

Aerodynamic Performance of Flat-Panel Boat-Tails and Their Interactive Benefits with Side-Skirts

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ABSTRACT

This paper describes an investigation of the performance potential of conventional flat-panel boat-tail concepts applied to tractor-trailer combinations. The study makes use of data from two wind-tunnel investigations, using model scales of 10% and 30%. Variations in boat-tail geometry were evaluated including the influence of length, side-panel angle and shape, top-panel angle and vertical position, and the presence of a lower panel. In addition, the beneficial interaction of the aerodynamic influence of boat-tails and side-skirts that provides a larger drag reduction than the sum of the individual-component drag reductions, identified in recent years through wind-tunnel tests in different facilities, has been further confirmed. This confirmation was accomplished using combinations of various boat-tails and side-skirts, with additional variations in the configuration of the tractor-trailer configuration. Key findings include the reduced performance associated with lowering the position of the top panel to retain visibility of marker lights, and an observed change in boat-tail performance based on the overall vehicle configuration.

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INTRODUCTION

The addition of a boat-tail to the base of a heavy-duty vehicle (HDV) has been shown to generate significant reduction in vehicle drag on the order of 6-12% [1, 2, 3, 4, 5, 6, 7, 8], resulting in a corresponding reduction in fuel consumption per vehicle (order of 2000 - 4000 L/year). The term boat-tail refers to a tapered fairing that is mounted to the rear of a trailer. The tapered surfaces guide the wake flow inwards, increasing the average pressure on the aft end of the vehicle, and providing a smaller pressure difference in the direction of motion. This reduced pressure difference from streamlining of the vehicle shape results in a lower drag force on the vehicle, and hence a fuel savings.

Although the boat-tailing concept has been known for decades to reduce the drag of ground vehicles, it has only been the last decade that the concept has demonstrated increased use [9], driven in large part by California's strict fuel economy measures [10]. In the latter part of the 2000's, the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) were promoting boat-tails with lengths on the order of 1.2 m (4 ft) that could achieve 5% fuel saving [11]. In Canada, extension panels up to only 0.6 m in length were permitted at the time, with some jurisdictions allowing longer devices with special permits. Faced with this discrepancy in policy, Canadian officials aimed to amend the current policy. In response, Transport Canada's Road Safety and Motor Vehicle Regulation Directorate [12] commissioned a study aimed at identifying the envelope within which a boat-tail could reside that would limit the extent of rear-end collisions that could result in a wind-shield strike prior to collision with the rear-impact guard. That

study was a preliminary step towards the change in the Canadian Motor Vehicle Safety Regulations allowing longer boat-tail concepts. As part of the study, performed by the National Research Council Canada (NRC), a wind-tunnel investigation was undertaken to examine the potential performance benefits of longer boat-tails. The study investigated the relative improvement in drag-reduction for several boat-tail configurations, considering the effects of panel angle, panel length, side coverage, and the influence of a lower panel. The study was performed at 10%-scale using an older-model aerodynamically-treated day-cab tractor with an equivalent 40 ft dry-van trailer, and the testing was done at a width-based Reynolds number of 1.3×10^6 with fixed floor and wheels.

In 2013, Transport Canada amended its Canadian Motor Vehicle Safety Regulations (Standard 223) [13] to provide allowance for boat-tails that extend further than the previous 0.6 m limit. The updated standard specifies the geometry of a region within which a flexible aerodynamic devices (non-structural) can protrude past the rear extremity of the vehicle. A schematic representation for the allowed extremity of the deployed device is shown in [Figure 1](#).

More recently, Transport Canada's ecoTECHNOLOGY for Vehicles program [14] commissioned the NRC to investigate the potential drag reduction and associated fuel savings for a range of current and emerging drag-reduction concepts for heavy-duty vehicles [8]. Five flat-panel boat-tail concepts were tested in this study, with changes in length, side coverage, and the presence of a lower panel. As part of that study, major improvements were made to the wind-tunnel technologies including the fabrication of a high-fidelity 30%-scale

model of a modern tractor-trailer combination with spinning wheels, mounted over a rolling road system, and with the NRC Road Turbulence System (RTS) designed to provide road-representative wind conditions in the wind tunnel [15]. This testing was performed at a width-based Reynolds number of 2.7×10^6 .

