Further Development of the Sound Intensity Method of Measuring Tire Noise Performance of In-Situ Pavements

Prepared for

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SUMMARY

Through analysis of earlier research and some recent on-road testing it is demonstrated that, with adequate precaution, accurate measurement of tire/pavement noise using on-board sound intensity (SI) can be accomplished with two intensity probes oriented vertically. As in the single probe method, SI is measured in the airflow alongside of a vehicle at locations opposite the leading and trailing edges of the tire contact patch. With the two-probe configuration, these data can be obtained simultaneously, reducing the number of test runs by a factor of two. It has also been found that with a slight risk of more wind induced noise contamination, the use of nose cones for the single probe configuration can be eliminated as long as a windscreen is used to protect the microphones. The use of a single microphone in exposed flow to measure tire/pavement noise sound pressure level (SPL) is not recommended even when fitted with a windscreen or nose cone. Although overall tire noise SPL measured in flow may show little effect of wind noise contamination when very little or no turbulence is present, individual 1/3 octave band levels are very likely effected, particularly when only a windscreen is used. When turbulence is present due such things as the ambient wind conditions, the wake of the vehicle, etc., the background noise due to wind noise contamination increases dramatically. The presence and magnitude of this contamination is difficult to determine and could vary from one test to another.

BACKGROUND

Since the first applications of the on-board sound intensity method to quantifying the tire/pavement noise performance of in-use highways[1], the measurement approach has remained virtually unchanged until now. The method originally followed that developed at General Motors for research purposes in the early 1980's[2]. The method was adapted and further applied for vehicle development purposes at the GM Proving Grounds[3]. The original SI method used two closely spaced ½-inch microphones mounted in a side-by-side configuration with the microphones fitted with nose cones pointed in the forward direction of vehicle travel (Figure 1). Over time with GM usage, this approach evolved somewhat as a windscreen was added to help further reduce wind-induced noise on the microphones and fixtures were improved to allow testing on different vehicles with little adaptation (Figure 2)[4]. The version of the SI probe fixture currently in use for the California Department of Transportation (Caltrans) tire/pavement noise studies is shown in Figure 3.

Figure 1: Configuration for first application of SI to tire/pavement noise measurement as used for truck tire noise source identification at General Motors Research (Ref. 2)

In the past few years, several issues have arisen that have motivated further investigation. These came both from applications of the Close Proximity (CPX) method as define in ISO Draft Standard 11819-2[5] and from users of the SI method. In most applications of the CPX method, a trailer or special vehicle is used to shield the microphones used to measure sound pressure levels from airflow and extraneous noise.

Figure 2: Configuration for SI application to tire/pavement noise measurement on passenger cars for use in quantifying tire noise source levels at the General Motors Proving Ground (Ref. 3)

Figure 3: Configuration for SI application to tire/pavement noise measurement for purposes of quantifying highway pavement performance as employed on Caltrans projects starting in 2002

However, some researchers have employed windscreen-protected microphones exposed to airflow along side of a tire mounted on normal light vehicle without further special provision. If this approach were viable, the expense and maintenance of a special trailer or vehicle would be negated and the use of the CPX approach would be more attractive. For SI, there has been some motivation to simplify the instrumentation and to measure SI simultaneously at the leading and trailing of the edges of the contract patch. To address some of these issues, additional investigation of the performance microphone windscreens and nose cones has been conducted both experimentally and through the previous literature. To investigate a two-probe approach in a non-enclosed trailer application, testing was performed recently using a prototype fixture design.

INTRODUCTION

The sound intensity method was first applied to tire/pavement noise for two reasons. First, because of its directivity, it was ideally suited for identifying source regions of tires under actual operation, and particularly for producing contours of equal sound intensity[6]. Second, it was found that signal processing done in the sound intensity calculation rejected flow noise on the microphones relative to a normal sound pressure by 10 to 15 dB[7]. Also, unlike sound pressure measurements, sound intensity can be used in the nearfield of an acoustical source to determine the acoustic energy propagating away from the source. SI measurements can also provide other metrics, ratio of SI to SPL, direction, and coherence between microphones which can be used to examine the validity of the data. In contrast, SPL measurement provides none of this information when used in airflows and will measure the reactive sound field (non-propagating energy) in the nearfield of a source. The extent of the nearfield is not well defined, however it is generally taken to occur at distances closer than an acoustic wavelength (λ) to the source and/or when the dimension of the source is greater than λ[8]. Applying these criteria, the nearfield for tire noise is expected to begin at about 12 inches from the source at 1000 Hz (λ ~ 1 ft). For lower frequencies, this distance would be even greater.

For measuring on-board tire/pavement noise, particularly on-board a vehicle and in a highway environment, SI is particularly well suited. As sound intensity is a vector quantity, it is directive and rejects noises that are not on its sensitivity axis. As a result, other noise sources on the vehicle and surrounding traffic will be attenuated. Because it can be employed close to the tire, the signal-to-noise ratio can be greatly improved relative a sound pressure level measurement. Further, because of SI directivity and short distance to the tire source region, the effects of any reflections from the vehicle body are minimized relative an SPL measurement. For SPL measurements, it is also very difficult to separate out self induced flow noise on a single microphone from other noises even in controlled environments such as in low background noise, aeroacoustic wind tunnels. Around vehicles, this is even further complicated by turbulence generated by the test and other vehicles, and ambient wind conditions.

The work reported in this document comes from three different activities. First, the laboratory performance of microphone windscreens is evaluated in the context of on-board tire/pavement noise measurement for both SPL and SI methods. Second, SI measurements with and without nose cones (with a windscreen in both cases) were made in June of 2005 on the of test sections of California State Route (SR) 58 on the Mojave Bypass. Third, SI measurements were made using the normal single probe method and a prototype two-probe approach for the same tire and pavements. The two-probe approach was originally conceived by the author in collaboration with Larry Scofield of the American Concrete Pavement Association (formally of the Arizona Department of Transportation, ADOT) and implemented with a modified fixture developed by Mr. Scofield. This concept was originally employed on the ADOT CPX trailer (Figure 4), but the approach was extended to exposed flow alongside of an actual vehicle (Figure 5) as tested in the Phoenix area in November 2005.

Figure 4: First application of a 2 probe SI method for measuring tire/pavement noise on CPX trailer as developed for ADOT use (July 2003)

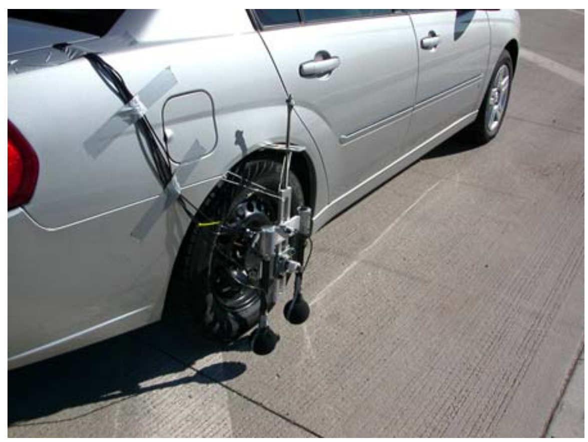

Figure 5: Application of a 2 probe SI method for measuring tire/pavement noise in exposed flow mounted on a test vehicle as used in joint ACPA/Caltrans testing (November 2005)

MICROPHONE WINDSCREEN & NOSE CONE PERFORMANCE IN RELATION TO TIRE/PAVEMENT NOISE MEASUREMENT

The performance of wind noise reduction devices, such as nose cones and windscreens, are not well documented in the literature. Two references, one for each type of device, were identified and used for the analysis in this section.

