

Track-Based Aerodynamic Testing of a Heavy-Duty Vehicle: Coast-Down Measurements

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ABSTRACT

In an effort to support Phase 2 of Greenhouse Gas Regulations for Heavy-Duty Vehicles in the United States, a track-based test program was jointly supported by Transport Canada (TC), Environment and Climate Change Canada (ECCC), the U.S. Environmental Protection Agency (EPA), and the National Research Council Canada (NRC) to assess aerodynamic evaluation methodologies proposed by the EPA and to provide a site-verification exercise against a previous test campaign with the same vehicle. Coast-down tests were conducted with a modern aerodynamic tractor matched to a conventional 16.2 m (53 ft) dry-van trailer, and outfitted with two drag reduction technologies. Enhanced wind-measurement instrumentation was introduced, consisting of a vehicle-mounted fast-response pressure probe and track-side sonic anemometers that, when used in combination, provided improved reliability for the measurements of wind conditions experienced by the vehicle.

Results from the coast-down tests compare well when analyzed using two different techniques: a conventional regression method, and the recently-proposed high-low iteration method. Drag-area results from the the coast-down tests for two vehicle configurations, analyzed with the EPA-proposed high/low iteration method, differ by no more than 3% from the EPA-derived values for a low-yaw range of $\pm 3^\circ$ yaw. Several modelling assumptions were included in the analysis to account for environmental factors and vehicle-component performance, such as the mechanical drive-line losses, the rolling-resistance speed dependence, and the winds experienced by the vehicle. These models are shown to improve the fidelity of the coast-down analysis, but require further validation for their real-world applicability. Additional considerations for the placement of on-board wind anemometry for improved accuracy of results are discussed.

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INTRODUCTION

The U.S. EPA is in the process of developing the second phase of its greenhouse-gas (GHG) regulations for heavy-duty vehicles (HDVs) [1]. In Canada, ECCC has issued a notice-of-intent to develop a second phase to its corresponding greenhouse-gas regulations [2]. The European Commission (EC) is also in the process of developing GHG regulation [3]. These regulations require vehicle manufacturers to demonstrate efficiency and emissions levels of the vehicles they sell for use in the various jurisdictions. The Greenhouse-gas Emissions Model (GEM), the simulation tool used by EPA and ECCC for these estimates, requires an aerodynamic input represented by the vehicle drag area (C_{DA}) [4]. The reference method to determine the drag-area, defined by the EPA and ECCC in their first phase of regulations [4] and proposed again by the EPA as the reference method for their second phase [1], is the road/track-based coast-down measurement technique. The coast-down test methodology is to allow a vehicle to coast un-powered from high speed to a stop or low-speed state, from which the road load exerted on the vehicle can be determined by the vehicle deceleration rate. Currently, no formal recommended practice exists for coast-down testing of HDVs. The

first phase of the EPA regulations was based on an SAE coast-down procedure for light-duty vehicles [5]. In contrast, the EC is proposing the constant-speed method for aerodynamic testing [6], for which the tractive torque at the drive wheels is measured under constant-speed conditions and assumed to represent the road load experienced by the vehicle. There is also no formal recommended practice for the constant-speed method. For both methods, assumptions about the manner in which external forces such as rolling resistance and aerodynamic drag behave with speed are then used to identify the drag area (C_{DA}) and rolling-resistance coefficient (C_{RR}) of the vehicle. At the time this work was undertaken, changes to the test coast-down methodology and analysis procedures were being considered by the EPA for the second phase of regulations.

The EPA previously contracted Southwest Research Institute (SwRI) [7] to conduct a series of coast-down and constant-speed tests using different tractor models, different trailer models, different tire models, and different trailer-mounted drag-reduction technologies [8, 9]. The SwRI results are being used to evaluate changes to the testing methodologies and to identify current levels of vehicle drag from which future drag-reduction targets will be set [1, 8, 9].

To support the regulatory development processes of the EPA and ECCC, Transport Canada (TC) [10] commissioned the NRC [11] to conduct coast-down and constant-speed testing using one of the vehicles that had been tested by SwRI. The test program was designed to supplement the SwRI data set as a site validation exercise, while introducing some enhanced wind measurement technology to the on-board measurement system. Two coast-down analysis methods were evaluated as part of the project and presented herein: one that is based on conventional regression techniques, similar to the SAE J1263 procedure for light-duty vehicle [5]; and one that is based on a force difference technique that has been recommended by a vehicle manufacturer and that is mathematically simpler to implement [1]. The use of different speed ranges in the latter method is evaluated, along with examining modelling assumptions regarding the speed dependence of rolling resistance and mechanical drive-line losses.