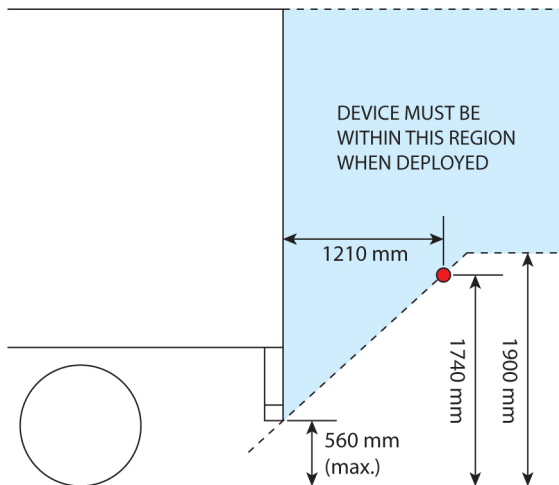


Figure 1. Schematic representation of allowable deployment range for back-mounted aerodynamic devices (according to CMVSS 223)

Results from initial 30%-scale high-fidelity test program [8] identified some interesting phenomena associated with boat-tails, leading to a follow-up study for which a large number of boat-tail variants were tested. The initial 30%-scale tests [8] showed lower performance from the boat-tails than anticipated, based on previous work at NRC and by others. A reduction in wind-averaged drag on the order of 0.04 (7%) was observed, while other studies [1, 3, 2, 5, 6, 7] have shown improvements of wind-averaged-drag in excess of 0.06 (>10%). The low performance was hypothesized to be a result of the vertical offset of the top panel from the trailer roof, set at 0.076 m (3 inches) full-scale, to retain visibility of the trailer marker lights.

Another important observation from the initial 30%-scale tests [8] was a beneficial aerodynamic interaction of the influence of side-skirts and boat-tails on the vehicle drag loads, such that the combined drag reduction was greater than the sum of the individual-component performances. It was unclear at the time whether this phenomenon was truck-shape-specific, or perhaps boat-tail-design specific. A question was raised to the generality of the phenomenon and whether it may be a by-product of the lower-performance boat-tails that were tested. Two other data sources have subsequently been identified that show this aerodynamic interaction between the influence of the two drag-reduction devices [7, 16], the details of which will be described later in this paper.

Described herein is part of a follow-up study to the initial test campaign with the 30%-scale model [8]. The follow-up study was designed to evaluate some additional design criteria for developing practical boat-tails, including not only the fuel-efficiency gains as measured through the vehicle drag, but to look at other operational and road-safety considerations such as the influence of boat-tails on vehicle

stability and on the dynamics of the wake structure within which other road users must operate. This paper focuses solely on the fuel-efficiency component the project, which includes some operational considerations such as the presence of the lower panel and the top-panel vertical offset required for marker-light visibility. A range of boat-tail shapes were designed and tested, some of which were also tested with several side-skirt designs and different configurations of the tractor-trailer combination to gain an appreciation for the vehicle-specific factors affecting boat-tail performance.

EXPERIMENTAL SETUP AND PROCEDURES

NRC 2 m × 3 m Wind Tunnel with 10%-Scale Model

The 10%-scale experiments were conducted in the NRC 2 m × 3 m Wind Tunnel [17] with a ground-board installed, using practices consistent with SAE J1252 [18]. The ground-board provides two levels of boundary-layer control: a new boundary layer that starts at the front of the ground-board; and a suction system to thin the boundary-layer through a series of perforated plates upstream of the turntable centre. These controls provide a sub-1 mm displacement thickness at the turntable centre. The blockage level of the model was 2.4%, and the tests were performed at a blockage-corrected wind-speed of 80 m/s, providing a width-based Reynolds number for the truck model of 1.3×10^6 . The turbulence level in the test section is 0.14%. Pictures of the test section with the ground-board and truck model are shown in Figure 2. Measurements were made using a 6-component external balance.

The truck model used in this 10%-scale study was an older-model day-cab tractor with a 40 ft (full-scale equivalent) dry-van trailer, shown in Figure 3. The standard configuration used for the boat-tail-evaluations included four pieces of aerodynamic hardware: the cab fairing with cab extenders and the fuel tank fairings (these two items are painted blue and together make up a standard aerodynamics package commonly seen on modern tractors), and the gap-seal and the side-skirts (these two items are painted red). The trailer base region is simplified with a flat surface, and hence no door or light details are present. The aft underbody is simplified, without a rear-impact guard or mud flaps.

