

A Comparison of Full Scale Aft Cavity Drag Reduction Concepts With Equivalent Wind Tunnel Test Results

Joshua P. Kehs and Kenneth D. Visser
Clarkson University

Jeff Grossman, Jared Niemiec, Andrew Smith, and Charles M. Horrell
ATDynamics

ABSTRACT

Comparison studies have been conducted on a 1:16th scale model and a full scale tractor trailer of a variety of sealed aft cavity devices as a means to develop or enhance commercial drag reduction technology for class 8 vehicles. Various base cavity geometries with pressure taps were created for the scale model. The studies confirmed that length has an important effect on performance. The interaction of the boat-tailed aft cavity with other drag reduction devices, specifically side skirts, was investigated with results showing no discernable drag performance interaction between them. Overall, the experiments show that a boat-tailed aft cavity can reduce the drag up to 13%. Full-scale tests of a commercially derived product based on these scale tests were also completed using SAE Type II testing procedures. Full-scale tests indicated a fuel savings of over 6.5%. The implementation of these devices is shown to be a viable, effective and economical way to reduce fuel consumption on ground transport vehicles.

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INTRODUCTION

The US Department of Transportation reported that over 2.5 million combination trucks were registered in the United States, driving a total of 175 billion miles and burning a total of 29 billion gallons of fuel in 2010 [1]. All of these vehicles possess the possibility of fuel economy gains through the use of drag reduction devices. At these levels of consumption, even a modest 5-10% reduction in fuel usage could save billions of gallons of fuel each year, would result in billions of dollars of savings for the transportation business, reduce the demand for domestic and foreign oil, have a significant environmental impact, and reduce global oil dependency.

Drag reduction on bluff bodies and tractor-trailers specifically using aft sealed cavities has been the focus of many studies in the past. These studies have shown that such a device has potential to reduce drag to a significant degree.

NASA began studies in 1974 [2][3][4][5] on full-scale bluff body ground vehicles (vans and tractor-trailers) using a "coast-down" type test, but all of these tests concentrated on various parts of the vehicle not including the base. Investigations on the base of the vehicles began around 1980

with NASA funded wind tunnel and full scale "coast-down" experiments by Muirhead [6] and Peterson [7] respectively. These tests showed that full boat-tails and truncated boat-tails (without cavity) are effective in reducing vehicle drag to a significant degree.

Lanser, Ross, and Kaufman [8], also at NASA, investigated a device that was essentially a straight walled cavity that was inset from the trailing edges of the trailer. This inset device was thought to have trapped re-circulating flow in the corner formed by the inset thereby turning the flow inwards at the trailing edge of the truck and effectively reducing the base area of the truck on which the base pressure acts. The experiments to test this used a full-scale tractor-trailer at the NASA Ames 80×120 ft wind tunnel. The authors reported a wind averaged drag reduction of 9.8% over a yaw range of $\pm 15^\circ$ and a significant increase in base pressure inside the enclosed region of the cavity.

Cooper [9] completed a study on angled base flaps on three and four sides (i.e. boat-tailed aft cavity when using 4 sides) of the base on the trailer. This is the first known study on the use of such a device. An optimization on the three sided base flap configuration yielded the best configuration to

be at a length of $l/W=0.2$ and a base flap angle of 15° . This configuration gave a wind averaged drag coefficient reduction of $\Delta C_D=0.047$ (approx. 8%) for a 1:10 scale model non-articulating truck. When using a 4th flap at a 0° angle to close the bottom, even more reduction was gained with a drag coefficient reduction of $\Delta C_D=0.059$. This suggests that sealing the cavity was important to the mechanism in which this device worked. When using the 4-sided boat-tailed aft cavity device on a tractor-trailer model, it gave a drag coefficient reduction of 0.039 or 4%. This and other experiments were reviewed by Cooper [10]. Further experimentation on a three sided angled base flap device was studied at full scale by Leuschen and Cooper [11] which reported an even higher wind averaged drag reduction at $\Delta C_D=0.0506$.

