

A Correlation Study of Wind Tunnels for Reduced-Scale Automotive Aerodynamic Development

Frank Meinert
General Motors Co.

Kristian Johannessen
GM Holden Ltd.

Fernando Saito
GM do Brasil

Bongha Song
GM Korea Co.

Jewel Barlow
University of Maryland

David Burton
Monash University

Taehwan Cho
Korea Aerospace Research Institute

Luis Fernando Gouveia de Moraes
Institute of Aeronautics and Space

ABSTRACT

Wind tunnel testing of reduced-scale models is a valuable tool for aerodynamic development during the early stages of a new vehicle program, when basic design themes are being evaluated. Both full-and reduced-scale testing have been conducted for many years at the General Motors Aerodynamics Laboratory (GMAL), but with increased emphasis on aerodynamic drag reduction, it was necessary to identify additional facilities to provide increased test capacity. With vehicle development distributed among engineering teams around the world, it was also necessary to identify facilities local to those teams, to support their work. This paper describes a cooperative effort to determine the correlation among five wind tunnels: GMAL, the Glenn L. Martin Wind Tunnel (GLMWT) at the University of Maryland, the Institute of Aeronautics and Space (IAE/ALA) TA-2 Wind Tunnel in Brazil, the Monash University Wind Tunnel in Australia, and the Korea Aerospace Research Institute Low Speed Wind Tunnel (KARI LSWT). Correlation tests were conducted using a vehicle model with interchangeable body modules and additional parts, to determine the relationships of measured aerodynamic force and moment coefficients among the tunnels. Despite the significant differences among facilities, the correlation results were satisfactory for reduced-scale wind tunnel development of future General Motors Co. (GM) vehicles. Correlation equations were defined, allowing conversion of data from one tunnel to equivalent values at another. This paper will present the physical descriptions and airflow characteristics of the wind tunnels, the test equipment and procedures, and the correlation results.

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INTRODUCTION

Wind tunnel testing of reduced-scale models has long been recognized as an efficient tool for aerodynamic shape development in the aircraft and automobile industries, among others [1]. At GM, reduced-scale models are used during the early stages of a new vehicle development program, when significant changes in design themes and features are evaluated. It is simply easier and faster to make large changes on a small model.

Increasingly stringent global requirements for fuel economy and CO₂ emissions require ever lower aerodynamic drag, which in turn drives additional development work, even with the continuing improvement of analysis tools. Consequently, it became necessary for GM to identify and qualify additional wind tunnel facilities as the demand for test time exceeded the available capacity at GMAL. In addition, GM's future product development programs are spread among regional technical centers around the world, and the ability to perform development in nearby wind tunnels would greatly improve the efficiency of the process.

For these reasons, wind tunnels suitable for testing 1/3-scale models were identified in the United States, Brazil, Korea, and Australia. A series of correlation tests was conducted, using a model with interchangeable rear body modules that provided a variety of basic shapes together with additional parts, which produced a large number of individual configurations and their associated increments. Correlation equations based on this data set provide common, comparable measures of aerodynamic performance regardless of the source. The following sections will describe the wind tunnels, the project approach and observations, and the comparative results.

WIND TUNNELS

General Motors Aerodynamics Laboratory (GMAL)

GMAL was built during 1977-1980 at the GM Technical Center in Warren, Michigan, USA [2]. It was intended primarily for aerodynamic shape development of full-scale cars and trucks. A significant fraction of the operation is also dedicated to aero-acoustic testing, with that capability enhanced by extensive acoustic modifications in 2001 and 2006. Various motorsports and nonautomotive tests have added variety to the everyday operations, but those have composed a very small portion of the total usage. Major upgrades of the data acquisition and control system were performed approximately every ten years, with the most recent in 2010.

GMAL is a large wind tunnel with a closed-jet test section measuring 5.44 m high x 10.36 m wide. For full-scale cars and light trucks, this produces a blockage ratio of 6% or less. It should be noted that the blockage with a 1/3-scale model in the other wind tunnels described

herein is of similar magnitude to the full-scale blockage in GMAL. The test section has a stationary floor with a boundary layer suction scoop at its entrance. A secondary distributed suction panel just ahead of the full-scale balance may be used to minimize the boundary layer thickness for especially low vehicles. A smaller balance at the front of the test section enables development of 1/3-scale models. This provides a fairly unique testing environment with extremely low blockage of the test section (<0.7%). The reduced-scale balance is located just behind the suction scoop to take advantage of the thin boundary layer. It is an external (under-floor), six-component, strain gage balance. Mounting studs that support either the wheels or axles of the model are adjustable for a range of track and wheelbase dimensions by rotating eccentric circles in the turntable surface.

