

Progress in Aeroacoustic and Climatic Wind Tunnels for Automotive Wind Noise and Acoustic Testing

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ABSTRACT

There has been significant progress in developing test facilities for automotive wind noise and automotive components since the early 1990s. The test technology is critical to the development of modern vehicles, and essentially every major automotive manufacturer owns and operates their own aeroacoustic wind tunnel, or has rental access to one and conducts a significant amount of wind noise testing. The current status for climatic wind tunnels is that many new CWTs are being defined with acoustic test requirements. These test capabilities in AAWTs and CWTs will continue to enable the development of vehicles with better wind noise attributes, fewer problems with sunroof 'booming', and lower noise levels for HVAC and auxiliary systems. In the future, it is expected that the test demand for AAWTs and CWTs with low acoustic background noise will continue to increase as customers expect better automotive products, especially across more of the product line.

The objective of this work is to present some of the progress and challenges involved in designing wind tunnels with low background noise in order to meet the requirements of automotive companies for their product development needs.

CITATION: Duell, E., Walter, J., Yen, J. and Nagle, T., "Progress in Aeroacoustic and Climatic Wind Tunnels for Automotive Wind Noise and Acoustic Testing," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(1):2013, doi: 10.4271/2013-01-1352.

INTRODUCTION

The automotive industry has seen a very significant increase in the role of aeroacoustic wind tunnels for wind noise testing since the early 1990s. One of the first purpose-built aeroacoustic wind tunnels (AAWT) for full scale automotive testing came on-line in 1986 [18]. Within ten years, four more wind tunnels were either built new or retro-fitted for automotive wind noise testing. The publication of "Automobile Wind Noise and Its Measurement", SAE SP-1184 [1], in 1996 included a survey of the status of automotive wind tunnels, and their applicability for wind noise testing. Since 1996, another 10 wind tunnels were either built new or retro-fitted for automotive wind noise testing.

The acoustic design requirements for wind tunnels also need to be balanced against aerodynamic, temperature control, and fan power requirements, along with the integration of test equipment such as ground simulation systems, traverses, etc. While the highest-level noise source in a wind tunnel (WT) is the fan, most mid and high frequency fan noise can easily be attenuated in a traditional WT layout with sufficient acoustic treatment. Since the fan is usually located in the backleg of the wind tunnel circuit, mid

and high frequency noise can be effectively reduced with circuit acoustic wall lining, baffles, or turning vanes. Low frequency ($f < 100$ Hz) noise is also attenuated with the components listed above, but with lower effectiveness of acoustic absorbing materials in this frequency range. It therefore becomes a major cost factor in the wind tunnel to reduce low frequency fan noise. Special emphasis needs to be made on the design and selection of the axial fan to produce low sound power, in addition to high aerodynamic efficiency and good downstream flow uniformity. Important factors in reducing fan noise are elimination of inlet guide vanes or nosecone supports, fan rotational speed, fan blade profiles, blade-stator separation distance, and stator sweep. Recently [2,3] emphasis has also been made on the relative number of blades and stators, to reduce the low frequency blade-stator interaction noise.

The result of these successful methods to reduce fan noise is that the lower level noise sources have become more important in defining WT background noise levels. These secondary sources include boundary layer noise in the test section, shear layer noise, and self-noise from flow through the heat exchanger, honeycomb, or screens. Therefore, it becomes important to identify, rank, and understand these

noise sources in order to make progress to reduce WT background noise levels. This has required changes in the designs of some wind tunnel components that allow the aerodynamic requirements to be met while also meeting the requirements for low levels of self-noise.

Secondary noise sources that contribute significantly to AAWT test section background noise levels include boundary layer noise in the contraction, nozzle, and along the test section floor, shear layer flow interaction with the collector, shear layer noise, and flow interaction with the boundary layer removal systems. Although these are relatively weak noise sources when compared directly with other noise sources (e.g. self-noise of airflow through screens or the heat exchanger), they are significant in magnitude in the test section, where the flow velocity is highest. The sound power of these dipole and quadrupole noise sources scale between V^5 and V^7 , where V is the local velocity. In addition, as there is essentially no distance between the noise sources in the test section and the test vehicle, direct acoustic damping of the noise is not possible. Instead, it is more critical to minimize or eliminate the noise sources in the test section. This paper examines the progress in minimizing some of these noise sources.