Windscreen Performance

The performances of 10 commercial and experimental windscreens were evaluated in laboratory conditions for airflow speeds from 2 to 14 m/sec (31 mph) in 2 m/sec increments[9]. Wind induced noise was measured for normal and grazing flow on the microphone diaphragm for flow conditions virtually free of turbulence. Data from this testing is reported in 1/3 octave bands from 12.5 to 12500 Hz and in overall linear and A-weighted level for each windscreen and flow orientation. Three of the windscreens included in the study were commercially available, 9.5cm diameter spherical foam windscreens. These windscreens were obtained from a well-known supplier of acoustical instrumentation and spanned the production limits of porosity allowed by the company. The overall A-weighted levels for these three windscreens are presented in Figure 6a and 6b. It should be noted that relationship is virtually identical for grazing and normal flow orientation. To extend these results to higher wind speeds such as would be

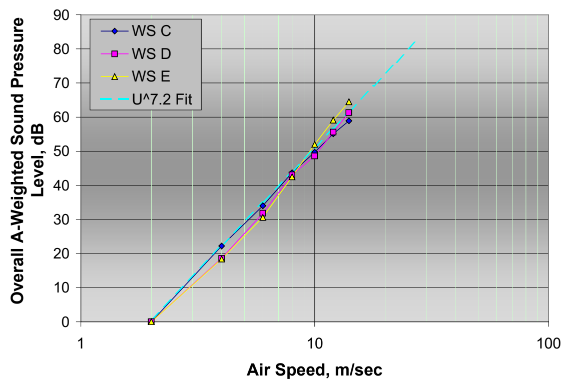

Figure 6a: Microphone windscreen performance for normally incident flow spanning range of production variation for commercially available windscreens

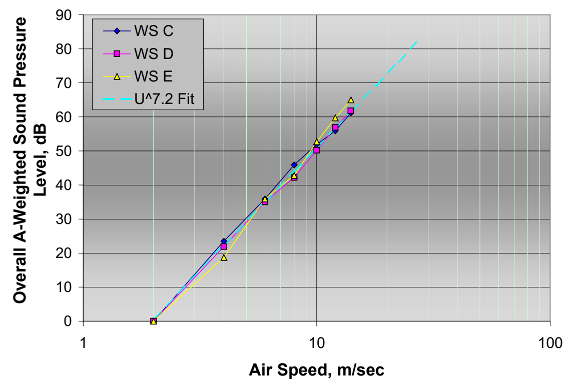

Figure 6b: Microphone windscreen performance for grazing incident flow spanning range of production variation for commercially available windscreens

encountered for on-board tire/pavement noise measurements, the data were approximated using a logarithmic relationship. Aeroacoustic noise generation is typically characterized by an exponential relationship with air speed. For dipole sources[i], the sound pressure would be proportional to V^6 where V is the air speed. For quadrupole sources[ii], the sound pressure would be proportional to V^8. For the data of Figure 6, the sound pressure of wind induced noise produced with the windscreens is well approximated by a $V^{7.2}$ relationship that falls in between the two types of source mechanisms. Using this relationship, the levels can be projected to higher speeds with some confidence as shown in Figure 6. At 60 mph, the overall level is projected to be about 82 dBA in the absence of in-flow turbulence. For comparison, the lowest CPX tire/pavement noise level reported from testing by the National Center for Asphalt Technology is 91.5 dBA at a test speed of 60 mph[10]. For SI, the lowest level in the Caltrans database is 94.6[11]. A typical criteria for the acceptable difference between signal and background noise is 10 dB which assures an error of less than ½ dB. On the surface, this implies that accurate tire noise measurements in exposed flow alongside of a vehicle is feasible using

[i] Dipole sources are due fluctuating forces arising from flow interaction with solid structures such as the fluctuating forces or "Aeolian" tones generated by flow past a cylinder
[ii] Quadrupole sources are due to fluctuating sheer stresses in the fluid such as those occurring in jet noise

commercial windscreens. However, as the authors of Reference 7 note, the laboratory results will under predict actual wind induced noise levels in situations where turbulence intensity is greater than zero[8], such as in the outdoor environment, in the presence of ambient wind, or in the flow field around a moving vehicle.

The difficulty with tire noise SPL measurements in exposed flow can also be seen when the 1/3 octave band levels are considered. For this purpose, it was found that for 1/3 octave band level from at least 200 to 5000 Hz, the increase in wind induced noise follows the same $V^{7.2}$ relationship defined by the overall A-weighted level. As a result, the wind induced 1/3 octave band levels can be projected to 60 mph. These results are plotted in Figure 7 along with the CPX (enclosed trailer) and SI results from testing one of the quieter Asphalt Rubber Friction Course (ARFC) sections in the Phoenix, AZ area[12]. From these comparisons, it is seen that the wind-induced noise (without turbulence) is well below the tire noise in the 400 to 1600 Hz 1/3 octave bands. However, starting at 2000 Hz, the background noise is within 10 dB of the tire noise and increases until it is greater than the tire noise. For these frequencies and flow with even low levels of turbulence, the tire noise data from sound pressure measurements would be contaminated in varying degrees by flow induced background noise. On a more positive note, these results also suggest that for a good portion of the tire noise frequencies, exposed microphones (with low levels of inflow turbulence) may measure tire noise similar to that of trailer protected microphones. However, the fidelity of these measurements will likely depend on source levels, both tire and pavement, ambient wind conditions, and vehicle wake effects assuming no appreciable noise generation by the microphone support system. Also, contamination by wind effects will not be obvious from the sound pressure data alone.

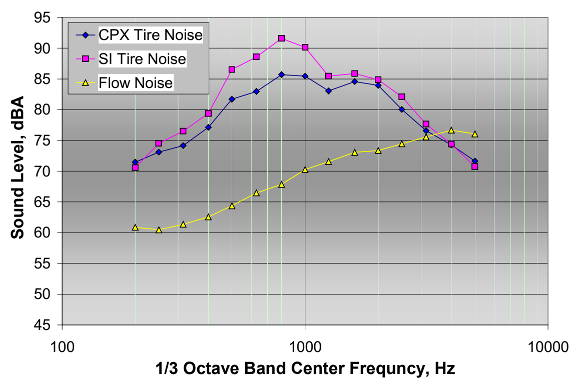

Figure 7: Wind flow induced noise (SPL) for microphone windscreen (#E) for grazing flow at 60 mph compared to CPX and SI tire noise for a quieter AZ ARFC pavement

For SI measurements made in flows of varying levels of turbulence, it has been found that the sound intensity of a source can be measured accurately even if the SPL of flow induced background noise measured by the microphones ***exceeds*** the source level to be measured by as much as 5 dB[13]. Stated differently, it was demonstrated that the flow induced background noise in a sound intensity measurement is 15 dB lower than the flow induced background noise in a SPL measurement exposed to the same flow conditions. As a result, 15 dB can be subtracted for the flow induced SPL background noise levels in Figure 7 to produce an equivalent flow induced background noise level for a SI measurement in the same flow. This flow induced background noise on the SI measurement is shown in Figure 8 in comparison to quieter tire/pavement noise levels and the SPL background level. From this figure, it is seen that the wind induced SI background is more than 10 dB below the tire/pavement SI for the entire range from 200 to 4000 Hz in conditions of low turbulence. At 5000 Hz, where the flow induced SPL background exceeds the source level by more than 5 dB, there is a possibility of contamination in the tire noise SI measurement on the order of ½ dB.

