

The Windshear Rolling Road Wind Tunnel

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ABSTRACT

The Windshear Rolling Road Wind Tunnel in Concord, North Carolina, is a full-scale commercial wind tunnel conceived primarily as a facility to serve the various motorsports communities, although it has already expanded beyond that base into production car and truck testing. The wind tunnel is a $\frac{3}{4}$ -open-jet, closed-return design with a 16.7 m² nozzle, a wide-belt moving ground plane, and a top speed of 80 m/s (180 mph). This paper describes the project history and design philosophy of the wind tunnel, commissioning results, and an overview of the force measurement methods on the wide-belt rolling road. Some results of a recently-completed correlation program are presented, along with performance validation results that include repeatability and reproducibility as well as an assessment of boundary corrections.

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INTRODUCTION

The Windshear Rolling Road Wind Tunnel grew from a passion for motorsports and technology. The entrepreneur Gene Haas, founder of the international machine tool company Haas Automation Inc., had been fielding the Haas CNC Racing team in NASCAR's premier Winston (Sprint) Cup racing series for several years. Mr. Haas had the idea to construct a facility that could support the ongoing aerodynamic development of race cars for his team, and generate revenue by selling the excess capacity to others in the racing industry. The initial thought was to build a rather simple open-return wind tunnel with a traditional under-floor balance. However, consultation with key technical specialists from NASCAR and Indy Car teams led to a considerably different solution, which was to be based on a wide-belt moving ground plane enclosed by an open-jet closed-return wind tunnel.

An order was placed for the moving ground plane system in the summer of 2006. However, although a location was planned so that the facility would be close to many of the NACAR teams, a specific site had not yet been selected. Property specialists Triliad Development Inc., having successfully managed previous Haas Automation capital projects, were retained to locate and develop a site, and to manage the overall project. Triliad selected a site near the Concord (North Carolina) Regional Airport and worked with local authorities to build a new electrical substation to support the facility and future development in the area. Jacobs Technology was selected to design and build the wind tunnel and serve as the general contractor.

Groundbreaking at the Windshear site took place in March 2007. The rolling road machine arrived on site in October 2007, followed by the main fan section in December. Construction of the concrete circuit and adjacent building were complete by the end of January 2008, when Windshear received its Certificate of Occupancy. The completed facility is shown in [Fig. 1](#).



Figure 1. Aerial views of the Windshear Facility

Haas Automation also selected Jacobs to provide ongoing operations and maintenance services as part of an overall philosophy to ensure the security and confidentiality of all Windshear customers. This included various security features designed into the facility. [Figure 2](#) shows the facility floor plan. Four separate work bays can be seen adjacent to the central corridor that leads to the test section and control room. Each work bay has separate, programmable security badge access, a machined floor plate for precise vehicle set-up, ample space for tools and computer hook-ups, and a kitchenette, lavatory, and television. Customers typically arrive the day before their allotted time in the wind tunnel and are able to prepare their vehicles for testing without interruption and unaware of other customers who may also be in the facility.

The facility was commissioned during the first quarter of 2008, followed by a period of operational readiness in which basic work process flows and test techniques were developed with key customers. The first commercial customer was a [Formula 1](#) team in June 2008, only fifteen months after groundbreaking. The remainder of the paper provides an overview of the technical features of the Windshear design and also discusses some basic performance results, including repeatability and reproducibility, correlation with other facilities, and an assessment of boundary corrections.

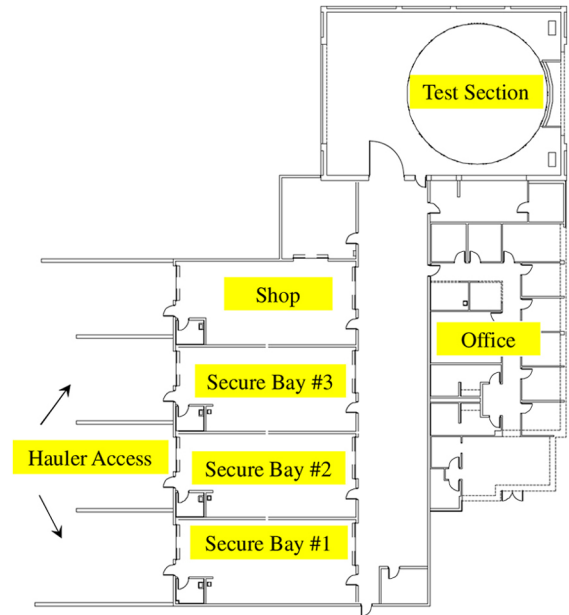


Figure 2. Building floor plan

DESIGN AND PERFORMANCE CHARACTERISTICS

AIRLINE

As shown in [Fig.1](#), the entire circuit was constructed from poured-in-place concrete, except the fan section. The site had a natural slope, which, while undesirable for most developments, was well-suited for a wind tunnel with large corner and plenum foundations at multiple levels.