This work also addresses the increase in acoustic test capabilities that are being incorporated into climatic wind tunnels (CWT). While acoustic testing in AAWTs is focused on identifying and reducing wind noise, acoustic testing in CWTs is focused on reducing noise from the engine (misfires), drivetrain (transmission hesitation), auxiliary components (air conditioning compressor) and passenger compartment temperature control systems.

The topics covered in this paper concern the frequency range for normal wind noise testing of full-scale vehicles, typically considered to be 20 Hz to 10 kHz. Infrasound levels ($f < 20$ Hz) are also an important consideration for open jet aeroacoustic wind tunnels, since it can influence the velocity stability and also the axial static pressure distribution in the test section. This importance of infrasound in wind tunnels is recognized, but not addressed in this paper. The reason is that the sources of infrasound and methods to reduce infrasound are fundamentally different than the sound sources and noise reductions methods for the acoustic frequency range [4].

SURVEY OF AEROACOUSTIC WIND TUNNELS FOR AUTOMOTIVE TESTS

During the 1980s, there was a need to improve automotive design by minimizing wind-induced noise in the passenger interior. This led to a need for increased testing in full-scale automotive wind tunnels. The first wind tunnels used for automotive wind noise testing were the available aerodynamic wind tunnels, especially those with lower background noise levels. The first generation of automotive aeroacoustic wind tunnels was built in the 1980s. These facilities are characterized by standard turning vanes with

acoustic treatment, traditional wedge shaped sound absorption in the test plenum, and limited acoustic lining of the wind tunnel circuit. These first-generation automotive aeroacoustic facilities used many of the design features of the earlier AAWTs used for aerospace work. These were typically 5 - 25 dBA quieter than the pure aerodynamic wind tunnels. The second-generation of wind tunnels used for automotive wind noise testing were built, or modified, since the early 1990s. These facilities are characterized by turning vanes integrated with acoustic baffle sections, open jet test section plenums with robust absorption material tuned for low frequencies, more acoustic lining of the circuit and fan section, and selection of fans with low acoustic signature. Typically, these facilities are 10 - 15 dBA quieter than the first-generation automotive aeroacoustic wind tunnels.

One important factor for automotive wind noise measurements is low test section background noise levels in the audible range from ~ 20 Hz to 10 kHz. Because full-scale vehicles are tested at actual road velocities, scaling of frequencies to the human audible range is not needed. Broadband noise sources that usually dominate the automotive interior acoustic signal are related to A-pillar vortex flows or separated flows on the side or rear of the vehicle. Tonal noise sources (roof racks, antenna, grill whistle) are also a concern with automotive designs, but once identified and controlled, tonal noise are typically not the dominant noise source. Significant automotive wind noise sources such as A-pillar side glass noise, mirror induced noise, and antenna or grill whistle usually are at mid and high frequencies [5, 6, 7], and the frequencies of these sources scale with velocity. Vehicle aeroacoustic sources at low frequencies, such as the separated wake region, are not particularly strong. Therefore, test section background noise at low frequencies needs to be specified to be low enough so that the background noise does not influence the vehicle's wind noise signal at low frequencies.

Another important factor for automotive wind noise measurements is a hemi-anechoic test environment. The preferred wind tunnel configuration for automotive wind noise testing is a $\frac{3}{4}$ open jet test section. It is simpler to integrate acoustic treatment into an open jet plenum than into closed test section walls, which are exposed to the maximum test section velocity. Also, the open jet configuration allows easier use of exterior sound measurement techniques such as phased arrays or microphone mirrors. Finally, the open jet is inherently quieter than a closed wall test section because there is less surface area for the boundary layer noise source. It is shown in the sections below that the high velocity flow in the test section creates significant boundary layer noise. For frequencies above ~ 6 kHz, boundary layer noise source is more significant than shear layer noise, at least up to velocities of 250 km/h.

Although the traditional goal for a wind tunnel test environment is a very low turbulence level, significant research since the mid 1990s has shown that this is not fully representative of the real on-road wind environment that

Table 1. Overview information and defining parameters for full-scale automotive aeroacoustic wind tunnels.