TEST SETUP AND PROCEDURES

Test Vehicle and Configurations

The test vehicle is a tractor-trailer combination supplied by ECCC for the test program. The tractor is a model-year 2014 International ProStar Long Sleeper [12] and the trailer is a conventional 16.2 m (53 ft) dry-van trailer manufactured by Manac Inc. [13]. The test vehicle is shown in Figure 1 with side-skirts and boat-tail installed on the trailer. Details of the vehicle and its test configuration are found in Appendix A, which are consistent with the configuration used in the SwRI test program [8], including the same combination of SmartWay-verified tire models.

Three vehicle configurations were tested during the test campaigns, two of which included trailer-mounted drag-reduction technologies. Figure 2 shows the fully-outfitted trailer configuration, and Table 1 provides the basic specifications of each technology. The side-skirt shape tested was based on the reference side-skirt for the SwRI test program [8]. The three vehicle configurations tested were:

- 1. Baseline: no drag reduction technologies
- 2. Skirts: side-skirts installed
- 3. Skirts+Tail: side-skirts and boat-tail installed



Figure 1. Photograph of the test vehicle.



Figure 2. Photograph of the trailer configured with side-skirts and a boat-tail.

Table 1. Drag-reduction-technology specifications.

Name	Description
Skirts	Plywood replica of commercial side-skirt design Flush with sides of trailer sides Length = 8.66 m (341 in), Height = 0.927 m (36.5 in) 45° taper on front and back edges
Tail	Collapsible commercial boat-tail Mounted to exterior surface of trailer loading doors 4-panel configuration (sides + top + bottom) Extension from rear of trailer = 1.2 m (48 in) Top panel ≈ 0.03 m (1 in) from trailer top edge

The vehicle mass was maintained within 1.5% of its fully-loaded value of 15,796 kg (34,824 lb) throughout the test campaign. When not installed on the trailer, the side-skirts and boat-tail were stored inside the trailer to maintain total vehicle weight. Both were stored near the rear of the trailer, which may have changed the the weight distribution of the vehicle between the three configurations. The fuel level was maintained at 3/4 full or greater, based on the dashboard gauge, throughout testing. Based on records of fuel fill-ups and estimates of fuel use during the test campaign, the vehicle mass for each coast-down or constant-speed run has been calculated for use during data processing, with an estimated uncertainty of ±25 kg (±55 lb). Apart from the drag reduction devices being stored in the trailer when not installed on the vehicle, the trailer was unloaded for all tests.

Test Site

Testing was performed at TC’s Motor Vehicle Test Centre operated by PMG Technologies in Blainville, Quebec [14]. The Bravo track was used for testing, highlighted in green in the aerial photograph of Figure 3. The track is a high-speed banked oval and the primary surface is rain-grooved concrete. The track is 6.4 km (4.0 miles) long with two straight 1.6 km (1.0 mile) sections, and two 1.6 km banked curves of constant 0.51 km radius. Only the north-side straight section was used for the coast-down tests.

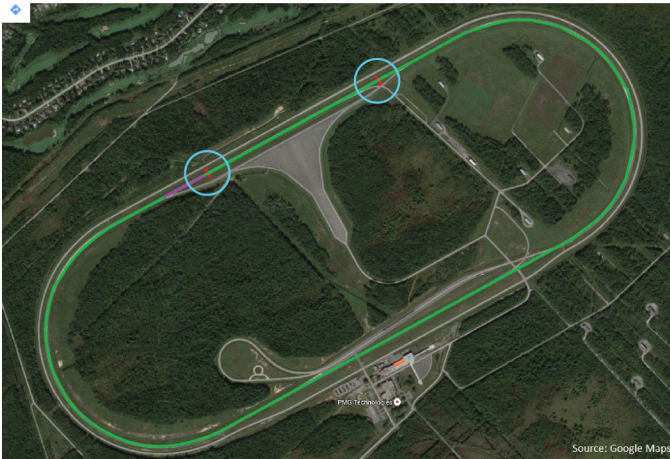


Figure 3. Aerial view of the Motor Vehicle Test Centre (Bravo track highlighted in green with asphalt section highlighted in purple, anemometer locations identified by red dots encircled in blue at each track-side location, photo adapted from Google Maps).

