# THE DEVELOPMENT AND APPLICATION OF AN ON-BOARD SOUND INTENSITY CALIBRATOR FOR TIRE NOISE MEASUREMENT

Paul R. Donavan, ScD. (Corresponding author)
Sr. Scientist
Illingworth & Rodkin, Inc
1 Willowbrook Court, Suite 120
Petaluma, CA 94954
1-707-794-0400
1-707-794-0405 (fax)
pdonavan@illingworthrodkin.com

Submitted: October 30, 2015

Word count: 3,370 text, 16 figures (7,370 total)

## ABSTRACT

With the standardization and growth of the application of the measurement of tire-pavement noise using on-board sound intensity (OBSI), the need for a method to perform relative calibration and validation of the complete data acquisition systems used by different users has developed. The devices available to perform sound intensity calibration generally rely on external signal generators to drive a coupler or are limited to calibration at only one frequency. A system has been developed using components from various suppliers to perform relative calibration between users over the range from 400 to 5,000 Hz. The repeatability of this OBSI calibrator was quantified in bench top testing and its reproducibility examined by application by multiple users. The stability of the calibrator has been confirmed over the last three years and found to be consistent when applied by multiple users. The availability and performance of this calibrator presents the opportunity for users to have a means to be confident of their systems, particularly if developed internally. The calibrator also facilitates the exchange of OBSI results between users enabling the use of noise performance as one basis for pavement selection. The development, validation, and application of the OBSI calibrator are presented in this paper.

## INTRODUCTION

A method for the standardized measurement of on-board tire-pavement noise near the source has been developed and published by the American Association of the State Highway Transportation Officials (AASHTO) as procedure TP 76 (1). Under this procedure, sound intensity measurements are made close to the sidewall of the tire opposite the leading and trailing edges of the tire contact patch as shown in Figure 1. The intended application for this procedure is for

**FIGURE 1 Sound intensity probe positioned for OBSI measurements with windscreens normally used (left) and without windscreen for illustration (right)**

characterizing the noise performance of different pavements to facilitate the identification and application of quieter pavements to reduce overall highway noise for the surrounding communities. Since the development of this application more than 10 years ago (2) and initial standardization in the mid 2000's, the on-board sound intensity (OBSI) method has become widely used by highway agencies for research and application of quieter pavements. The OBSI practitioners include consultants, universities, and individual state highway agencies. Further, the systems used for acquiring the sound intensity data include commercially available analyzers, commercial software-based systems, and independently developed systems. Unfortunately, there is no convenient, standardized way to calibrate these different systems using commercial self-contained sound intensity calibrators in a similar manner to that done for sound pressure level measurements. In principle, calibration could be performed using sound power following the procedures of ANSI S12.12, Engineering Method for the Determination of Sound Power Levels of Noise Sources Using Sound Intensity; however, this requires the use of special facilities and equipment not generally available to individual users or suitable for routine checking of systems. As a result, those interested in comparing their OBSI system to another's system have had to rely on OBSI "rodeos" in which users gather at one location, perform OBSI measurements on the same pavements under the same environmental conditions, and compare the results. Because of other uncertainties in the on-road measurements, this method is not conclusive in identifying differences that are solely due to the measurement systems. Even with tire swaps between participants in closely monitored rodeo conditions, unaccounted for differences of up to 0.8 dB remain even with participants all using the same type of sound intensity analyzers (3). Further, there is often considerable expense for the organizer and participants in conducting such rodeos.

To address this need, the Federal Highway Administration Transportation Pooled Fund (TPF) Program, TPF-5(135) Tire/Pavement Noise Research Consortium, sponsored the development of an OBSI calibrator that could be used to check the performance of the various systems in a lab or field environment, at least on a relative basis. The goals for this calibrator were that it has stability over time, insensitivity to environmental conditions, and reproducibility for single and multiple users. It was also desirable that the calibrator consist of off-the-shelf components rather than specially fabricated components.

## DEVELOPEMNT OF THE OBSI CALIBRATOR

There are several commercially available couplers available that can be used for checking the phase matching of the channels comprising a sound intensity probe. These devices expose the two microphones and acquisition chain to identical sound pressures, simultaneously producing an essentially zero phase shift between the pressures presented to the individual channels. These devices provide a means of quantifying and validating the phase shift relative to zero phase shift and are useful for matching specific requirements. These devices can also be used to determine the residual sound intensity of the instrumentation system, which is effectively the sound intensity noise floor of the system. Some commercial couplers do simulate a progressive sound field by introducing a prescribed phase shift between the microphone channels. This is accomplished using a flow resistive element between the two microphone channels as shown in Figure 2 for a G.R.A.S Type 51AB coupler/calibrator. The transducer within the coupler is

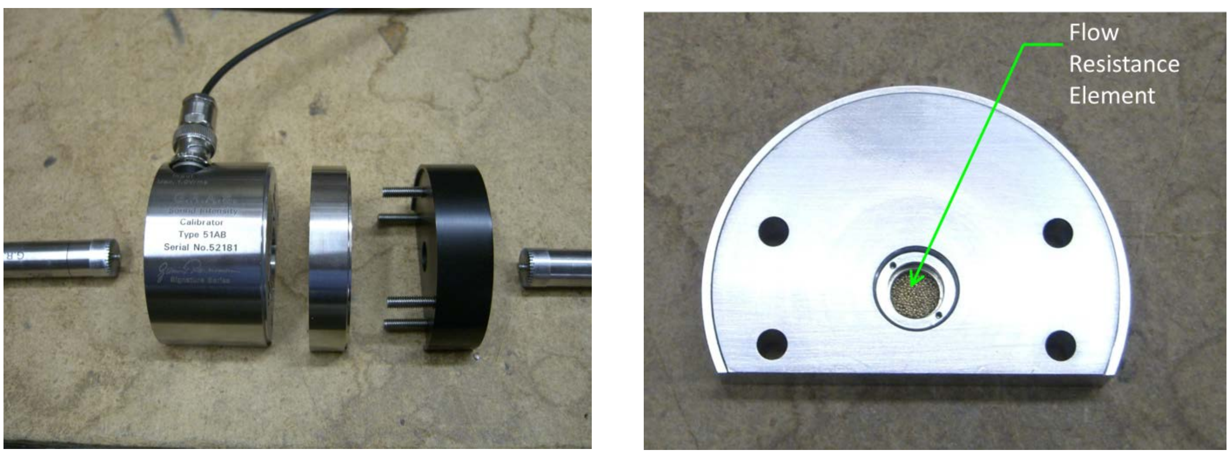


**FIGURE 2 Coupler for simulating a progressive sound field for intensity calibration**

driven by an external electrical noise source (signal generator) that is supplied by the user. Such couplers can be used in one of two modes: with the flow resistive element to simulate sound intensity or without the element to verify phase matching the same sound pressure applied to both microphones.