Table 1. GMAL Specifications

Year opened	1980
Test section type	Closed jet, stationary ground
Nozzle/test section area	56.3 m ²
Nozzle/test section H x W	5.44 x 10.36 m
Contraction Ratio	5:1
Maximum speed / speed for flow specs	62 m/s / 55 m/s
Boundary layer control	Suction scoop
Boundary layer displacement thickness	$\delta^* = 5.4 \text{ mm @ } X = -0.8 \text{ m}$
Static pressure gradient near model	$dC_P/dX = -0.0017/\text{m}$
Turbulence Intensity	0.5%
Corrections	Continuity

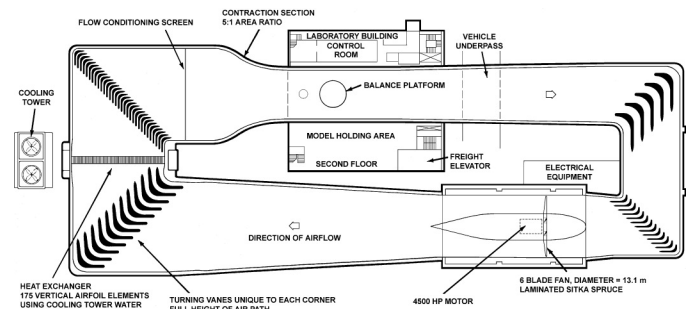


Figure 1. GMAL floorplan



Figure 2. GMAL exterior

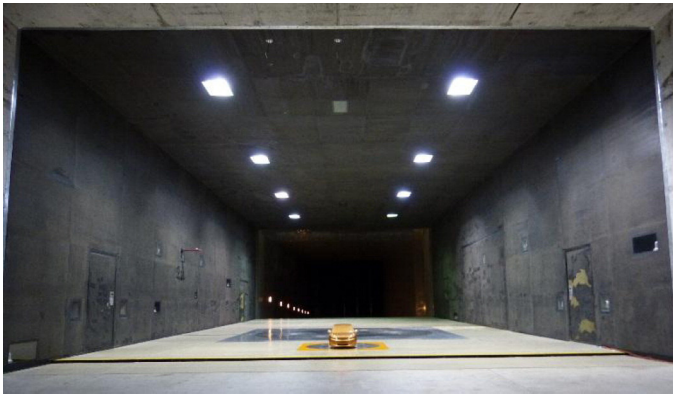


Figure 3. Model in GMAL test section

Glenn L. Martin Wind Tunnel (GLMWT) - University of Maryland College Park

The GLMWT has been actively involved in aerodynamic research and development since 1949. It was constructed as part of a gift to the University in the late 1940s. A very broad range of subjects have been tested, with over 1800 tests to date [3]. Frequent upgrades have maintained its state of the art capabilities. The tunnel has an external, six-component balance with structure under and alongside the test section, permitting the measurement of forces and moments on models mounted on the floor or in the center of the test section.

The test section is of closed-jet design, and for automotive testing a secondary floor assembly is installed with provision for boundary layer suction and a model support structure enclosed in a turntable. A unique feature of the GLMWT compared to the other wind tunnels described in this paper is the model mounting hardware. Four circular pads of approximately 150 mm diameter support the model wheels, and are exposed to the airflow. Pressure taps in the pads allow for subtraction of the aerodynamic loads on the pads.

Table 2. GLMWT Specifications

Year opened	1949
Test section type	Closed jet, stationary ground
Nozzle/test section area	7.7 m ²
Nozzle/test section H x W	2.30 x 3.36 m (with fillets)
Contraction Ratio	7.5:1
Maximum speed / speed for flow specs	103 m/s / 55 m/s
Boundary layer control	Suction scoop
Boundary layer displacement thickness	$\delta^* = 3.0 \text{ mm @ } X = -0.8 \text{ m}$
Static pressure gradient near model	$dCP/dX = 0.0018/\text{m}$
Turbulence Intensity	0.21%
Corrections	Continuity