In the early 2000s, Storms et al. [12][13][14] under a NASA contract, began an in depth study of drag reduction on tractor-trailers. Storms experimented on what he called base flaps (i.e. boat-tailed aft cavity), which were attached to the base corners of the trailer and could be angled inward, as well as a straight walled inset aft cavity much like the device tested by Lanser, Ross, and Kaufman [8]. For the base flap case, the flap length was 25 inches (63.5cm) and they were capable of being angled inward. The best case for the angle was reported to be at a flap angle of 20° which yielded a wind averaged drag coefficient reduction of 0.0954. Pressure analyses over the length of the truck showed that the addition of the base flaps had little upstream effect on the cab and front of the trailer, but did significantly increase the base pressure. Unfortunately no experimental methods other than drag and pressure were used to study the base flaps. Storm's studies on the straight walled inset cavity included 2 length cavities (24 inch and 30 inch full-scale) with an inset of 5 inches on the top and sides. These devices were shown to be less effective in reducing drag than the base flaps with a drag coefficient reduction of $\Delta C_D=0.0582$ for the longer 30 inch case. A Reynolds number effect study was also completed by this team (Storms 2004) and reported that Reynolds number effects on the baseline case between $Re=500,000$ and $Re=1$ million show up to 7% difference in drag, but show almost no difference in base pressure over this same range suggesting that Reynolds number effects may be present due to variations in flow on the front and sides of the model.

Khalighi et al. [15], from General Motors Corporation, has also completed a detailed study of a straight walled inset aft cavity that was also much like the device in Lanser, Ross, and Kaufman [8]. Using a simplified model with a rounded leading cone rather than a tractor, and cavity walls 35% of the model width, the authors reported a drag coefficient reduction of approximately $\Delta C_D=0.06$. Khalighi also used surface pressure transducers, hotwire probes, and PIV to help understand the flow in the wake. From that experimentation, the authors showed that the base pressure increased significantly, the turbulence intensity of the flow in the wake and large-scale vortical structures were suppressed, and the

recirculation region was narrower with the device attached. The authors suggest the drag reduction was due to the flow having formed a vortex ring in the step region where the inset for the cavity existed as in Figure 1. The fluid that flowed in the vortex ring then re-attached to the cavity walls. This reattachment was claimed to have decelerated the outer flow and thereby increased the pressure at the edge of the plates where the flow then re-separated into the wake flow, which in effect caused the wake to be smaller and increase the pressure within the cavity.

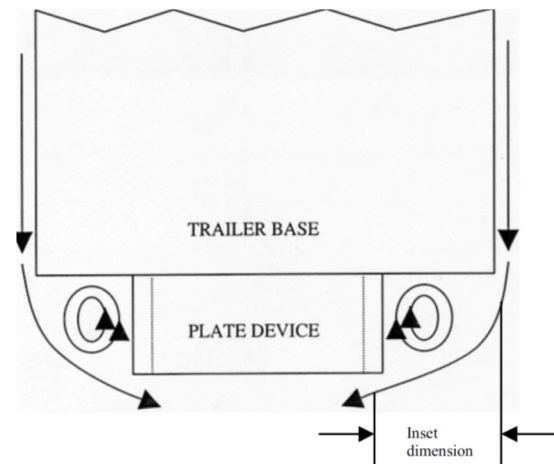


Figure 1. Straight Walled Aft Cavity Suggested Flow [18].

At Clarkson University, experimental scale model and full-scale studies have been ongoing for the past decade beginning with an internal investigation (Allen et al. [16]). Maragno and Visser [17] investigated the effectiveness of boat tail angle of the side plates, inset from the side edges, length of the boat tail and the number of plates, at a Reynolds number of $2.3e5$, and found that the best configuration was a sealed 4 sided aft cavity with a 10° side boat-tail angle, no inset, and a 48 inch (full-scale) length. A ΔC_D of approximately 0.12 was reported.

Coon and Visser [18] reported in a numerical and experimental study of straight walled, variable inset aft cavities, that a 4 sided, 48 inch deep cavity with a 6 inch inset on the sides and top was the best case at zero yaw with a drag reduction of $\Delta C_D=0.075$. Full-scale over the road tests by Coon and Visser (Figure 2) saw a fuel efficiency increase of 0.5mpg or 8.3% when implementing their best configuration.

Browand et al. [19] conducted a full-scale over the road test using a three-sided angled base flap device similar to Cooper [9][10]. The length of the flaps was 25% of the width of the truck (approx 25 inches) and an optimization was performed on the base flap angle. Fuel consumption was measured using the trucks computer broadcast fuel rate and converted to change in coefficient of drag using a simple equation. This experiment reported a savings of 0.25mpg for a $\Delta C_D=0.057$ at an optimum base flap angle of 13° . This optimum angle is lower than the

(Storms et. al. [12][13][14]) and slightly lower than the NRC studies, but is the first such experiments to use over the road test to optimize this parameter. The drag reduction, however, is within the range of previous experiments.



Figure 2. Full-Scale Over the Road Test Setup (Coon and Visser, 2004).

A full-scale over-the-road study by Grover and Visser [20] on a tractor-trailer at Clarkson University indicated an optimal boat-tailed aft cavity geometry of 15° on the side and top panels, and a 7° inset on the bottom. An improvement of 0.63 mpg was observed in the back-to-back runs, which resulted in a fuel savings of about 10%.

