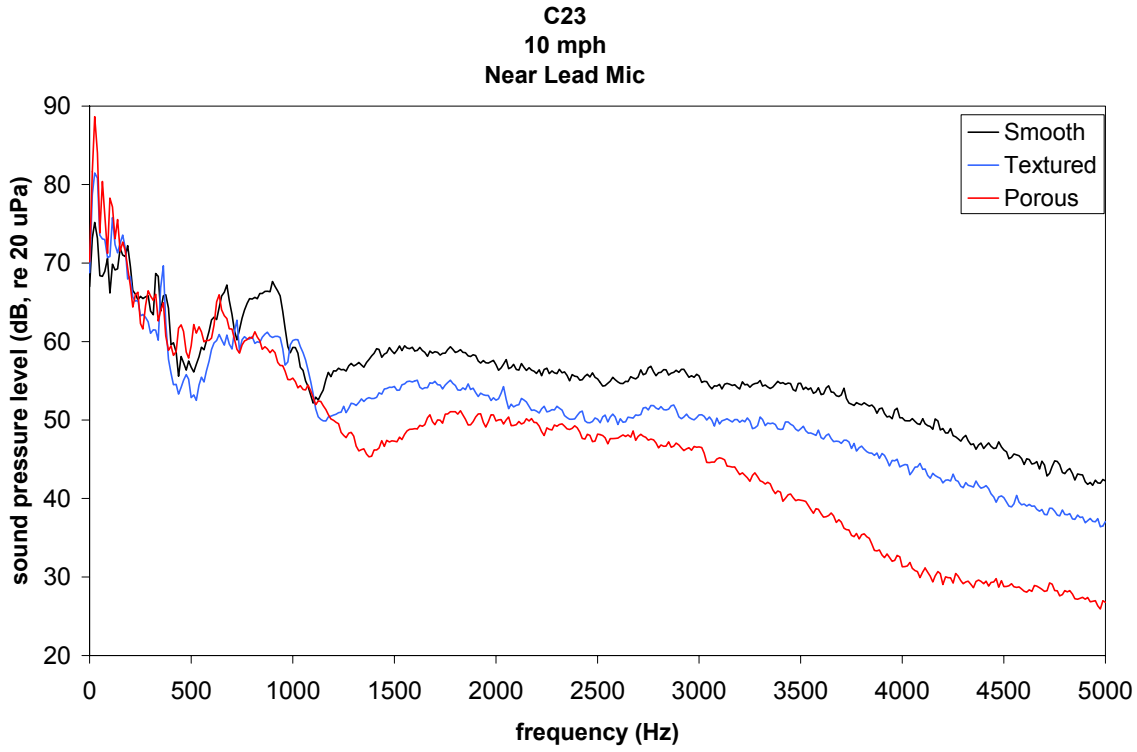
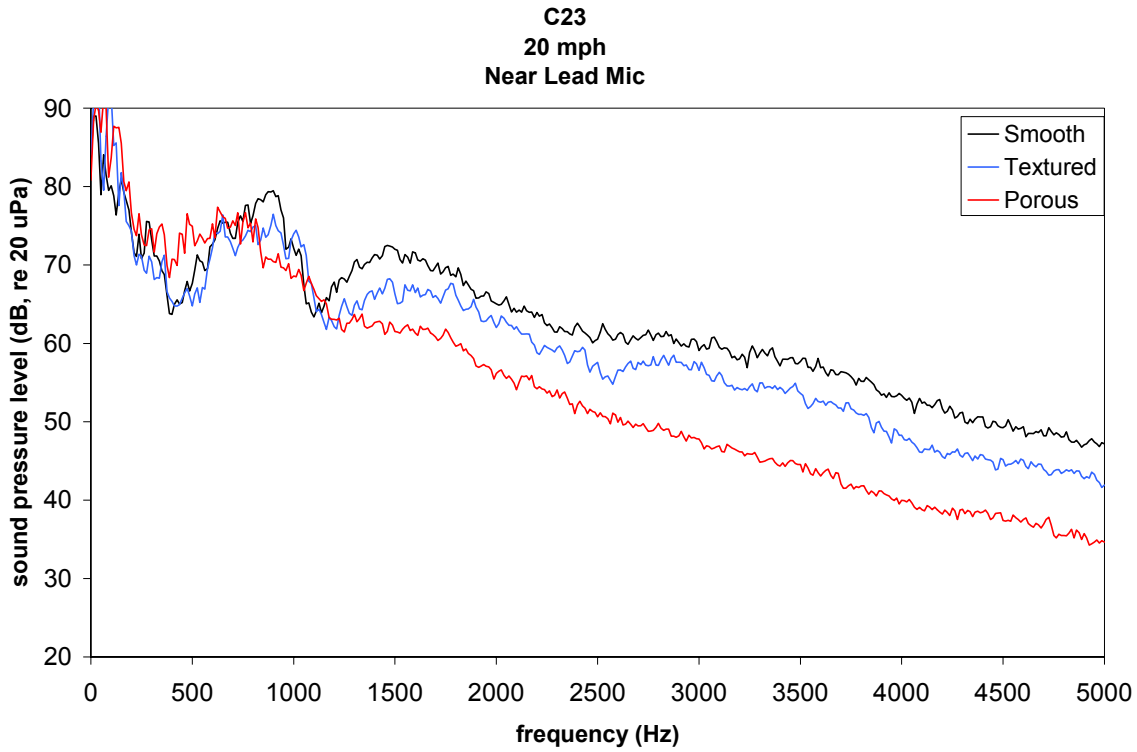
4500
5000


C23
10 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


C23
20 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
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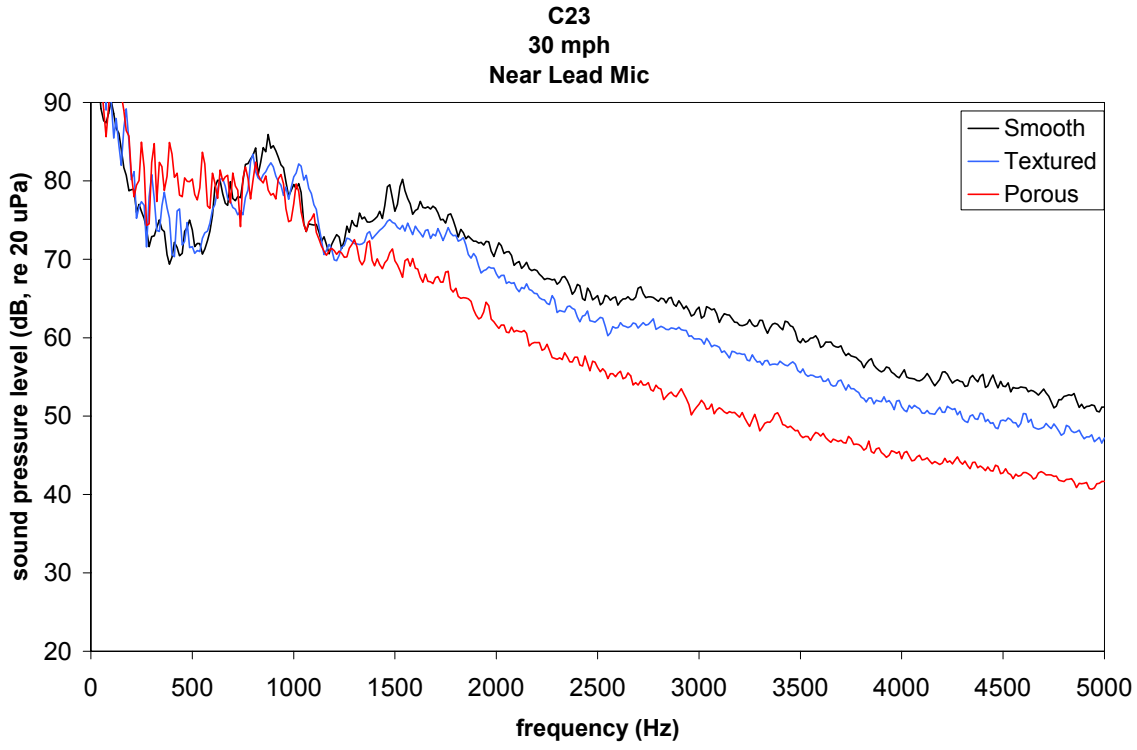
4500
5000


