

The Effects of Ground Simulation on Tractor-Trailer Combinations

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ABSTRACT

The 9-meter wind tunnel of the National Research Council (NRC) of Canada is equipped with a boundary layer suction system, center belt and wheel rollers to simulate ground motion relative to test articles. Although these systems were originally commissioned for testing of full-scale automotive models, they are appropriately sized for ground simulation with half-scale tractor-trailer combinations. The size of the tunnel presents an opportunity to test half-scale commercial vehicles at full-scale Reynolds numbers with a model that occupies 3% of the test section cross-sectional area.

This study looks at the effects of ground simulation on the force and pressure data of a half-scale model with rotating tractor wheels. A series of model changes, typical of a drag reduction program, were undertaken and each configuration was tested with both a fixed floor and with full-ground simulation to evaluate the effects of this technology on the total and incremental drag coefficients. The question was whether ground simulation affected predictions of the drag change due to typical model changes. Effects of the ground simulation were further considered by employing wheel rotation or the center belt alone. This was undertaken to determine whether a simplified ground simulation system would suffice for commercial vehicle testing.

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INTRODUCTION

A fundamental simplification encountered when testing a ground vehicle in a traditional wind tunnel, i.e. one in which the floor is fixed or does not move, is that the air moves in relation to the vehicle and the "ground", in direct opposition to the conditions encountered on the road where there is practically no relative motion between the air and ground. The movement of the air with respect to the wind tunnel floor generates a boundary layer which, depending on the sensitivities of the model, can have a significant impact on the flow field and resulting forces the model experiences.

The first hurdle to testing a commercial vehicle at high Reynolds number with a moving ground was a scarcity of facilities with this capability. Ground simulation is sometimes neglected for vehicles with large ground-to-underbody clearances but it remained to be seen whether this was an appropriate approach to commercial vehicles.

Following the renewal of full-scale tractor-trailer testing at the 9-meter wind tunnel [1] a half-scale to full-scale correlation test was undertaken to evaluate the effects of test section blockage and the procedures used for correcting these

effects [2]. The testing of the half-scale model employed in this study offered the opportunity to test a commercial vehicle model at full-scale Reynolds number over a ground simulation system originally designed for automotive models but appropriately sized for the half-scale tractor-trailer combination.

In 1999 a floor boundary layer treatment system consisting of two levels of distributed suction, immediately upstream of the model turntable, was installed in the 9-meter wind tunnel [3]. Responding to demands for an increased fidelity ground simulation a ground effect simulation system (GESS) was commissioned in 2009. The GESS consists of a center belt, with an exposed area 1-m × 5.7-m, four wheel rollers and four chassis struts for ride height control. The wheel rollers and chassis struts, being intended for automotive use, could not be located in the positions necessary for the half-scale model.

Custom mounts were used which mounted the model so the wheels were just above the floor, while a motor inside the model rotated the truck wheels. A motor was not installed to rotate the trailer wheels due to weight/structural restrictions of the model and mounts. This necessary compromise still

allowed the study of wheel rotation effects though results with all model wheels rotating may differ. For the remainder of the paper “full ground simulation” will refer to use of boundary layer suction, center belt and internal wheel motors. The term “fixed floor” applies to the same setup as above, with the model over the belt, but without belt or wheel rotation. Upstream boundary layer suction was employed in the fixed floor tests in the same locations and at the same levels as applied to the full ground simulation.

TEST SETUP

Test Section Configuration

The test section of the NRC 9-meter wind tunnel has a square 9-meter cross section, with corner fillets, and is 23-meters long. Figure 1 is a plan view showing the boundaries of the test section along with the layout of the 45° corner fillets. The test section is equipped with a rotating floor turntable, containing a rolling road (shown in red) over an under-floor balance. Upstream of this are two plenums for a distributed suction system (shown in blue), calibrated to reduce displacement thickness of the floor boundary layer to 4-mm [3] at the leading edge of the model, without inducing flow angularity at the model. Breathers on the floor (shown in yellow) and walls, at the test section exit, are vented to the tunnel surroundings to raise the otherwise negative gauge pressure in the test section closer to atmospheric pressure.

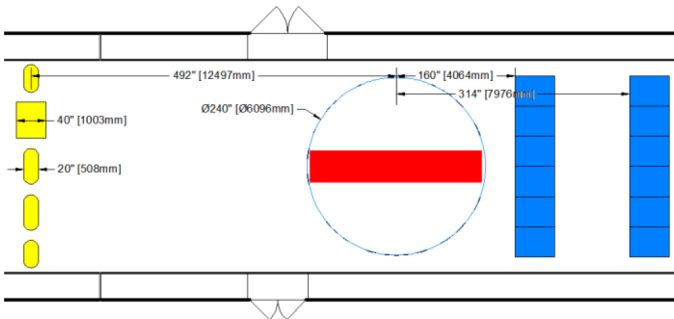


Figure 1. Test section layout for full-scale test; Wind direction from right to left (dimensions in meters).

