Fan Manufacturer Sound Power Data: Trust but Verify

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This article describes the extensive efforts and important conclusions reached by Parsons Brinckerhoff (PB) involving in-tunnel jet fan noise emissions associated with the I-264 Midtown/Downtown Tunnels project where more than 50 jet fans were scheduled for installation in four new tunnels connecting Norfolk and Portsmouth, Virginia. PB performed in-tunnel noise predictions during the design phase using the fan manufacturer's published sound power data that indicated in-tunnel noise levels should be compliant with NFPA 502 guidelines. However, when the first jet fans were installed and tested, in-tunnel noise levels were nearly 20 decibels louder than PB had predicted. This led to PB performing *in-situ* sound power tests of the jet fans in accordance with ISO 3747 and visiting the fan manufacturer's factory to verify its sound power testing methods. The results proved that the manufacturer's published sound power data were wildly inaccurate and that PB's prediction model algorithm and testing methods were correct. PB then provided guidance to correct the manufacturer's methods and reduce the fan screen noise to comply with the project's in-tunnel noise limit. The conclusion: beware of sound power data provided by fan manufactures; trust but verify its validity.

Ceiling-mounted, high-velocity, axial jets fans are becoming the preferred method for ventilating highway tunnels in the United States. They are needed in the event of an emergency in the tunnel such as a buildup of excessive carbon monoxide or smoke from a fire. Jet fans can be controlled to run in either the forward or backward direction so that the dangerous air can be evacuated from the tunnel most effectively and fire sources can be starved of oxygen.

Parsons Brinckerhoff (PB) was part of a design-build team for constructing and rehabilitating four highway tunnels connecting Norfolk and Portsmouth, Virginia. The project's jet fan noise criterion was taken from NFPA 502 guideline that limits in-tunnel sound pressure levels not to exceed 92 dBA at a height of 5 feet above the highway pavement (ear height). This is done to ensure adequate speech intelligibility in the tunnel in the event of an emergency. As such, it must be viewed as a critical life and safety criterion to satisfy.

Historical Content

PB had been receiving jet fan sound power data from "Acme Fans," a fictitious name to protect the fan manufacturer, since March 2013 for the four tunnels involved in this project, namely DTWB, DTEB, MTWB and MTEB. PB would then take Acme Fans' reported sound power data and insert it into proprietary noise prediction models to evaluate expected noise conditions inside the various tunnels. The goal was to ensure that in-tunnel noise levels would remain comfortably below the project's in-tunnel noise limit of 92 dBA SPL as measured 5 feet above the roadway anywhere in the tunnels.

Based on Acme Fans' sound power data used as input, PB's DTWB models were predicting that noise levels in the tunnels would be acceptable, as summarized in Table 1. This expectation continued throughout 2013 based on several iterations of Acme Fans' estimated jet fan sound power data, all of which tended to be around 99 dBA PWL. Then in March 2014, PB received another set of Acme Fans test data, this time reportedly collected on a prototype jet fan and indicating the sound power levels would only be about 91 dBA PWL, dropping by a surprising 8 decibels from previous estimates. Acme Fans assured PB this was not unusual, since they try to be overly conservative in initial theoretical estimates. So when plugged in to PB's models, predicted noise levels in the tunnels, and in particular the DTWB tunnel, appeared to be a complete non-issue.

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Figure 1. Approximate midpoint of DTWB tunnel.

Figure 2. Jet fan No. 8.

Problem Revealed

In October 2014, work in the DTWB tunnel had progressed well enough to allow for the first jet fan noise compliance measurements to be made inside the tunnel (also in Table 1). Surprisingly, the results were *significantly louder* than the model predictions, with noise levels of about 91 dBA SPL being measured under a single jet fan, and as high as 101 dBA SPL for multiple jet fans operating simultaneously. For comparison, PB's noise model for the DTWB tunnel had been predicting an in-tunnel noise level of only 72 dBA SPL under a single jet fan. So there was a discrepancy between modeled versus measured noise levels inside the tunnel of nearly 20 decibels! It became clear to everyone that jet fan noise levels inside the DTWB tunnel would *not* comply with the project's 92 dBA SPL criteria 5 feet above the roadway.