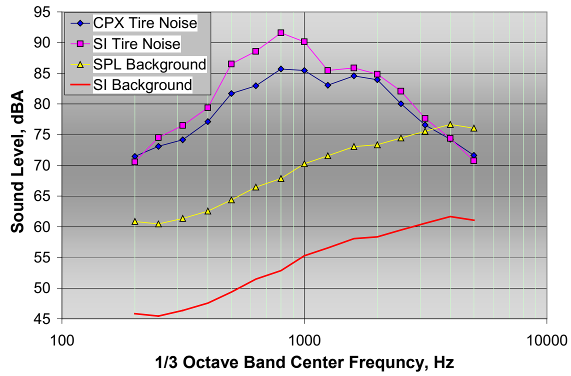

Figure 8: Comparison of flow induced background noise in SI and SPL measurements relative to tire noise and wind flow induced at 60 mph for windscreen protected microphones

The work of Reference 8 leads to several very useful criteria for assessing flow induced noise contamination in SI tire noise measurements. As discussed above, when the flow induced SPL exceeds the source sound intensity level by more than 5 dB, wind noise contamination is present. For tire noise measurements, the source levels are not known apriori, but the difference between measured SPL and SI level can be examined. If the SPL is 5 dB or higher in level, then the measured SI does not accurately measure the tire noise source level. This becomes a very practical criterion for evaluating the validity of tire/pavement noise SI measurements and presence of wind induced noise contamination. It was also shown in this study that rapid variations of SI direction with frequency in narrow band data indicated the presence of wind induced noise contamination. A further indicator of background noise contamination from wind-induced noise is the coherence between the two microphones comprising the SI probe[14]. This criterion requires that the coherence be greater than 0.5 for valid measurement.

Nose Cone Performance

Historically, microphone nose cones have been used in the measurement of noise in the presence of mean flow for higher wind speeds of a known direction[15]. As a result, in the initial development of the SI method, nose cones were used to reduce wind-induced noise on the SI measurement microphones used for the measurement of tire/pavement noise for speeds in the range of 30 to 70 mph. The effectiveness of different sizes of nose cones/microphones in the presence of flow has also been investigated in low noise wind tunnels. In one study, the self noise and turbulence factors were investigated for 1", ½, and ¼ inch microphones with varying levels of turbulence[16]. For a ½" nose cone and a turbulence level of 0.5%, the overall A-weighted sound pressure level of wind induced noise at 60 mph was 71.4 dB in comparison to the 82 dB cited above for a windscreen protected microphone in the absence of turbulence. The 1/3 octave band spectra for this case is compared to the windscreen case and tire noise examples in Figure 9. For sound intensity measurements, the flow induced would be a further 15 dB lower than the sound pressure levels with the nose cone only (Figure 10). As a result, SI measurements of tire noise should contain virtually no contamination by flow induced noise for low levels of turbulence. At a higher level of turbulence, 3%, it

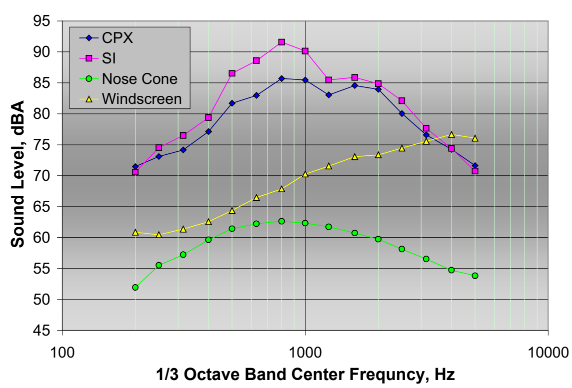

Figure 9: Comparison of flow induced noise (SPL) for a nose cone and a windscreen protected microphone relative to CPX & SI tire noise

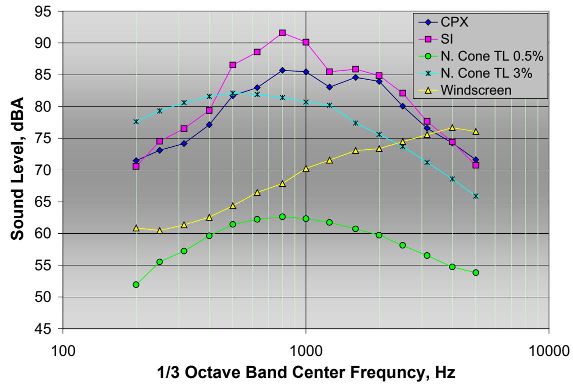

Figure 10: Increase in flow induced noise (SPL) with increase in turbulence level from 0.5% to 3% for a nose cone compared to windscreen performance and tire noise

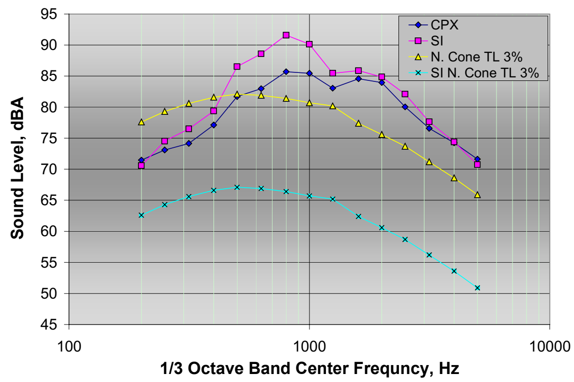

Figure 11: Comparison of the flow induced background noise for SPL and IL using nose cones with a 3% turbulence level relative CPX & SI tire/pavement noise

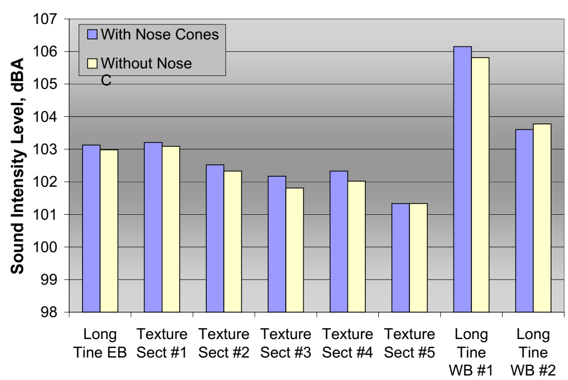

Figure 12: Comparison of overall SI levels with and without nose cones for a windscreen protected probe measured on PCC pavements on the Mojave Bypass

was found that flow induced noise increased considerably[15]. For this case, the equivalent A-weighted overall level was found to be 87.7 dB, a 16.3 dB increase over the 0.5% case. For SI measurements at 3% turbulence, the overall flow induced background level is expected to be about 73 dBA and the 1/3 octave band SI levels will be 10 dB below the tire noise source levels for frequencies of about 400 Hz and above (Figure 11). For windscreen protected sound pressure level measurements in exposed flow, the effects of turbulence are expected to be similar to that of the nose cone case and the flow induced will be greater than that indicated in Figure 7 for the no turbulence case.

