

Wind Tunnel and Track Tests of Class 8 Tractors Pulling Single and Tandem Trailers Fitted with Side Skirts and Boat-tails

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ABSTRACT

A 1:10-scale wind tunnel development program was undertaken by the National Research Council of Canada and Airshield Inc. in 1994 to develop trailer side skirts that would reduce the aerodynamic drag of single and tandem trailers. Additionally, a second wind tunnel program was performed by the NRC to evaluate the fuel-saving performance of boat-tail panels when used in conjunction with the skirt-equipped single and tandem trailers.

Side skirts on tandem, 8.2-m-long trailers (all model dimensions converted to full scale) were found to reduce the wind-averaged drag coefficient at 105 km/h (65 mi/h) by 0.0758. The front pair of skirts alone produced 75% of the total drag reduction from both sets of skirts and the rear pair alone produced 40% of that from both pairs. The sum of the drag reductions from front and rear skirts separately was 115% of that when both sets were fitted, suggesting an interaction between both. The reductions in wind-averaged drag coefficient for single trailers with skirts only were 0.0524 for the 14.6 m trailer and 0.0406 for the 16.2 m single trailer. The data are quoted for skirt ground clearances of 305 mm (12 in.).

The 0.50-m-long boat tail panels combined with the tandem-trailer skirts to increase the wind-averaged drag coefficient reduction to a total of 0.1177. Boat-tails combined with skirts on the single trailers also increased the wind-averaged drag coefficient reductions to totals of 0.1051 and 0.0979 for the 14.6m and 16.2 m trailers, respectively. Each Boat-tail assembly consisted of angled panels attached to the top and the side rear edges of a trailer. The boat-tail panels on the single trailers and the rear trailer of the tandem pair were set at the optimum angle of 15°. The boat-tail panels on the front trailer of the tandem pair were set at 0°.

Skirts were predicted to provide fuel savings for the tandem trailers at 105 km/h of 3.79 liters per hundred kilometers (L/(100 km)) (1.61 US gallons per 100 miles - US gal/(100 mi)) and 2.18 L/(100 km) (0.93 US gal/(100 mi)) and of 1.95 L/(100 km) (0.83 US gal/(100 mi)) for the 14.6 m and 16.2 m single trailers, respectively. It is not known why the longer trailer had the smaller fuel saving.

The addition of boat-tail panels increased the predicted fuel savings for the skirt-equipped tandem trailers to 5.88 L/(100 km) (2.50 US gal/(100 mi)) and increased the fuel savings of the 14.6 m and 16.2 m single, skirt-equipped trailers to 5.25 L/(100 km) (2.23 US gal/(100 mi)) and to 4.89 L/(100 km) (2.08 US gal/(100 mi)), respectively.

Track tests were undertaken using 8.2-m-long, skirt-equipped tandem trailers to verify the fuel-saving predictions based on the wind tunnel drag data. The boat-tails were not track tested. The track tests were performed by the staff at the Goodyear Proving Grounds in San Angelo, Texas. They demonstrated that skirts provided fuel savings of from 0.86 L/(100 km) to 3.54 L/(100 km), with the largest savings in the strongest side winds. The average track-test fuel saving measured over all runs was 2.29 L/(100 km) at an average road speed of 88 km/h. The average wind-tunnel-based prediction for these track runs was 2.25 L/(100 km), using a wind-averaged drag coefficient calculated for the wind conditions of each run. This was within one percent of the average of the track measurements. The wind speeds during the track tests were generally lower than the national average 11.3 km/h wind at truck mid height, averaging only 8 km/h. This indicated that the average fuel saving on the track was less than would be expected annually in North America.

The track-test results confirmed the fuel-saving potential of skirts and demonstrated the reliability of fuel-saving predictions made from high-quality wind tunnel data. This correlation was only possible because the track-side winds were measured during each run.

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INTRODUCTION

Aerodynamic drag reductions obtained through cab reshaping and the additions of sophisticated cab-mounted aerodynamic packages have lowered the aerodynamic drag of heavy-duty trucks by approximately 30% in the past few decades. These drag reductions have provided the single largest reduction in fuel consumption amongst all the fuel conserving techniques that have been introduced to heavy-duty trucking during this period. The primary remaining avenue for further aerodynamic fuel saving is through modification of the trailer.