The boat-tail models tested in the 10%-scale study, 31 in total, were constructed out of folded steel pieces, that were welded together. Samples of these boat-tail models are shown in Figure 4. Four boat-tail lengths were tested, with full-scale equivalent dimensions of 0.6 m (2 ft), 0.9 m (3 ft), 1.2 m (4 ft), and 1.5 m (5 ft). Dimensional tolerances of the boat-tail models were within ± 1 mm (10 mm full scale) on linear dimensions and $\pm 1^\circ$ on panel angle. A magnetic end plate was attached to the rear of the trailer, allowing rapid model changes because each new panel set could be easily and quickly slid on and off the magnetic panel. Aluminum tape was used to seal any gaps at the trailer/boat-tail interface. The bottom panels of the boat-tail models were manufactured separately, and were taped into place on the equivalent three-sided set for the runs with the bottom panel. Details of the tested configurations and the nomenclature for their identification are provided later in the paper.

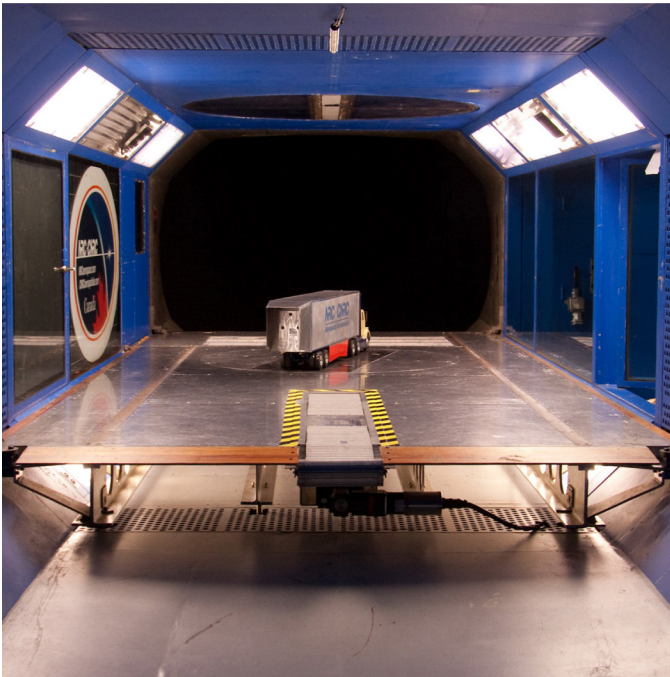


Figure 2. Test section of the NRC 2 m × 3 m Wind Tunnel with the ground-board and truck model installed.



Figure 3. 10%-scale tractor-trailer model with aerodynamic treatments.



Figure 4. Sample boat-tail models installed on the 10%-scale tractor-trailer model.

NRC 9 m Wind Tunnel with 30%-Scale Model

The 30%-scale experiments were undertaken in the NRC 9 m Wind Tunnel with the Ground Effect Simulation System [19], as shown in Figure 5. Testing was conducted using practices consistent with SAE J1252 [18]. The GESS consists of a boundary-layer suction system ahead of the test-section turntable, providing a displacement thickness of 4 mm at the turntable leading edge, combined with a $1.0 \text{ m} \times 5.6 \text{ m}$ rolling road mounted in the turntable. The blockage level was 1.2%, and the tests were performed at a blockage-corrected wind-speed of 50 m/s, providing a width-based Reynolds number for the truck model of 2.6×10^6 . At this Reynolds number, the drag-coefficient has not yet reached a stable value, but is decreasing at a rate lower than 0.01 per 10^6 Reynolds number. Testing was performed with a turbulence generation system [15] that provides road-representative turbulence with a turbulence intensity of 4% and turbulence length scales on the order of 1 m full-scale-equivalent dimension relative to the 30%-scale model. During the commissioning of the 30%-scale model and the turbulence-generation system, it was demonstrated that the performance of a boat-tail is higher in the smooth-flow conditions of conventional wind tunnels, with a difference on the order of 1% of overall vehicle drag [15].



Figure 5. 30% tractor-trailer model in the NRC 9 m Wind Tunnel.

The truck model used in this 30%-scale study consists of a sleeper-cab tractor with a 53 ft (full-scale equivalent length) dry-van trailer, shown in Figure 5. The tractor is based on an International ProStar [20] but with modifications to the shape of the bumper, roof fairing, A-pillar, and hood, such that it does not represent the aerodynamic performance of the commercial product. The trailer does not represent a specific commercial product, but has geometry consistent with many 53 ft dry-van trailers in operation. For the current study,

additional details were added to the base of the trailer including brake and marker lights, door hinges and latches, and a rain gutter along the top edge (shown in Figure 6). In addition to the rolling road, the model has spinning wheels synchronized with the speed of the road, both of which are controlled to match the the blockage-corrected wind speed. The wheels are raised 5 mm from the rolling road to prevent mechanical fouling between the balance-mounted model and the turntable/rolling-road system, differing from the SAE J1252 recommendation for driving the wheels with the moving ground plane. Measurements presented herein were performed using the 6-component external balance, located below the test section. A set of six low-interference struts support the model over the rolling road and connect it to the balance under the test section. The struts were designed to provide low drag using a streamlined shape (combined $C_D < 0.035$ based on truck-model frontal area), and low aerodynamic interference with the model (combined $\Delta C_D < 0.010$ based on truck-model frontal area). Per SAE J1252 recommendations, the strut-tare and interference loads were characterized for data correction purposes (see next section for description of data corrections).