C23
30 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
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0
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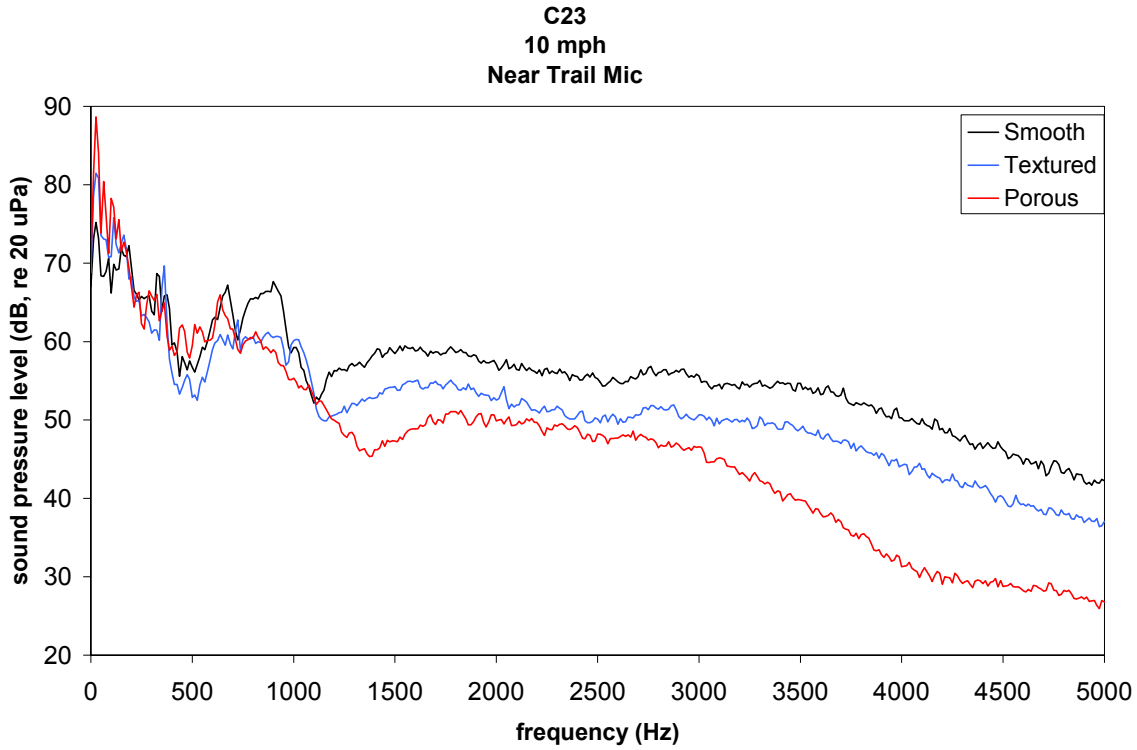
5000


C23
10 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
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2500
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3500
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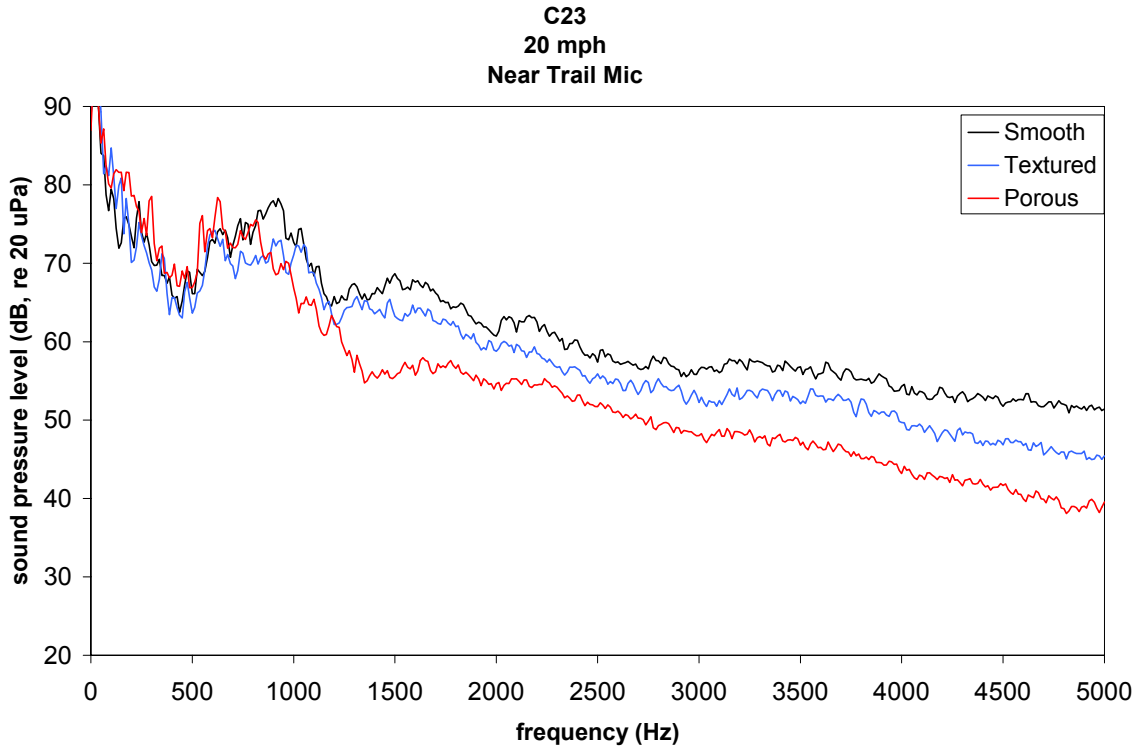
4500
5000