A study by Kehs and Visser [21] in conjunction with ATDynamics, who has commercialized these types of devices, reported on various folding boat-tailed aft cavity geometries. The pressure and drag experiments in this study showed a reduction in drag and an increase in base pressure while using such devices.

The purpose of the current study was to characterize the performance of aft cavity devices with respect to length and bottom panel height and to compare the results to test data acquired on full-scale configurations. In this study, drag and pressure measurements were acquired on a 1:16th scale model of a tractor-trailer with multiple interchangeable rear end configurations. Full-scale SAE-J1321 [22] tests were then completed.

METHODOLOGY

A 1:16th scale model of a generic tractor-trailer was fabricated from a Nylon and aluminum powder matrix using selective laser sintering. The model was designed to resemble a modern aerodynamic cab and standard 53 ft trailer. The total length of the model was approximately 1.4 m. The model included a mounting location for the stings and a method for mounting the different rear end configurations and is shown in Figure 3.

The 8 rear end configurations included one baseline configuration (flat rear end) and 7 aft cavity configurations. All of the aft cavity configurations have an inset of 2.5mm on the top and 0mm on the side panels but the inset on the bottom panel was lowered for one configuration. The panels were at an inward angle of approximately 12° . Table 1

contains drawings of the rear end configurations. Additionally, a side-skirt was fabricated from 1.6mm (0.063") aluminum sheet metal. The skirts were 1.88" (47.7mm) tall and 17.2" 436.9mm long with a 0.75" (19mm) inset on the leading edge. The skirts are shown in Figures 5 and 6.

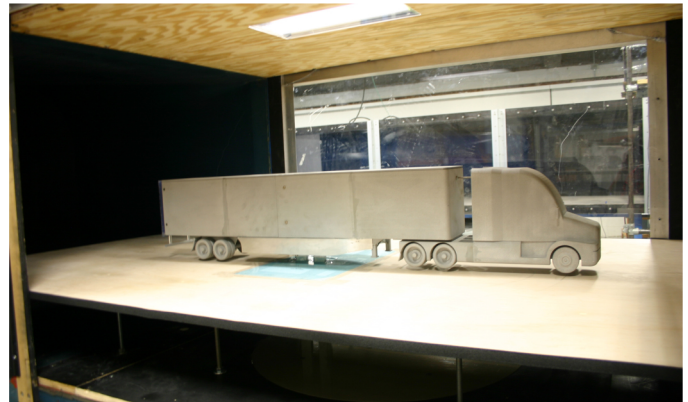


Figure 3. Photographs of Tractor Trailer Scale Model

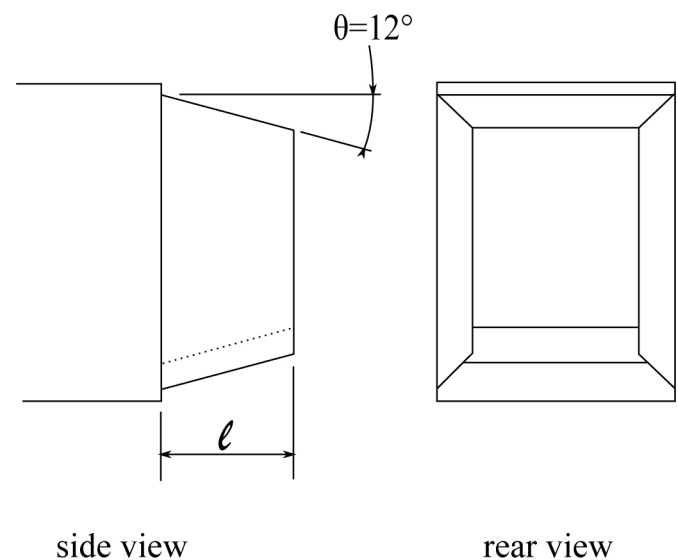


Figure 4. Boat-tailed Aft Cavity Geometry (θ is Panel angle and l is Cavity Length)

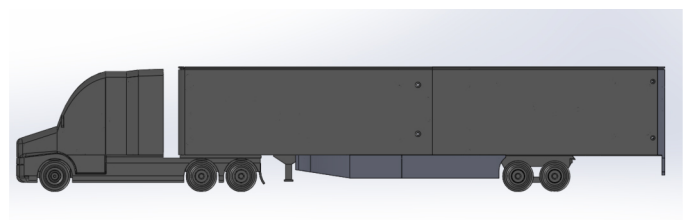


Figure 5. Drawing of Side Skirts Attached to Model