Figure 6. Trailer base details (left - lights and door hardware, right -rain gutter).

The boat-tail configurations tested in the 30%-scale study, 30 in total, were fabricated from aluminum sheet material, and welded to a standard installation-plate shape, two examples of which are shown in Figure 7. As with the 10%-scale study, the main assemblies were 3-panel configurations, with a fourth lower panel added as a separate component for some configurations. Aluminum tape was used to seal gaps at the trailer/boat-tail interface along the sides of the model, and along the top for the configurations with the top panel flush-mounted with the trailer roof. Dimensional tolerances of the boat-tail models were within ± 2 mm (7 mm full scale) on linear dimensions and $\pm 0.5^\circ$ on panel angle. Vertical adjustability of the mounting position allowed an assessment of the vertical offset from the trailer roof up to 0.076 m (3 inch) full-scale. The top panels also have a removable middle section to allow changes to the basic flat-panel shape. All boat-tails tested in the 30%-scale experiments were designed to conform to the amended CMVSS 223 defining the regions beyond the rear impact guard that a flexible aerodynamic device can reside. Details of the tested configurations and the nomenclature for their identification are provided later in the paper.

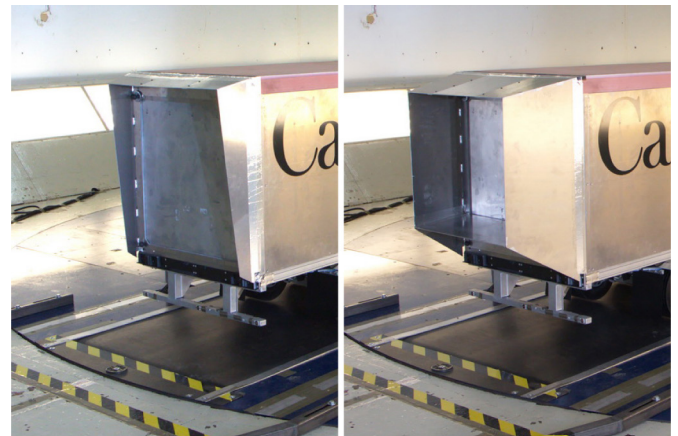


Figure 7. Sample boat-tail models installed on the 30%-scale tractor-trailer model.

Data Analysis

The parameter of interest for the current paper is the drag coefficient, defined as

$$C_D = \frac{F_D}{1/2 \rho U^2 A} \quad (1)$$

where F_D is the measured drag force, ρ is the air density, U is the wind speed, and A is the vehicle reference area (taken here as vehicle height $\times$ vehicle width).

The wind-tunnel drag-coefficient measurements have been corrected for the following influences, according to standard wind-tunnel practice:

- Blockage effects: Confinement of the air around the model in the closed-wall test section of the wind tunnel causes a local speed-up of the air in the vicinity of the model. The 10%-scale model in the NRC 2 m $\times$ 3 m Wind Tunnel has a blockage ratio of 2.4%, for which the Maskell III method [21] was used to correct the the wind speed, and its influence on the drag coefficient. The 30%-scale model in the NRC 9 m Wind Tunnel has a blockage ratio of 1.2%, for which the Thom-Heriot method [22] was used to correct the measurements.
- Strut loads (30%-scale only): The wind loads measured by the under-floor balance system also measure the wind loads experienced by the struts that support the tractor-trailer model over the rolling road. The strut wind loads and their aerodynamic interactions were characterized during the commissioning of the model and have been subtracted from the model+strut measurements to provide the wind loads experienced by the model in the absence of the struts. The corrections are on the order of 2% to 4% of the measured drag coefficient, depending on the yaw angle, the vehicle configuration, and the strut configuration.
- Wheel aerodynamic resistance (30%-scale only): The overall aerodynamic resistance to the motion of a ground vehicle includes not only the drag force of the vehicle in-line with the direction of motion, but also the aerodynamic torque experienced by the wheels. The engine must overcome