[Figure 3](#) shows the Windshear airline. The air is driven by a 6.7-m diameter, 3.8 MW fan provided by Flakt-Woods, with a Rockwell variable frequency drive for precise airspeed control. While the details of individual facilities are always different, the overall philosophy employed in the design of the airline components was the same as other recent automotive wind tunnels [[1,2,3,4,5](#)] - to minimize the circuit footprint (capital cost) while taking care not to create flow separations and other instabilities throughout the circuit, which can then be only partially cleaned up in the flow conditioning section at the cost of increased fan power and circuit length.

Corners 1, 2, and 4 consist of plate steel circular-arc turning vanes with leading and trailing edge extensions. Corner 3 is an expanding corner (outlet area 37% greater than the inlet area), so double circular arc airfoil vanes are used to control the diffusion as the flow turns. Whenever an element of the airline departs from a previously-proven design, additional efforts are necessary to ensure proper performance, such as computational or physical modeling. In the present case, the Corner 3 layout was sufficiently different from earlier designs to warrant computational simulations to ensure attached and relatively uniform flow coming out of the

turn. Figure 4 shows an example result, in which symmetry about the horizontal centerline has been assumed.

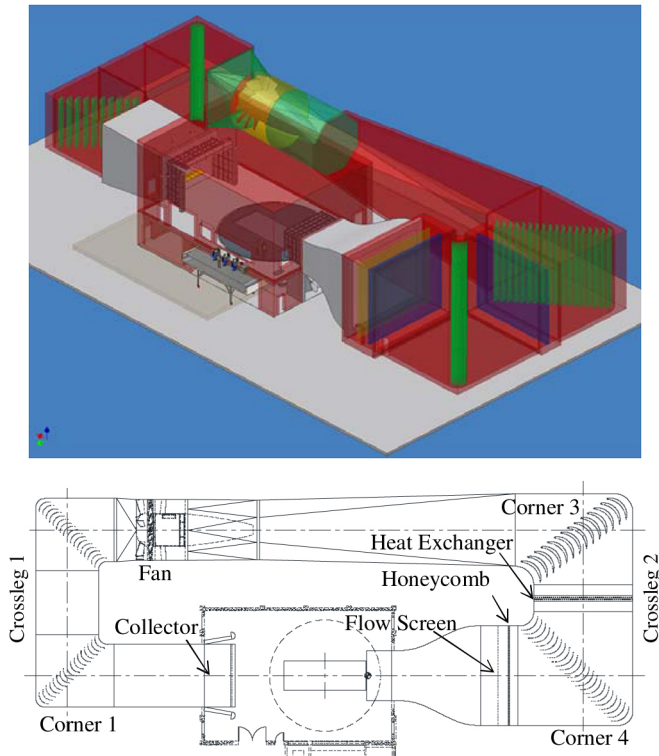


Figure 3. Windshear airline

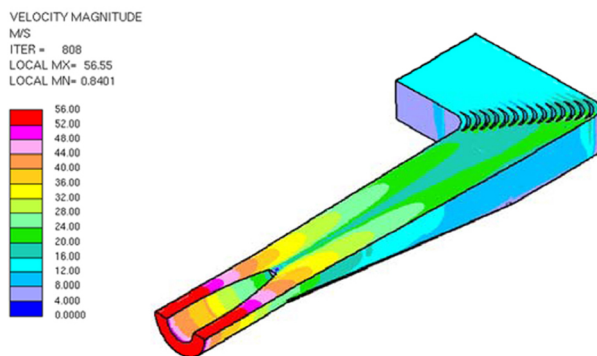


Figure 4. Calculated velocity contours in the backlog diffuser through Corner 3

The tube and fin heat exchanger is located downstream of Corner 3 in the second crossleg. Flow through the circuit is maintained at $24^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$ by regulating the temperature of secondary coolant through the heat exchanger tubes. The secondary fluid is a water/glycol mixture from a standalone chiller plant adjacent to the backlog of the circuit (Fig. 1).

The settling chamber contains a honeycomb flow straightener and a single turbulence reduction screen. While minimizing the crossleg length and overall circuit footprint, the diffusing third corner also provides a long settling length into the contraction, as the cross-sectional area does not

change from the outlet of Corner 3 all the way through the settling chamber. So, a properly-designed diffusing corner is consistent with the philosophy of maintaining a clean circuit flow and minimizing the need for additional flow conditioning elements. The contraction ratio from Corner 4 to the start of the constant-area nozzle section is 5.9. The primary suction scoop of the boundary layer control system is inside the nozzle, so accounting for this, the net contraction ratio is 6.0 at the nozzle exit plane, whose cross-sectional area is 16.7 m^2 .