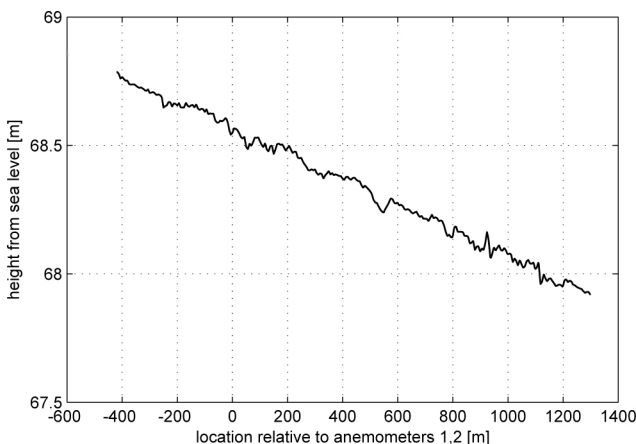


Figure 4. Track elevation profile for coast-down test segment.

The track grade can have an influence on the results of coast-down tests, but there is no formal recommended practice defining a level below which its effect can be ignored for HDV coast-down analysis. The EPA requires grade to be accounted for if it exceeds 0.02% [4]. The elevation profile for the north-side straight segment of the track is shown in Figure 4. This profile is based on two elevation surveys. The first is a precise but low-resolution elevation survey of the track, comprising elevation data at 100 m spacing along the length of the track. To achieve the high resolution shown in Figure 4, a second profile was defined based on high-speed Global Positioning System (GPS) data collected with the on-board instrumentation. The GPS-based elevation profile was high-pass filtered with a 200 m filter cut-off, and numerous passes of the same segment of track (more than 25 passes) were averaged to provide the high-frequency component of the final elevation profile, superimposed on the high-precision survey results. The filtering process removed the low-frequency drift component of the GPS signal, such that the variation between the 25+ filtered elevation profiles is characterized by a root-mean-square value of approximately 0.01 m, providing confidence that the profile of Figure 4 is a reasonable representation of the true track elevation. This segment of the track used for the coast-down tests has a consistent nominal grade over its length, but with local unevenness.

For coast-down analyses, the magnitude of the grade is important. Figure 5 shows two grade profiles based on the elevation profile of Figure 4. The data shows the high-resolution grade profile in black that accounts for the local unevenness of the track, with the green dashed line showing the nominal grade over the full length. Although the nominal grade is on the order of 0.05%, locally the grade can exceed a magnitude of 0.2%. The uneven surface of the track may cause vertical accelerations of the vehicle but will not necessarily introduce a grade force in the direction of motion of the vehicle because the vehicle's weight is distributed over a much greater horizontal extent than the local wavelengths. Therefore, the nominal grade of 0.050% was used in calculating the coast-down results presented in this paper.

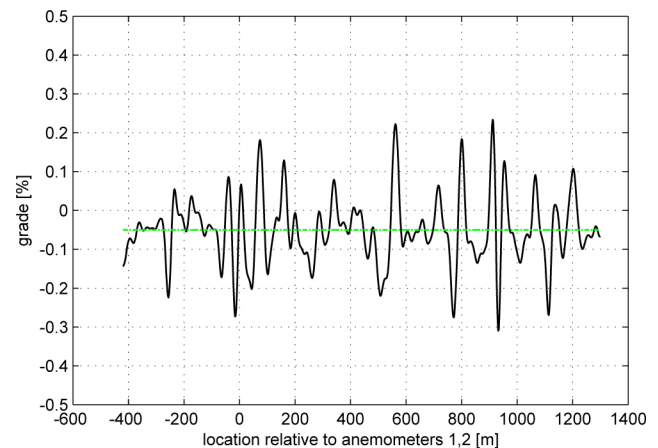


Figure 5. Track grade profile for coast-down test segment (black solid line - high-resolution grade profile, green dashed line - nominal constant grade value).

Instrumentation and Data Acquisition

The coast-down method requires measurement of the vehicle position, the vehicle speed, the air properties (temperature and barometric pressure), and the wind conditions (speed and direction, as experienced by the vehicle). Vehicle speed and position were measured by an on-board GPS system that uses built-in inertial measurements to augment the conventional GPS signal and provide a higher update rate than the conventional GPS signal alone could provide [15]. Other vehicle-specific parameters such as gear selection, indicated speed, engine temperature, and other data available on the vehicle network were also recorded using a J1939 datalink. Some of this data, such as gear selection, were useful to identify measurement segments of interest. The high-speed GPS data and the vehicle-parameter data were acquired at 100 Hz, whereas the conventional GPS data was acquired at 5 Hz.

The wind conditions experienced by the vehicle were measured using a fast-response four-hole pressure probe that measures the fluctuations in wind speed, wind direction, and pressure [16]. This velocity probe has pressure transducers built into the stem which, combined with the short length of tubing between the probe tips and the transducers, allows correction for the frequency response of the system with a resolution up to 1.5 kHz, above which the on-board electronics filter the output signals. The reference-pressure port of the velocity probe was connected to the static port of the same probe mounted in close proximity to the velocity probe. This reference.

pressure was also measured by an absolute pressure transducer to allow calculation of the air density from the local static pressure. The velocity-probe data were acquired at 2 kHz.

