

# Full-Scale Wind Tunnel Tests of Production and Prototype, Second-Generation Aerodynamic Drag-Reducing Devices for Tractor-Trailers

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## ABSTRACT

The National Research Council of Canada (NRC) has completed the second round of full-scale wind tunnel tests on Class-8 tractor-trailer combinations. The primary intent of the program is to effect a reduction in greenhouse-gas emissions by reducing the fuel consumption of trucks through aerodynamic drag reduction. Add-on aerodynamic components developed at the NRC several decades ago have become important contenders for drag reduction. This program has encouraged the commercialization of these technologies and this round of tests evaluated the first commercial products.

Three primary devices have been evaluated, with the combination able to reduce fuel consumption by approximately 6,667 liters (1,761 US gal) annually, based on 130,000 km (81,000 miles) traveled per tractor at a speed of 100 km/hr (62 mi/hr).

## INTRODUCTION

The NRC program has advanced through three phases. The first phase utilized 1:10-scale model and full-scale development programs [1] to reintroduce the concept of tractor/trailer gap closure, trailer skirts and trailer boat-tails. The second test program [2] optimized the component designs. This, the third program, tested commercial products of these and prototypes of other possible devices.

In the past, aerodynamic improvements to heavy trucks, especially the current cab-mounted aerodynamic packages, have provided large improvements in fuel consumption. Similar gains are also possible with the combinations of devices just mentioned. However, as is usually the case, one has to work somewhat harder to make these gains. In this case, three devices can be used alone or in combination. Two of these devices are trailer mounted, which impairs their economics, since there are approximately 3 trailers per tractor, on

average, across North America. In spite of this, their relatively low installed cost and the rising cost of fuel make them economically viable. In any case, where fewer trailers are run per tractor, the economics are even better. The third approach, closing the tractor-trailer gap uses hardware that can be either tractor or trailer mounted. It would seem beneficial to use tractor-mounted equipment, but both types of hardware are becoming available.

This paper will discuss the current state of product development and will show that beneficial products are available. In the end, it will be the willingness to try these products, and the patience to evolve them into operationally effective, reliable tools for fuel savings that will ensure their success.

## PHASE 3 PROGRAM OUTLINE

The test program was run in March 2006 in the 9-meter wind tunnel of the NRC, located in Ottawa, Canada. This is a closed-wall, closed-return, atmospheric wind tunnel having a test section that is 9.14m high, 9.14 m wide and 22.5 m long. It has a maximum speed of 200 km/h (120 mi/h) and a turbulence level of 0.5 percent.

The tractor drive wheels sat on pads attached to the main balance below the tunnel floor. The front tractor wheels and the trailer bogey were floated on low-profile air bearings to allow the balance to measure the wind-axis drag and side forces, and to permit the turntable to rotate up to a yaw angle of at least 13°. Both forces are necessary to compute the body-axis drag.

The installation used in this test is seen in Figure 1. The tractor under test was a Volvo VN 660 provided by Robert Transport Inc. of Quebec, Canada. The trailer could be configured to be either 8.5 m (28 ft) or 12.2 m (40 ft) long by removing a section of the body. The kingpin was set for a 1.14 m (45 inch) gap between the front face of the trailer and the rear face of the cab. The

side corners at the front of the trailer are rounded with a 127 mm (5 inch) radius but the top edge is square.



Figure 1: Volvo VN 660 and 28-ft. Trailer in the NRC 9m x 9m wind tunnel.

The model frontal area was 10.9 m<sup>2</sup>, which is 13.3 percent of the 82 m<sup>2</sup> test section. Blockage corrections were calculated using the Velocity Ratio method as detailed in [3] and described for tractor applications in [2]. The dynamic pressure correction factors were in the range of 1.30 to 1.38, depending on configuration and yaw angle. The yaw angle interference was calculated to be approximately 1° at 10° yaw angle and proportionately less at smaller yaw angles.

#### Test procedure

The measurements were made by performing a yaw sweep with the wind off. The wind-off measurements of drag and side force were fitted by cubic splines and the fitted values were subtracted from the wind-on drag and side forces at each yaw angle for which a measurement was made. Repeatability was estimated to be ± 0.002 on wind-averaged drag coefficient.

Measurements were made at boundary-interference-corrected yaw angles of -3.3°, 0.0°, 3.3°, 6.6° and 9.9°, at a corrected speed of 28.6 m/s (60 mi/h).