To evaluate the suitability of this device for OBSI calibration, five Type 51AB couplers were tested using the pink noise signal generator of the Larson-Davis 3000 real-time analyzer (RTA). From these tests it was found that although the input signal was verified to be pink noise (equal energy in each ⅓ octave band), the response in the coupler either with or without the flow resistive element inserted was not entirely flat on a ⅓ octave band basis. Although not desirable, this finding did not preclude using the coupler as a component for relative comparison among different OBSI users. From testing of the multiple units, variation from one unit to the next was documented as shown in Figure 3. However, this too did not preclude the use of the coupler for the intended purpose. The testing also revealed that any one coupler produced repeatable results

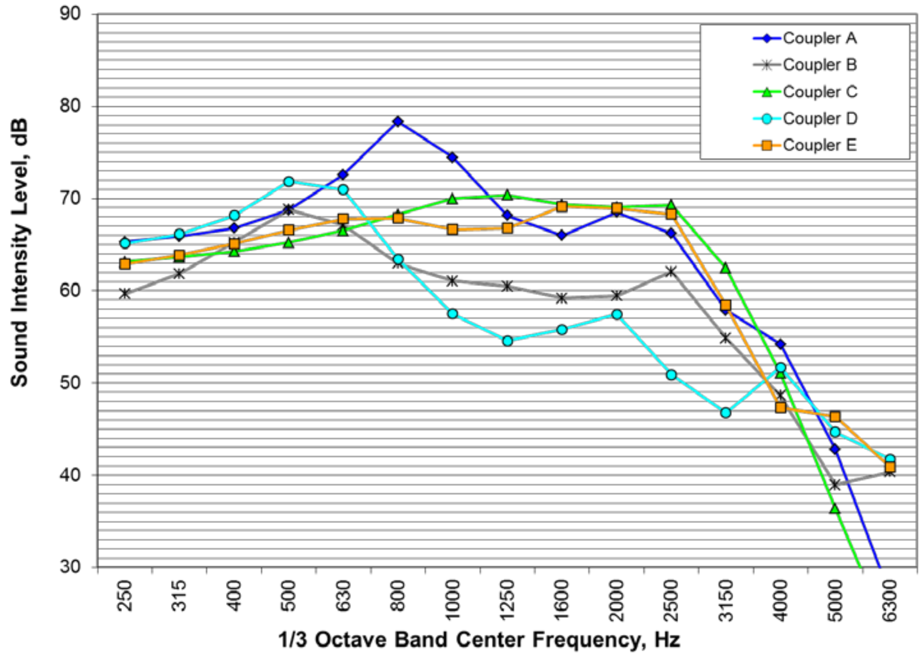


**FIGURE 3 Sound intensity level measured with several different Type 51AB couplers with pink noise input of the same level**

over long periods of time. This was clearly a necessary characteristic for the intended purpose. One specific coupler of this type was then selected for the OBSI calibrator.

The second issue for the OBSI calibrator was a stable source of the pink noise signal to drive the coupler. Although the RTA signal generator was found to meet this requirement, it was deemed to be too bulky, expensive, and sensitive to operator error to be sent around to various users of the calibrator. Besides being compact and relatively inexpensive, it was necessary to find a device which could produce a consistent output without any adjustment of the output controls. An ACO Pacific 3025 Noise Generator was selected for this purpose and is shown in Figure 4. It does have a step attenuator and a variable amplitude control as well as


**FIGURE 4 Noise generator selected for the OBSI calibrator**

reference positions for both controls. To assure proper use, the knobs for both controls were removed, and control shafts were hot glued to the reference positions. As a result, the user need only turn the device on and set the remaining control to pink noise.

Once the initial calibration system was defined, bench-top testing was performed over a period of two months over a range in temperature of 18.9°C to 27.8°C (66°F to 82°F) and atmospheric pressure of 1,010.3 to 1,022.1 hPa. Although this range was not extensive, it likely would include most laboratory or instrumentation room conditions. These conditions correspond to a range in density corrections from +0.11 dB to -0.04 dB. Applying corrections did not improve the reproducibility of the measurements, which are shown unadjusted in Figure 5. For all measurements the analyzer was set for standard conditions of 20°C and 1013.25hPa. The measurements were made on eight different days, periodically throughout each day, and Figure 5 presents both average day-to-day variation and the variation within a day. On average, the range in daily sound intensity level was ±0.2 dB, and the range over a day was typically ±0.1 dB. The average, standard deviation, and range of the ⅓ octave band spectra for all of the tests performed in the two month period are shown in Figure 6. Consistency of the phase between channels, the sound pressure levels of the channels, the pressure to intensity (PI) index, and coherence were also tracked over this period and found to be similar in variation to the sound intensity level.