From this discussion, it is apparent the best configuration for minimum flow induced noise effects in tire/pavement noise measurements is to use SI with nose cones aligned with the flow (direction of vehicle travel) and protected by a windscreen. However, this may be "overkill" based on the results of Figure 8. As a first step toward simplifying the SI measurements, tests were conducted using the method illustrated in Figure 3 except with the use of conventional spherical windscreen. In these tests, measurements were made with and without nose cones installed on the microphones using the windscreen in both cases. These tests were conducted on PCC experimental texture sections located on the Mojave Bypass of state route 58 in California[17]. Comparison of the overall A-weighted sound intensity levels with and without nose cones is given in Figure 12. These data indicate the overall levels were virtually identical whether the nose cones were used or not. The 1/3 octave band levels for one of the quieter sections are presented in Figure 13 also indicating virtually identical results at 500 Hz and above. In comparing the difference between sound intensity level and sound pressure level, some differences between the with and without nose cone cases are seen (Figure 14). With the nose cones, the SI levels are typically slightly higher (less than ½ dB), throughout the range from 500 to 5000 Hz.

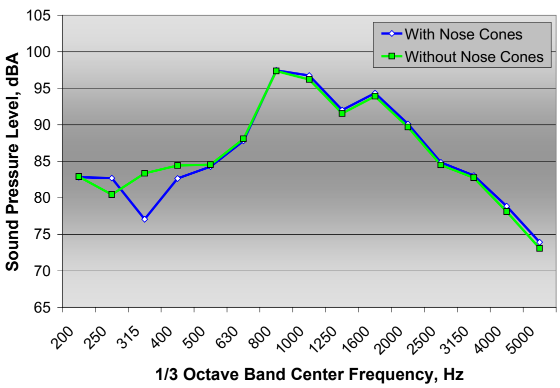

Figure 13: Comparison of 1/3 octave band SI levels with and without nose cones for a windscreen protected probe measured on PCC pavements on the Mojave Bypass

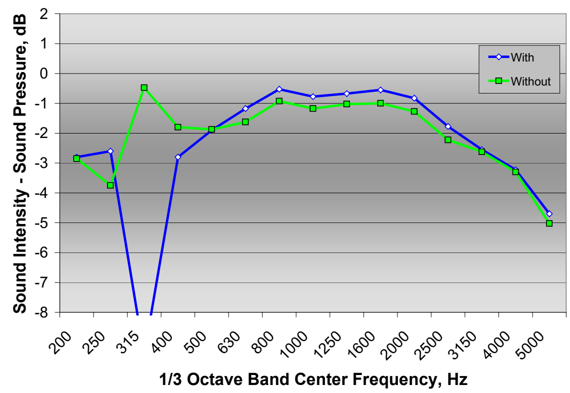

Figure 14: Comparison of 1/3 octave band differences bewteen SI and SPL levels with and without nose cones for a windscreen protected probe measured on PCC pavements on the Mojave Bypass

This is consistent with a very small increase in flow induced sound pressure on the microphones when only the windscreen is used. However, for both cases, the SI-SPL difference is well above the –5 dB criteria discussed above for wind noise contamination. Below 500 Hz, the results are more ambiguous. In this one example, there is a "dropout" in the nose cone case at 350 Hz. However, in the data for other sections, both cases can have similar dropouts, or peaks beyond zero. Generally, the results for both cases become erratic below 400 Hz and there appears to be no clear indication that with nose cones or without cones has any clear advantage. Overall, particularly for the range from 500 to 5000 Hz, these data suggest that it maybe safer to use nose cones in combination with a windscreen, however, with due attention to the SI-SPL metric, nose cones are not essential.

TWO PROBE SI MEASUREMENT SYSTEM

Initial Application – ADOT CPX Trailer

Through a cooperative work effort between Caltrans and ADOT, the SI method as developed for Caltrans applications was first used on a CPX trailer on May 21, 2002 (Figure 15). Tests were conducted with both methods to evaluate pavement test sections and to examine the relationship between ARFC pavement age and noise performance[18]. In these tests, CPX data was collected for the right side of the trailer while SI data was collected for the left side. For more direct comparison between the methods, additional testing was conducted on September 19, 2002, in which CPX and SI measurements were made separately and together on the same tire for three different pavements. From this limited testing, it was found that average overall A-weighted level difference was about 3.4 dB

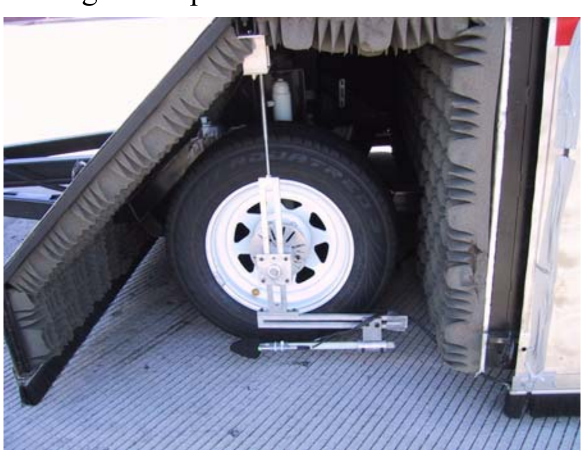

Figure 15: Single probe SI fixture as installed on the ADOT CPX trailer for joint ADOT/Caltrans pavement noise studies (May 2002)

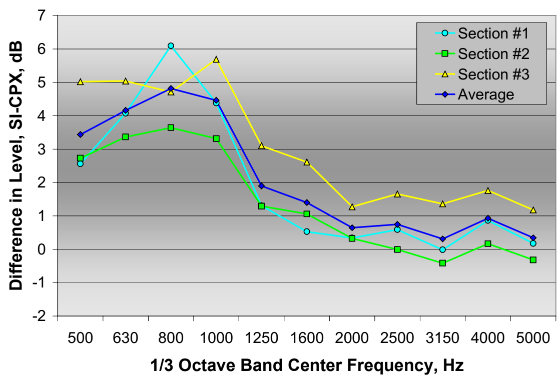

Figure 16: Difference in 1/3octave band levels between SI and CPX measurements made with the ADOT CPX trailer on 3 AC pavements for the same test tire

with the individual and average spectral differences between the two types of measurements shown in Figure 16. Also from these tests, no effects of the presence of the SI fixture on the simultaneous CPX measurements were found.

After this testing, ADOT became interested in adapting the sound intensity technique to on going pavement measurements in light of Arizona's Quiet Pavement Program which had been proposed to the FHWA in December of 2002. A portion of this program required conducting on-board monitoring of pavement performance at each milepost in the 115 mile project area over a 10 year period. ADOT was interested in migrating the measurements toward sound intensity; however, a roadblock to this migration was the need for separate measurement of the leading and trailing edges of the tire contact patch that required two passes over the same pavement. Three possible configurations to capture SI data simultaneously at the leading and trailing edge were conceptualized in January of 2003 by the author and are illustrated in Figure 17. The initial application of a two probe fixture was to be