#### Configurations evaluated

Various vehicle configurations and components were evaluated in addition to the new drag-reducing hardware. This was done to understand the influence of common components on aerodynamic drag.

The vehicle components evaluated were:

- Volvo roof deflector
- Volvo cab side extenders

- Volvo cab side extender extensions
- Volvo fender mirrors
- Volvo side mirrors
- Volvo bug deflector
- Deer bumper
- Volvo cab and tank skirts
- Volvo wrap-around splash guards
- Disk hub caps

The new or prototype drag-reducing hardware that was tested included:

- Freight Wing NXT Leading Edge Fairing
- Freight Wing Belly Fairing (standard & low rider)
- Laydon Composites trailer side skirts
- Laydon Composites nose fairing
- Transtex Composite folding rear trailer deflector
- Aerolution inflatable rear trailer fairing
- Labyrinthine tractor-trailer gap seal
- Trailer vortex generators
- Manac prototype trailer leading edge fairing
- Francis Cardolle bogey fairings

The prototype labyrinthine gap seal and vortex generators were similar to a recently-developed commercial product and were based on the information provided in [4], but not on company-supplied geometry.

#### Drag coefficient and fuel calculations

The drag coefficient is defined as,

$$C_{Db} = \frac{D_b}{1/2\rho V_r^2 A} \quad (1)$$

The body-axis drag (Newtons),  $D_b$ , is given in terms of the wind-axis drag,  $D_w$ , and side force,  $Y_w$ , by,

$$D_b = D_w \cos \psi - Y_w \sin \psi \quad (2)$$

$\psi$  is the yaw angle (deg.),  $\rho$  is the air density (kg.m<sup>3</sup>),  $V_r$  is the resultant wind speed (m/s) and  $A$  is the frontal area of the tractor (m<sup>2</sup>).

The data presented in this paper are given as the wind-averaged drag coefficient at 29.6 m/s (107 km/h, 65 mi/h). The procedure for the calculation of the wind averaged drag coefficient comes from [5] and is summarized in [1]. This wind-weighted drag coefficient contains the average effects of winds in North America and is normalized by road speed. The drag resulting from the wind-averaging is given by,

$$\overline{D_b} = 1/2\rho V_t^2 \overline{AC_D}(V_t) \quad (3)$$

Note that the wind-averaged drag coefficient is a function of road speed ( $V_t$ ). A change in wind-averaged drag coefficient is defined as,

$$\overline{\Delta C_D}(V_t) = \overline{C_D}(V_t)_{\text{baseline}} - \overline{C_D}(V_t)_{\text{modified}} \quad (5)$$

Thus, a positive drag increment and the resulting positive fuel increment represent a drag reduction and a fuel saving. Based on the change in wind-averaged drag, the expected fuel-savings is calculated from,

$$\Delta\mu(V_t) = \frac{1.225 \times 1.072 \times 0.275 \times 10^{-3} V_t^2 \overline{\Delta C_D}(V_t) A}{0.85} \quad (4)$$

$$\Delta\mu(V_t) = 4.25 \times 10^{-4} V_t^2 \overline{\Delta C_D}(V_t) A \text{ L/100 km} \quad (5)$$

Where A was 10.9 m<sup>2</sup> (the value used in calculating the drag coefficients) and  $V_t$  was taken as 100 km/h (62 MPH). The constants in equation (4) assume a transmission efficiency of 0.85, an air density of 1.225 kg/m<sup>3</sup> and an average specific fuel consumption of 0.275 liters/kW-h (0.073 US gal/hp-h) and a unit conversion factor of 1.072.

It is possible to calculate the annual fuel savings realized by installing these aerodynamic devices for an average fleet. Average annual distances covered by heavy trucks are now in the range of 200,000 km (125,000 mi), but only a portion of this distance is covered at cruise speed. For the purposes of this paper, the distance covered at cruising speed will be assumed to be 130,000 km (81,000 mi). This will result in a conservative estimate of fuel-savings because these devices continue to provide fuel savings at lower speeds, which have been neglected here. Thus, the annual fuel saving is 1,300 times that for the 100 km distance given in equation (5).

## DISCUSSION OF RESULTS

The standard vehicle components that were evaluated are shown in Figure 2. The drag and resulting annual fuel consumption changes are summarized in Table 1.