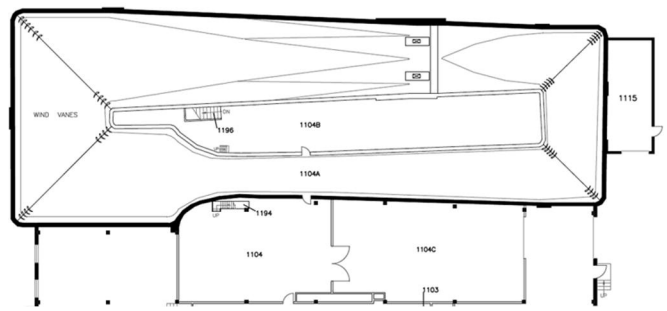
WIND TUNNEL BUILDING #081
FIRST FLOOR

Figure 4. GLMWT floorplan



Figure 5. Model in GLMWT test section

Korea Aerospace Research Institute Low Speed Wind Tunnel (KARI LSWT)

The KARI Low Speed Wind Tunnel was developed in 1998 for the primary purpose of supporting aeronautical and aerospace development programs. However, the facility was also designed to support other test objectives, including ground vehicles [4]. The primary, closed-jet test section with 3 m x 4 m rectangular cross-section was installed in 1998. The maximum wind speed in the closed test section is 120 m/s and the turbulence intensity level is less than 0.13%. The alternate, open-jet test section with a 3.75 m x 5 m nozzle was installed in 2008. The maximum wind speed in the open jet test section is 70 m/s and the turbulence intensity level is less than 0.4%.

More than 200 models such as a fixed wing airplane, helicopter, launching vehicle, high-speed train, wind turbine blade, ship, and motor vehicle were tested in this facility since 1998. Most of the tests focused on the aerodynamic forces and moments and surface pressures. Some of the tests were conducted to measure the aeroacoustic noise and flow field around the model. The six-component balance, electronic pressure scanner, laser beam, and acoustic measuring devices were installed to support those kinds of tests.

An elevated ground board system was installed in 2010 to reduce the boundary layer thickness for simulation of the ground effect of airplanes. The total length including the leading edge and tail flap was 6.5 m and the height from the tunnel floor to its center was 0.85 m. It was modified in 2013 for automotive testing. An automotive support frame was designed and built with attachment directly to the external balance. Four adjustable wheel supports permit various sizes of models to be mounted. The front wheel position can be adjusted from 2.5 m to 2.7 m behind the leading edge of the ground board.

Table 3. KARI LSWT Specifications

Year opened	1998
Test section type	Closed jet, stationary ground
Nozzle/test section area (total/above groundplane)	12.0 m ² / 8.4 m ²
Test section H x W above groundplane	2.10 x 4.00 m
Contraction Ratio	8.24:1
Maximum speed / speed for flow specs	120 m/s / 55 m/s
Boundary layer control	Elevated ground board
Boundary layer displacement thickness	$\delta^* = 3.48 \text{ mm @ } X = -0.8 \text{ m}$
Static pressure gradient near model	$dCP/dX < 0.003/\text{m}$
Turbulence Intensity	0.13%
Corrections	Continuity

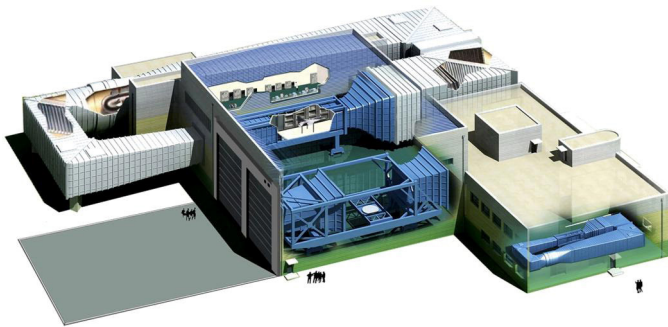


Figure 6. KARI LSWT layout



Figure 7. KARI LSWT test section

Monash University 1.4 MW Wind Tunnel

The Monash 1.4 MW Wind Tunnel is the largest wind tunnel in Australia. It is a multi-purpose wind tunnel that is capable of full-scale vehicle aerodynamic and aero-acoustic testing. It is also used for a variety of wind engineering studies and for applications such as aircraft, truck, train, cycle, and other aerodynamic tests. A schematic of the tunnel's layout is shown in Figure 8. The tunnel is a closed return design, where the air path follows a vertical circuit. In standard configuration it has two test sections: a $2.6 \text{ m} \times 4 \text{ m}$ $3/4$ -openjet automotive test section (downstairs) and a $4 \text{ m} \times 12 \text{ m}$ closed-jet wind engineering section (upstairs). By raising the top of the nozzle, the automotive test section can be increased to $4 \text{ m} \times 4 \text{ m}$. The air is driven by two 5 m diameter fans, while a number of acoustic splitters and dampeners are employed to reduce the noise level in the open-jet test section for aero-acoustic testing.