Figure 6 shows the installation of the velocity probe and the pitot-static probe on the front of the trailer. The velocity probe was mounted 1.0 m above the trailer roof with its tip 0.3 m forward of the front face of the trailer. The pitot-static probe was mounted such that its static-pressure ports were 0.3 m below the tip of the velocity probe.

The velocity probe was mounted sufficiently close to the vehicle (1.0 m above the trailer) such that its measurement of wind speed and direction do not represent the true wind speed and direction experienced by the vehicle. To provide a means of calibrating the on-board measurement for this vehicle-proximity influence, four sonic anemometers [17] were installed at two locations on the north side of the track with one on each side of the track (see locations in Figure 3). The anemometers were mounted on tripods with the sensing element elevated to be coincident with the test vehicle's mid-height dimension, which was approximately 2.05 m above the track surface. The anemometers were located to the sides of the track 8 m from the track centerline. The anemometers were oriented to provide orthogonal wind velocity components aligned to the vehicle travel direction so as to provide a direct reading of headwind and crosswind components. Alignment of the track-side anemometers is estimated to be within 2° of the desired orientation. Figure 7 shows the installation of the track-side anemometers.



Figure 6. Wind-measurement probes mounted to front face of the trailer (velocity probe - high, pitot-static probe - low).

The track-side data acquisition systems were installed inside weather-resistant cases located beside each anemometer. The system consisted of a data acquisition system, appropriate cables, connectors, 12 VDC deep-cycle lead-acid battery, and a 120 VAC power inverter. The track-side anemometers have a maximum sampling rate of 32 Hz, but were up-sampled to 100 Hz for synchronization with the vehicle data.



Figure 7. Track-side sonic anemometers.

The tractor data acquisition system was installed inside the cab of the tractor. The system consisted of a laptop, a data acquisition system, software and appropriate cables, connectors and a power supply. As part of the data processing process, all data was either up-sampled or down-sampled to match the 100 Hz acquisition rate for the vehicle speed measurement. The data from the four track-side acquisition systems were synchronized using the GPS time stamp. The 5 Hz GPS update rate thus provides an accuracy on synchronization to the tractor-based data to the track-side anemometer data of 0.2 s.

Wind Limits and Calibrations

Generally, wind constraints are imposed for track-based test procedures to minimize the influence of the winds on the measurements, and to provide justification for neglecting the effect of the winds in the analysis procedures. For the current test program, for which the inclusion of wind effects in the analysis was required, the enhanced wind-measurement capabilities provide the potential to capture and account for wind effects to a greater extent than typical track-based tests. These data can also serve to test the viability of existing procedures vis a vis maximum wind speed. For the current test campaign, standard SAE wind limits, per the J1263 coast-down procedure [5] were targeted for a specified number of measurement runs, with a set of expanded wind limits specified for additional testing if time permitted. The J1263 and the expanded wind limits are tabulated in Table 2. The winds for the majority of the test program were within the J1263 limits, in large part due to the the dominant winds of the local region being aligned with the track direction. Furthermore, the forested areas surrounding the track and in the middle of the track act to channel the winds along the straight sections, as observed from comparisons between data from the nearest weather station and the track-side anemometers. As such, any strong winds resulted in predominantly head- or tail-winds for the vehicle with very few conditions encountered with strong crosswinds. This limited the ability to capture high yaw angles of the wind relative to the vehicle.

As noted in the previous section, the on-board wind measurement (velocity probe) was mounted sufficiently close to the vehicle (1.0 m above the front face of the trailer) that the wind-speed and angle measurements do not represent the true free-stream conditions. To correct for this vehicle-proximity influence, the on-board wind

measurement was calibrated against the track-side wind measurements. In the presence of terrestrial winds, the calibration of the on-board to the track-side measurement can only be done when the vehicle is in close proximity to the track-side anemometer of interest. For the purpose of the current test campaign, the data for all valid coast-down and constant-speed runs was processed and the on-board and track-side wind measurements were each averaged during the period over which the anemometer was within the range 2 m and 12 m of the vehicle position along the track direction. Other more advanced techniques are available for calibrating the on-board wind measurement, such as the Taylor-hypothesis method implemented by Tanguay [18] which accounts for the advection of turbulence in the terrestrial winds. For the current test campaign, the track-side measurements were sufficiently close to the track (8 m from track centreline) that an average of the anemometer measurements on the two sides of the track have been used as a measure of the winds the vehicle experiences when in the range 2-12 m ahead of the vehicle. Furthermore, the height differential between the on-board and track-side measurements (2 m and 5 m, respectively) can introduce some uncertainty in the turbulence-advection method because the wind speed and angle change with height relative to the vehicle in a sheared terrestrial boundary-layer wind. A discussion of this shear influence and its potential impact on the accuracy of the results is discussed later in the paper.

