

Examination of the Maskell III Blockage Correction Technique for Full Scale Testing in the NRC 9-Meter Wind Tunnel

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ABSTRACT

The 9-meter wind tunnel of the National Research Council (NRC) of Canada is commonly employed in full-scale testing of class 8 tractors. In this configuration the model blocks 10 - 15% of the test section cross-sectional area, which is greater than generally advocated blockage limits. The NRC utilizes the Maskell III method to correct data for wall interference but the effectiveness of this technique at such blockage levels remained to be seen. Corrected full-scale data was compared to data acquired with a half-scale model to determine how closely the corrected high-blockage data would agree with the low-blockage baseline. The half-scale model presented an opportunity to test at full-scale Reynolds numbers, with less than 4% blockage, which falls within most recommendations of maximum allowable blockage. It will be shown that after correcting the data using the Maskell III method, the wind-averaged drag coefficient of the full- and half-scale baseline cases were within 3 drag counts ($\Delta C_D = 0.003$) of each other.

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INTRODUCTION

In 2006 the ability to test full-scale commercial vehicles was revived at the NRC 9-meter wind tunnel [1]. Since then the facility has undergone several upgrades to improve data quality and efficiency for truck testing. Undertaking several months of full-scale truck testing every year, it was critical that concerns regarding the validity of the full-scale simulation at this facility be addressed. The facility is heavily-utilized by government organizations for research and regulation development and several truck and aftermarket device manufacturers undertake development, benchmarking and validation work here.

The 9-meter wind tunnel was not designed for commercial vehicles but for short takeoff and landing aircraft. This design afforded a large test section though an even greater cross-section and length would be ideal to alleviate concerns that the boundaries are too close to full-scale truck models to simulate the free air case [2]. This effect, known as wall interference, or blockage, is well summarized in Reference 3 along with descriptions of several candidate correction methods and an extensive comparison of various correction methods for testing of simplified automotive models in various facilities.

At the NRC the Maskell III method is generally recommended for correcting wall interference effects for low-speed, bluff-body testing. The Maskell method was originally

developed from momentum theory applied to flat plates oriented normal to the flow at the center of the test section. This approach only accounted for interference due to separation at the base of the model. Maskell III was developed by Hackett and Cooper as an extension of the original Maskell method with additional solid and wake-induced blockage terms [4].

The presence of the model and its wake inside the test section induces an increase of the velocity due to the reduction of the available area. The velocity increment is composed of a solid and a wake blockage component. The total blockage can be expressed as follows:

$$\varepsilon_T = \varepsilon_S + \varepsilon_W \quad (1)$$

where ε_T is the total velocity increment, including the solid (ε_S) and wake (ε_W) contributions. These terms are based on a notional duplex tunnel where H is the width of the actual test section but B and C are twice the actual test section height and area respectively. Similarly S and V are two times the model frontal area and volume and the aspect ratio (AR) is twice the model height divided by the model width. These corrections are applied to the uncorrected drag coefficient in the wind axis (CD_{UW}); see [Equation 8](#) for the definition of ΔCD_{Wi} .

$$\varepsilon_s = 0.36 \left(\frac{B}{H} + \frac{H}{B} \right) \left(\frac{V}{C^{1.5}} \right) \quad (2)$$

$$\varepsilon_W = \sqrt{1 + \theta \left(\frac{1}{1 + \theta} - \frac{\Delta CD_{wi}}{CDUW} \right)} - 1 \quad (3)$$

Where $\theta = (0.96 + 1.94e^{-0.06AR})CDUW S/C$

The corrected velocity (V_C) and dynamic pressure (Q_C) are computed relative to the uncorrected measurements (V_U and Q_U) as follows:

$$V_C/V_U = (1 + \varepsilon_T) \quad (4)$$

$$Q_C/Q_U = (1 + \varepsilon_T)^2 \quad (5)$$

The corrected wind axis drag coefficient (CD_{CW}) is computed from the uncorrected coefficient as shown in Equation 6. This process is repeated for the remaining force and moment coefficients.