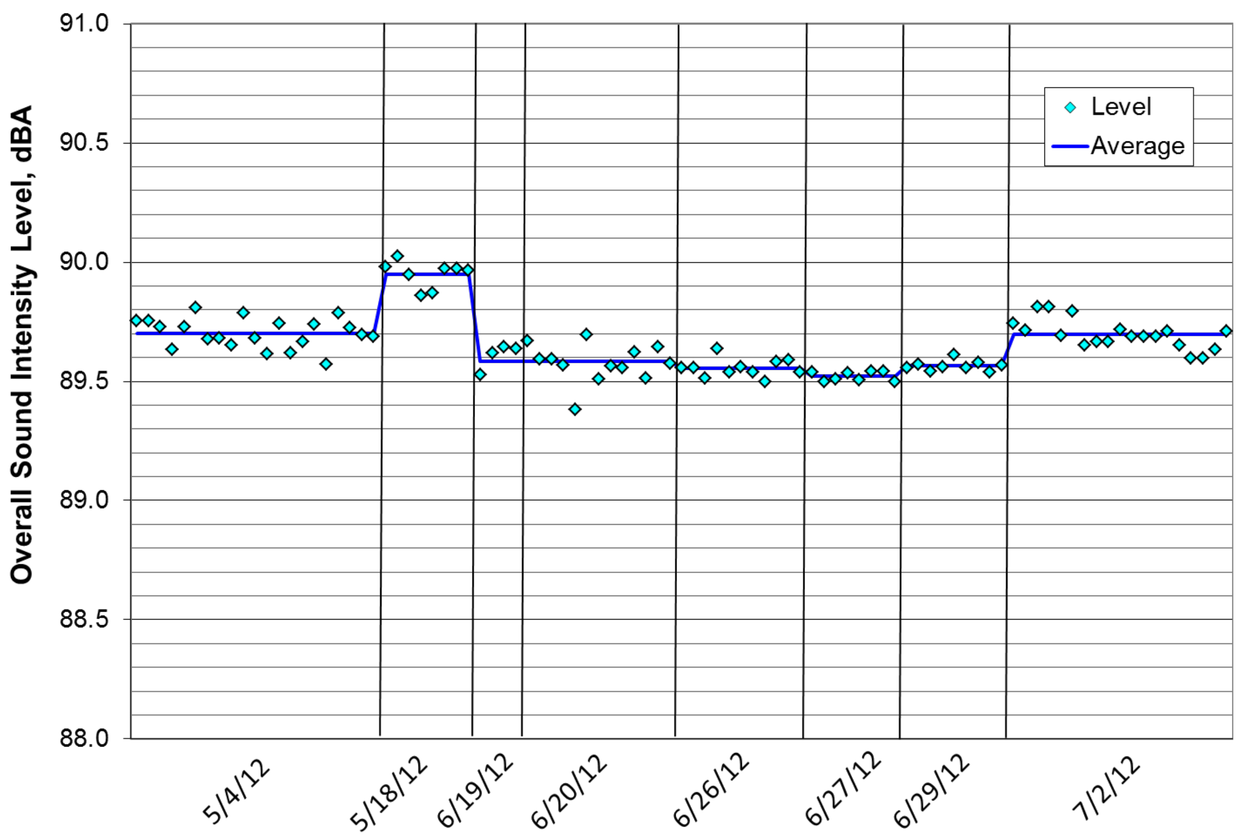


**FIGURE 5 Overall sound intensity levels measurement for the OBSI calibration over a two month period**

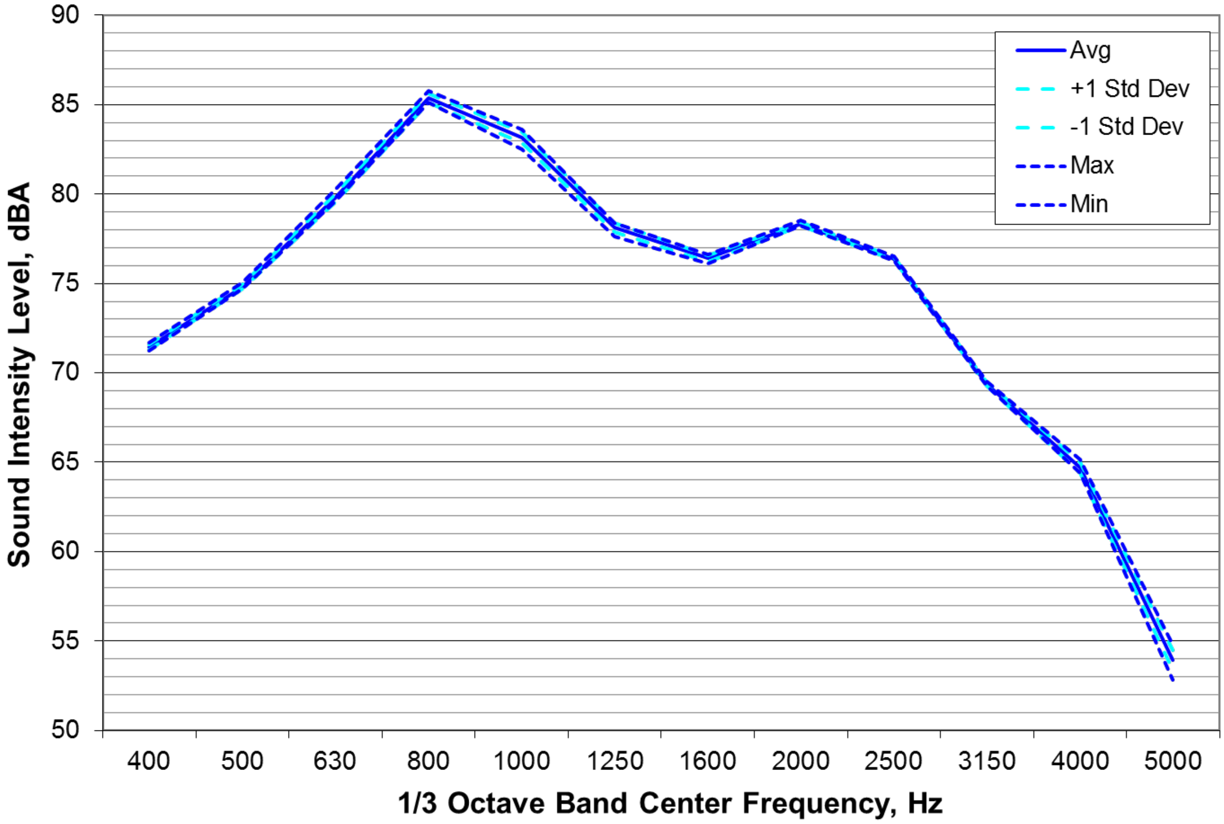


**FIGURE 6 Average, standard deviation, and range of ⅓ octave band levels measured for the OBSI calibrator over a two month period**

## APPLICATIONS TO DIFFERENT ANALYZERS

Prior to sending the calibrator around to different users, it was used to evaluate several different sound intensity measurement systems, including a Brüel & Kjaer (B&K) PULSE, a Soft dB system, and the Larson-Davis (LD) RTA. These tests were all done using the same pair of microphones and preamplifiers. The initial comparison of sound intensity produced results that were within 0.3 dB of each other for overall A-weighted sound intensity level over the OBSI range from 400 to 5,000 Hz. The overall levels and spectra are shown in Figure 7. This was quite encouraging as this comparison was exactly what the intended use of the calibrator would be. However, initial comparison of the sound pressure levels used to calculate PI index was not as encouraging as shown in Figure 8. The cause of this discrepancy was found to be in the manner in which each analyzer calculated the average pressure level for the intensity probe. The TP-76 procedure and ANSI S1.9 define the PI index as the arithmetic average of the sound pressure levels (SPL) of both probe microphones minus the sound intensity level (IL). Of the three systems, only the Soft dB analyzer calculated the average pressure level in this manner. The B&K system, in its default mode, calculated the average pressure as the square of the sum of the pressures. The LD RTA used the sound pressure level of channel 1 only for the calculation. Once these calculations were made consistent, the comparison shown in Figure 9 was produced.