The front side posts of trailers are already rounded sufficiently and the top rails are generally protected by a cab-mounted fairing, leaving only the trailer underbody and the rear end of the trailer to be modified. Modifications to these areas act to reduce the underbody drag, especially that due to the trailer bogies, and reduce the base drag due to aerodynamic suction over the flat base region of the trailer. The underbody drag is reduced by blocking flows beneath the trailer with side skirts, where these skirts are panels that extend the trailer sides toward the ground over the region between the tractor drive or B-train wheels and the trailer bogies. The base-drag reduction is effected by 0.50-m-long boat-tail panels that are attached to the rear of the trailer and hinge to swing open with the doors. The panels are fitted to the top and sides of the trailer only (triple boat-tails) and are inclined inward from the top and sides of the trailer at an angle of 15 degrees. Both skirts and boat-tails can be used with either single or multiple trailers and they can be combined effectively with the current cab-mounted aerodynamic packages. It has been known for some time that skirts and rear boat-tail panels are effective [1, 2, 3, 4, 5, 6, 7, 8, 9]. Now that most tractors have been aerodynamically refined and fitted with roof fairings and cab extenders, the trailer-mounted technologies provide the next logical, cost-effective steps in increasing vehicle fuel efficiency.

WIND TUNNEL PROGRAM

Aerodynamic Development

The best tool for the aerodynamic development of truck fuel-saving devices has consistently proven to be the wind tunnel. It offers a controlled environment for the accurate measurement of the small performance improvements that must be pursued as a product is being optimized. It has always been found that the performance gains through aerodynamic drag reduction measured in the wind tunnel translate to fuel savings on the road and that the levels of savings predicted from these measurements are realistic. For these reasons, the program to develop skirts for tandem and single trailers was performed in the 2m × 3m wind tunnel of the National Research Council of Canada (NRC) in collaboration with Airshield Inc.

The NRC has been actively involved in research and development in the area of surface vehicle aerodynamics in

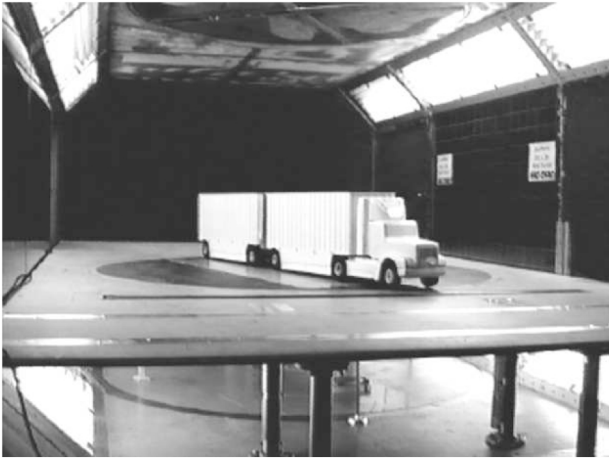
general, and in the aerodynamics of heavy-duty trucks in particular, for over 40 years. The NRC has supported SAE activities through the SAE/DOT Voluntary Truck and Bus Fuel Economy Program and through thousands of hours of testing to develop and demonstrate effective aerodynamic devices for the trucking industry. The NRC has both a 2m × 3m, model-scale wind tunnel for the groundboard testing of 1:10-scale to 1:8-scale truck models as well a 9m × 9m, full-scale wind tunnel for testing 1:3-scale to full-scale tractor trailers. The latter facility now includes a moving belt suitable for 1:2-scale truck development work.

The development work reported in this paper was done in the 2m × 3m wind tunnel, which actually measures 1.89m high by 2.94m wide (6.2ft high by 9.0ft wide). It has a maximum speed of 130 m/s (300 mi/h) and is fitted with a groundboard that was designed to provide a good ground simulation for road vehicle testing. The 1:10-scale models were attached to pins that held them just clear of the floor and that carry the aerodynamic loads from the model to an accurate six-component balance. The combination of this model size and a 70 m/s test speed provide a sufficiently high width-based Reynolds number (1.6×10^6) to accurately reflect road experience. The front of the tractor was 864 mm downstream of the leading edge of the groundboard. The rear face of the trailer was no closer than 2,300 mm from the end of the groundboard. Thus, there was no interference between the finite ground board and the flow over the model. A flow calibration was used that accounted for the changing flow split above and below the groundboard due to the drag of the model.

Three tractor-trailer combinations were utilized in this program. One combination consisted of a conventional Freightliner 120 N/S tractor (CONV) pulling tandem 8.2-m-long (27 ft), external-rib trailer. The other consisted of a Cab-Over-Engine Navistar 9670 tractor (COE) with either a 14.6-m-long (48-ft) or a 16.2-m-long (53-ft) single, smooth-sided trailer. The purpose of the wind tunnel program was to develop a trailer side skirt design for use with tandem trailers. Side skirts are panels that extend the trailer sides toward the ground over the region between the tractor drive or B-train wheels and the trailer rear bogies. A secondary purpose was to evaluate the use of trailer boat-tail panels with tandem trailers.

