

Evaluation of the Aerodynamics of Drag Reduction Technologies for Light-duty Vehicles: A Comprehensive Wind Tunnel Study

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ABSTRACT

In a campaign to quantify the aerodynamic drag changes associated with drag reduction technologies recently introduced for light-duty vehicles, a 3-year, 24-vehicle study was commissioned by Transport Canada. The intent was to evaluate the level of drag reduction associated with each technology as a function of vehicle size class.

Drag reduction technologies were evaluated through direct measurements of their aerodynamic performance on full-scale vehicles in the National Research Council Canada (NRC) 9 m Wind Tunnel, which is equipped with a the Ground Effect Simulation System (GESS) composed of a moving belt, wheel rollers and a boundary layer suction system.

A total of 24 vehicles equipped with drag reduction technologies were evaluated over three wind tunnel entries, beginning in early 2014 to summer 2015. Testing included 12 sedans, 8 sport utility vehicles, 2 minivans and 2 pick-up trucks.

Two categories of drag reduction technologies were evaluated: i) those currently offered by the original equipment manufacturers (i.e. active grille shutters, partial underbody covers, bumper and wheel air dams); and, ii) emerging technologies that have market introduction potential, i.e., active ride height control, actively deployable bumper air dams and full under-body covers.

The main findings of the experiments are presented in this paper by categories of vehicles and drag reduction technologies. A discussion on the use of wind averaged drag to evaluate the full impact of the technologies on fuel consumption is also presented.

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INTRODUCTION

At highway speeds (i.e., 80 km/h and above), aerodynamic drag is the most significant force that a vehicle must overcome. Therefore, improvements in a vehicle aerodynamic design can significantly improve fuel efficiency and contribute to the reduction of greenhouse gas (GHG) emissions. Most vehicle manufacturers have placed a renewed emphasis on aerodynamic design for passenger cars and trucks in recent years to meet increasingly stringent GHG emissions regulations in North America. Many of the latest aerodynamic technologies are known as "active aerodynamics", which activate under predetermined conditions to improve aerodynamic efficiency or overall performance such as heat/cooling management, aerodynamic stability and handling.

However, vehicle aerodynamics is a highly technical and complex issue. Adding a new active aerodynamic feature, such as an air dam or grille shutter, to a vehicle optimized aerodynamically in their absence, may not necessarily improve performance. Rather, a manufacturer may need to design a new vehicle as an "integrated system", particularly when it is seeking to maximize the benefits from newer active aerodynamic features. Currently, due to the proprietary nature of automotive design and development, limited public information exists about the optimal design of passenger vehicle aerodynamics, including how beneficial some of the newer active aerodynamic features may be in the "real-world". Furthermore, current U.S. and Canadian test procedures used to demonstrate compliance with regulated GHG standards may not fully reflect the GHG benefits of these active features. Instead, the U.S. and Canadian regulations provide "allowances" or "credits" that aim to encourage

and recognize innovative technologies such as active aerodynamics. The experimental study put forward here helps assess these allowances or credits for a variety of US EPA vehicle size classes.

A series of 2013 to 2015 model year production vehicles were tested in this multi-year project. The two main objectives of the experiments were i) to quantify the aerodynamic drag changes due to new original equipment manufacturer (OEM) aerodynamic treatments and ii) to explore the potential for improvement that could be realized by expanding the application of the current state of the art (defined as emerging drag reduction technologies that could be seen on production cars within two to four years). Treatments are add-on parts which primarily serve an aerodynamic function as opposed to aerodynamic features designed into the shape of the body.

The new drag reduction technologies covered by the first objective above were: active grille shutters, partial underbody panels, and bumper and wheel air dams. The emerging technologies covered by the second objective simulated the effects of deployable bumper air dams, active ride height where the clearance between the underbody and the road can be systematically reduced as a function of the road conditions, and full underbody covers.