TEST SECTION AND DATA SYSTEMS

Figure 5 shows a view looking downstream from the nozzle exit plane (NEP). A NASCAR vehicle is shown in the photo restrained at three of the four wheel hubs. At the end of each restraint is a bi-axial load cell on top of a mounting tower that is fixed to the T-slots on either side of the stainless steel moving belt. The methods for vehicle restraint and force measurement are discussed in more detail later in the paper. In Fig. 5, the control room is on the left, so the customer sees flow from right to left. The control room extends along nearly the entire plenum wall. The vehicle entry door is at the rear of the test section just upstream of the collector and is visible in the figure.

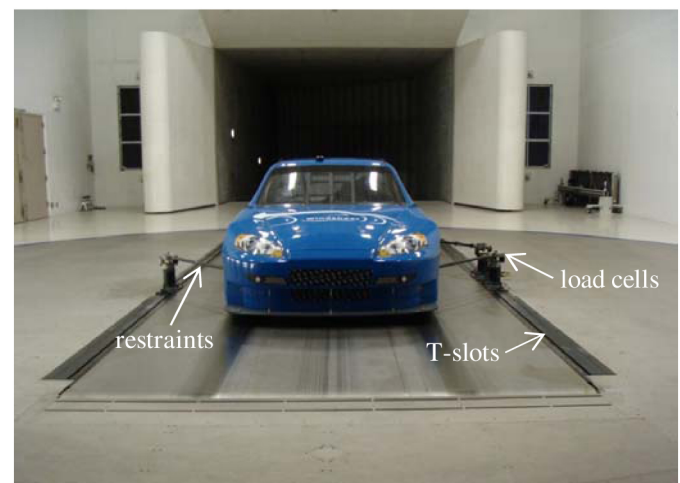


Figure 5. Windshear test section

The nozzle is 5.49 m wide by 3.05 m high. The vehicle center is normally installed 4.07 m downstream of the NEP, which is consistent (scaled by nozzle diameter) with similar test section designs [1,2]. The test section length is 14.5 m from the NEP to the inlet plane of the collector flaps. The long test section combined with a large collector area (2.73 times the nozzle area) is appropriate for the large wakes behind motorsports vehicles. The plenum is vented to the outdoor atmosphere by several openings in the plenum walls.

The moving ground plane surface is a single-belt Rolling Road system provided by MTS Systems Corporation. Wide-belt ground simulation is widely regarded in the motorsports industry as a requirement for proper aerodynamic simulation.

particularly for downforce measurements. It was envisioned from the beginning that this constituency would make up the majority of Windshear's customer base, so a 5-belt or other simpler ground simulation configuration was not considered. The belt is 8.9 m long, 3.2 m wide, and the front roller is even with the nozzle exit plane. A view of the moving ground plane from below the test section floor is shown in [Fig. 6](#). The belt is integrated into a turntable to provide ± 8 deg yaw capability. The entire system rests on hydrostatic bearings at the foundation interface to allow for the yaw. The maximum vehicle weight per corner, including aerodynamic downforce, is 7000 N. The wheelbase range is 2.12 m to 3.67 m, and the track width range is 0.66 m to 2.21 m. The wheel load pads under the belt and air bearing system are remotely adjustable. Each contains three load cells to track the tire's center of pressure in real time. Each load pad moves independently from the other three, which allows fore/aft adjustability in the vehicle installation.



Figure 6. Windshear wide-belt moving ground plane viewed from below the test section

Extensive modifications to road-ready vehicles are not necessarily required before a test. However, fluids must be removed for safety reasons, so if a particular vehicle has driveline components that require circulating fluids for lubrication, then they must be disconnected, which also means some provision must be made to hold bearings in place. Disconnecting driveline components also reduces variability if drag measurements are of interest, as does removal of the brake pads. For production vehicles, the steering is typically locked in the straight-ahead position. Many configuration changes can be made to the vehicle without removing it from the belt; protective mats are placed on the belt during such changes. If the vehicle has to be removed for a model change, the process requires about ten minutes, as does re-installation. Initial vehicle installation, shakedown, and warm-up usually require about thirty minutes.