Model Details

The model was a 2008 Volvo VNL630 with a roof deflector, tank skirts, side extenders and sun visor, as shown in Figure 2. Some compromises in model geometry were required due to cost and practicality, for instance the rear axles of the trailer utilized off-the-shelf components that were not exact 50% replicas of the full-scale unit. The engine and accessories were simulated with simplified components. The baseline trailer for this work represented the 28' trailer normally employed in full-scale testing at the 9-meter wind tunnel. Flush, static pressure taps were located along the centerline of the model's upper surface in addition to taps evenly distributed over the side of the cab and rear face of the

trailer. Table 1 describes the location of the taps according to the label numbers used in the following discussion of data.



Figure 2. Baseline Configuration of VNL630.

Table 1. Description of the pressure taps.

Port Number(s)	Location on Model
1 – 12	Hood
13 - 19	Windshield
20 – 24	Forward face of roof fairing
25 – 28	Rear face of cab
29 - 33	Driver-side of cab
34 - 38	Passenger-side of cab
40 – 44	Front face of trailer
45 – 54	First meter of trailer roof
55 – 57	Remainder of trailer roof
58 – 66	Base of trailer

Model Mounting

The model was completely supported by the under-floor balance and rested almost entirely over the floor turntable. The model mounting points did not match the locations of the struts and wheel rollers, normally employed for automotive testing, and model width exceeded belt width. 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 plywood covers were fabricated to minimize tare drag loads as shown in Figure 3.

The model was mounted with the front bumper 140-mm downstream of the leading edge of the exposed belt. With a baseline tractor-trailer gap of 0.55-m, equating to the manufacturer-specified 43" in full-scale, the overall model length was 6.8-m. The model was longer than the exposed belt length of 5.7-m so the aft-most 1.3-m of the baseline model overhung the fixed floor. For select runs a trailer

extension was added to represent a full-scale 48' trailer; in these cases the overall model length increased by 3.2-m resulting in 4.5-m of the model being over the fixed floor.



Figure 3. Details of the forward mounts and floor covers.

Ideally the distance between the base of the model and the end of the test section exceeds two times the square root of the frontal area of the model [4], equating to approximately 3.3-m for the half-scale model. In the 9-meter wind tunnel the end of the test section is defined by the breathers, where the constant static pressure region ends. There was 8.1-m and 4.9-m between the test section breathers and the base of the half-scale 28' and 48' trailers respectively.

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 4. The mounts were attached to the balance so they were subject to tare and interference drag.

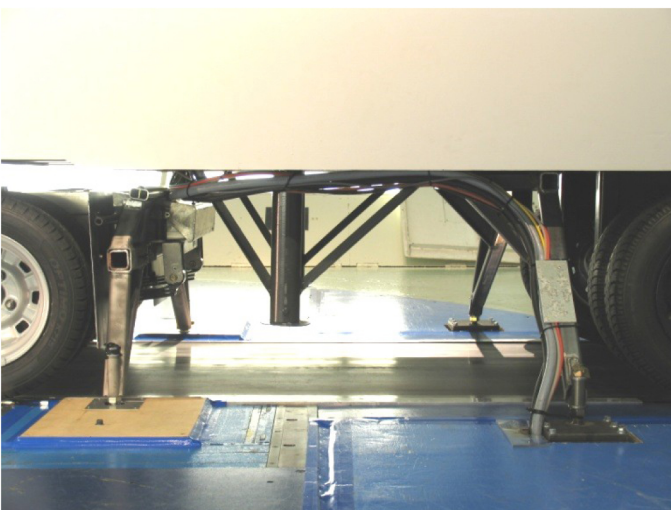


Figure 4. Details of the rear mounts and cabling.

The track width of the 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 extend outwards as they approached the floor. The struts are attached to the balance below, on either side of the belt, as

shown in Figure 5. Note that all of the mounting struts pass through clearance holes in the floor and are not attached to the floor itself.