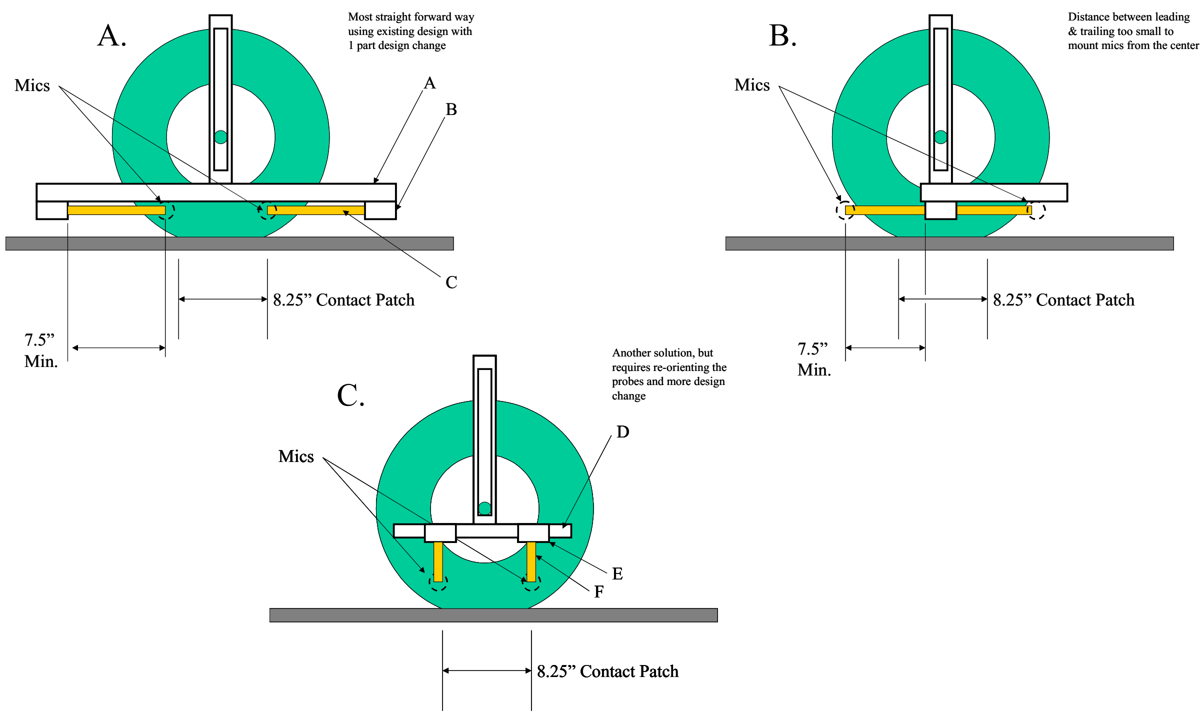

Figure 17: Alternative configurations conceptualized for a two probe tire/pavement noise SI measurement method

done using the ADOT CPX trailer. As such, there were no concerns of any flow induced noise effects due to either microphone self-noise or noise generated by flow over the fixture. After some consideration in collaboration with Mr. Scofield (then) of ADOT, it was decided to use a

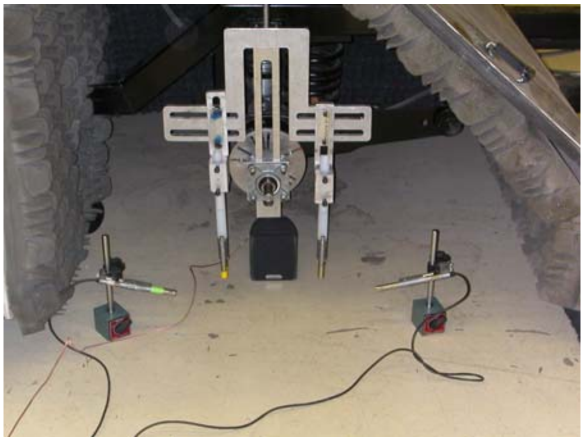

Figure 18: In-lab testing to detect reflections or other effects of CPX 2 probe SI fixture on sound pressure levels received at the CPX microphone locations using a loudspeaker source in July 2003 (measurements made with the ADOT trailer door closed)

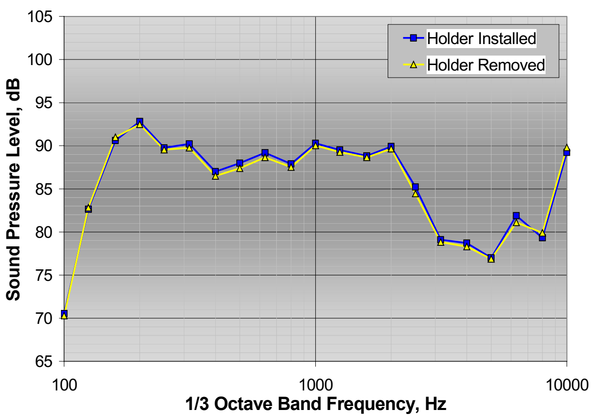

Figure 19: Comparison of CPX sound pressure levels measured with and without the two probe SI fixture installed on the CPX trailer in the lab for a loudspeaker noise source

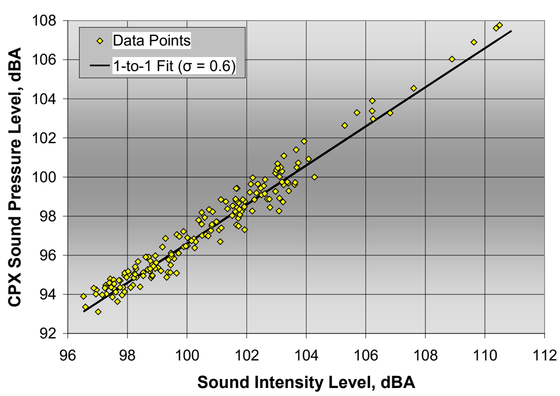

Figure 20: SI vs. CPX tire/pavement noise levels measured simultaneously on the ADOT CPX trailer using a two probe SI fixture

vertical orientation of two probes (Figure 17c) resulting in the fixture shown Figure 4. This approach moved most of the supporting structure away from the microphones to minimize reflections and obstructions for both the SI and CPX measurements. Mr. Scofield designed and had fabricated the hardware necessary to implement Figure 17c concept. Upon completion of a prototype fixture validation tests were performed beginning on July 22, 2003. The influence of the fixture on the CPX measurements was studied in a lab environment using a small loudspeaker noise source to represent the tire/pavement noise (Figure 18). These tests indicated that CPX levels with and without the fixture were nearly identical (Figure 19) with the levels with the fixture installed being on average 0.3 dB higher. Initial on-road tests were conducted on July 23, 2003 and as of March 17, 2005, 193 different sections of freeway in the greater Phoenix have been measured using both the 2 probe SI fixture and CPX microphones simultaneously. All of the data have been collected using the Goodyear Aquatred 3 test tire at a speed of 60 mph. The pavements included the ARFC recently installed in the Phoenix area, PCC pavements of several texture types, ARFC of different ages outside of Phoenix, and other experimental AC test surfaces. The overall levels for these tests correspond well to a one-to-one relationship (Figure 20) in which the SI levels are 3.4 dB higher than the CPX levels with a standard deviation of 0.6 dB. The difference in 1/3 octave band spectra follow a band of about 1 to as much as 2 dB wide from 315 to 5000 Hz (Figure 21). The difference in overall level between the SI and CPX measurements using the two probe fixture was found to be the same as that determined with the single probe method. Given the limited amount of data for the single probe tests, the average 1/3 octave band spectrum also compares well with that measured with the two probe fixture (Figure 22).