This realization led to great concern within PB regarding the potential liability for correcting the "error." Corrections could include:

- Applying acoustical absorptive materials to the walls and ceiling of the tunnel.

- Modifying all 16 jet fans in the DTWB tunnel.
- Replacing the fan's 2D silencers with more capable attenuators – at a cost of multi-millions of dollars.

Accordingly, PB started investigating from where the 20-decibel error could have come. After extensive reconsideration and review of all previous data, two potential causes of the error remained as possibilities, namely (1) PB's in-tunnel noise prediction model could have grossly underestimated the reverberant noise contribution produced inside the tunnel, or (2) Acme Fans' jet fan sound power level data could have been grossly under-reported.

Determining Source of Error

Both potential sources of the error could be investigated at once if carefully controlled acoustical measurements could be performed inside the DTWB tunnel. After coordinating with project officials, it was agreed that PB's acoustical engineers could get access into the DTWB tunnel the evening of March 23, 2015 to perform these measurements while the tunnel was shutdown to traffic for unrelated reasons.

The sound power level emissions of Acme Fans' jet fans could be tested inside the DTWB tunnel *in-situ* through a process described in ISO Standard 3747.[1] The process involves measuring a jet fan's SPL levels at prescribed locations and comparing the results against SPL levels measured in the same locations using a reference sound source (RSS) of known sound power level emissions. PB used a Brüel & Kjær Type 4204 reference sound power source (RSS) to accomplish the jet fan sound power tests.

The accuracy of PB's in-tunnel noise model and, in particular, its ability to account for reverberant noise contribution, could be tested by measuring the reverberation time inside the tunnel. Reverberation time, or T_{60}, is defined as the time it takes, in seconds, for sound to decay by 60 decibels from a constant state. T_{60} is a function of the acoustically absorptive qualities of the surface materials inside a room or space as well as the enclosure's effective volume. In essence, a loud noise is produced, turned off instantaneously, and the time it takes the noise level to reduce (or decay) by 60 decibels is then measured. PB used a Bruel & Kjaer Type 4224 loudspeaker with a built-in pink noise generator to accomplish the reverberation test. Pink noise is full spectrum random noise of equivalent sound energy in each octave or third-octave band so it was used to test all frequencies simultaneously.

In-tunnel Jet Fan Sound Tests. On the evening of March 23, 2015, PB acoustical engineers met with the contractors and were escorted into the DTWB tunnel to perform these acoustical tests, as shown in Figure 1. The tunnel had been closed to traffic several hours earlier. An ideal testing position was selected in the vicinity of Jet Fan No. 8 (JF-8), located near the mid-point of the DTWB tunnel. All jet fans and other unnecessary equipment were shut off to provide as quiet a background noise condition as possible.

JF-8 was selected as a representative jet fan to perform these in-tunnel sound tests because it was located deep inside the tunnel away from openings where reverberant noise contributions would be greatest, and previous sound data from it could be used for comparison. Like the other jet fans in the DTWB tunnel, JF-8 is a 44-inch-diameter jet fan running at 1,780 RPM producing a nominal air velocity of 8,000 feet/minute with fore-and-aft 2D (7-foot) absorptive-wall cylindrical silencers with internal absorptive pods. This fan is shown in Figure 2. There are wire screens or grilles attached to the outside of each silencer to prevent debris from entering the fans.