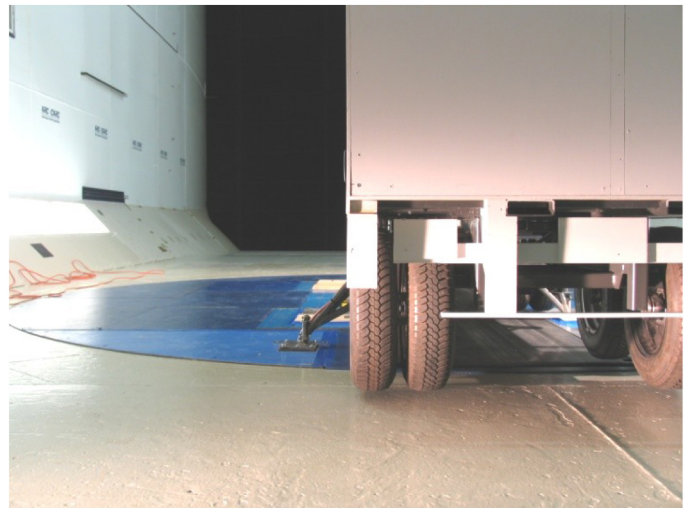


Figure 5. End view of the rear mounts.

Methodology of Runs & Reduction

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

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

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

The weighting values are calculated using Equations 2 and 3. 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].

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

$$\varphi_i = 15 + 30(i - 1) \times \frac{\pi}{180} \quad (3)$$

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 perfectly symmetric so WACD should be calculated as the average of WACD for the positive and negative halves of the yaw curve.

Each run consisted of a wind-off tare and fouling check. Once the wind speed was up to specification and had stabilized, acquisition began. Data were acquired for 60 seconds at each angle, starting at 0°, then the most negative angle, proceeding through 0° to the most positive angle and ending with a third point at 0°. The three repeats at 0° provided an in-run check of system repeatability which was further bolstered by periodic repetition of a baseline case. Before acquiring data at a new angle the control system waited until the dynamic pressure and under-floor balance had stabilized.

Test section dynamic pressure was measured by a pitot-static probe at the test section entrance which had been calibrated against a pitot-static probe 1.2-m above the center of the turntable, with the test section empty. The boundary layer suction fan was automatically controlled based on tunnel dynamic pressure. The under-floor balance was a nulling, weighbeam balance which measured wind-on loads from which the wind-off tares were subtracted. The data were automatically processed by the tunnel reduction system which applied all calibration factors, buoyancy corrections, axis transformations and wall interference corrections.

At the NRC, the Maskell III method is generally recommended for correcting wall interference (blockage) 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 [6].

DISCUSSION OF RESULTS

In the following discussion, all absolute drag data have been offset by the same randomly-chosen constant to prevent the determination of the model drag coefficient while still allowing relative comparison of the results. Model dimensions cannot be reported but approximate values of critical parameters such as area blockage ratios are noted.

In the following results all drag coefficients, pressure coefficients and yaw angles have been corrected for blockage effects according to the Maskell III method. Wind-averaged drag coefficients are in body axis and are calculated for a vehicle speed of 105-km/hr (65-mi/hr).

The results of tests on the baseline model, Figure 6, show that the implementation of the full ground simulation increases drag throughout the yaw range, resulting in a 28 count difference between the fixed floor and full simulation cases. Commercial vehicles have rough underbodies occupied by large, bluff objects such as axles and bogies; by minimizing the floor boundary layer the volume of air impinging on these objects is now greater and travelling at a higher velocity. This should be more representative of the flow field experienced in on-road operation.

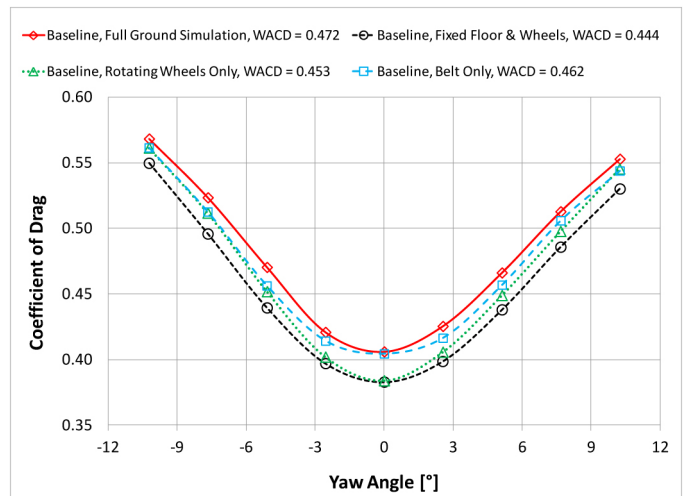


Figure 6. Comparison of baseline drag curves with four levels of ground simulation.

To see if it was possible to approximate this flow with something less than the full ground simulation, the model was run with just wheel rotation and then with only belt movement. Wheel rotation had little effect on drag at zero yaw, whether or not the belt was on, but became significant at higher yaw angles. The wind-averaged drag for the wheel-only case deviated from the full ground simulation results by 19 counts. The belt-only case almost matched the reference case at low yaw angles but began to deviate at higher angles. Because low yaw angles are more commonly encountered in operation they have a greater influence on the wind-averaged