There is no external balance associated with the moving ground plane. Horizontal forces are measured at each vehicle restraint shown in [Fig. 5](#). Horizontal forces at the tire contact patch are either measured with wheel force transducers or

removed by tare. Methods developed at Windshear to determine the aerodynamic forces and moments are discussed in further detail below. MTS has developed technology to measure vertical forces using load cells under the belt that can measure through it. This technology has been applied widely in [Formula 1](#) wind tunnels. Windshear was the first full-scale wind tunnel to employ through-the-belt measurement capability. BMW [3] subsequently put a wind tunnel into operation in 2009 with a wide-belt rolling road capable of testing full-scale vehicles, followed by Honda R&D [4] in 2010.

The boundary layer control system is shown in [Fig. 7](#). It consists of a primary suction scoop, sized and calibrated to remove the entire boundary layer build-up through the settling chamber and contraction, and two tangential suction slots, which are just inside the NEP and are immediately upstream of the belt's leading edge. The secondary system is integrated into the yawing turntable. A large flexible hose connects the ductwork into a stationary exhaust fan. All mass removed by the boundary layer control system upstream of the vehicle is ducted around the plenum and re-injected in the floor of the first diffuser, just downstream of the collector exit plane.

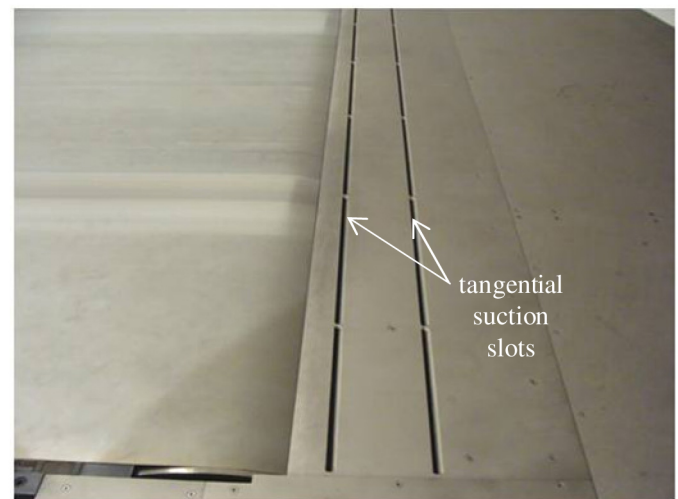
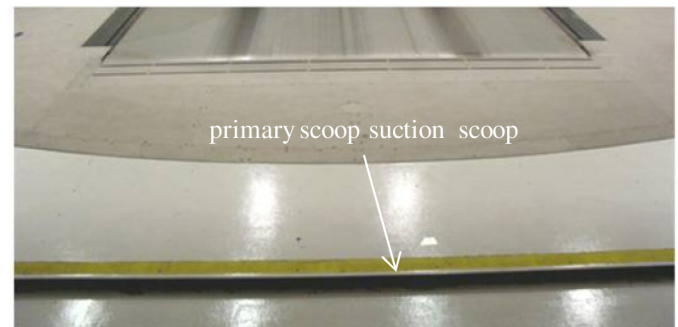


Figure 7. Primary boundary layer scoop and secondary tangential suction slots

The wind tunnel operates using the Jacobs Test SLATE automation software, which provides supervisory control of

all wind tunnel and vehicle on-board sub-systems, including the rolling road, on-board safety systems and automated vehicle ride height actuators. Nearly all tests are executed through programmed sequences which check for subsystem stability, acquire data, and change the appropriate set points for next measurement. This ensures maximum efficiency and allows customers to estimate test times with high precision.

The airspeed measurement system includes pressure instrumentation for the simultaneous and independent measurement of plenum and nozzle method dynamic pressures, as well as a redundant tertiary system that monitors for calibration drift in real time. The airspeed and dynamic pressure can be controlled based on the nozzle method or the plenum method, or both can be monitored, which allows the rolling road to be controlled to an airspeed that is corrected for blockage [6,7] in real time.

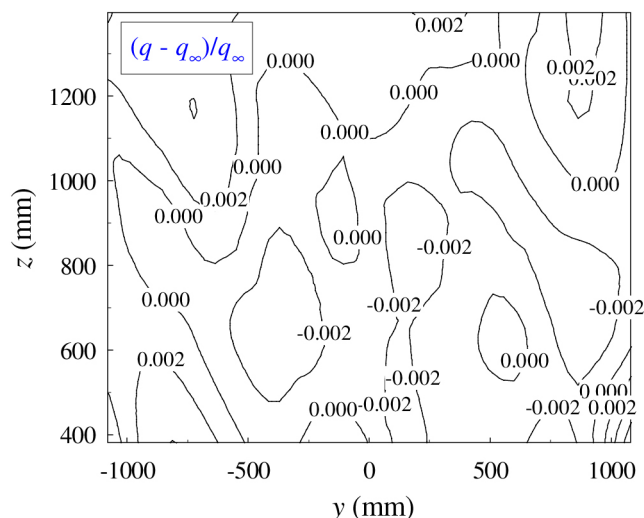
COMMISSIONING RESULTS

Final commissioning and calibration of the wind tunnel occurred during the first quarter of 2008. Some of the key results are presented in the following paragraphs. Unless otherwise noted, the coordinate system used throughout the remainder of the paper follows SAE J1594 [8], in which +x is downstream, +z is up, and +y is toward the passenger side.