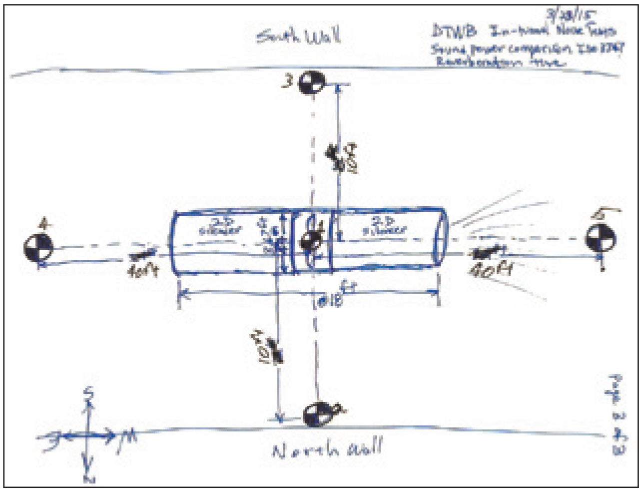

Figure 3. Sketch of noise measurements sites.

All noise measurements were performed using a CEL Instruments Model 593 sound level analyzer. The CEL 593 analyzer complies with ANSI Standard S1.4 for Type 1 (precision-grade) instrumentation. It was configured to measure third-octave band sound levels in unweighted (linear) decibels (dB) as well as the broadband A-weighted decibel level (dBA). The data were stored in the CEL 593 as 1-minute L_{eq} values as well as being streamed as raw data into a Marantz Model PMD670 digital recorder, where it was recorded as an uncompressed audio wave file. The CEL 593 was calibrated before testing with a Brüel & Kjær Type 4231 acoustical calibrator that produces a reference-quality sound level of 94 dB at 1,000 Hz.

The first acoustical test to be performed was determining *in-situ* sound power levels for JF-8 in accordance with ISO Standard 3747. As shown in Figure 3, a series of five noise measurement test points were laid out under JF-8, each 5 feet above the pavement surface, to take into account any directivity effects of the fan as follows:

- Site 1 – directly under the jet fan.
- Site 2 – 10 feet lateral of the jet fan, 2 feet from the tunnel's north wall.
- Site 3 – 10 feet lateral of the jet fan, 2 feet from the tunnel's south wall.
- Site 4 – 40 feet axial of the jet fan, east of the jet fan.
- Site 5 – 40 feet axial of the jet fan, west of the jet fan.

Background noise levels were first measured at the five sites with none of the jet fans or unnecessary equipment operating. The background noise level averaged over the five test sites was a fairly quiet level of approximately 38 dBA SPL. Then JF-8 was turned on in the forward air flow direction, and noise measurements were performed at the five sites, as shown in Figure 4. The average noise level with JF-8 operating was approximately 93 dBA SPL. There was clearly a directivity effect, with the axial noise levels being the loudest.

As the last step, noise measurements were performed using the B&K 4204 RSS mounted at the apex of the tunnel ceiling approximately 50 feet west of JF-8 (see Figure 5). In this manner, the same general tunnel acoustical (room) conditions would apply to noise measurements performed using both the JF-8 fan and the RSS as the noise source. The same arrangement of five measurement test sites was laid out under the RSS, and its noise levels were measured, as shown in Figure 6. The B&K 4204 emits a reference quality sound

Table 1. Acme Fans' jet fan sound power data and PB's in-tunnel noise predictions for the DTWB tunnel.

Model Rev. Date	Jet Fan Desciption	Acme Fans Sound Power Data, PWL dBA	PB's In-Tunnel Model Sound Pressure Level, SPL dBA
7/28/2013	Acme Fans 11R1892C-67 with 2D silencers, DTWB	104	84
12/17/2013	Acme Fans 11R1892C-67 with 2D silencers, DTWB	99	80
12/22/2013	Acme Fans 11R1892C-67 with 2D silencers, DTWB	99	80
3/28/2014	Acme Fans 11R1892C-67 with 2D silencers, DTWB (Tested)	91	71
10/15/2014	Acme Fans 11R1892C-67 with 2D silencers, DTWB (Average)	91	72
10/28/2014	Directly below Jet Fan 8 only DTWB (Measured)	N/A	91

Figure 4. Jet fan 8 noise measurements (Site 4).