A project was undertaken to develop a new closed test section that could be inserted into the automotive test section to provide the capability to conduct $1/3$ -scale vehicle aerodynamic tests. The design of this new scale model test section needed to incorporate a new scale model force balance and turntable, and its geometry had to be carefully designed to ensure adequate flow uniformity, minimal static pressure gradient, and minimal boundary layer height at the model.

The new scale test section was designed to be installed into the wind tunnel's open-jet automotive test section as a closed-jet configuration. The walls of the insert attach to the nozzle exit of the existing open-jet automotive section and extend 10.8 m downstream to the collector. The insert needed to be removable so that the wind tunnel could be converted back to its full-scale open-jet configuration. Therefore the walls were designed as modular sections that are bolted together to form the closed-jet walls.

An elevated ground plane design was used to minimize boundary layer effects at the model. A CFD-optimized nose profile was developed with the final dimensions for the ground plane being 8.8 m long with the leading edge 2.8 m upstream of the turntable center. A half ellipse profile was selected for the nose geometry and the ground plane was tapered over the last 1.2 m at the trailing edge. The ground plane is supported by ten $100 \times 50 \text{ mm}$ rectangular steel columns and is modular to allow easy installation and removal.

Following tests in the closed-jet configuration, an open-jet configuration was evaluated using the same ground plane and force balance as the closed-jet configuration but without the wall and roof insert. This was done primarily to improve the operational efficiency of the tunnel and to minimize the downtime when converting from full-scale to reduced-scale configuration. Due to time and resource limitations, corrections were not applied to data from the open-jet test section at the time of this study. Based on the test section geometry and static pressure gradient profile, it is expected that the corrections would be small and therefore they could (mostly) be encompassed by the correlation factors. Further study is intended.

Table 4. Monash Closed-Jet Specifications

Year opened	2011 (closed-jet section upgrade)
Test section type	Closed jet, stationary ground
Nozzle/test section area (total/above groundplane)	10.40 m ² / 7.92 m ²
Test section H x W above groundplane	1.98 x 4.00 m
Contraction Ratio	5:1
Maximum speed / speed for flow specs	56 m/s / 48 m/s
Boundary layer control	Elevated ground board
Boundary layer displacement thickness	$\delta^* = 4.9 \text{ mm @ } X = -0.8 \text{ m}$
Static pressure gradient near model	$dCP/dX = -0.003/\text{m}$
Turbulence Intensity	1.4%
Corrections	Continuity

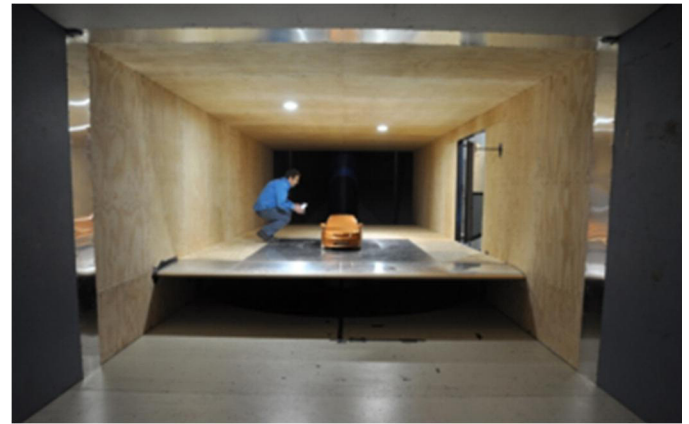


Figure 9. Model in Monash closed-jet test section

Table 5. Monash Open-Jet Specifications

Year opened	2013 (open-jet upgrade)
Test section type	¾-open jet, stationary ground
Nozzle/test section area (total/above groundplane)	10.40 m ² / 7.92 m ²
Nozzle H x W above groundplane	1.98 x 4.00 m
Contraction Ratio	5:1
Maximum speed / speed for flow specs	56 m/s / 48 m/s
Boundary layer control	Elevated ground board
Boundary layer displacement thickness	$\delta^* = 4.9 \text{ mm @ } X = -0.8 \text{ m}$
Static pressure gradient near model	$dCP/dX = 0.005/\text{m}$
Turbulence Intensity	1.4%
Corrections	None