The vehicles have been chosen to represent the range of "advanced" aerodynamics models equipped with active grille shutters, aerodynamic underbody panels, and air dams. Many have an OEM *ECO* designation suggesting that the vehicle is marketed having components or parts installed to improve fuel efficiency and reduce environmental impacts. Attention was given to choose vehicles from different utility and price segments. With reference to the US EPA vehicle size class, vehicles in the following classes were selected: i) subcompact and compact cars; ii) midsize cars; iii) large cars; iv) sport utility vehicles (small and standard); v) minivans; and, vi) standard pickup trucks.

The vehicles were selected by a steering committee that was established to guide this project. The committee was composed of representatives of Transport Canada's ecoTECHNOLOGY for Vehicles Program, Environment Canada's Transportation Division, US Environmental Protection Agency, National Research Council Canada, Röchling Automotive of Germany, and Magna International, Exteriors and Interiors of Canada. The new drag reduction technologies were evaluated for the following vehicles:

- 2013 BMW 528i;
- 2013 Chevrolet Malibu Eco;
- 2013 Dodge Dart SXT;
- 2013 Dodge Ram 2013 Ram 1500 HFE Regular Cab;
- 2013 Ford F-150 XL 3.5L EcoBoost;
- 2013 Ford Focus SE;
- 2013 Ford Fusion Hybrid SE;
- 2014 BMW X5 Xdrive 35i;
- 2014 Chevrolet Cruze Eco;
- 2014 Chevrolet Spark BEV;
- 2014 Chevrolet Impala, mild hybrid;
- 2014 Ford Escape SE, EcoBoost;

- 2014 Ford Edge SE EcoBoost;
- 2014 Ford Taurus SEL;
- 2014 Honda Odyssey;
- 2014 Jeep Cherokee;
- 2014 Mazda 3 i-loop (S Grand Touring);
- 2014 Mazda 6 i-loop Grand Touring;
- 2014 Nissan Versa Note Plus;
- 2014 Subaru Crosstrek XV Hybrid 2.0i;
- 2015 Chevrolet Tahoe LS;
- 2015 Nissan Pathfinder;
- 2015 Nissan Murano; and,
- 2015 Toyota Sienna.

Full-scale wind tunnel testing is the ideal choice for this work as it allows production vehicles to be evaluated without the expense of modelling (digitally or physically) and therefore provides a reliable evaluation of the aerodynamic drag most efficiently. To ensure appropriate boundary layer conditions, critical to the performance of underbody systems, the vehicles were tested with the Ground Effect Simulation System (GESS) in the NRC's 9 m Wind Tunnel.

TEST SETUP AND PROCEDURES

NRC 9 m Wind Tunnel

The test program was undertaken in the NRC 9 m Wind Tunnel located in Ottawa, Ontario, Canada. The wind tunnel is a horizontal closed circuit atmospheric facility with a large test section (9.1 m wide $\times$ 9.1 m high $\times$ 22.9 m long) that is suitable for testing up to the largest light-duty vehicle (LDV) and even tractor-trailer combinations up to full scale. It is powered by an air-cooled 6.7 MW DC motor that provides a maximum wind speed of approximately 55 m/s (200 km/h) in an empty test section. An external mechanical, pyramidal balance senses the six-components of aerodynamic forces and moments. One of the vehicles of this study is shown in [Figure 1](#) installed in the test section of the wind tunnel. A turntable (blue circle in [Figure 1](#)) allows rotation of the model about a vertical axis to simulate the effect of cross winds.



Figure 1. View of a large car from this study on the GESS in the NRC 9 m Wind Tunnel.

The test section is equipped with a GESS composed of a centre belt, with an exposed 1 m x 5.7 m area, four wheel rollers and four chassis struts for ride height control. Upstream of the turntable are two plenum for a distributed suction system, calibrated to reduce the displacement thickness of the floor boundary layer to 4 mm at the leading edge of the model, without inducing flow angularity at the model [1]. Breathers on the floor and walls at the test section exit are vented to the tunnel surroundings to equalize the otherwise negative pressure in the test section with atmospheric pressure.