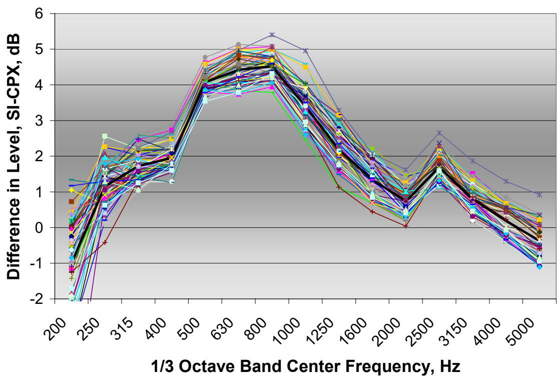

Figure 21: Difference in 1/3octave band levels between SI and CPX measurements made simultaneously on the ADOT CPX trailer using the two probe fixture on different pavements

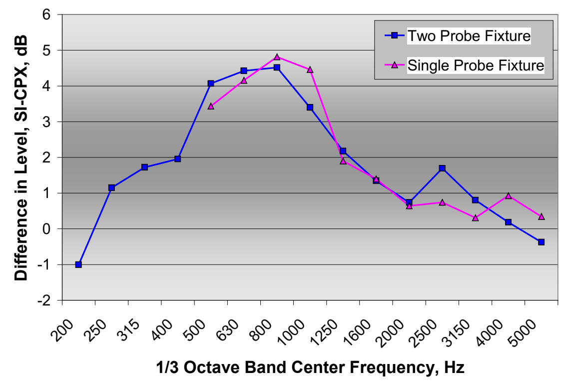

Figure 22: Comparison of averages of differences in 1/3octave band levels between SI and CPX measurements made with the ADOT CPX trailer using single and dual probe fixtures

Vehicle Application - ACPA/Caltrans Evaluation

In order to reduce test time, the American Concrete Pavement Association (ACPA) and Caltrans became interested in applying the two probe fixture concept to SI measurements on a vehicle with the probes exposed to airflow. From the testing conducted in Mojave, it was demonstrated that nose cones were not essential for reducing wind induced noise on the microphones as long as a windscreen is used and criteria for evidence of wind noise contamination are met. From the windscreen research[8], it was found that windscreens performed equally well for reducing noise with wind flowing normal to a microphone or grazing to it (Figure 6). As a result, it was concluded that a two probe approach similar to that used on the ADOT CPX trailer might also perform adequately on a test vehicle. Aside from flow-induced noise on the microphones, an additional issue is noise generated by the supporting fixture of the two probe method. However, almost of the supporting structure is located in a vertical plane which coincides with the least sensitive axis of the sound intensity probes and, hence, any noise generated by these components should be attenuated relative to the tire noise measurement.

After initial, successful demonstration testing performed by Mr. Scofield (now) of ACPA, joint ACPA and Caltrans sponsored testing was conducted on November 28, 2005 to compare sound intensity measurements made with the single probe fixture and the two probe fixture. The ACPA fixture was installed on a Chevrolet Malibu test vehicle for the two probe measurements (Figure 5). Measurements on the same vehicle and tire were also made using the single probe fixture typical of Caltrans SI testing (Figure 3). The test tire was a P205/R15 Goodyear Aquatred 3. Measurements were made on four different pavement surfaces located on SR202 at exit 55 in an area south of Phoenix. The pavements included one section of ARFC, one of longitudinally tined PCC, and two experimental sections of ground PCC. The test speed was 60 mph. The air temperature was between 56° and 60°F during the testing and the sky was clear with virtually no wind. With the single probe fixture, a total of six passes over all of the pavements were made, three for the leading edge of the tire contact position and three for the trailing edge. For the two probe fixture, three passes were made and data was collected using two Larson Davis 2-channel analyzers. The acoustic signals were also recorded on two DAT recorders for later, additional processing. For these tests, the SI probes were supplied by ADOT. A second set of measurements was made in which the leading edge was measured with the same probe used in the single probe measurements while the trailing edge were repeated using the ADOT probe.

Overall A-weighted sound intensity levels for the three sets of measurements are shown in Figure 23. The levels from all testing are within about ½ dB or less of each other and there is no consist trend apparent in the level comparison. The 1/3 octave band spectra for the three sets of measurements are shown in Figures 24 through 27 for each pavement section. The spectrum levels are typically within about 1 dB of each other in each frequency band with the exception of the second dual probe test on the ARFC. In this case, for 1000 Hz and below, the levels for the second dual probe test are consistently lower than either the first dual probe test or the single probe test. Above 1000 HZ, the levels from the second dual probe test are slightly higher than the other two.

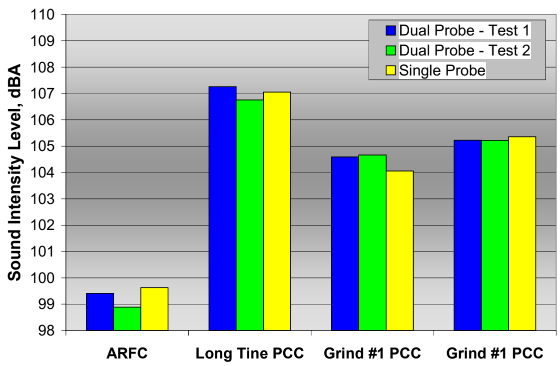

Figure 23: Comparison of overall A-weighted SI levels measured with single and dual probe fixtures on 4 pavements

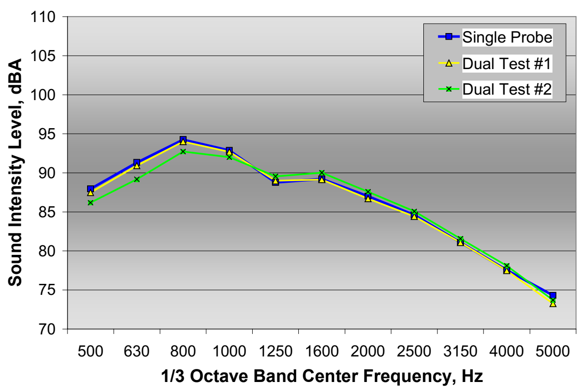

Figure 24: Comparison of 1/3 octave band SI levels measured with single and dual probe fixtures on ARFC

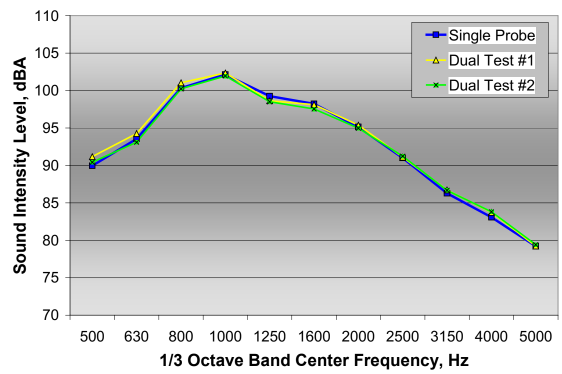

Figure 25: Comparison of 1/3 octave band SI levels measured with single and dual probe fixtures on longitudinally tined PCC

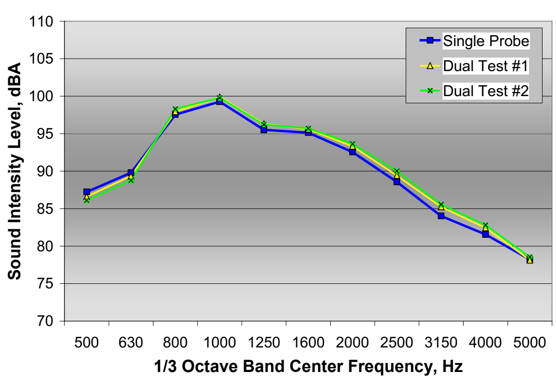

Figure 26: Comparison of 1/3 octave band SI levels measured with single and dual probe fixtures on Whisper grind PCC

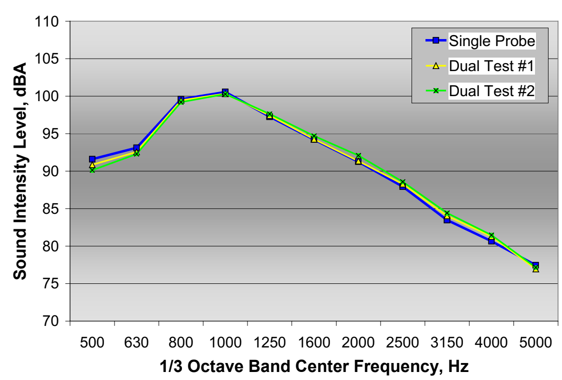

Figure 27: Comparison of 1/3 octave band SI levels measured with single and dual probe fixtures on Whisper grind PCC section #2

The reason for this variation is not know, however, the ARFC did produce more audible variation than the PCCP surfaces.