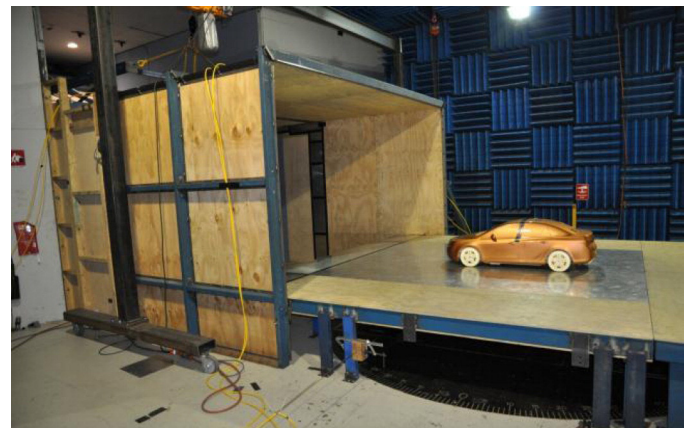
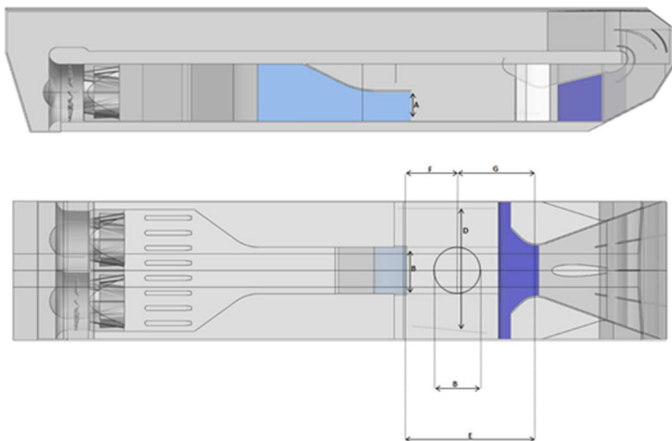


Figure 10. Model in Monash open-jet test section

Key Dimensions (approximate only)
Wind Tunnel Standard ¾ Open Jet configuration (2015)

A. Nozzle exit plane (NEP) height	2.6m
B. NEP width	4.0m
C. Turntable (TT) Diameter	4.2m
D. Plenum section width at TT centre (to acoustic wedges)	9.5m
E. Test section length (NEP to Collector MOA)	11.9m
F. NEP to TT centre	4.8m
G. TT centre to Collector MOA	7.1m
H. Collector MOA - 3.0m H x 4.4m W	13.2m ²
I. Collector Area at splitter 3.22m H x 5.1m	16.4m ²

Figure 8. Monash Wind Tunnel layout

Tunel Aerodinâmico 2 (TA-2) - Brazil

The TA-2 Wind tunnel was built during 1950-58 in the city of Sao Jose dos Campos, state of São Paulo, Brazil. Its initial role was to serve as a laboratory of aerodynamics for the course of aeronautical engineering at the Instituto Tecnológico de Aeronautica (ITA) and to be a basic tool for establishing and consolidating the aviation industry in Brazil, in particular the internationally known EMBRAER. The portfolio of tests includes cars, buses, ships, submarine, military artifacts, construction models, and various studies. However, the most extensive campaigns are those involving the aircraft of EMBRAER. Since the 1970s the TA-2 is a facility of the Instituto de Aeronautica e Espaço (IAE). The TA-2 is the largest wind tunnel in Latin America in commercial operation.

In 1968 load cells were installed and the data acquisition and reduction system became completely automated. In early 2000 the TA-2 underwent an update of its propulsion system relying on a 7-blade propeller of composite material and variable pitch. This reduced the time to turn the tunnel on and off and streamlined model configuration change processes. At that time, a PIV system (2D and S-PIV) and LDA were acquired, adding to the hot wire anemometer system (HWA / CTA) and the existing pressure sensors.

The tunnel has a closed-jet test section, and for automotive testing a ground board with an elliptical leading edge and dimensions of 1.3 m wide × 5 m long × 60 mm in thickness is installed at 275 mm above