It can be seen that many components produce noteworthy drag and fuel changes. In particular, the bug deflector raises fuel consumption and the mirrors are also an area worth study. Mirrors have been singled out since they are a large source of drag that are dictated by current safety regulations. It would be possible to eliminate mirror drag if regulations were changed to allow modern video cameras to replace mirrors as the means of providing rearward vision. The price of the video system would be covered by fuel savings and the cameras may increase safety by offering a larger field of view with infra-red capabilities that can penetrate fog, rain or darkness.

All of the other components are beneficial, especially the standard cab-roof fairing, cab side extenders and tank skirts, which form the current aerodynamic package.

The sun visor was an OEM product, its design obviously having been developed in conjunction with the roof deflector, so it actually produced a small drag reduction. This may not be the case if the sun visor is used with trucks without a roof deflector.

Table 1: Tractor Component Drag and Fuel Increments.

	$\overline{\Delta C_D}(100 \text{ kph})$	Annual fuel savings (L)
OEM side mirrors	-0.0156	-938
OEM bug deflector	-0.0150	-903
OEM fender mirrors	-0.0098	-588
engine cooling inlets blocked	0.0001	6
sun visor w/ roof deflector	0.0009	54
hub caps (truck & trailer)	0.0020	120
deer bumper	0.0020	120
wrap-around splash guards	0.0049	292
prototype roof deflector filler	0.0137	825
fifth wheel forward 254 mm	0.0163	982
OEM tank and cab skirts	0.0265	1,596
OEM side extenders	0.0415	2,499
OEM roof deflector	0.0717	4,318

Eliminating the cooling flow, by covering the front grille and the lower intake in the front bumper, had a negligible effect on drag. This has been observed in several full- and model-scale tests of modern tractors.

Prototype hub caps consisting of solid metal disks on the outside wheels of the trailer and tractor showed a negligible change in drag. Recall that this test was performed with fixed wheels and the effects of wheel rotation on the results are unknown. Furthermore, these disks could be expected to have a harmful effect on brake cooling.

Another prototype considered was a panel to fill the large cut-out on top of the roof deflector that provides space for the trailer during sharp cornering maneuvers. The fuel savings from this panel are significant and it is envisioned that a simple, lightweight, flexible panel should be able to provide this function at low cost.

Finally, the effect of reducing the tractor-trailer gap was studied. There are operational issues to be addressed in doing this, such as axle weights, ride quality and turn clearance, but the potential savings are significant for no capital cost. The expected change in drag depends upon the original gap size. In this case, the gap was reduced from 1.14m (45 in) to 0.89m (35 in). If the original gap were larger or smaller than 1.14m, the drag reduction may be smaller or larger, respectively, than that measured here. A related note is that the optimum angle of the tractor roof deflector is partly a function of the gap size. Thus, a significant change in gap size should be accompanied by a re-optimization of the roof deflector. In previous studies an overall drag increase has been observed after significantly reducing the gap without adjusting the roof deflector, likely because the airflow is under-deflected and strikes the trailer which is now closer.

The results presented in Table 1 are application specific and will only apply strictly to the particular model of tractor and component tested. Nevertheless, the results are useful as guidelines to the expected magnitudes in similar applications. As an example, the deer bumper showed a slight reduction in drag, a surprising result considering its large form. This shows that a properly designed and positioned deer bumper can provide a drag reduction.

The new components that were evaluated are shown in Figure 3 and the aerodynamic drag and fuel results are summarized in Table 2.

The large region of separated flow at the rear of a van-style trailer is the largest untreated source of drag on a modern tractor trailer. Not surprisingly, this is the area where the greatest reductions in drag were found. Two devices were tested in this area, the inflatable Aerolution and triple-panel Transtex boattails. Each device addresses the issues of access to the trailer doors, though in different manners, while producing significant reductions in drag. These devices would be complementary to trailer skirts, and vice versa, and the choice between them comes down to non-aerodynamic issues.

The vortex generators at the rear of the trailer increased overall drag. The measured base pressure did not change, so the extra drag must be tare drag on the angle sections. They were made from 51mm x 51mm aluminum angle, 914 mm long, installed six per side on the trailer, 30° nose up from the horizontal. Four were mounted on the roof in an asymmetrical arrangement about the trailer centerline.

As has been seen before [2], a fairing on the front top face of the trailer provides little additional benefit when a cab-roof deflector is present. However, if a roof deflector is not present, a leading-edge fairing can provide significant fuel savings, although only about half as much as a full roof deflector. This may be a consideration for trucks that often operate without a van trailer, for instance switching between flatbeds and vans, when a fixed roof deflector may increase the drag with a flatbed.