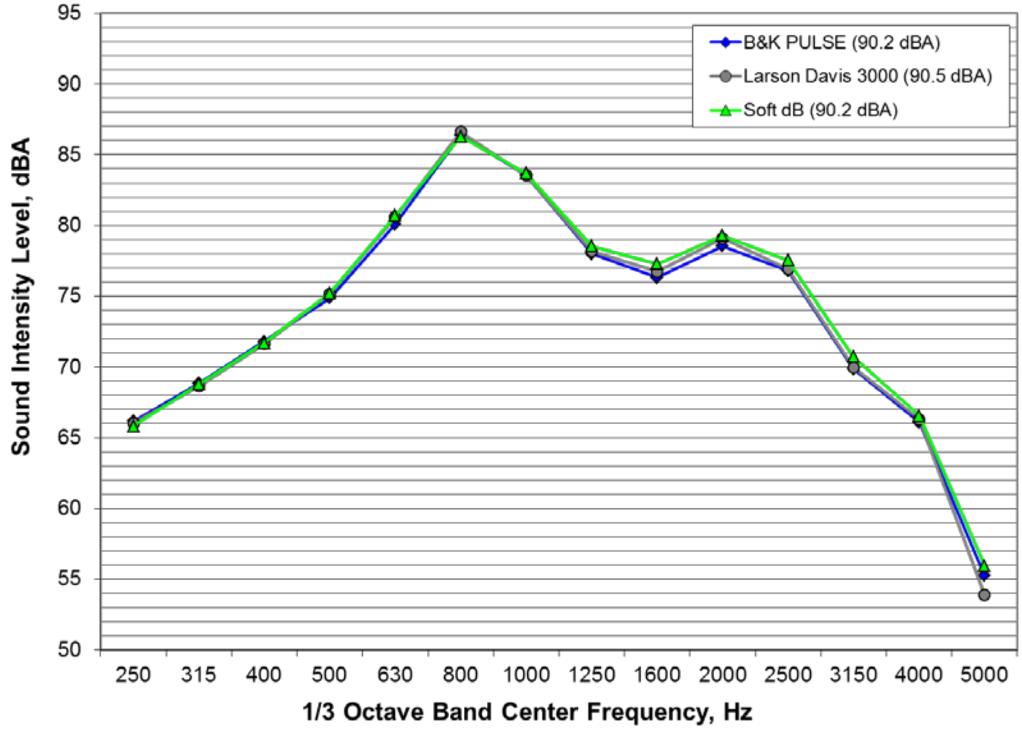


**FIGURE 7 Comparison of ⅓ octave band sound intensity levels measured for the OBSI calibrator using three different analyzers**

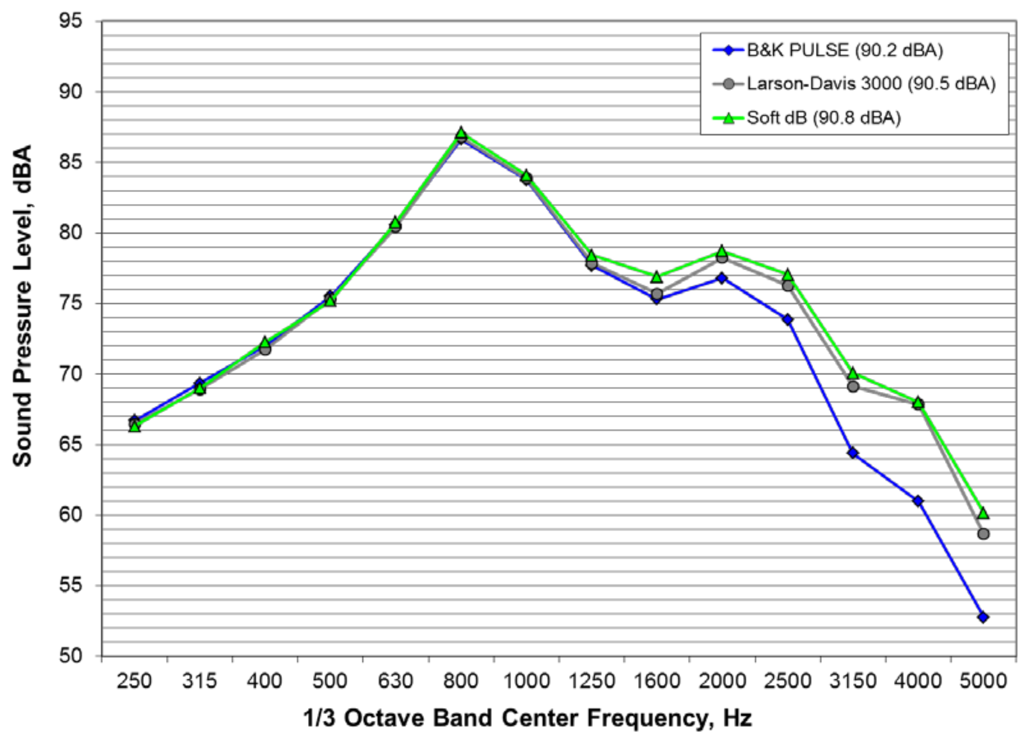


**FIGURE 8 Initial comparison of ⅓ octave band sound pressure levels measured for the OBSI calibrator using three different analyzers**