C23
20 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
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4500
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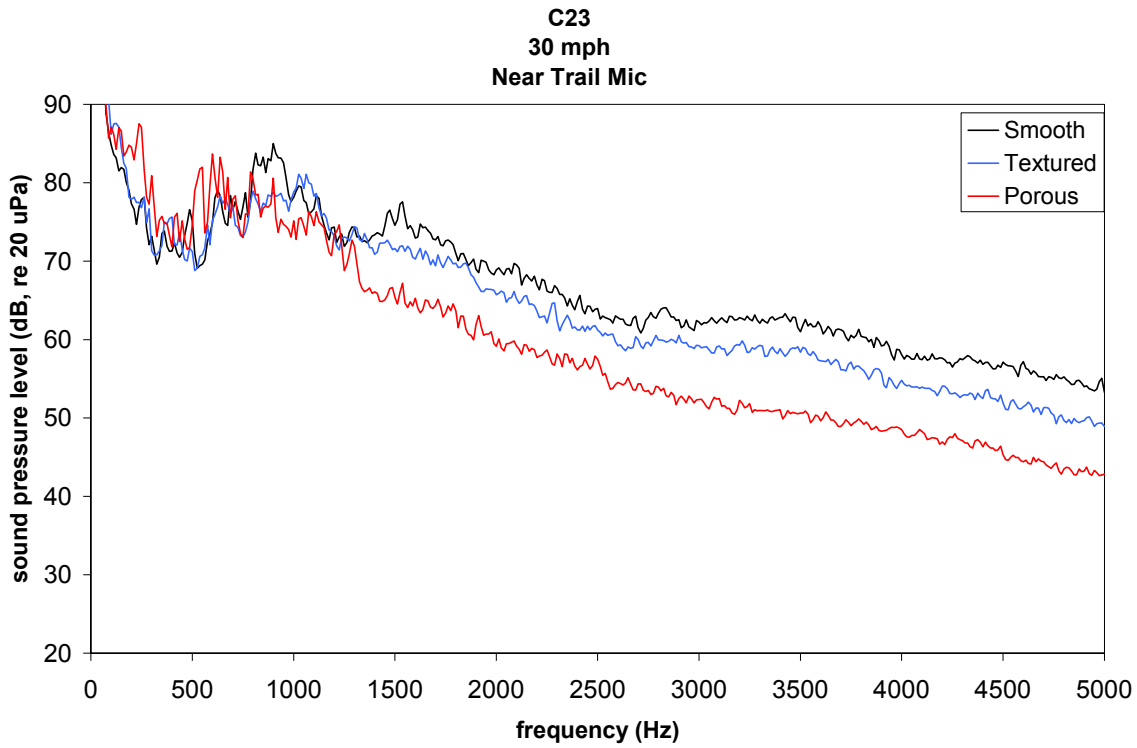
C23
30 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
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60
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40
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20