Both brands of trailer skirts tested showed similar drag reductions to each other and to those previously reported [1, 2]. The rear skirts, behind the trailer bogeys, showed no reduction in drag, although they may be effective when paired with a boat-tail [2]. It should be noted that the skirts were not installed as prescribed by the manufacturers. Ground clearance was approximately 100 mm (4 in) greater than normal due to the air bearings, which would decrease the drag reduction. The trailer was 12.2 m (40 ft) in length instead of the typical lengths of greater than 14.6 m (48 ft) that the skirts are designed for.

A lower skirt provides better performance, as shown in [1]. Previously [1,2], skirts had been tested on an 8.5 m

long trailer with results close to those measured with the 12.2 m trailer presented here. Thus, it is expected that trailer length is not a critical parameter since most of the drag reduction comes from sheltering the trailer bogey.

Table 2: Performance of new add-on components.

	$\overline{\Delta C_D}$ (100 km/h)	Annual fuel liters
<b><u>base drag reduction</u></b>		
Transtex Composite folding trailer rear deflector	0.0506	3,047
Aerolution inflatable trailer rear fairing	0.0438	2,638
Trailer vortex strakes	-0.0195	-1,174
<b><u>trailer leading-edge fairings</u></b>		
Freight Wing Inc. NXT Leading Edge Fairing wo/ roof fairing	0.0369	2,222
Manac prototype trailer leading-edge fairing	0.0335	2,017
Freight Wing Inc. NXT Leading Edge Fairing w/ roof fairing	-0.0019	-114
<b><u>underbody drag reduction</u></b>		
Freight Wing Belly Fairing (low rider)*	0.0478	2,879
Laydon Composites main and rear skirts*	0.0391	2,355
Laydon Composites main skirts*	0.0376	2,264
Freight Wing Belly Fairing*	0.0367	2,210
Francis Cardolle trailer bogey fairing	0.0145	873
Francis Cardolle trailer wheel fairings	0.0078	470
<b><u>gap sealing</u></b>		
Laydon Composites Trailer Nose Fairing	0.0135	813
Volvo cab-extender extensions	0.0123	741
Labyrinthine tractor-trailer gap seal	0.0018	108

\* Modified to fit a 12.2 m (40 ft) trailer.

A fairing on the trailer bogey was less effective than the skirts. This suggests that the skirts may also reduce the drag on the rough underbody of the trailer. It would be interesting to cover the trailer floor ribs to verify this.

The labyrinthine gap seal provided almost no drag reduction. The seal was made up of six 305 mm deep 17 mm thick plywood panels that were 2.44 m (8 ft) high. It would appear that they did not significantly block the gap flow, and only served to move the trailer front face closer to the tractor. The Laydon Composites Nose fairing provides a modest drag reduction and would be useful in situations where complete gap closure is not possible. Fully closing the gap is clearly the target to aim for, although partial closure through additional cab-extender extensions is simple and still beneficial.



OEM side mirror



OEM fender mirror



OEM bug deflector



blocked engine cooling inlets



roof deflector, sun visor and side extenders



standard cab-mounted deflector and side extenders



OEM tank & cab skirts



disk hub caps and wrap-around splash guards



roof deflector filler panel



deer bumper

Fig. 2: Common components whose drag effects were measured



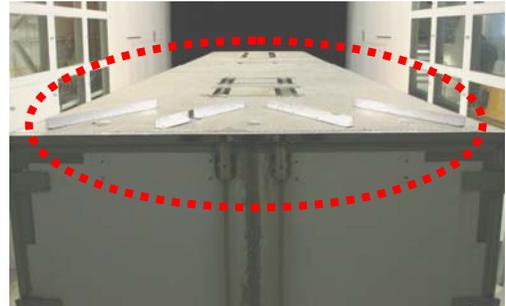
*Transtex Composites folding rear trailer deflector*