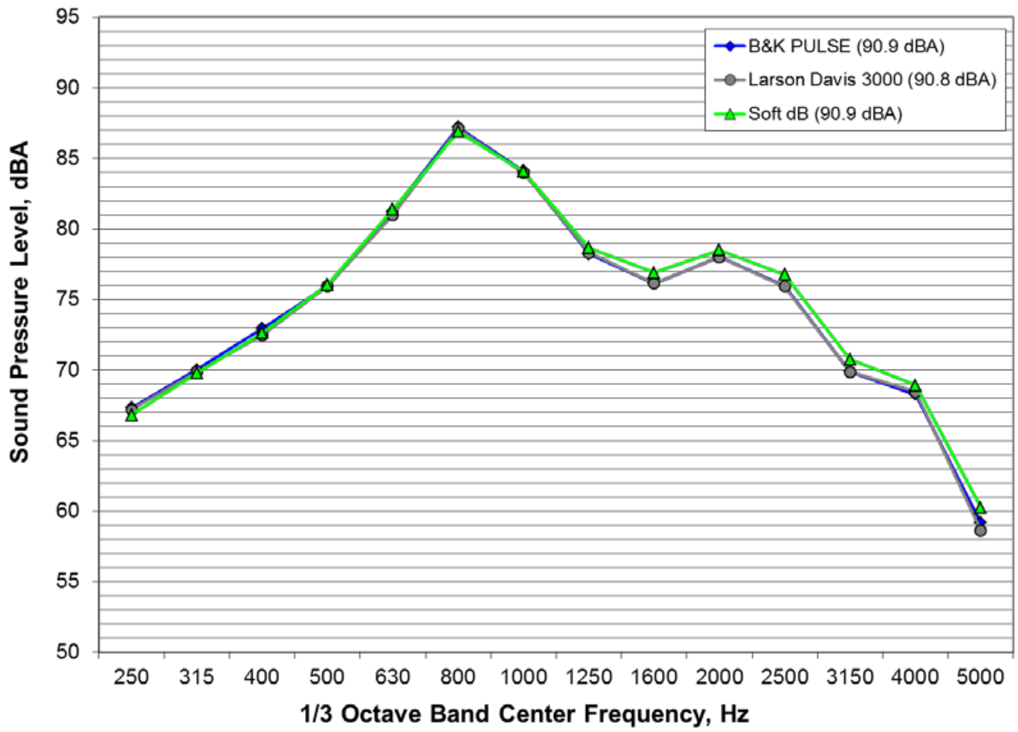


**FIGURE 9 Final comparison of ⅓ octave band sound pressure levels measured for the OBSI calibrator using three different analyzers**

With the resolution of differences in average sound pressure level, the OBSI calibrator can be used for examining the PI index. In the TP 76 procedure, limits are set on PI index as an indicator of valid data. Ideally, the PI index of the OBSI calibrator would be 0 if the coupler simulated totally progressive sound waves. However, some residual effects are seen when the PI index is actually calculated. The PI index was determined for all three analyzers and the result is shown in Figure 10. As expected from the results of Figures 7 and 9, the PI index values for the different analyzers was quite comparable to each other with an average difference of 0.4 dB over the range of ⅓ octave bands and a maximum difference of 0.8 dB. Although the behavior of the calibrator does deviate from the ideal 0 dB PI index, it can still be used to evaluate differences between systems keeping in mind the spectrum shape demonstrated in Figure 10.

The use of the calibrator for evaluating coherence is more problematic. In TP 76, limits are also set on the coherence between the two microphone channels that comprise an OBSI probe. The limits are set in terms of the allowable amount that the coherence can drop below the ideal coherence of 1. As part of the analyzer system comparison, coherence was measured without the insert in the OBSI calibrator so that the same sound field was imposed on both microphones. This resulted in the comparison shown in Figure 11. In this configuration, all three analyzers produced the idea coherence with measured values of 1.00. Coherence measurements were repeated with the insert in place in the OBSI calibrator configuration. The resultant coherence values for the three analyzers are shown in Figure 12. For this configuration, only the LD 3000 produced coherence values very close to 1.00. The other two deviated to varying degrees with the

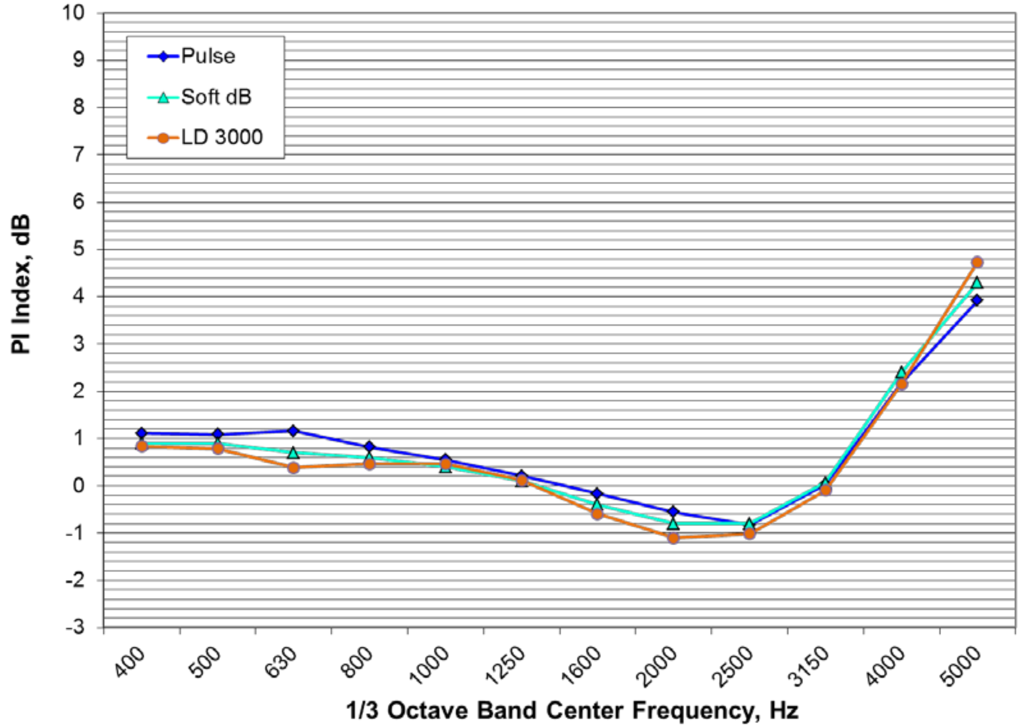


**FIGURE 10 Comparison of ⅓ octave band PI index levels measured for the OBSI calibrator using three different analyzers**