Aeroacoustic Wind Tunnel	Location	Year Opened / (Latest Acoustic Upgrade)	Test Section / Nozzle				Max Velocity (kmh)	Cont. ratio	Fan Power	Ref. #
			WxH (m)	Area (m ²)	T.S. Length (m)	T. S. Type				
Audi (AAWK)	Ingolstadt, Germany	1999	3.94 x 2.8	11.0	9 to 10	3/4 Open Jet	300	5.5	2.6 MW	2
BMW Technik	Munich, Germany	1987 / (2002)		10.0	9.8	3/4 Open Jet	250	3.0	1.9 MW	28
BMW AVZ (2 nozzles)	Munich, Germany	2008	6.5 x 3.85	25.0	14.0	3/4 Open Jet	250	5.7	4.1 MW	33
			5.43 x 3.32	18.0	14.0	3/4 Open Jet	300	8.0		
Chrysler AAWT	Detroit, USA	2002	6.9 x 4.03	27.9	15.25	3/4 Open Jet	257	5.4	4.6MW	20
DNW (4 test sections)	Netherlands	1980	9.5 x 9.5	90.2	20.00	Closed	223	4.8	12.6MW	1, 15
			8 x 6	48.0	20.00	Closed	417	9.0		
			6 x 6	36.0	16.00	Closed	547	0.5		
			8 x 6	48.0		Open Jet	306	9.0		
Ford - Europe	Cologne, Germany	1984 / (1997)		20.0	10.50	3/4 Open Jet	190	4.8	~2 MW	27
Ford DTF WT8 (2 nozzles)	Detroit, USA	2001	5.56 x 3.34	18.6	14.33	3/4 Open Jet	192	6.0	1.93MW	35
			4.15 x 2.54	10.5	13.41	3/4 Open Jet	241	10.9		
General Motors (GMAL)	Detroit, USA	1980 / (2001)	10.3 x 5.5	56.0	21.30	Closed	233	5.0	2.25 MW	32
GIE S2A	Paris, France	2003	6.38 x 3.7 (w/ fillets)	24.0	15.1	3/4 Open Jet	245			24
Honda	Japan	1991	7 x 4	28.0	13.25	3/4 Open Jet	200	6.0		17
Honda	Sakura, Japan	2010	6.7 x 3.6	24.0	14.50	3/4 Open Jet	200	6.0	3.6MW	21,22
Hyundai (HAWT)	Korea	2000	7 x 4	28.0	18.00	3/4 Open Jet	200		2.55 MW	23
IVK (FKFS)	Stuttgart, Germany	1988 / (1994)	5.8 x 3.87	22.5	9.94	3/4 Open Jet	263	4.4	2.98 MW	26
Nissan (2 nozzles)	Japan	1986	7 x 4	28.0	12.00	3/4 Open Jet	190	6.4	2.2 MW	18
			5 x 3	15.0	12.00	3/4 Open Jet	270	12.0		
Pininfarina	Italy	1972 / (1996 & 2005)	2.82 m radius semi-circle	11.0	8	3/4 Open Jet	260	6.9	3.1 MW	29 - 31
RTRI (2 test sections)	Japan	1999	5.0 x 3.0	15.0	20.00	Closed	300	8.0	7 MW	34
			3.0 x 2.5	7.5	8.00	3/4 Open Jet	400	16.0		
Tongji Univ. / SAWTC	Shanghai, China	2009	6.5 x 4.25	27.0	15.00	3/4 Open Jet	250		4.12MW	25

automobiles experience [8, 9, 10]. Research has shown that turbulence levels can affect both mean and time dependent aerodynamic values [11], vehicle wind noise measurements [12], and vehicle cooling. The Pininfarina wind tunnel has been modernized to include a Turbulence Generation System (TGS) that can produce controlled levels of turbulence with varying frequency and length scale [13]. The TGS also can be retracted so that the normally low levels of turbulence in the wind tunnel can also be produced. This allows vehicle test engineers the possibility of testing across a range of turbulence levels to ensure that a vehicle design that is optimized in a low turbulence environment is also suitable in a realistic, higher turbulence on-road environment. This unique test capability among aeroacoustic wind tunnels offers engineers a new tool to develop more efficient and quieter vehicles.