Figure 5. Attaching RSS to tunnel ceiling.

power level of 96 dBA PWL, which in this case resulted in an average level of 80 dBA SPL inside the DTWB tunnel.

Jet Fan Sound Power Level

With the noise measurements completed for JF-8 and the RSS inside the DTWB tunnel, the next step was to calculate JF-8's sound power level in accordance with ISO Standard 3747. This is done on a third-octave band basis; however, the most important result in this case is the broadband A-weighted sound power level (dBA PWL). The fundamental steps involved in calculating a source's sound power level per ISO Standard 3747 are as follows:

1. The measured background noise levels are logarithmically subtracted from the measured JF-8 and RSS noise levels. In this case, it had no effect, because the background noise levels were so low relative to JF-8 and RSS noise levels. In general, if the background noise level is at least 10 decibels below the source noise level, the background noise level can be ignored as being noncontributory. ISO 3747 requires that the background noise levels be at least 6 decibels below the source noise levels.
2. If the noise measurement sites were significantly different distances from the source, their results would need to be normalized for equivalent distance. This is only a concern if the environment is less than ideal from a reverberant perspective. However, reverberation conditions in the DTWB tunnel were acceptable for these measurements, so no adjustments for distance were made on the measured DTWB tunnel noise data.
3. The background-corrected measured noise levels from the various test sites are then logarithmically averaged together for JF-8 and the RSS. This process takes directivity differences into account to yield the source's total mean noise emission levels regardless of direction.
4. The "room factor" is then computed by arithmetically subtracting the RSS's measured SPL levels from the RSS's known PWL levels. The room factor takes into account all aspects of the space contributing to the measured SPL levels, including aspects such as room volume and shape, acoustical absorption coefficients of all surface materials, and frequency-dependent effects. Again, all these calculations are done on a third-octave band basis.
5. The room factor is arithmetically added to the measured SPL levels from the jet fan. This yields the PWL level of the source under question, in this case the JF-8 fan. The third-octave band sound power level results can then be converted into full-octave bands or broadband A-weighted levels as desired.

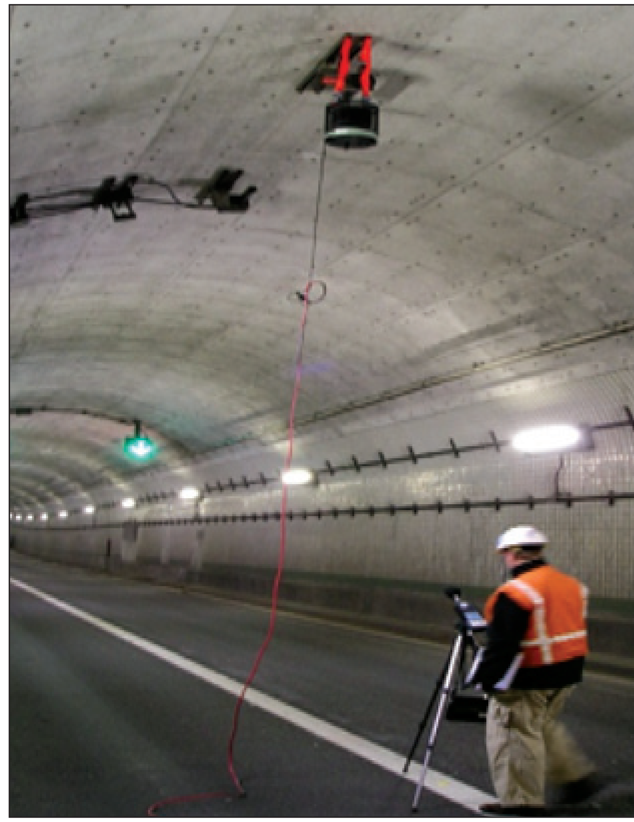

Figure 6. RSS noise measurements (Site 1).