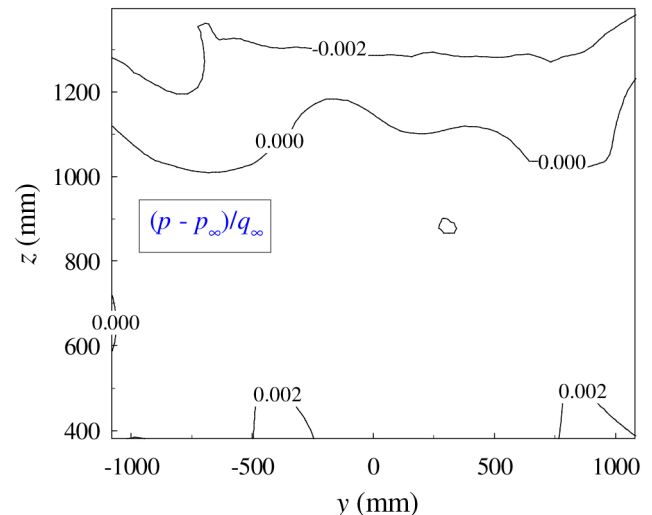
Flow Quality

Pressure uniformity, flow angularity, and turbulence intensity were all measured at maximum speed, 2.5 m upstream of the turntable center (nominally, the front bumper location), with the aid of a portable 2D (y-z) traverse anchored in the T-slots of the rolling road mechanism.

The pressure uniformity was measured on a 50-point grid with a 1-m long Pitot-static probe mounted into a 3-m long boom, which was in turn mounted to the traverse. Figure 8 shows results for these measurements, with no clear trends present, which is desirable.



(a). dynamic pressure, $\sigma = \pm 0.22\%$



(b). static pressure, $\sigma = \pm 0.18\%$

Figure 8 (cont'd). Pressure uniformity 2.5 m upstream of the turntable center at 80.5 m/s

Flow angularity was measured on a 12-point grid. A 4-hole probe and high-accuracy pressure transducer setup [3] was used, which has a repeatability of ± 0.008 degrees. Figure 9 shows the measured yaw and pitch angles. The yaw angle is almost uniformly negative for $y < 0$ and positive for $y > 0$, meaning that the horizontal cross-flow is away from the wind tunnel centerline, leading to an average value of 0.07 deg. The pitch angle is uniformly positive with an average value of 0.27 deg. A slight upwash is not uncommon in open-jet wind tunnels due to the asymmetric boundary conditions unless measures are taken to have adjustability [2,3,5] in the nozzle walls. In the present case, an artificial upwash was suspected (and subsequently confirmed with computational simulations) due to interference from the portable traverse, so no changes were made to the nozzle walls.

Turbulence was measured with a TSI IFA-300 constant-temperature thermal anemometer and a dual-sensor hot-film probe. A 5 kHz analog low-pass filter was applied in combination with a 10 Hz digital high-pass filter to attenuate electronic noise at the high end of the spectrum, and control system and infrasonic flow interactions at the low end. Measurements were made on a 12-point grid. Figure 10 shows results for longitudinal turbulence intensity, which range from 0.15% near the centerline to 0.26% at the edge of the grid. Spectra of the highest and lowest turbulence levels from Fig. 10 are shown in Fig. 11. The spectra are strikingly similar (even without consideration of the electronic noise corruption at 300 Hz and beyond). The only substantial difference appears around 15 Hz, where a peak of -52 dB is observed in the point measured at the edge of the grid. The peak does not exist in the measurement near the centerline. This peak is almost certainly a result of shear layer oscillation at this frequency that does not extend to the center of the

wind tunnel at this longitudinal location, and accounts for nearly all of the difference.