Because most automotive companies develop several new vehicles each year and continue to upgrade existing models, there is a growing need for aeroacoustic wind tunnel test time. This has led most automotive companies to acquire aeroacoustic wind tunnels, or perform aeroacoustic upgrades on existing full-scale wind tunnels. Worldwide, in the past twenty years there are at least fifteen new, upgraded, or planned (or in construction) full scale AAWTs in the

automotive industry. Table 1 is a comparison of defining parameters for these wind tunnels that are currently in operation. Data presented in this table are from the literature listed in the references. The table is an updated version of information presented by Hucho [14], Mercker and Pengel [15], and Duell, et. al. [16].

Comparison of Modern Full Scale Aeroacoustic Wind Tunnels

Figure 1 and Figure 2 compare the overall sound pressure levels (OASPL, dBA) in AAWTs as a function of test velocity. The out-of-flow OASPLs shown in Figure 1 contain data from wind tunnels used by the automotive industry. Measurements in most of these wind tunnels were made 6 m to the side of the turntable center (exceptions are 5 m at Hyundai, and 5.5 m at Chrysler). Therefore, the data in Figure 1 are generally comparable. The inflow data shown in Figure 2 contains OASPL data [17] measured at the turntable center.

It should be noted that a comparison of wind tunnel background noise OASPL (dBA) does not capture all of the important elements of the acoustic characteristics of a wind tunnel. For example, differences in low frequencies are not

well represented by an OASPL (dBA) comparison. To more compare two facilities more accurately, the acoustic background noise spectra at the same velocity should be compared. This is important if wind noise testing is conducted in multiple AAWTs. With global automotive firms and multi-company collaboration on vehicle platforms, vehicle development in multiple wind tunnels is becoming more common. However, considering the objective of this work and the number of facilities compared in this paper, space constraints preclude that level of comparison.

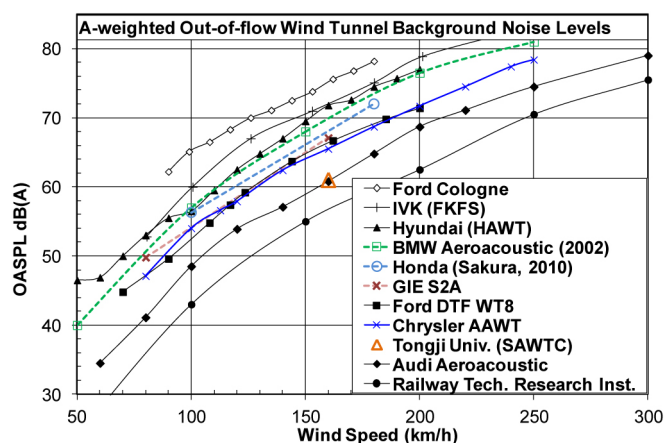


Figure 1. A-weighted out-of-flow background noise levels (OASPL) vs. wind speed for several automotive aeroacoustic wind tunnels. Note that the top to bottom order in the legend corresponds to the OASPL relative order on the plots.

km/h, showing the recent emphasis that the automotive industry has placed on aeroacoustic wind tunnels.

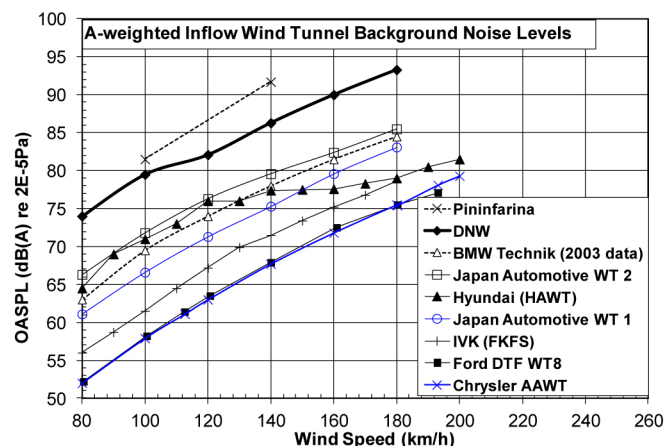


Figure 2. A-weighted in-flow background noise levels (OASPL) vs. wind speed for several automotive aeroacoustic wind tunnels.