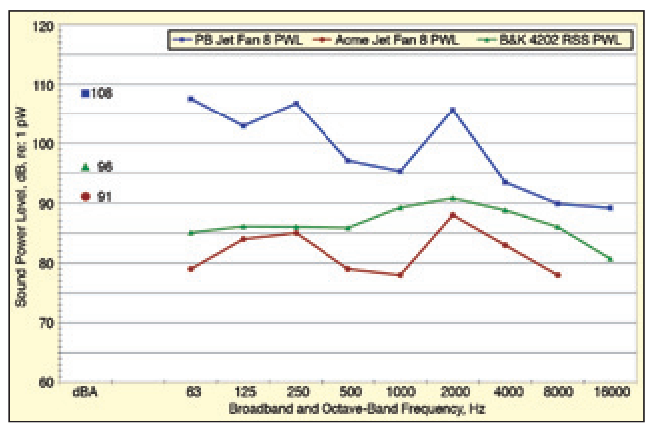

Figure 7. Comparison of sound power levels for JF-8 inside DTWB tunnel.

Table 2. Summary of sound power levels for JF-8 inside DTWB tunnel.

	Broadband and Octave Band Sound Power Level (PWL), dB re: 1 pW									
Data Source	**dBA**	**63 Hz**	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**	**16 kHz**
Measured by PB via ISO 3747	108	108	103	107	97	95	106	93	90	89
Data Provided by Acme Fans	91	79	84	85	79	78	88	83	78	N/A

Figure 8. Reverberation time test (Site 5).

Figure 9. Reverberation time test (Site 2).

Based on the test results, the broadband A-weighted sound power level for JF-8 that PB determined *in-situ* in the DTWB tunnel per ISO Standard 3747 methods was 108 dBA PWL. That is 17 decibels louder than Acme Fans' factory-tested sound power level data that claimed these jet fans produced only 91 dBA PWL. The resulting octave band and broadband sound power levels for JF-8 are summarized in Table 2 and shown in Figure 7. These results fully explain why there had been a difference of nearly 20 decibels between PB's in-tunnel noise model SPL predictions and actual SPL levels measured in the DTWB tunnel. Consequently, it was clear the error laid with Acme Fans and not with PB.

Tunnel Reverberation Time

As noted above, the other acoustical test PB performed in the DTWB tunnel the evening of March 23, 2015 was to measure the reverberation time inside the tunnel. The purpose of the T_{60} measurements was to compare measured reverberation times with those predicted in PB's in-tunnel noise model to confirm that the model was properly accounting for indirect (reverberant) noise contributions.

The reverberation time tests were performed in the same vicinity as the tests involving JF-8 and the RSS. Reverberation time was measured using a B&K 4224 loudspeaker broadcasting full-spectrum pink noise into the tunnel. When the pink noise was switched off, decaying noise levels in the tunnel were sampled very quickly in third-octave bands using the CEL 593 analyzer set to "Fastore" mode. This process was repeated at four measurements locations, equivalent to Sites 2, 3, 4 and 5, with the B&K 4224 loudspeaker placed in the middle of the roadway at Site 1, as shown in Figures 8 and 9. The data were then post-processed using CEL's dB3 software package to calculate the reverberation time (T_{60}) in each band, as shown in Figure 10.

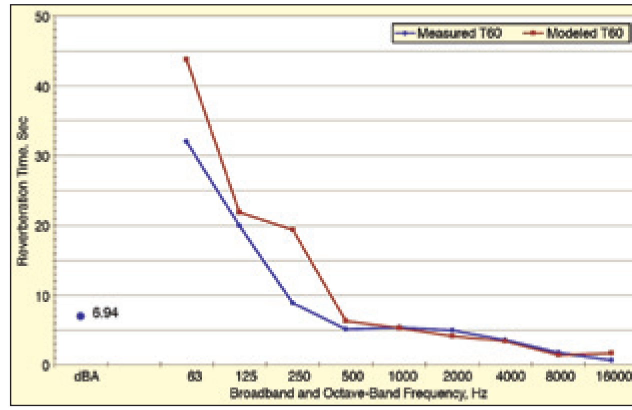

Figure 10. Reverberation time inside DTWB tunnel.