Table 2. Wind limits for the test campaign.

Component	SAE J1263 limit	Expanded limit
average	16 km/h (10 mph)	20 km/h (12.4 mph)
peak	20 km/h (12.4 mph)	25 km/h (15.5 mph)
avg. cross	8 km/h (5 mph)	14 km/h (8.7 mph)

Based on a few restrictions on the difference between the opposing track side anemometer measurements and differences from the track-side to the on-board measurements, a large data set of 518 data points collected over the entire test campaign were used to develop a calibration between the on-board velocity-probe measurement and the track-side anemometers. The calibration of wind speed and yaw angle are shown in Figure 8. From this data, the calibrations are:

$$U_{wind} = 0.946 U_{probe} \quad (1)$$

$$\psi_{wind} = 0.94 \psi_{probe} + 0.07 \quad (2)$$

The calibrated wind speed, U_{wind} , was used along with stationary barometric-pressure and temperature measurements to calculate the reference dynamic pressure.

Under low-speed and reverse-flow conditions (≈ 1 m/s), the velocity probe provides a zero output. At the lowest vehicle speed for which data is evaluated in this study, of 8 km/h (5 mph), and for the maximum tail-wind condition of 20 km/h (7.5 mph), the vehicle-referenced tail wind of 12 km/h (7.5 mph) has a low dynamic pressure (≈ 7 Pa) compared to that experienced under the high speed

conditions (≈ 500 Pa at 104 km/h wind speed), and therefore the error introduced when the velocity is forced to zero under the low-speed/reverse-flow conditions is small.

Test Procedures

Pre-run inspections and checks were conducted to ensure that the vehicle condition was consistent from test to test. Prior to the start of testing, the vehicle was warmed up by driving normally for several laps of the track at a speed of at least 80 km/h (50 mph). During this time, the track-side instrumentation was initialized and checked. The general procedure to be followed for this test is covered by one or more of the following documents:

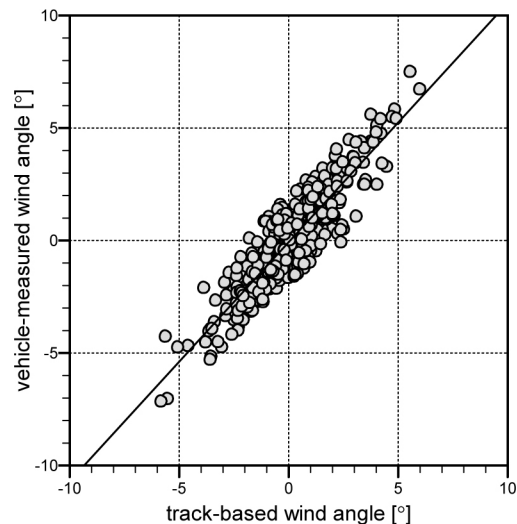
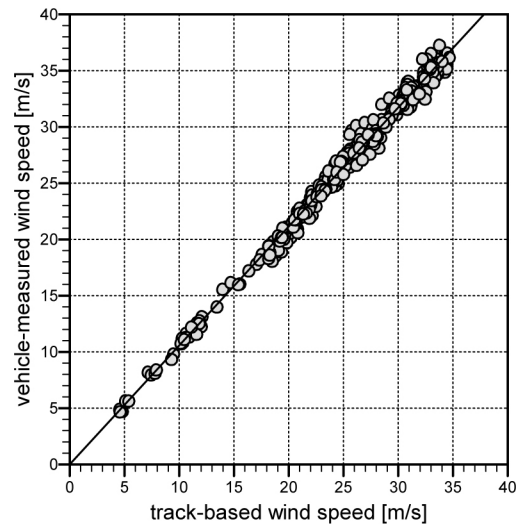


Figure 8. Calibration data between on-board and track-side wind measurements (top - wind speed, bottom - yaw angle).

- US CFR Title 40, Section 1066.310, "Coastdown procedures for heavy-duty vehicles" [4]
- SAE J1263, "Road load measurement and dynamometer simulation using coastdown techniques" [5]
- SAE J2263, "Road load measurement using onboard anemometry and coastdown techniques" [19]