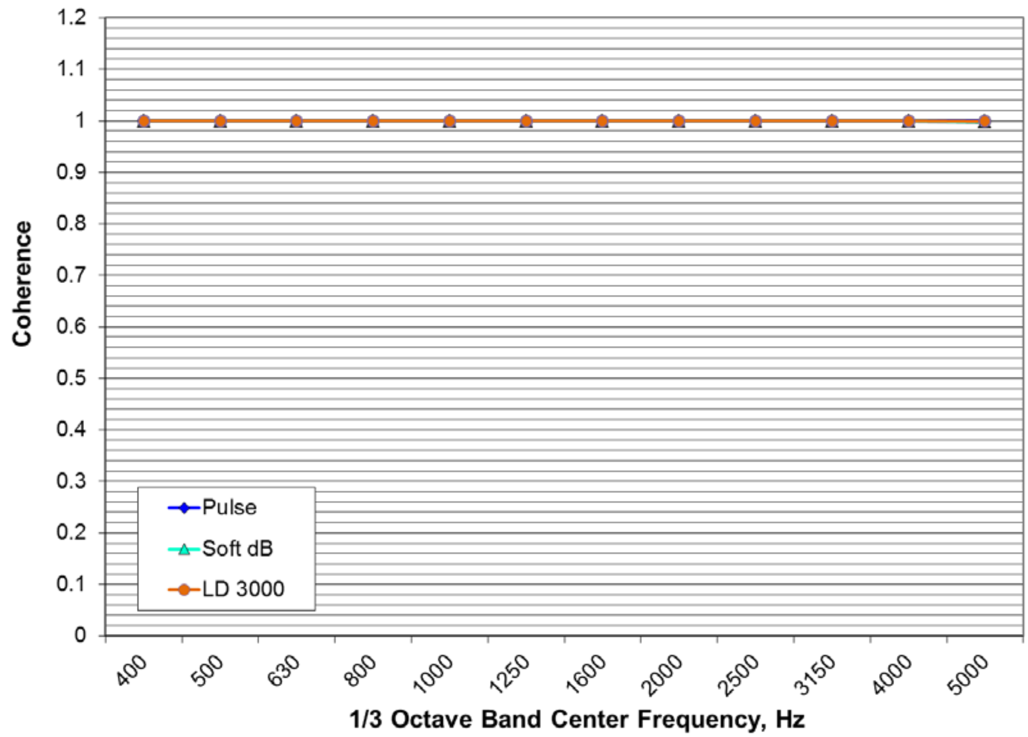


**FIGURE 11 Comparison of ⅓ octave band coherence measured without a sound intensity insert in the OBSI coupler using three different analyzers**

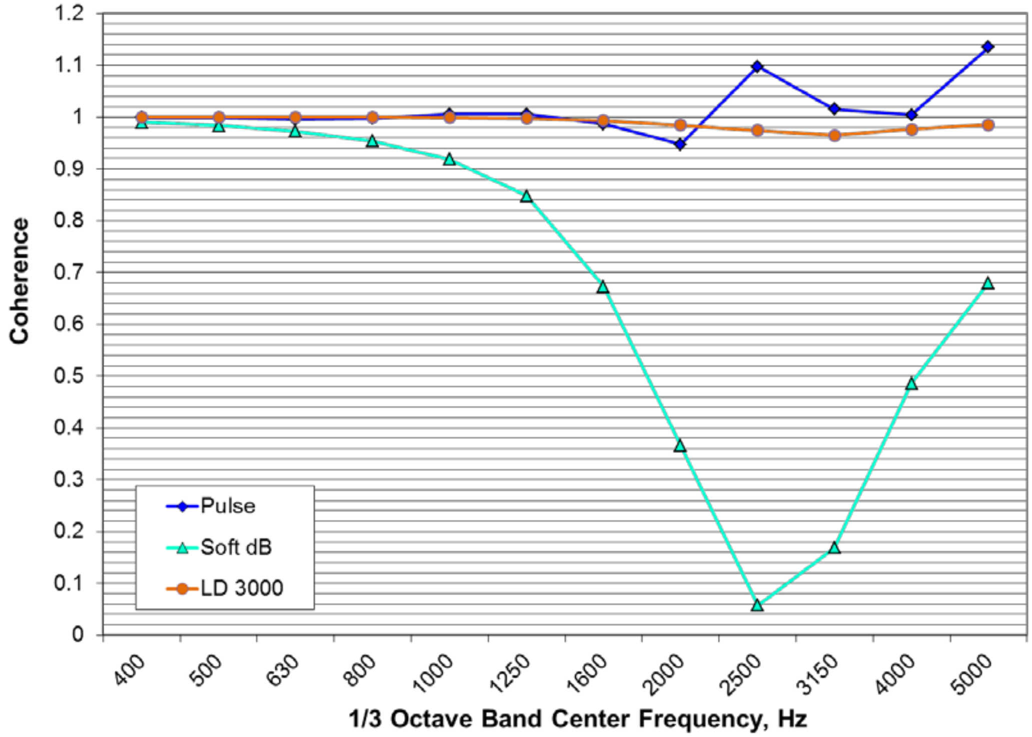


**FIGURE 12 Comparison of ⅓ octave band coherence measured with a sound intensity insert in the OBSI coupler using three different analyzers**

Soft dB system displaying very large differences above 1,000 Hz. The reason for these discrepancies was not resolved in this testing; however, it appears that there is some interaction between the presence of the insert and the coherence measurement when the results of Figure 11 are considered. In the case of the Soft dB system, the supplier was able to identify the cause and rectify it so that coherence is now measured properly. Similar remediation should be considered for other analyzers for which the measured coherence is not very close to 1.0. In principle, the OBSI calibrator could also be used for verifying phase matching between microphone channels. However, since the insert imparts its own phase shift, using the calibrator in this way maybe problematic.

## APPLICATIONS AMONG DIFFERENT USERS

After this initial application, the components of the calibrator were packaged into a shippable unit and instructions for its use were prepared. These were sent to users at the Departments of Transportation in Washington State (WSDOT) and Texas (TxDOT). At TxDOT, two systems were compared: a LD RTA and a newer, National Instrument/LabView (NI) based system also developed under the TPF-135(5) program. WSDOT used a B&K PULSE system. The overall levels for the three different systems are shown in Figure 13, along with the original calibration results obtained by Illingworth & Rodkin, Inc. (I&R). The TxDOT NI levels for both the tire contact patch leading and trailing edge probes match exactly the I&R results, while the WSDOT results were 0.4 and 0.6 dB lower, and the TxDOT LD RTA were 0.2 and 0.4 dB higher. This range is slightly higher than that of Figure 5 and Figure 7. However, the DOT measurements included the use of different microphones, preamplifiers, and acoustic calibrators possibly