$$CD_{CW} = Q_U/Q_C \times CDUW \quad (6)$$

Another level of correction is needed for the drag and side force. The wall-constrained wake behind the model produces a wake drag increment denoted ΔCD_{wi} .

$$CD_{CW} = Q_U/Q_C \times CDUW + \Delta CD_{wi} \quad (7)$$

$$\Delta CD_{wi} = CDUW \left(\frac{1}{1+\theta} \right) + \left(\frac{1}{2\theta} \right) (1 - \sqrt{1+4\theta}) \quad (8)$$

The side-wash increment is computed using the lifting line theory adapted from airfoil to bluff body applications [2]. For surface vehicles, this increment in flow angle is proportional to the uncorrected coefficient of side force (CSFU) at non-zero yaw angles:

$$\Delta\psi [\text{rad}] = \delta_o CSFU (S/C) \quad (9)$$

where $\delta_o = 0.124$ is a boundary correction factor determined from the model and tunnel dimensions [2]. As a result of the side-force-induced side-wash, the yaw angle of the model increases by an angle $\Delta\psi$. The corrected yaw angle (ψ_c) is calculated by adding the increment to the turntable yaw angle (ψ_u). Transformation to stability axes requires a rotation through the corrected yaw angle [4].

$$\psi_c = \psi_u + \Delta\psi \quad (10)$$

The drag coefficient of a typical tractor-trailer unit may increase by more than 30% due to the introduction of a side

wind that generates a resultant yaw angle of only 9°. This yaw sensitivity coupled with the fact that operation in conditions lacking side wind is rare, means the prediction of average on-road performance requires assessment of probable wind conditions in addition to the characterization of vehicle performance in these conditions. These factors can be accounted for by calculating the wind-averaged coefficient of drag (WACD) [5]. The WACD distills the drag coefficient over a range of yaw angles resulting in a single value which describes aggregate performance in normal operational conditions.

To determine WACD, drag is measured at several yaw angles and a statistical weighting is applied which accounts for how much time a truck is exposed to various real-world wind conditions. This weighting is based on national wind statistics and as such describes the average wind seen by a truck operating over a long period of time. It is not possible to predict the performance of a vehicle in this average wind unless the drag coefficient is known as a function of yaw angle, generally between 0° and 10° for calculation of WACD at typical highway speeds. Other performance characterization methods, such as track testing, do not generally control yaw angle so their results cannot be extrapolated to predict performance at yaw angles other than those observed during testing.

The wind-averaged drag coefficients contained within were calculated as follows:

$$WACD = \sum_{i=1}^6 [(C_{Df}(\psi_i)) \times (Wt_i)] \quad (11)$$

Where $C_{Df}(\psi_i)$ is the body axis coefficient of drag measured at yaw angle and Wt_i is the weighting value.

The weighting values are calculated using Equations 12 and 13. The velocity ratio is defined as the average wind speed divided by the road speed, making sure the units are consistent. These values were calculated using an average national wind speed of 11.3 km/hr (7 mi/hr) [5].

$$Wt_i = \frac{1 + (\text{VelocityRatio})^2 + 2(\text{VelocityRatio})\cos(\varphi_i)}{6} \quad (12)$$

$$\varphi_i = 15 + 30(i - 1) \times \frac{\pi}{180} \quad (13)$$

Generally $C_{Df}(\psi_i)$ will be calculated by applying a polynomial fit to measured data, then interpolating for the drag coefficient at the desired yaw angle. For a truly symmetric object it is possible to calculate WACD from only positive or negative yaw angles. In reality most trucks are not absolutely symmetric so WACD should be calculated as the average of WACD for the positive and negative halves of the yaw curve.

DIFFERENCES BETWEEN THE FULL- AND HALF-SCALE SETUP

Model scale was the primary independent variable modified in the examination of wall interference correction effectiveness; the full-scale model blocked approximately 13%, while the half-scale test blocked approximately 3% of the test section cross-sectional area. Ideally the model and test section parameters for the two models would have been identical in every other way; unfortunately there were some variables which could not be controlled as noted below.