Vehicle Preparation and Installation

The vehicles were installed so that their front bumpers were approximately 500 mm downstream of the leading edge of the centre belt. The belt runs under the vehicle, but inboard of the wheels, as shown in [Figure 1](#).

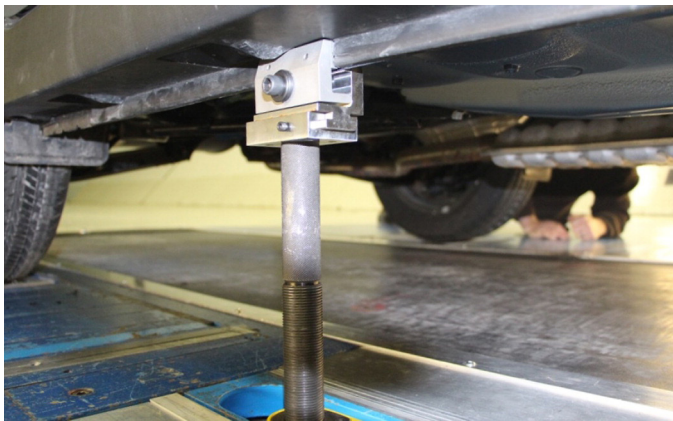


Figure 2. Close-up view of a rear GESS strut and rear GESS clamp attached to the rocker panel of a small SUV.



Figure 3. View of a SUV on the GESS with hydraulic lift extended in the NRC 9 m Wind Tunnel.

The GESS wheel rollers do not support the full weight of the vehicle, so pre-test preparations included measuring the baseline ride height and removing the suspension springs. The vehicles were mounted in the test section on four chassis jacks, clamped to the rocker panels, as shown in [Figure 2](#). To allow for the possibility of adjusting the ride height independently between the rear and front support points, new clamps were designed and built. The new clamps are made in two parts that can slide longitudinally independently, allowing small

longitudinal displacement of the vehicle associated with pitching nose up or down, and were installed to link the rear GESS mounting struts to the vehicle rocker panel.

The hydraulic lift system can raise the vehicle 500 mm for model work between runs (see [Figure 3](#)), and during testing was retracted into the floor.

Since the engines/motors were not operated during testing, the vehicle driveshafts were removed to prevent transmission damage from wheel rotation without oil pressure. In most cases, this was accomplished by disassembling the constant velocity (CV) joints, removing the axle, and reinstalling the CV joints to seal the differentials/transmissions and hold the wheel bearings in place.

Once the suspension springs were removed and the axles disengaged, no other modifications to the wheels and tires were necessary. The tire pressures were adjusted to the manufacturers' specifications when the vehicles were received at NRC, and the baseline ride height was measured with 68 kg (150-lbs) of ballast on both front seats before removal of the springs. The wheels rolled freely on the GESS roller (wheels could be easily spun by hand) and the GESS system ensured that the wheel rotation matches well with the speed of the flow. [Figure 4](#) shows a close up of a wheel on a roller.



Figure 4. Close-up view of a LDV wheel and GESS wheel roller in the NRC 9 m Wind Tunnel.

Baseline Conditions

The baseline condition describes the vehicle as received i) with all doors and windows closed and external mirrors adjusted to driving positions; ii) ride heights adjusted with the GESS struts to the baseline height as defined earlier, and iii) active grille shutters 100% closed. With the exception of one SUV, the grille shutters of the vehicles of this study generally closed when the engine/motor was turned off.