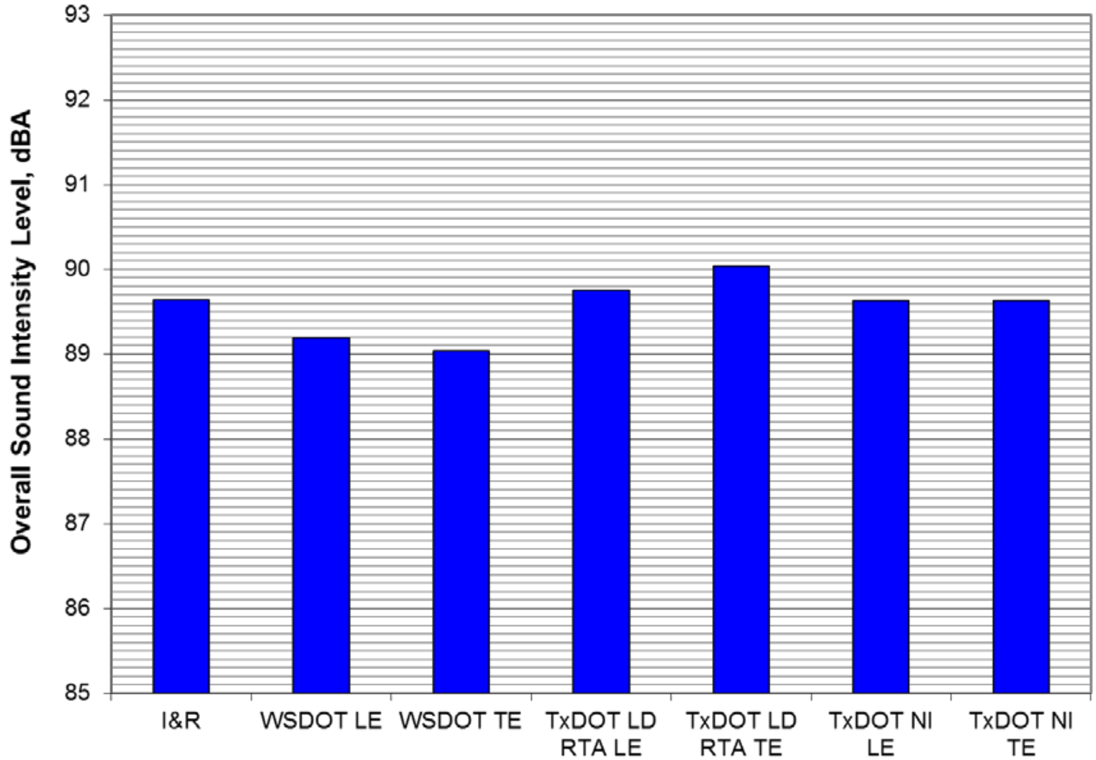


**FIGURE 13 Comparison of overall sound intensity measured for the OBSI calibrator by users at I&R, Washington, and Texas DOTs**

contributing to the increased variability. The ⅓ octave band sound intensity spectra for all three users are shown in Figure 14. In general, the shapes of the spectra are similar in the bands from 400 to 4,000 Hz, although as with the overall levels, the data indicate more variation than that seen in Figures 6 and 7 for measurements done exclusively at I&R. In the 5,000 Hz band, the TxDOT results with the LD RTA are about 5 dB higher than the rest, including the measurements made by TxDOT with the NI system. The reason for this divergence is not known and was not further pursued by TxDOT as they were migrating to the newer, 4-channel NI system.

APPLICATIONS OVER TIME

Sometime after the calibrator was returned to I&R, its performance was verified in December 2013 after a period of about 1½ years since the time of the results shown in Figure 6. The overall level was measured to be 89.4 dBA, or 0.2 dB lower than that measured initially. The spectra shape was virtually identical to that of July 2012, with values in each ⅓ octave band being within one standard deviation of the original data set, except at 500 Hz where the sound intensity level was 0.2 dB lower than the range of the 2012 results.

In May of 2015, the OBSI calibrator was used to assess the performance of microphone and preamplifier components of another OBSI user. This was done using the I&R LD 3000. Compared to the original 2012 performance, the 2015 measurements with the different

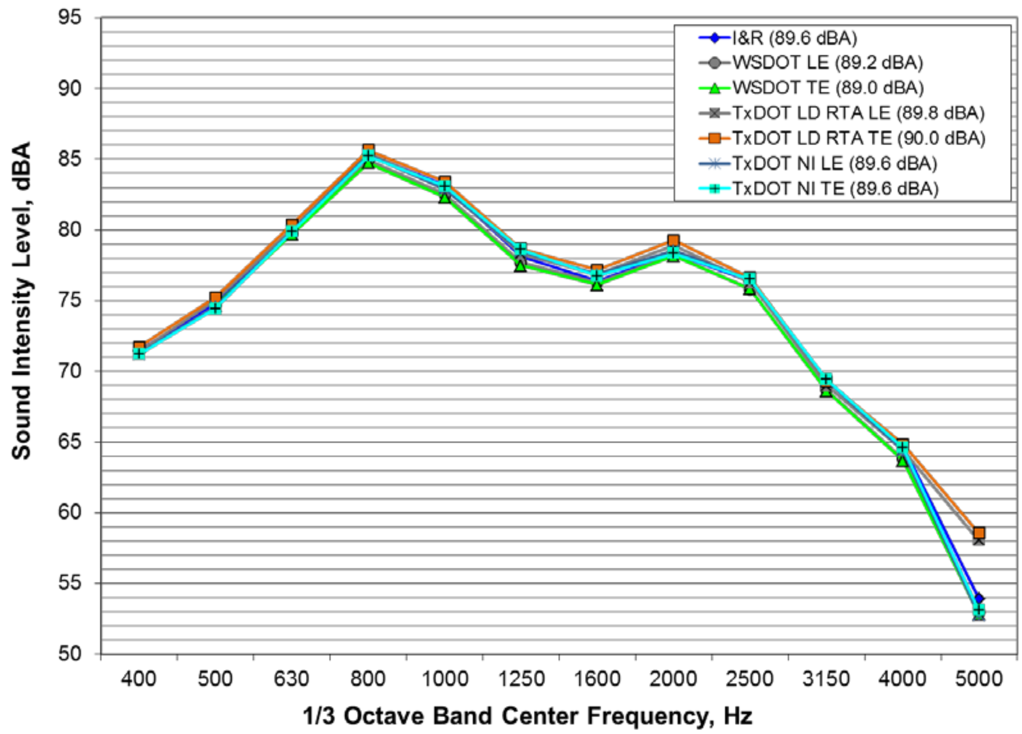


**FIGURE 14 Comparison of ⅓ octave band sound intensity measured for the OBSI calibrator by users at I&R, Washington, and Texas DOTs**

components resulted in the overall level being 0.2 dB higher and average ⅓ octave band levels being 0.1 dB higher. Also at this time, measurements were made with the I&R NI system using I&R microphones and preamplifiers. Compared to 2012, the overall level was identical and there was no difference in the average of the ⅓ octave band levels. The spectra for all four of the data sets are shown in Figure 15.

The overall levels for all of the applications of the OBSI calibrator are shown in Figure 16. This includes the data from multiple users and systems and the repeated measurements through 2015. The average of overall levels since the time that the performance of the calibrator was completed in 2012 is 89.6 dBA which is the same as the original level. The extremes of level are ±0.5 dB with a standard deviation of 0.3 dB. Comparing the original 2012 results to the average of 2015 results, the difference in overall level is 0.1 dB.