To examine any presence of wind induced noise contamination, the recorded DAT signals were analyzed in constant band width or “narrow-band” manner. This analysis included the sound intensity data, the difference between intensity level (IL) and SPL, and the coherence between microphone pairs comprising an intensity probe. This analysis was completed for both the single and dual probe configurations for all four pavements with the dual probe analysis corresponding to “Test 2” as referred in Figure 23. For the purposes of these comparisons, the data for the leading and trailing edges of the tire contact patch were considered separately in order to gain more insight into the quality of the data. In Figure 28, the data for the leading edge on Section #1 are presented for the three passes of the single probe. The corresponding data for the dual

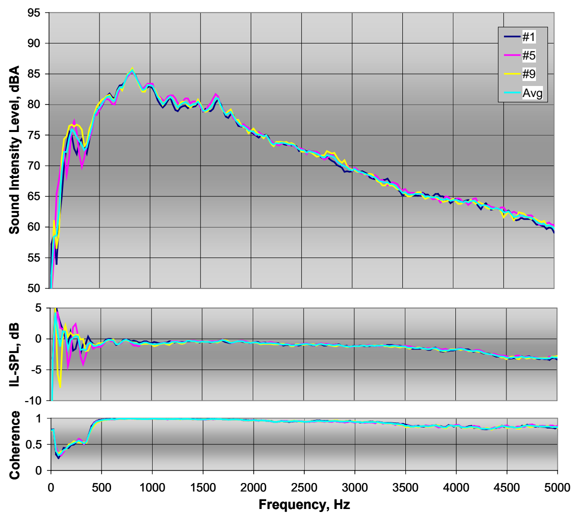

Figure 28: SI for multiple runs on ARFC for the leading edge of the tire contact patch using the single probe fixture

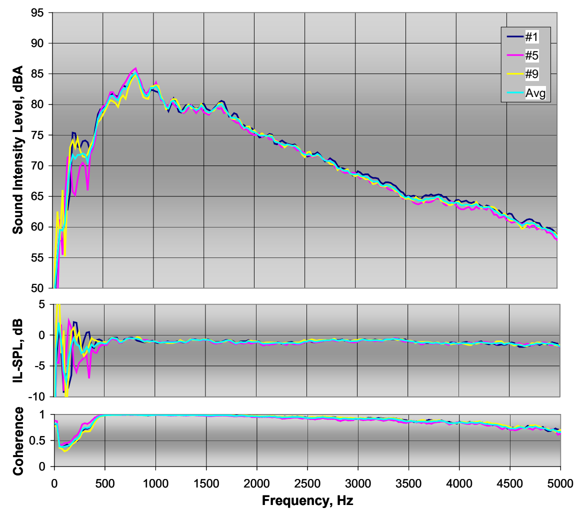

Figure 29: SI for multiple runs on ARFC for the leading edge of the tire contact patch using the dual probe fixture

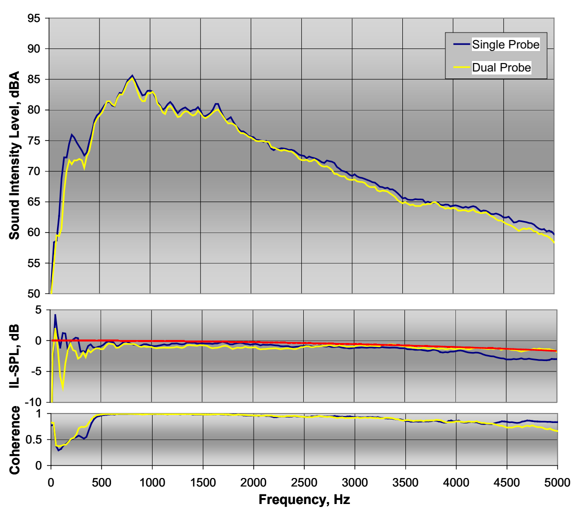

Figure 30: Comparison single and dual probe SI averages of multiple runs on ARFC for the leading edge of the tire contact patch

probe fixture are presented in Figure 29 and the average of runs for both the single and dual configurations are presented in Figure 30. For the individual runs (Figures 28 and 29), scatter in both the sound intensity level and difference between IL and SPL is apparent below about 400 Hz indicating the likelihood of wind induced noise effects. This is also supported by the occurrence of the IL-SPL level approaching –5 dB and going above 0 dB in these lower frequencies. For both probe configurations, the coherence also tends to drop below about 400 Hz, again indicating wind noise effects in this region. Above about 400 Hz, the IL-SPL levels are consistently above –5 dB and below 0 dB indicating that the sound intensity data is not contaminated by flow induced wind noise. The averages of passes for the single and dual probe configurations (Figure 30) lead to similar conclusions as the individual pass data. That is, the coherence begins to fall below 400 Hz and IL-SPL begins to vary more. Also, the SI levels for the two configurations begin to diverge below about 400 Hz bringing into question whether the peak in the single probe data at about 250 Hz is actual tire noise or wind noise effect. Also included in Figure 30 in the IL-SPL plot is the theoretical value of this indicator. As shown in red, at higher frequencies, this value becomes systematically lower due to the error introduced by finite difference approximation used in the sound intensity algorithm[19,20]. As noted in the discussion of Figure 14 for data with and without nose cones, without the cones, the IL-SPL values are slightly lower in the mid frequencies between 400 and 2500 Hz likely due slightly more wind induced SPL on the individual microphones. However, as discussed previously, this has no effect on the measured SI levels. At higher frequencies (above about 3000 Hz), the two probe configuration follows the theoretical finite difference line closely, while the single probe orientation drops down somewhat. According to the manufacturers' specifications, the nose cones will produce elevated SPL at higher frequencies beginning at 3000 to 4000 Hz[14]. As a result the IL-SPL drops while the SI level does not due to its rejection of background noises. Similar trends as noted here for the leading edge also occur for the trailing edge (Figures 31, 32, and 33). For the trailing edge, the wind induced noise effects at low frequency do appear to be somewhat more pronounced. However, starting at about 500 Hz, the data indicators imply that wind related criteria are satisfied and SI levels are essentially equal.

The observations noted in regard to Figures 28 through 33 for the low noise ARFC surface were also found to hold for all of the PCC test sections. An additional example of the average of three passes for the single and dual probe configurations for test section #4 are compared in Figure 34 for leading edge and Figure 35 for the trailing edge of the test tire.