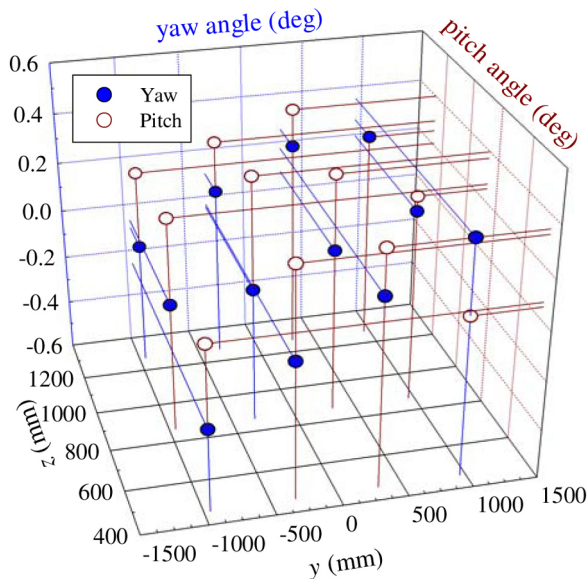


Figure 9. Flow angularity 2.5 m upstream of the turntable center at 80.5 m/s. Mean (yaw, pitch): (+0.07, +0.27) deg

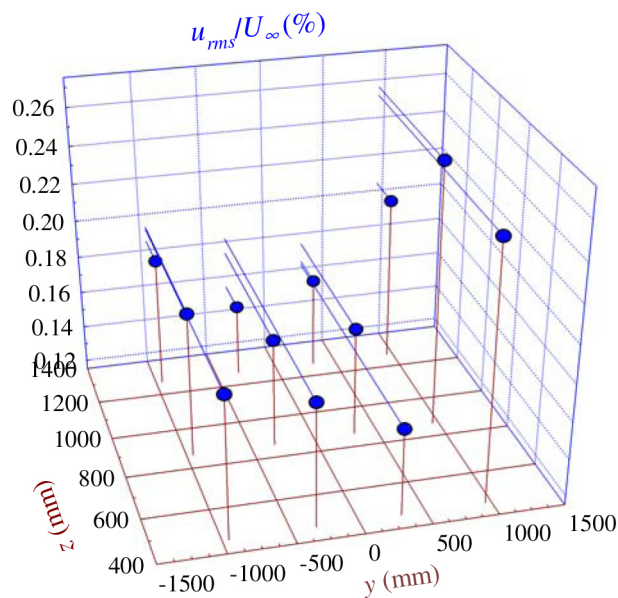


Figure 10. Turbulence intensity 2.5 m upstream of the turntable center at 80.5 m/s

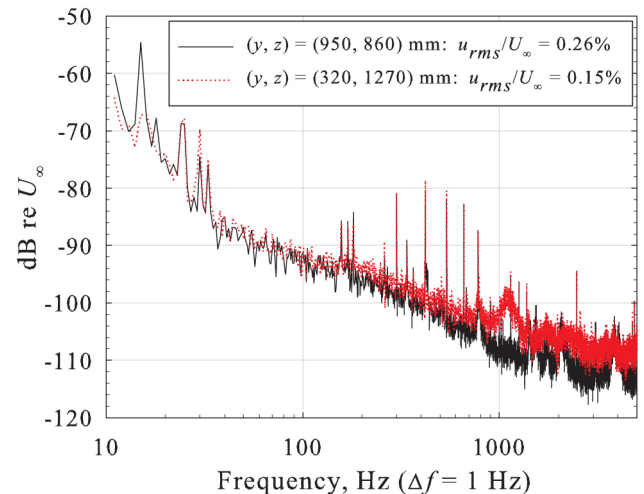


Figure 11. Selected turbulence spectra from the rms results in Fig. 10

Boundary Layer Control and Longitudinal Static Pressure Distribution

Boundary layer profiles were measured with a lightweight truss fixture having very low aerodynamic blockage that straddles the rolling road and is fixed by bolts into the T-slots. It can easily be moved fore and aft along the slots to make measurements at different longitudinal stations. The boundary layer probe rake can be lowered to within 2 mm of the moving ground surface. Figure 12 shows boundary layer profiles 2.5 m upstream of the turntable center, for both moving and static ground conditions. Full boundary layer control was in operation in both cases. The profiles are independent of speed in all cases, which indicates a proper system calibration and is to be expected for this relatively small Reynolds number range. As shown in Fig. 12, suction-only boundary layer systems are capable of producing extremely good boundary layer profiles, but this is at the expense of degradation in longitudinal static pressure gradient. The level of degradation depends on the amount of suction applied; as mass is removed from the flow field, it decelerates locally and the pressure rises.

The static pressure distribution was measured with a 1-m Pitot-static probe mounted to the top of the truss fixture, 1 m above the floor. This setup is also used for wind tunnel airspeed calibrations. Figure 13 compares the Windshear pressure distribution to several wind tunnels newly commissioned in the past decade. The Windshear pressure distribution changes in a roughly linear fashion from +0.003 to -0.003 over the central 6-m region, resulting in an average gradient of -0.001/m, which is quite low and extends over the full length and near-wake of many vehicles. Upstream of the model center, a negative gradient is observed. Although the slot suction approach used at Windshear results in a lower local pressure gradient than distributed porous suction

systems [9,10], the effect is unavoidable when mass is removed from the test section and not replaced.