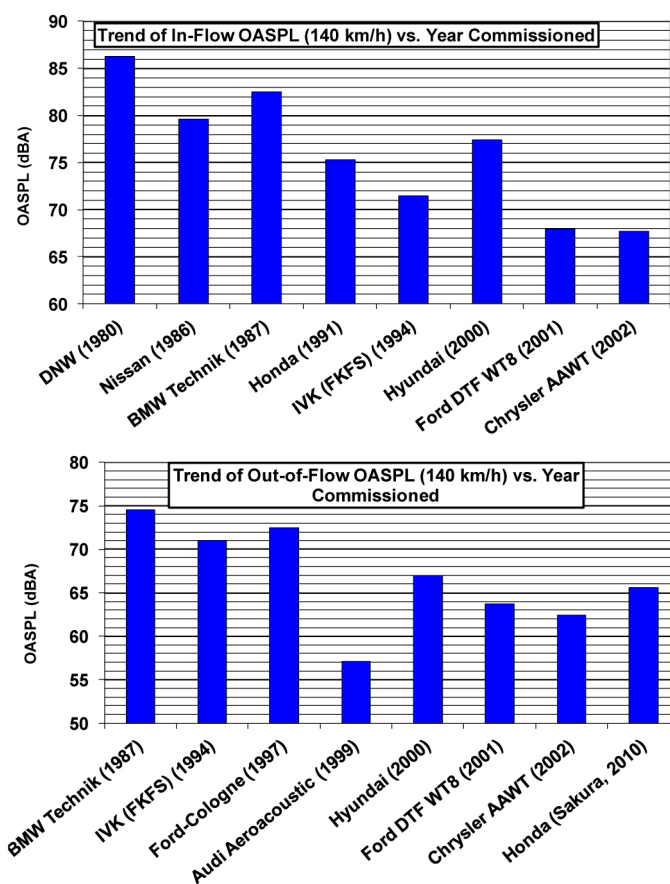


Figure 3. Chronological progress of improvements in full scale automotive aeroacoustic wind tunnels since the late 1980s as reflected by reduced test section noise levels at 140 km/h. Both inflow and out-of-flow data shown.

In the early 1990s, Mercker and Pengel [15] published a detailed comparison of the acoustic capabilities of wind tunnels used by the automotive industry. They concluded that only 6 of the 13 European and North American wind tunnels evaluated in the study were 'fully suitable' for automotive aeroacoustic development work. At the time of their analysis, much vehicle wind noise development work was still done in pure aerodynamic wind tunnels, due to the lack of available aeroacoustic wind tunnels. The data shown in Figure 1 and Figure 2 present the progress made in aeroacoustic wind tunnels since the late 1980s. Since then, most of the automotive wind tunnels (besides DNW, and Nissan [17,18,19]) presented in Table 1 have been newly built (Audi [2], Chrysler [20], Honda (2 WTs) [17, 21,22], Hyundai [23], Ford DTF WT8 [35], GIE S2A [24], Tongji Univ/ SAWTC [25]) or have had significant aeroacoustic upgrades (IVK [26], Ford Cologne [27], BMW Technik [28], Pininfarina [29,30,31], GMAL [32]). Some of the most recent wind tunnels, optimized in the design stage for minimum test section acoustic levels, have out-of-flow levels that are 10 to 15 dBA lower than the quietest automotive wind tunnels that existed in the early 1990s. The year after year improvements for aeroacoustic wind tunnel background noise OASPL are shown in Figure 3 for inflow and out-of-flow data at 140

The list of full-scale automotive aeroacoustic wind tunnels in Table 1 contains more entries than shown in Figure 1, Figure 2, Figure 3; the results presented in these figures contain the available open literature data. For example, some open jet wind tunnels have not published out-of-flow noise level data, and other facilities have not published any background noise level information. The noise levels from the BMW AVZ facility [33] are not published because the plenum acoustic treatment has not been installed and therefore the full acoustic capabilities have not yet been realized. The RTRI facility in Japan [34] has very low noise levels, but with a 15 m² closed wall test section, it is designed and more suitable for scale model high speed train tests than for automotive tests.

NOZZLE / TEST SECTION LENGTH AND SURFACE ROUGHNESS

Experimental Description

The authors conducted an experimental test program to better understand and quantify the effects of test section length, nozzle surface area and nozzle surface roughness on noise generation in an open jet test section AAWT. The tests were conducted in the DTF WT8 wind tunnel [35] in the small nozzle (10.5m²) configuration with different nozzle extensions. Prior work [36] showed that the noise at frequencies above about 300 Hz in the test section of this wind tunnel could be attributed to noise sources in the test section. These noise sources include boundary layer noise from the contraction, nozzle, and test section floor, shear layer flow interaction with the collector, shear layer noise, and flow interaction with the boundary layer removal systems. To study the effects of the boundary layer noise, five nozzle configurations were investigated.