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500
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4500
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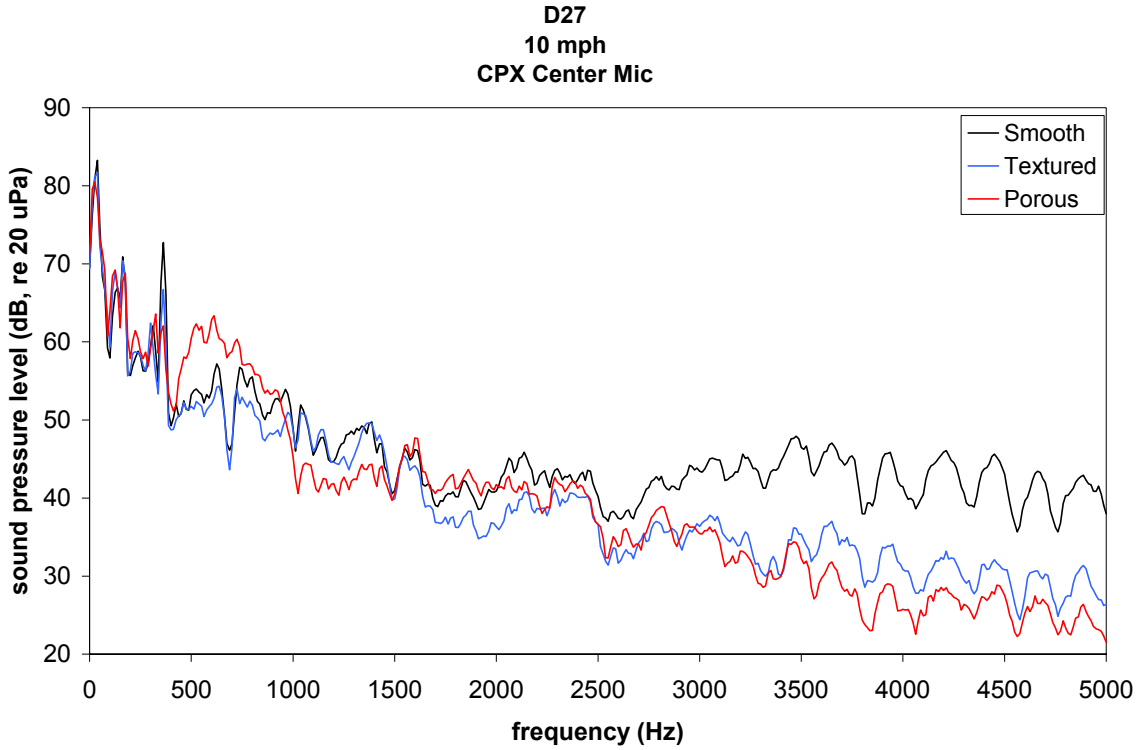
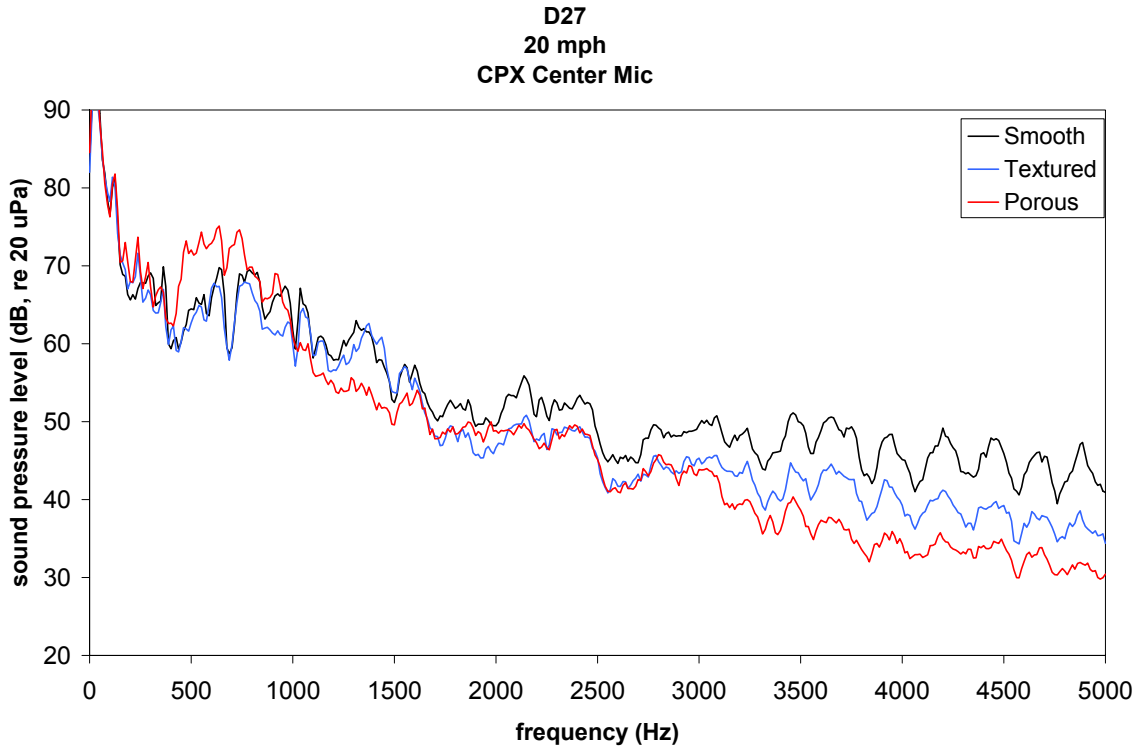
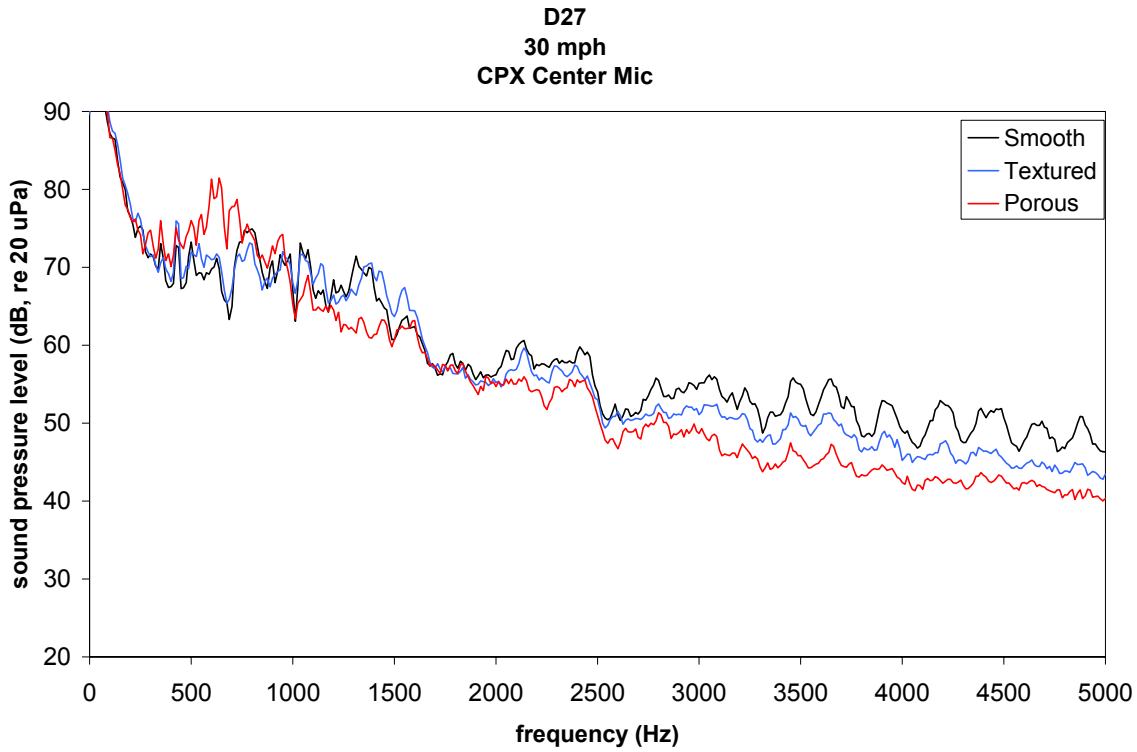
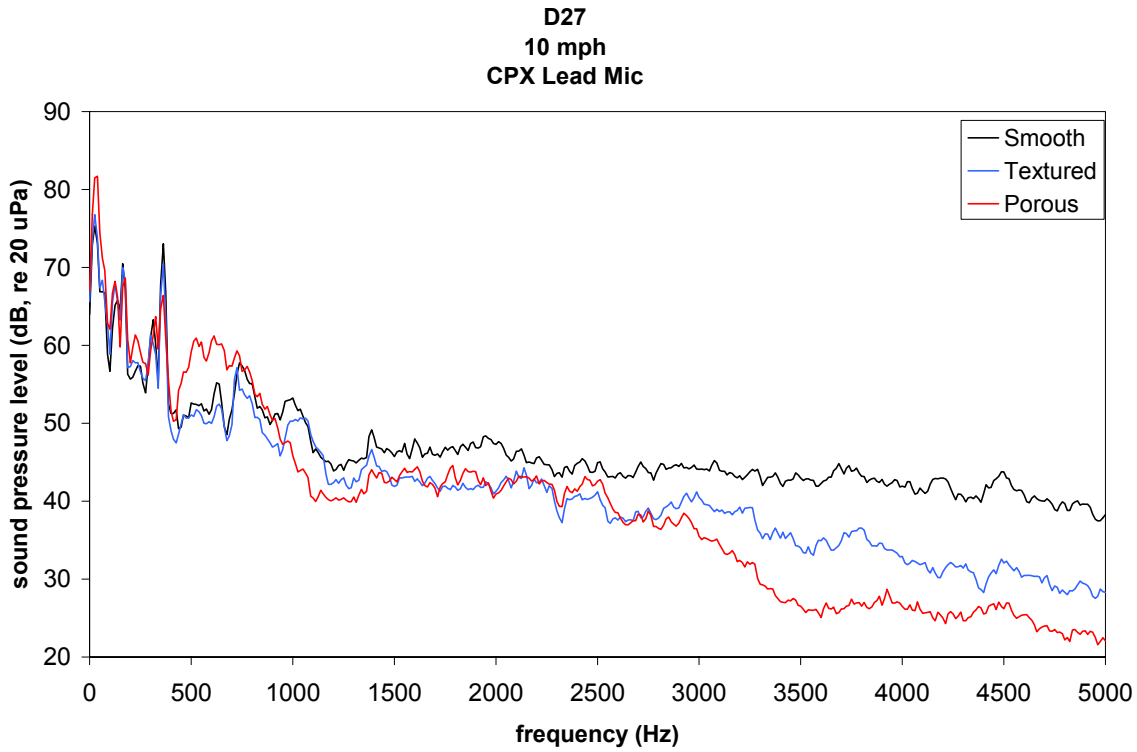
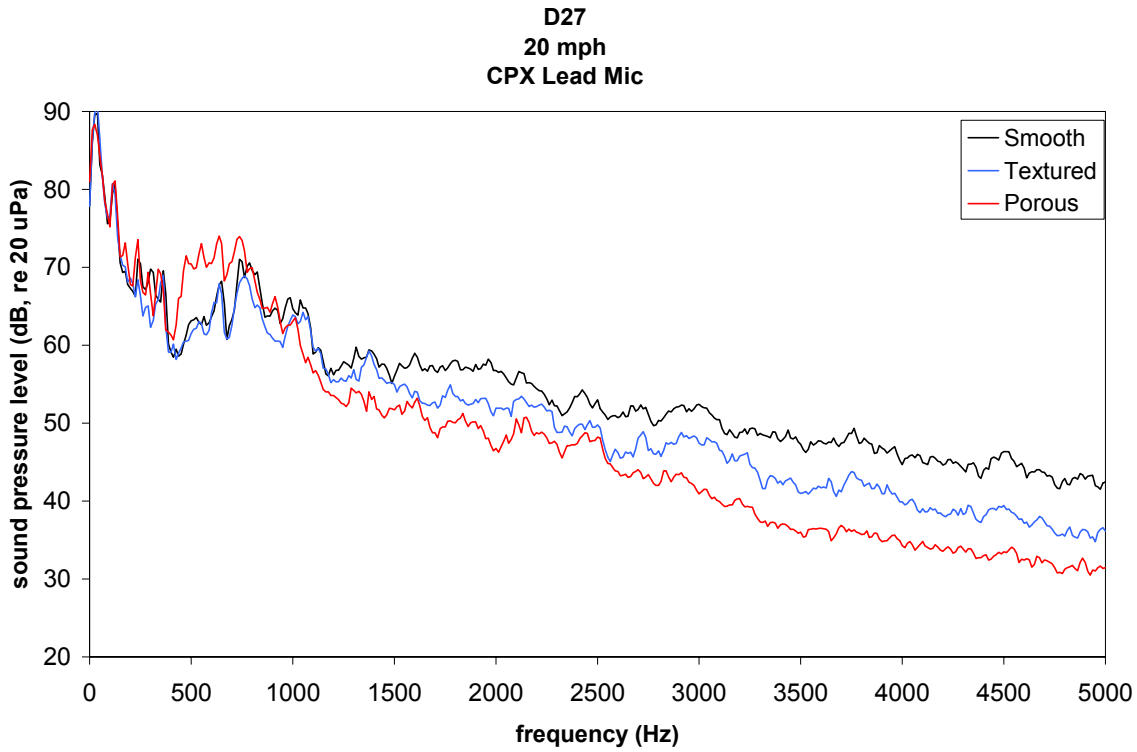
Appendix H: Narrow band spectra for tire D27; multiple surface textures at one speed and microphone location.