Model Mounting Details

The mounting arrangement of the full- and half-scale models could not be identical due to the different types of models employed. The half-scale model is lighter and smaller which enabled it to be completely supported by the under-floor balance and rest almost entirely within the floor turntable. The model mounting points did not match the locations of the struts and wheel rollers normally employed for automotive testing therefore it was necessary to mount the model so the wheels were just above, but not in contact with the floor. The unused rollers and struts that normally support automotive models are part of the main balance structure so covers were fabricated to minimize tare drag loads as shown in [Figure 1](#). By necessity the full-scale tests were performed with stationary floor and wheels so the half-scale model was similarly configured for the tests presented in this paper; tests employing wheel rotation and the center belt will be reported in a future paper.



Figure 1. Details of the forward mounts and floor covers.

Taking advantage of existing mounting points on the model, the truck was also supported at the rear bumper and the trailer was secured through the kingpin and a set of struts near its midpoint. The instrumentation cables were routed along one of the trailer struts as shown in [Figure 2](#).

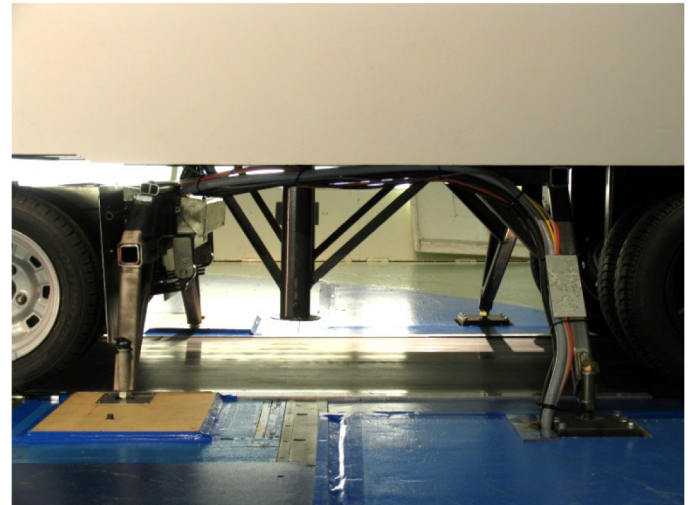


Figure 2. Details of the rear mounts and cabling.

The track width of the existing half-scale model coincided with the edges of the moving belt. The wide center belt is not attached to the balance therefore it was necessary for the struts to spread outwards as they approached the floor. The struts extend down to the balance below, on either side of the belt, as shown in [Figure 3](#). Note that all of the mounting struts pass through clearance holes in the floor and are not attached to the floor itself.

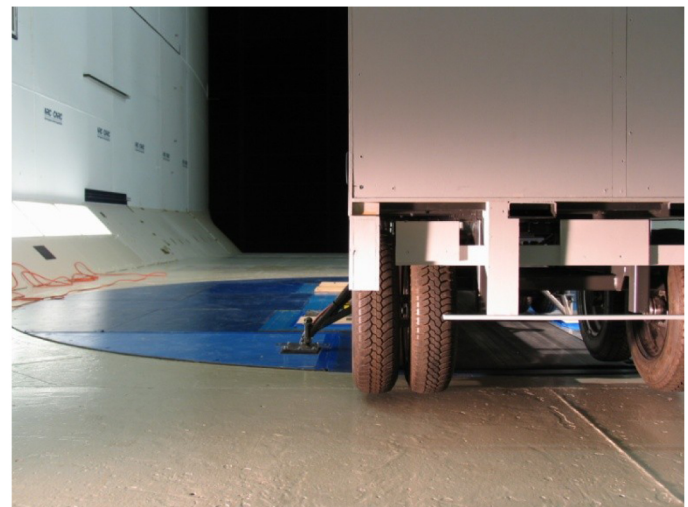


Figure 3. End view of the rear mounts.

The full-scale test was performed on a production truck which had to return to roadworthiness at the conclusion of the test. As a result the structure of the model could not be permanently modified for strut attachment points. Because it utilized road-going engine and drivetrain components, the weight of the model also exceeded the capacity of the under-floor balance. An 8.5-meter (28 ft) trailer was used for full-scale testing as the longest that could fit through the test section access hatch. Even with this relatively short trailer the