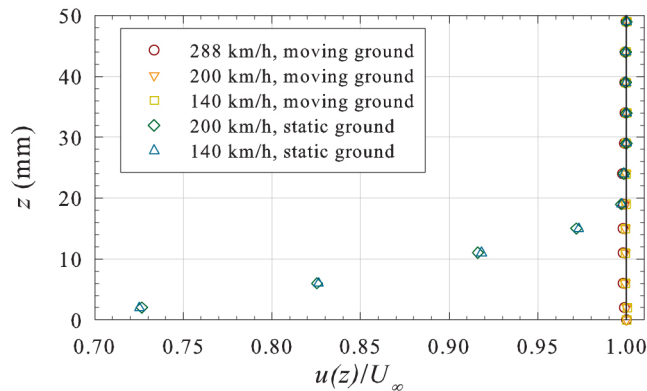


Figure 12. Boundary layer profiles 2.5 m upstream of the model center

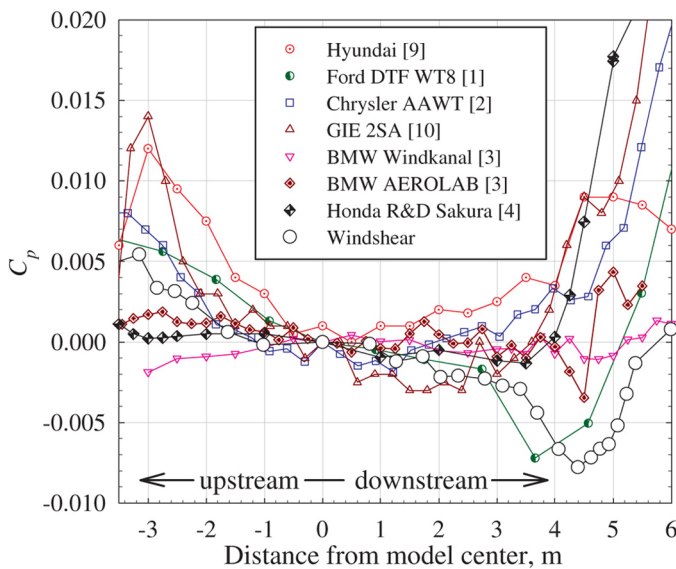


Figure 13. Comparison of pressure gradients in recently-commissioned wind tunnels

A relatively large dip (in this expanded scale) is evident between 3 m and 5 m. This is due to a complex interaction as the flow enters the gap between the rear roller and the fixed floor. (The interface is similar to the upstream roller interface shown in Fig. 7.) Apparently, the flow spills over the fixed floor plate and a stagnation point occurs at the lip of the floor plate. This would cause a pressure build-up upstream of the roller, near the belt. To maintain mass continuity, the flow farther away from the belt (e.g., 1 m, as in this measurement) would have to accelerate, which would result in the pressure drop observed in Fig. 13. A similar result was observed in the BMW AEROLAB [3] data, which also has a wide-belt rolling road. Duell et al. [11] also concluded that the pressure dip was due to the flow at the rear roller gap. The dip in pressure was not observed in the BMW Windkanal [3]; indeed, Duell

et al. [11] showed the same pressure distribution whether the belt was in operation or not. The BMW Windkanal has a 5-belt system with a much narrower roller and gap. Although the roller gap and floor plate are of a similar design, the influence of the local stagnation line on the flow far above may be less - the narrower stagnation line on the 5-belt system's floor plate allows for lateral (3D) relief.

Interaction with the downstream flow also likely influences the nature of the pressure distribution upstream of the roller gap. For example, the Honda R&D wind tunnel [4] also has a wide-belt rolling road very similar to Windshear and BMW AEROLAB, but the pressure dip is barely visible in Fig. 13. Those measurements were made 700 mm above the ground. The distance between the rear roller gap and the collector inlet plane is almost identical at Windshear and Honda R&D, and both have similar collector designs. However, the Honda wind tunnel is physically larger, and in particular the collector area is larger than that of Windshear. Consequently, the upstream influence of the collector's Bernoulli effect at Honda is observed in the pressure distribution all the way upstream to the aft end of the rolling road, whereas this evidently is not the case at Windshear. Indeed, it is shown later in this paper that the pressure dip is completely removed at Windshear when an adverse pressure gradient is introduced artificially downstream of the rolling road.