D27
10 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


D27
20 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


D27
30 mph
CPX Center Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


D27
10 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


D27
20 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
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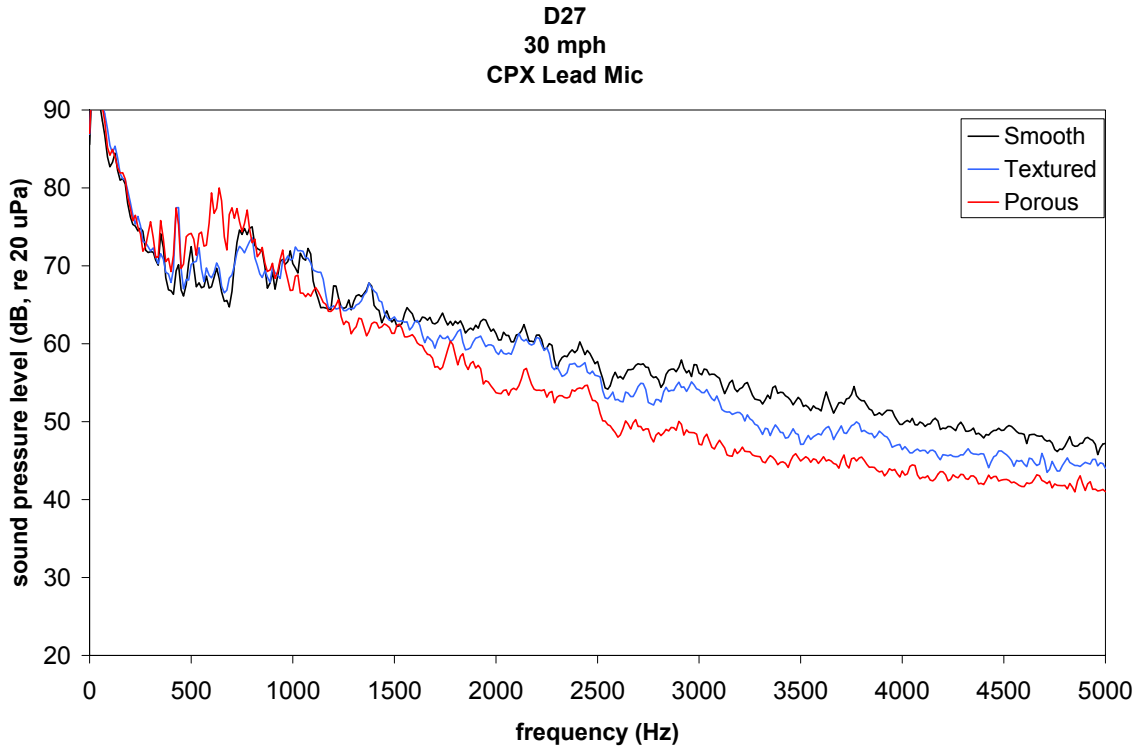
5000


D27
30 mph
CPX Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
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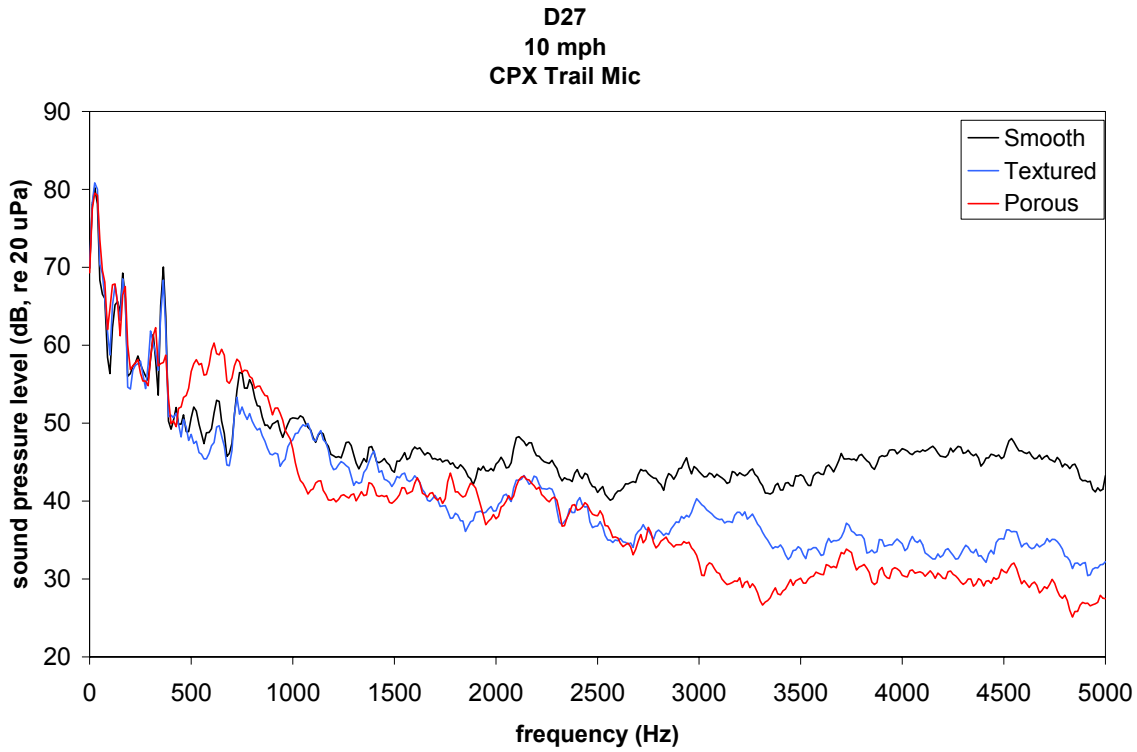
5000