The resulting measured reverberation times were then compared against the reverberation times predicted in PB's in-tunnel noise model for the DTWB tunnel, as shown in Table 3. As can be seen, the matches between measured and predicted reverberation times were very good, especially in the critical mid-frequency bands. This confirms that PB's in-tunnel noise model was properly accounting for indirect jet fan noise contribution and was not the cause of the initial 20-decibel discrepancy.

Conclusions

The results of PB's measurements and evaluation of acoustical conditions inside the DTWB tunnel explained why the jet fan noise levels measured inside the tunnel were so much louder than what had been expected based on PB's noise prediction model. The louder-than-expected fan noise was due to inaccurate sound power level data being provided by Acme Fans during the entire fan design process. The 20-decibel discrepancy between measured and predicted jet fan noise levels inside the DTWB tunnel was clearly attributable to the company under-reporting the actual sound power levels emitted by its jet fans. PB's *in-situ* sound power level measurements and calculations of Jet Fan 8 done in accordance with ISO Standard 3747 produced a level of 108 dBA PWL, where Acme Fans had been reporting a level of just 91 dBA PWL for its jet fans.

Also, PB's measurements of reverberation time inside the DTWB tunnel produced results that matched PB's in-tunnel noise model predictions very well, especially in the critical mid-frequency octave bands. For example, the measured T_{60} results in the 500 Hz and 2,000 Hz octave bands were 5.39 and 3.36 seconds, respectively, where the model's predicted T_{60} times were 5.35 and 3.40 seconds, respectively. So PB's in-tunnel noise model was properly accounting for the indirect (reverberant) noise contribution of the jet fans as a function of the tunnel's unique acoustical environment.

In conclusion, relying on the accuracy of fan manufacturers' sound power data is essential for acoustical engineers to be able to predict project noise levels with any degree of confidence. For the vast majority of the industry, fan manufactures are well versed in the methods to measure and calculate sound power levels of their products. However, acoustical engineers should not blindly accept

Table 3. Measured vs. modeled reverberation times for DTWB tunnel.

	Broadband and Octave Band Reverberation Time (T60), Seconds									
Data Source	**dBL**	**32 Hz**	**63 Hz**	**125 Hz**	**250 Hz**	**500 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**
Measured	6.94	31.94	19.96	8.84	5.16	5.39	5.02	3.56	1.77	0.66
Modeled	N/A	43.79	21.89	19.36	6.31	5.35	4.14	3.40	1.42	1.65

the makers' published sound power data. Good professional practice and due diligence requires the acoustical engineer to trust but verify the validity of any data they use as input for their prediction models. For as the old GIGO adage says, "garbage in, garbage out."

Postscript

In the months that followed, PB acoustical engineers visited Acme Fans' manufacturing facility to review its sound power test procedures. Several errors were found including:

- Inadequate emission levels from its RSS given the high-background-noise conditions.
- Inappropriate measurement point locations.
- Acme Fans' RSS was long out of calibration.
- The company had a fundamental misunderstanding of calculating octave band levels from third-octave-band data.
- Acme was inconsistent using unweighted versus A-weighted spectral sound data in its sound power calculations.

PB identified these shortcomings in Acme Fans' sound power testing procedure and provided guidance on the correct methods to perform the tests. Acme Fans embraced and implemented PB's recommendations, and its more recent jet fan sound power data are much more realistic.

Acknowledgements

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Reference

1. *Acoustics – Determination of Sound Power Levels and Sound Energy Levels of Noise Sources Using Sound Pressure – Engineering/Survey Methods For Use* In-Situ *in a Reverberant Environment,* International Standard ISO 3747:2010, International Organization for Standardization, Geneva, Switzerland, 2010.

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