Active Grille Shutters

All vehicles of this study were equipped with grille shutters that could be 100% closed and 100% opened. If a vehicle was not already equipped with an OEM-installed active grille shutter, the shutter consisted of a frame, flaps and an actuator, Röchling Automotive

purchased and installed a system made for the vehicle. For the vehicles where no production AGS system existed already, Röchling Automotive built mock-ups of grille shutters that could cover the radiator completely with one solid panel and a mock-up frame. The solid panel could be removed to leave only the mock-up frame which represented the 100% open condition. Finally, the mock-up frame could be removed to mimic no active grille shutters at all. Figures 5 and 6 show a view of a mock-up AGS, the solid panel and the mock-up frame for a standard SUV.

For the vehicles equipped with an OEM AGS, an electronic system was devised so that the AGS actuator could be controlled remotely from the passenger seat. In this way, tests to depict the level of drag reduction as a percentage of closure of the grille shutters could be conducted, as well as tests at 100% closed, 50% closed and 100% open.

For the majority of the vehicles of this study, the OEM-installed AGS covered only the lower portion of the radiator. In general, this is to prevent overheating of the engine in case of failure of the AGS system since the default position is closed.



Figure 5. View of the solid panel covering the radiator as part of the custom AGS of a standard SUV built for the study, front bumper removed.



Figure 6. View of the mock-up AGS frame covering the radiator of a standard SUV, front bumper removed.

To evaluate the effectiveness of the OEM-installed AGS in reducing the volume of flow through the radiator for selected vehicles, the area covered by the AGS was completely sealed with tape, and a system was devised to remove the tape by pulling on a lead wire through the vehicle external grille. The aerodynamic drag was measured with the AGS 100% closed and sealed with tape, followed by tests with the AGS 100% closed but unsealed with tape. The difference between the two measurements indicated the influence of potential AGS leakage on the aerodynamic drag of the vehicle.

Test Procedures and Analysis

The data acquisition system of the 9 m Wind Tunnel was configured for a sampling time of 40 seconds per test condition at a sampling frequency of 10 Hz. Data sampling was initiated when the flow conditions were stabilized. The recorded time series data were averaged over this sampling period to ensure reliable and repeatable aerodynamic force, dynamic pressure, and wind speed measurements. A repeatability study indicated that the uncertainty margin on the drag area measurements was on the order of 0.25% difference between measurements. Therefore, all variations of drag area in excess of 0.3% or more are considered as statistically significant in this study.

For yaw angle sweeps, after a 5-point yaw angle tare of the wind-off values, the wind speed was set to 110 km/h and data were acquired from 0 degree yaw to +10 degree yaw (positive clockwise when facing the flow) in increments of 2 degrees. In some instances, the yaw sweep was extended to negative angles, from -10 degrees to +10 degrees, to capture any asymmetry in the aerodynamic forces.

For speed sweeps, after a 1-point tare of the wind-off values at 0 degree, the speed was increased from 60 km/h to 140 km/h in increments of 20 km/h, and aerodynamic force data were measured at each speed step for 40 seconds. Note that in all cases, the wheel rollers and centre belt speeds were synchronized with the blockage-corrected flow velocity in real time.

Wind-tunnel testing occurs in a current of air with finite boundaries (walls and ceiling) that influence the flow around the model as it blocks part of this current. This contrasts real driving conditions where the air is free to expand around the model blockage, without interference from nearby walls or ceiling. Though the vehicles only blocked 3 - 5% of the test section area in the current investigation, corrections for boundary interference effects using the Maskell III [2] blockage correction technique were carried out for all test runs. The maximum adjustment to velocity was 4% and to drag area was 9%, for the largest vehicles. All force, speed and yaw data contained in this paper have been corrected for blockage effects.

Since precise frontal area data were not available, absolute drag coefficients as typically reported in automotive publications are not presented in this paper. Instead, the results are presented in terms of $C_D A$ (drag area in m^2) or percentage changes of drag area with respect to the $C_D A$ of the baseline configuration. $C_D A$ offers a more complete understanding of aerodynamic resistance as it captures the effect of frontal area, which is equally as important as C_D in the thought of as a quantitative measure of the efficiency of the vehicle.