*Aerovolution inflatable boattail*



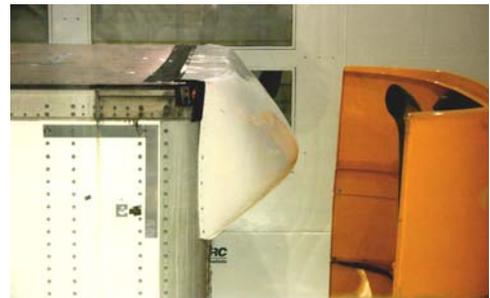
*Vortex generators (side)*



*Vortex generators (top)*



*Freightwing NXT leading edge fairing*



*Manac prototype leading edge fairing*



*Freightwing belly fairing (low rider extension shown unattached)*



*Francis Cardolle bogey trailer fairing*

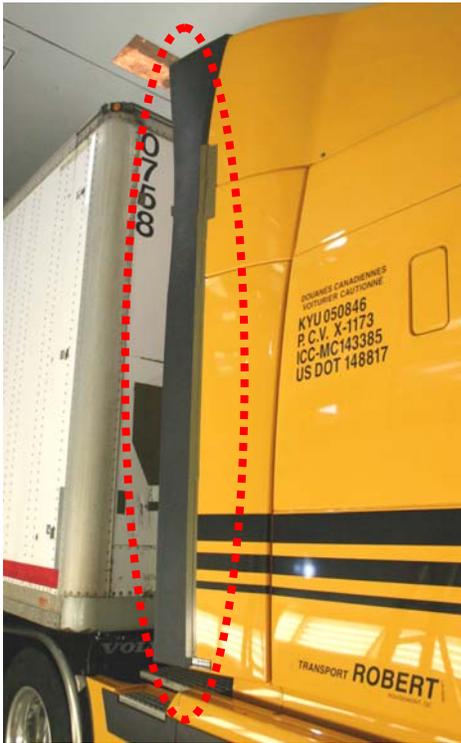


*Laydon Composites skirts*



*Francis Cardolle wheel fairings*

*Fig. 3: New add-on components.*



*Small cab extender extension*



*Laydon Composites nose fairing*



*Labyrinthine gap seal*

*Fig. 3: New add-on components (continued).*

The results obtained for the production devices were sensibly like those found in the development tests. The combination of: tractor-mounted gap sealing with the largest available side extenders, trailer side skirts and trailer boat-tailing combine to provide a total drag reduction of  $\Delta C_D(107) \approx 0.111$ . On a single tractor-trailer combination, this provides an estimated annual fuel saving of 6,667 liters (1,761 US gallons) operating at 100 km/hr (62 MPH) for 130,000 km (81,000 mi) a year. Assuming a total cost of US \$2,200 to install the devices, they will pay for themselves in 5 months at US \$0.79 per liter (US \$3.00 per gallon). Assuming it would cost US \$6,200 to equip the tractor and the average three trailers per tractor, then the tractor gap seal and three sets of trailer components would be paid for in 14 months. These savings are in addition to the gains realized with a full aero package including roof deflector, side extenders and tank/cab skirts.

Payback periods will vary based on fleet statistics, but the savings for any particular operation mode can be calculated with the data in Tables 1 and 2 using Equation (5). The critical parameters are fuel cost, device cost, annual cruise mileage and cruise speed. Keep in mind that while fuel savings will increase with speed, overall consumption will increase by a greater amount.

There is potential for even greater gain, to  $\Delta C_D(107) \approx 0.140$ , by developing longer side extenders but these are not currently available. While acknowledging there are operational issues with these devices, it should be possible to solve them with basic

mechanical engineering by the device suppliers or the OEMs.

## CONCLUSIONS

Full-scale wind tunnel measurements were made on new production add-on devices meant to reduce the aerodynamic drag of Class-8 tractor-trailers beyond that provided by the current aerodynamic package. They consisted of devices to reduce the tractor-trailer-gap drag, to reduce trailer underbody and bogey drag, and to reduce trailer base drag.

Simple estimates of fuel consumption at steady speed on a flat road indicated annual fuel savings of 6,667 liters (1,761 US gallons). This estimate was predicated on a cruising speed of 100 km/h (62 mi/h) and 130,000km (81,000 miles) traveled annually at this speed.

The analysis considered a single tractor-trailer unit and a tractor with the average three trailers. The former case paid for the aerodynamic modifications in 5 months. The latter required a payback period of 14 months, since two of the trailers were at rest at any given time. In either case, the economics are promising.

The main remaining issue is to spread the word, to convince the trucking industry to try these new components and to encourage the manufacture of the long cab extenders. It is likely that there will be teething problems in the operational and service aspects of these devices. However, these will be overcome by the large financial incentive that they offer. The trucking industry

will improve its competitive position in a time of high fuel costs, the country will benefit from reduced fuel demand and the environment will be cleaner. How can we lose?

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