OPERATIONAL CHARACTERISTICS

The following sections describe some results of operations at Windshear since 2008. Methods for vehicle restraint, attitude control, force measurement, and tare process are discussed first. A rigorous process monitoring program has been implemented to ensure the measurements remain in statistical control. Some results of that ongoing program are provided next. A correlation with several production-car wind tunnels was conducted in 2011; some of those results are summarized below. Finally, an assessment of boundary corrections is presented, accounting for blockage effects, horizontal buoyancy, and wake distortion.

VEHICLE RESTRAINT AND FORCE MEASUREMENT

Vehicle Restraint and Attitude Control

The vehicle is usually restrained on the moving ground plane using a strut with circular cross-section that connects to a bi-axial load cell as shown in Fig. 14. Although a more streamlined shape may seem preferable, the local flow direction, especially very close to the vehicle, is always unknown, so the judgment was made early on to use a shape that is less sensitive to complex local flows, in spite of the fact that the tare forces are higher. Cables and combinations of cables and struts have also been used; any combination is possible as long as the vehicle remains mechanically stable

and each restraint tether leads to a load cell so that the reaction force can be measured.



Figure 14. Typical restraint locations for NASCAR vehicles (above) and production vehicles (below)

The bi-axial load cell provides force components in the x and y directions, and was developed by MTS to minimize crosstalk specifically in this application. The load cell tower is fixed to the T-slots. The clevis connection at the load cell end (Fig. 15, top) has ± 3 deg of rotation in the vertical direction. For a NASCAR vehicle, the connection is made at the hub of the wheel. The connection at the wheel is another bearing assembly that mounts to the wheel studs and uses two angular contact bearings that allow the strut to stay fixed while the wheel rotates. Although connection to the wheel hub can produce interference effects, this approach has significant advantages. First, installation and removal of vehicles is extremely fast and repeatable. A vehicle can typically be installed in about ten minutes. Second, the height of the strut does not need to be adjusted even as the vehicle body undergoes extreme attitude changes during a typical run. Tire growth due to centrifugal acceleration is possible. This would cause the height of the restraint strut at the wheel to be higher than at the load cell, and introduce an unmeasured vertical force component. However, tire growth on race tires has been observed to be very small.

Owing to the rather severe asymmetry of a track-ready NASCAR vehicle's suspension system, restraint connections are necessary at three wheels to keep the vehicle on the road:

both front wheels and the left rear wheel. For production vehicles, only two connections are normally needed for a stable installation; they are typically made at holes in the chassis frame rail (Fig. 15, bottom). The clevis connection at the vehicle end has as much as ± 13 deg of rotation in the vertical direction. (In reality, we expect 1 deg or less at both clevis connections, so a correction to the measured forces, if the restraint strut leaves the horizontal plane, is small or at least is not a first order concern.) The freedom to rotate in the vertical direction at both clevis connections allows the vehicle attitude to change without adjusting the strut height or binding/fouling the load cell. This means that a vehicle at Windshear does not necessarily require ride height control, and therefore the suspension and vehicle body are free to react to the wind forces as they would in a fixed-floor wind tunnel or indeed on the open road.

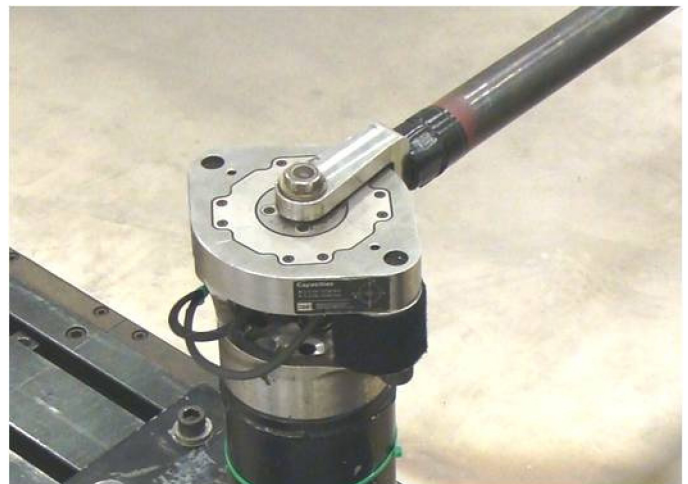


Figure 15. Restraint connection points at the load cell tower (above) and in the chassis frame rail (below)

Attitude control is nearly always used in motorsports tests but can also be used on production vehicles when requested by the customer. The attitude is adjusted with a ride height system on the vehicle. The system consists of three actuators, three lasers and a control system. The three actuators replace the four shock absorbers on the car: one actuator on the left front, one on the right front and a balanced hydraulic pair for the rear corners. The actuators attach to the upper and lower