D27
10 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
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20
0
500
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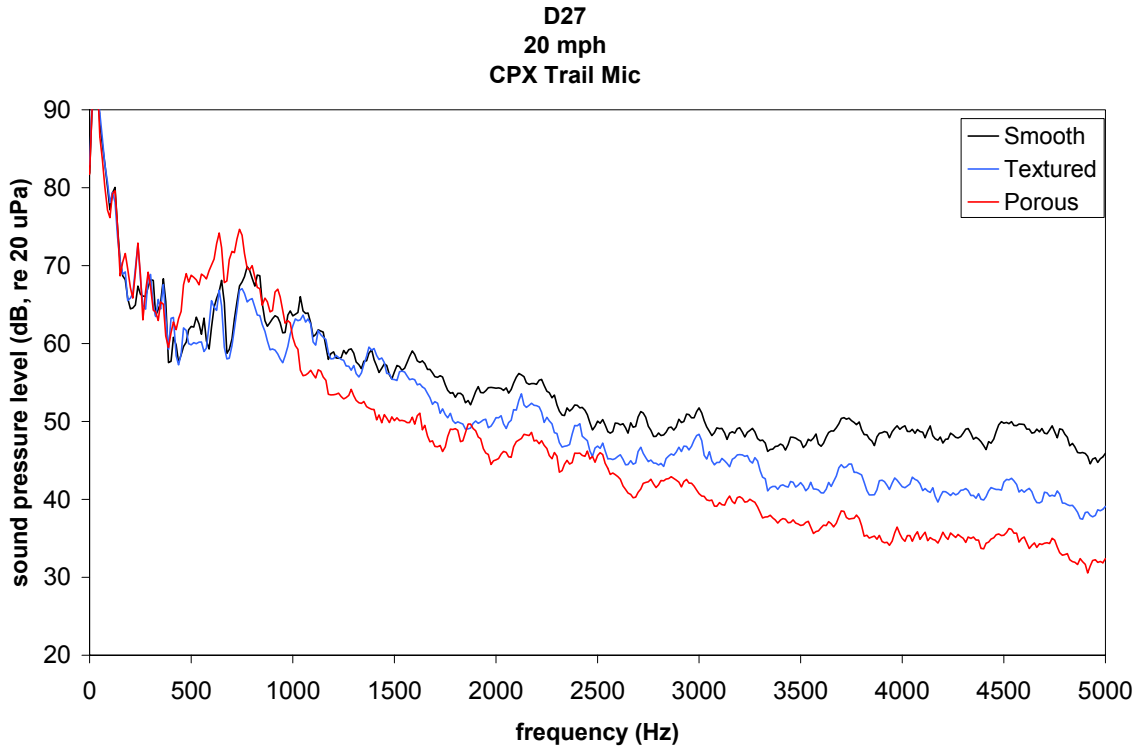
4500
5000


D27
20 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
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0
500
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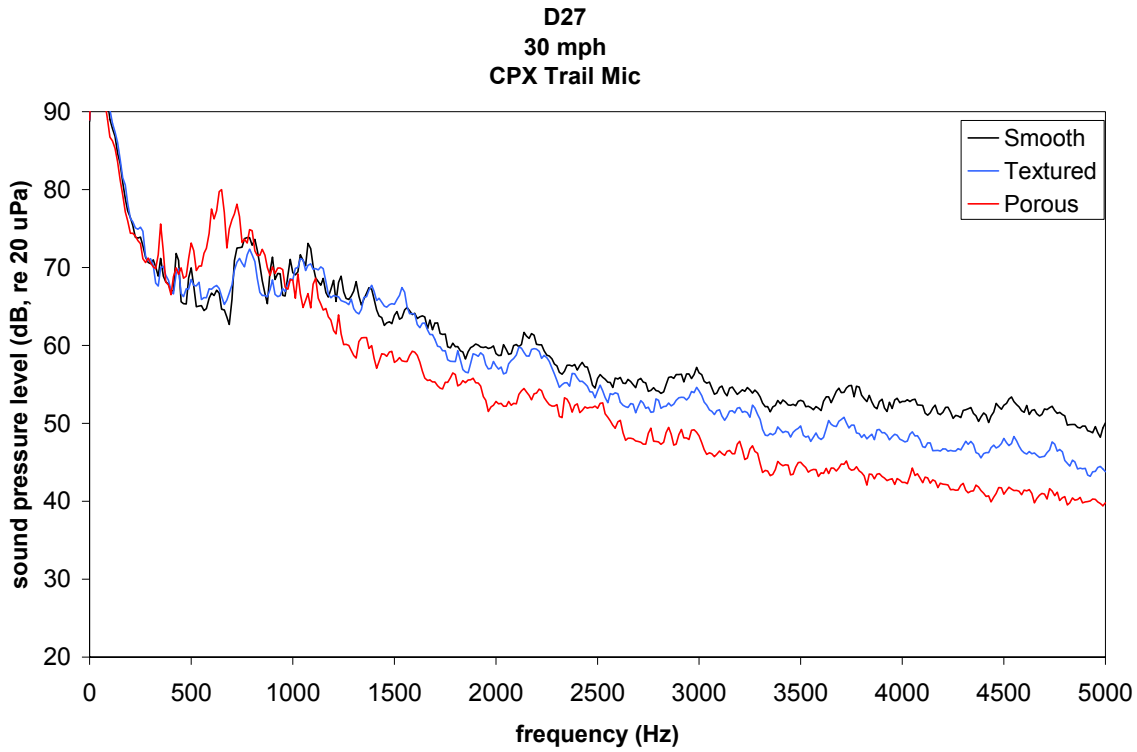
4500
5000