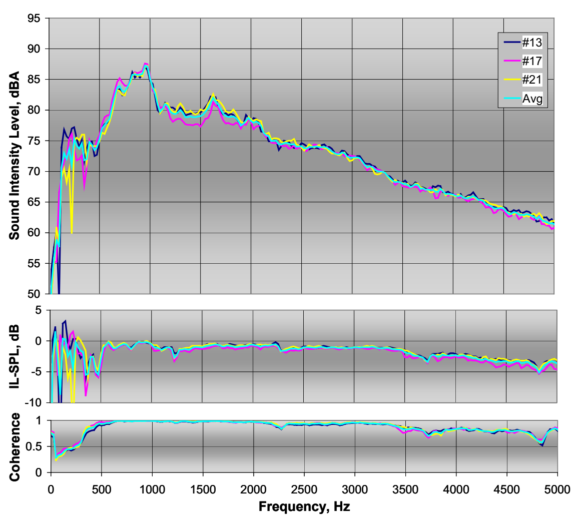

Figure 31: SI for multiple runs on ARFC for the trailing edge of the tire contact patch using the single probe fixture

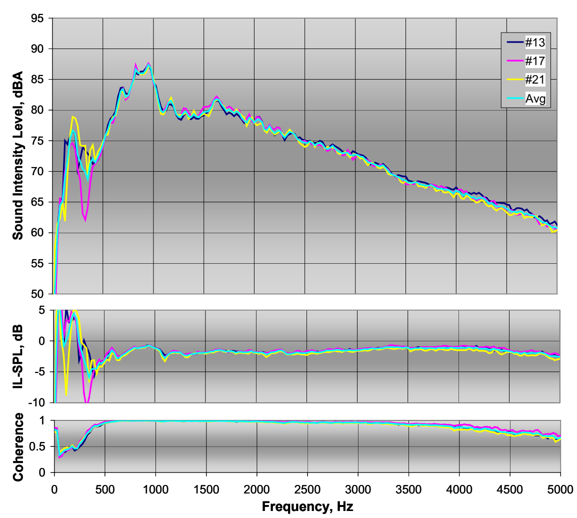

Figure 32: SI for multiple runs on ARFC for the trailing edge of the tire contact patch using the dual probe fixture

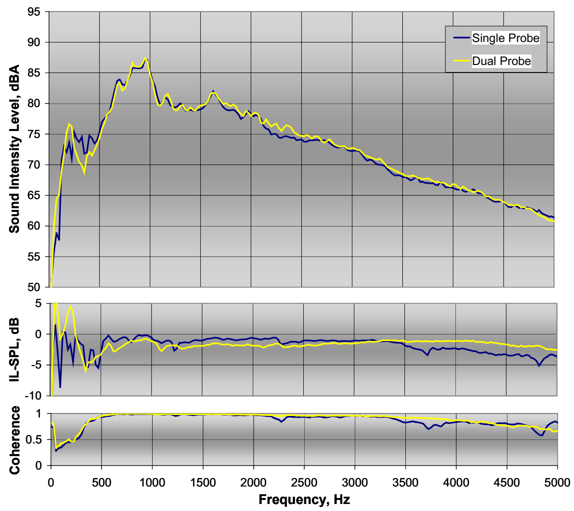

Figure 33: Comparison single and dual probe SI averages of multiple runs on ARFC for the Trailing edge of the tire contact patch

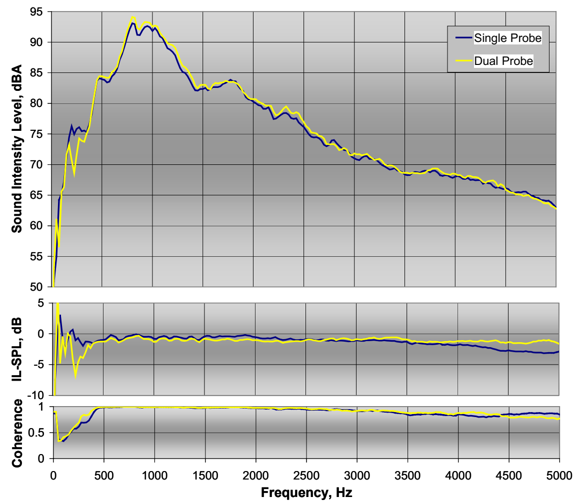

Figure 34: Comparison single and dual probe SI averages of multiple runs on grind #2 PCC for the leading edge of the tire contact patch

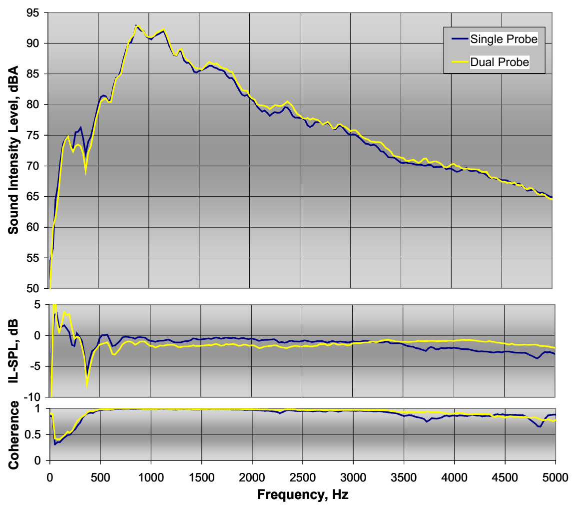

Figure 35: Comparison single and dual probe SI averages of multiple runs on grind #2 PCC for the trailing edge of the tire contact patch

CLOSING REMARKS

From the testing and analysis described here, accurate measure of the tire/pavement noise source levels using a two probe arrangement as shown in Figure 5 is feasible providing that the criteria for identifying wind noise contamination are observed. This particularly necessary as the testing reported here was under a no wind condition combined with the fact that quietest pavement tested was about 4 dB higher in level than the quietest measured elsewhere to date. In the development of future data acquisition systems, checks against the wind noise contamination criteria should be built-in so that they can be assessed at or near the time of the measurement.

For assessing other configurations of SI fixtures and microphone orientations as applied to on-vehicle testing in exposed air flow, the current single probe configuration with microphones pointed into the flow should be used as the reference of performance. This configuration should include microphone nose cones and a protective windscreen. Care should be taken that there is no foam or other material between the microphones themselves as this would change the acoustic velocity and may affect the accuracy of the SI measurement. Although there appears to be some added higher frequency sound pressure level created by the use of the nose cones, this is offset by their improved rejection of flow induced wind noise in the region from 500 to about 3000 Hz. Further, the accuracy of the SI measurements with the nose cones is not affected even for frequencies above 3000 Hz. Measurements with only a windscreen can be accurately made, but as with all SI measurements in flow, the criteria for flow-induced noise should be observed.

Sound pressure measurements of tire/pavement noise with the microphones exposed to flow are not recommended. Under ideal conditions of little or no turbulence, tire noise sound pressure levels may be accurately measured using a windscreen only up to about 2000 Hz depending on the tire and pavement surface. With the use of microphone nose cone and with little or no turbulence, this may be extendable into higher frequencies, however, as turbulence levels become higher, the effects of wind induced noise become greater. Further, there is no quantitative method for determining the level of contamination present in the SPL measurement. The amount of contamination will vary with ambient wind conditions and the tire/pavement source levels, hence "certifying" a measurement system under one circumstance will not necessarily carry over to other circumstances.

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