## CONCLUSIONS

To meet the needs of the OBSI user community, an OBSI system calibrator was successfully developed from commercially available components. This calibrator has proven to be very stable over both short and long time periods with the results being within 0.1 dB over three years. Although this calibrator does not provide an absolute sound intensity calibration, it does allow the comparison of different systems on a relative basis. This has been successfully done with several different users and measurement systems. This device is well suited for comparing

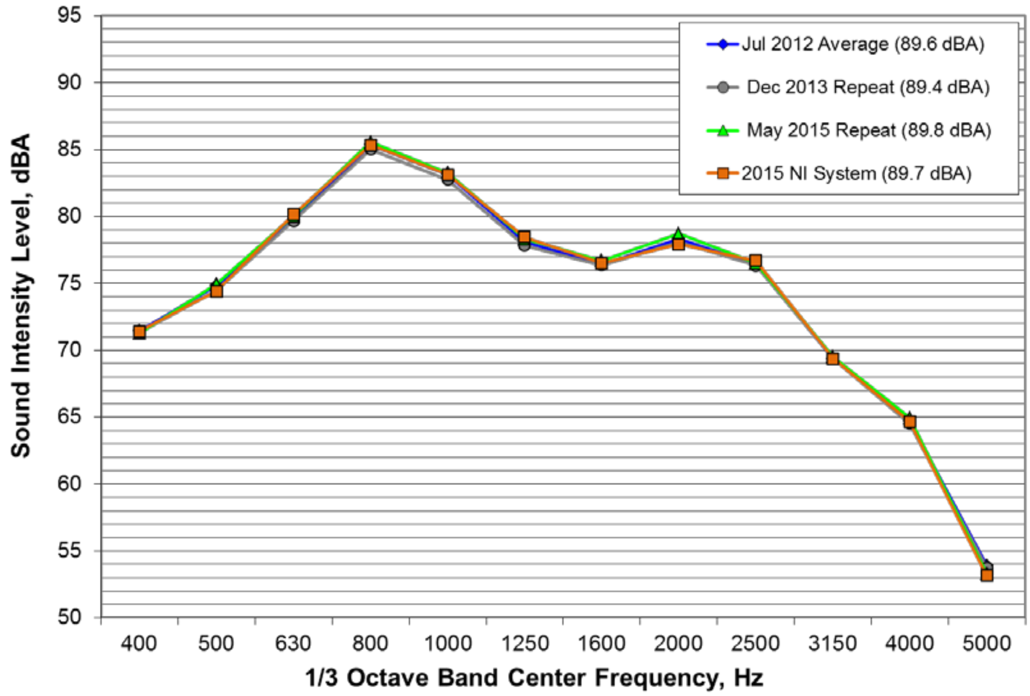


**FIGURE 15 Comparison of ⅓ octave band sound intensity levels measured for the OBSI calibrator by I&R in July 2012 and December 2013 with a B&K Pulse, in May 2015 with a LD RTA and the I&R NI system**

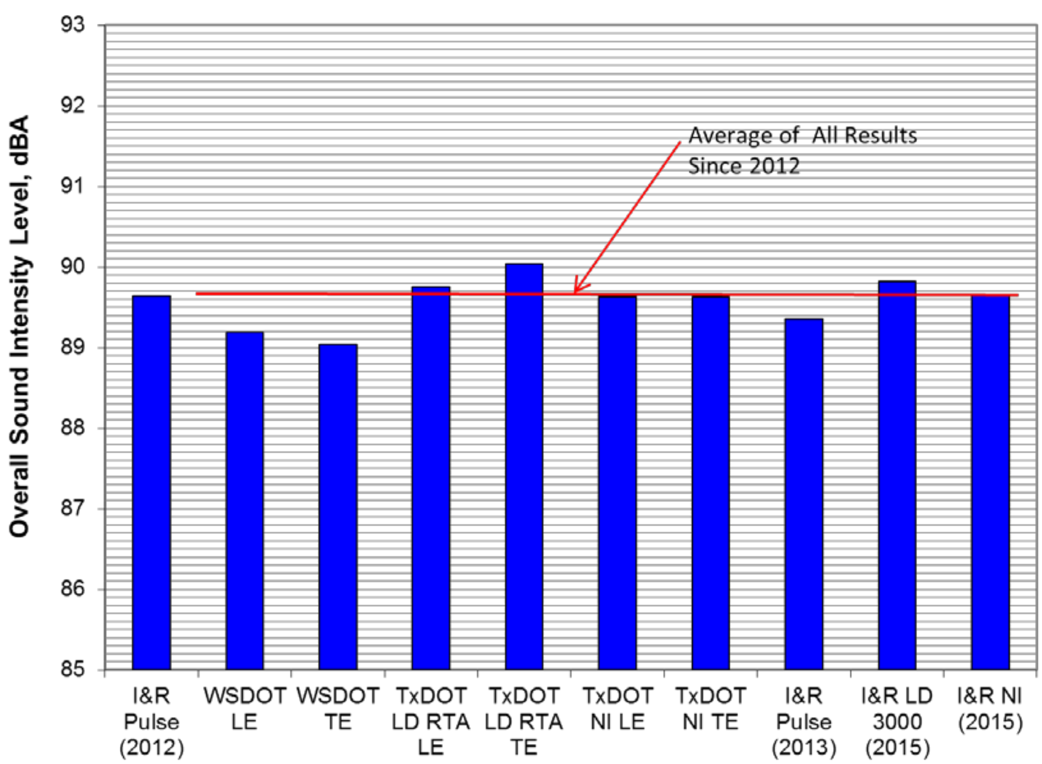


**FIGURE 16 Comparison of overall sound intensity levels measured for the OBSI calibrator over time and different users**

commercially available OBSI based systems, as well as validating systems that are individually developed. This device may not negate the need of OBSI rodeos, but it does provide a means for eliminating one potential source of uncertainty between users. In addition to OBSI, SPL, and PI index comparisons, the calibrator can be useful in identifying issues with coherence measurement in specific analyzers. A user's manual for the OBSI calibrator is available by contacting the author.

ACKNOWLEDGEMENTS

The work done to develop the OBSI calibrator was supported by the TPF-5(135) Tire/Pavement Noise Research Consortium. G.R.A.S. was particularly helpful in allowing the use of different Type 51AB couplers during the development and validation of the OBSI calibrator.

REFERENCES

1. *Standard Method of Test for the Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method TP 76-13.* American Association of State Highway and Transportation Officials, 444 North Capitol Street N.W., Suite 249, May 2013.Washington, D.C. 20001.
2. P. R. Donavan and B. Rymer, "Quantification of Tire/Pavement Noise: Application of the Sound Intensity Method", Proceedings of Inter-Noise 2004, Prague, the Czech Republic, August 2004.
3. Donavan, P.R., "Comparative OBSI Testing in North Carolina: the North Carolina Rodeo", prepared for the Washington State Department of Transportation under Agreement Y-10704 and Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135), by Illingworth & Rodkin, Inc., Petaluma CA, March 2011.