D27
30 mph
CPX Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
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4500
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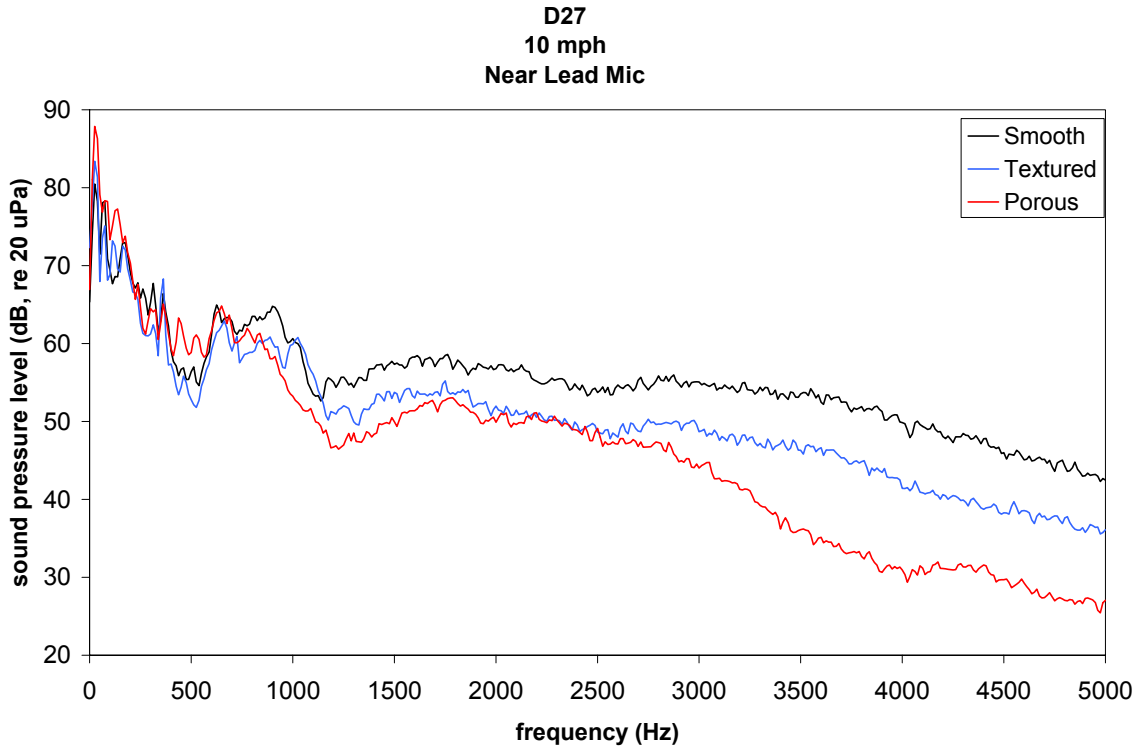
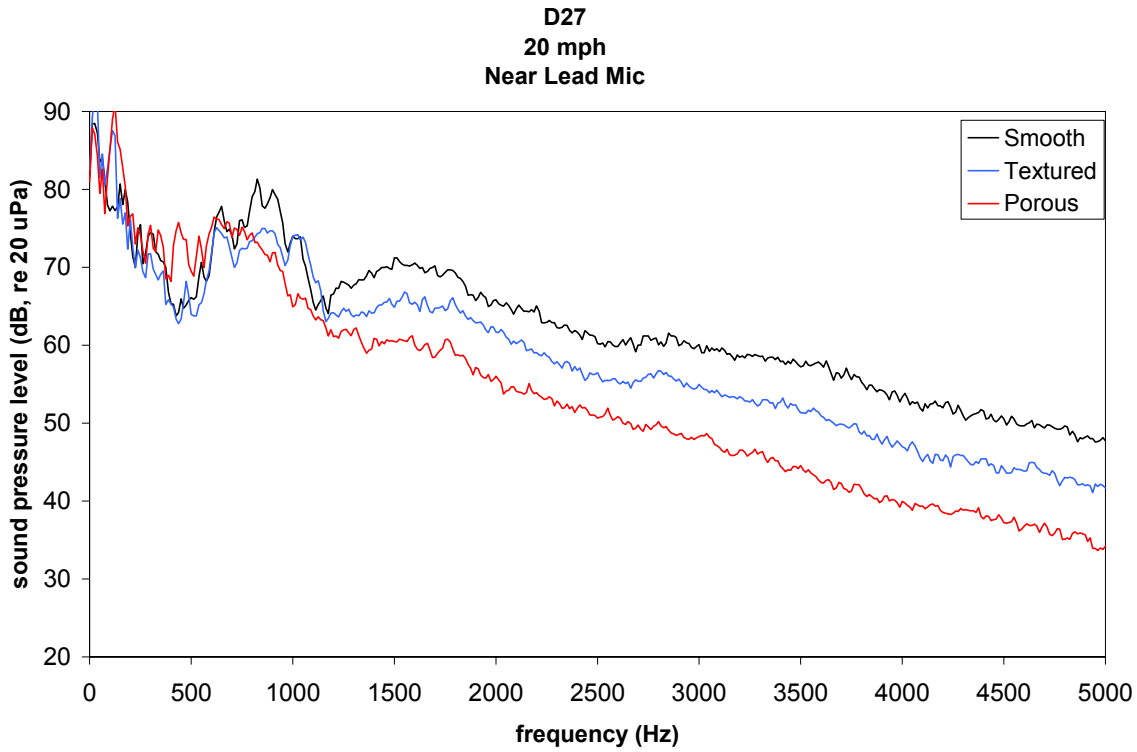
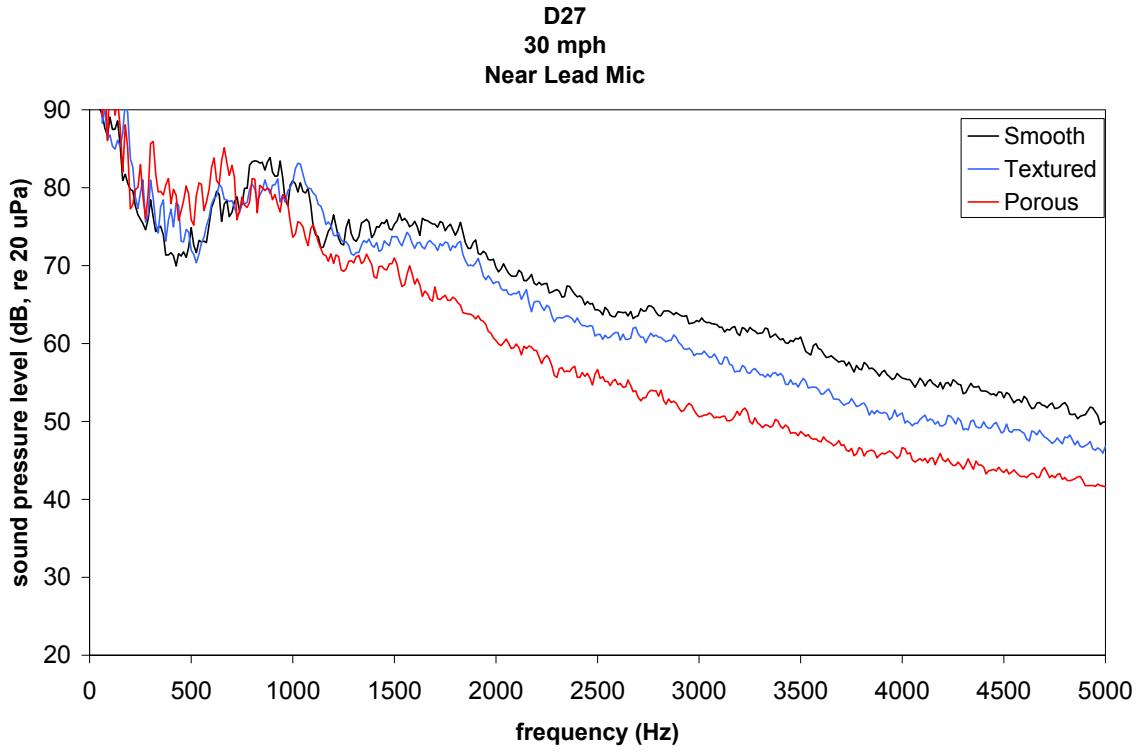