Config 1. Baseline small nozzle

Config 2. add 2.5 m smooth steel nozzle extension

Config 3. add 4.2 m smooth nozzle extension

Config 4. add 4.2 m nozzle extension, final 1.7 m 'rough'

Config 5. add 4.2 m nozzle extension, final 1.7 m with 'pile fabrics' material

For the study, microphones were located out-of-flow at $\theta = 90^\circ, 60^\circ, 45^\circ, \text{ and } 30^\circ$ relative to the test section centerline axis, as shown in Figure 4. The microphones were 5 m from the centerline axis and 1 m above the floor. When the nozzle extensions were added, the microphones were moved so that the angles of the microphones relative to the centerline were kept constant.

The smooth nozzle extensions for configuration 2 and 3 had an estimated roughness between 0.05 and 0.1 mm. The 'rough' nozzle configuration was created with 24 grit sandpaper (~ 0.75 mm grit) installed on the last 1.7 m of the nozzle walls and ceiling, for a total of 15.7 m² of 'rough' area.

Results from Nishimura [37], Pollenske [38], and Bergmann [39] show that 'pile fabric' material are useful for reducing noise sources in AAWT test sections. Nishimura defines 'pile fabrics' as "cloth materials with fine and high density fibers like fur or down, that are used to cover the body surface." In the wind tunnel community, pile fabrics are commonly referred to as 'teddy bear fur' due to the original usage. For this study, the use of pile fabrics on the nozzle surface was investigated as a means to reduce boundary layer self-noise from the nozzle. This configuration was created by gluing ~ 10 mm deep pile fabric material on the last 1.7 m of the nozzle walls and ceiling before the nozzle exit.

Figure 5 shows the DTF WT8 small nozzle with the 4.2 m nozzle extension (configuration 3) and microphones located out-of-flow. Figure 6 show the overview setup of the 'rough' nozzle surface installation (configuration 4) and the details of the pile fabric that was installed and tested (configuration 5).

Out-of-flow background noise data in the empty test section were recorded at 110, 140, 160, and 180 km/h at a 22 kHz sample frequency. For $f > 250$ Hz, the uncertainty in the measurements was estimated to be ~ 0.4 dB.

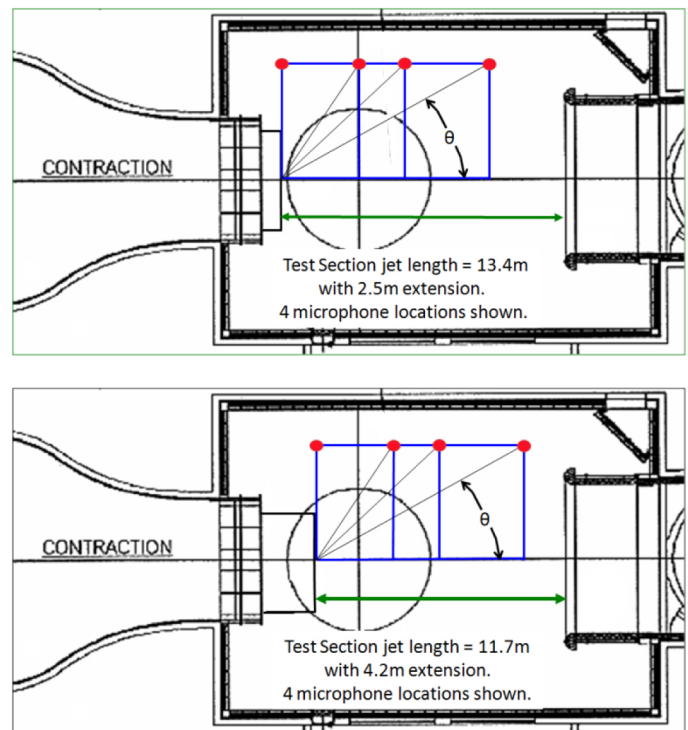


Figure 4. Plan view of test section with two nozzle extensions and locations of microphones for study of nozzle length and surface roughness noise. θ is the angle between the centerline axis and the microphone position.