D27
10 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


D27
20 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


D27
30 mph
Near Lead Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
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2000
2500
3000
3500
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4500
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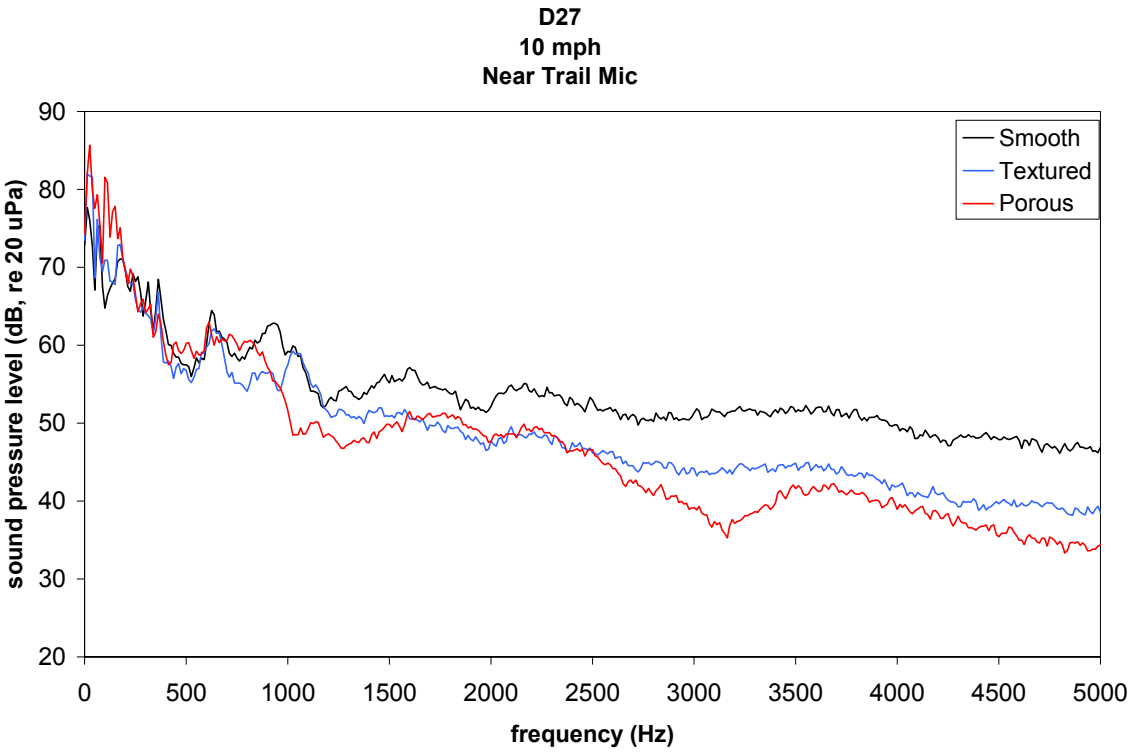
D27
10 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
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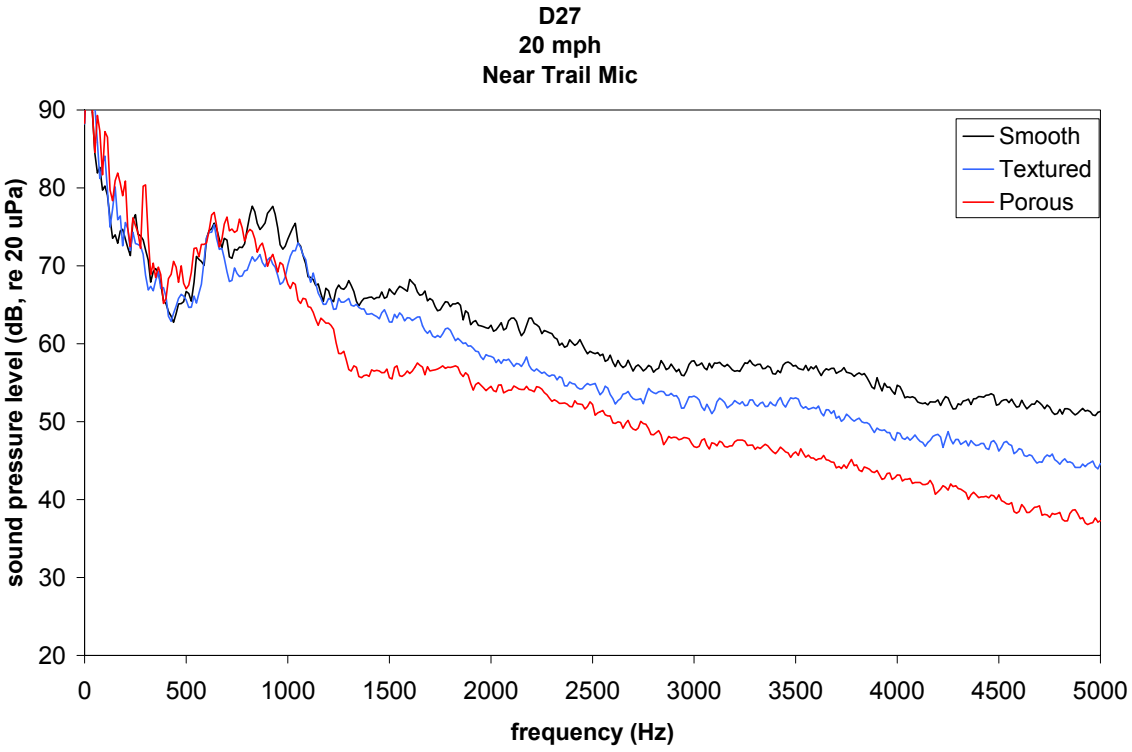
4500
5000


D27
20 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
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2000
2500
3000
3500
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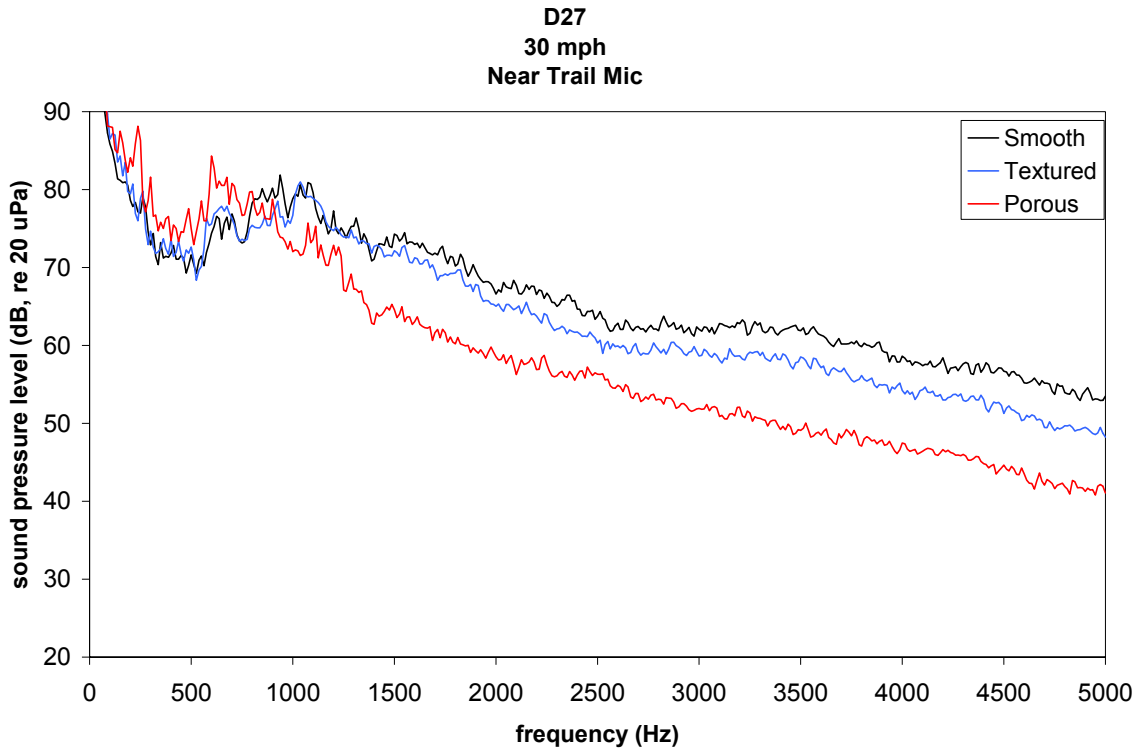
4500
5000


D27
30 mph
Near Trail Mic
sound pressure level (dB, re 20 uPa)
frequency (Hz)
Smooth
Textured
Porous
90
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000