An overview of the wind tunnel installation is shown in [Figure 1](#) and the conventional-tractor-tandem-trailer model is seen on the groundboard, with and without skirts, in [Figure 2](#). The COE-tractor-trailer is shown in [Figure 3](#) in its standard configuration and with the preliminary skirts. [Figure 4](#) shows the details of the rear boat-tail panels mounted on the single and the tandem trailers.

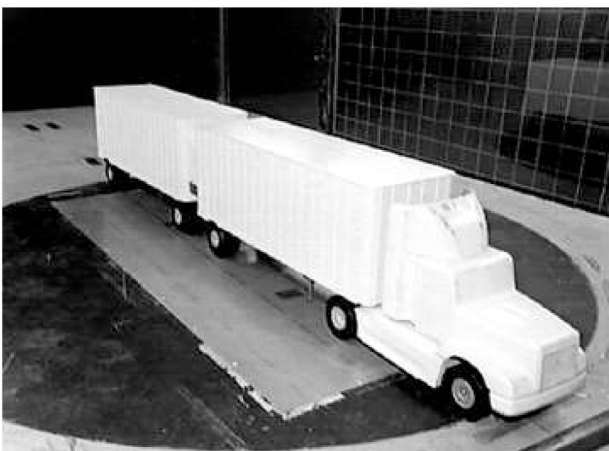
The wind tunnel development was done in two phases. The first phase used generic thin, flat-plate skirts with adjustable lower edges to evaluate skirt height effects. It was followed by a short test to verify the performance of the production skirt design.



1a). Freightliner 120 N/S with tandem 8.2 m trailers fitted with preliminary skirts on the groundboard turntable of the NRC 2m × 3m wind tunnel.



1b). skirts being fitted to the 1:10-scale model.
Fig. 1. Installation of the Model in the NRC 2m × 3m Wind Tunnel.



2a). standard configuration



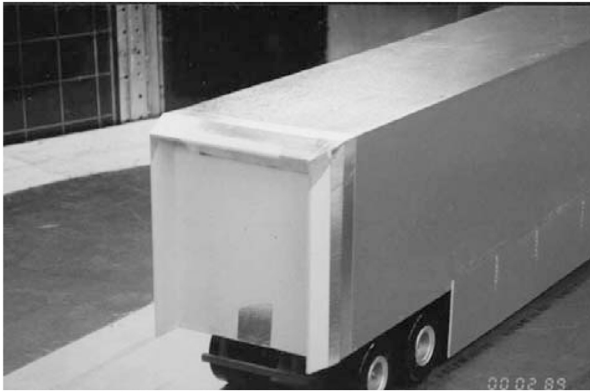
2b). preliminary skirts at 152 mm clearance
Fig. 2. Freightliner Conventional Tractor and Tandem 8.2 m Trailers.



3 a). standard COE truck



3b). preliminary skirts at 152 mm clearance
Fig. 3. Navistar COE Tractor and 14.6 m Single Trailer.



4a). single trailer, 15° triple boat-tail panels



4b). tandem trailers, 15° rear and 0° front triple boat-tail panels

Fig. 4. Triple Boat-tail Panels.

The models were rotated from -2.5° to 15.0° relative to the wind tunnel airflow to simulate the effect of winds blowing from all probable directions. The drag measurements made at these angles were then combined in a fashion that incorporates the effect of the average, annual winds in North America on truck aerodynamic drag to produce a 'wind-averaged drag coefficient' [10, 11]. This wind-averaged drag coefficient is an estimate of the annual average aerodynamic drag of a truck operating all over North America at a constant road speed. Once this drag coefficient has been evaluated from wind tunnel drag data, then accurate, national-average estimates of on-road fuel savings can be made.

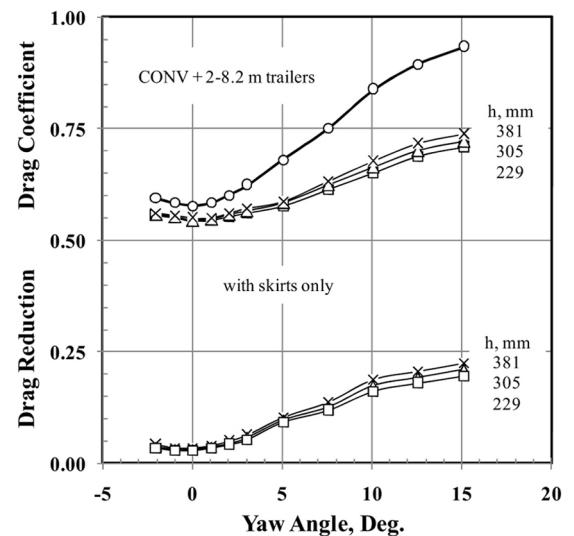
Tunnel Test Results and Predicted Fuel Savings

Skirts

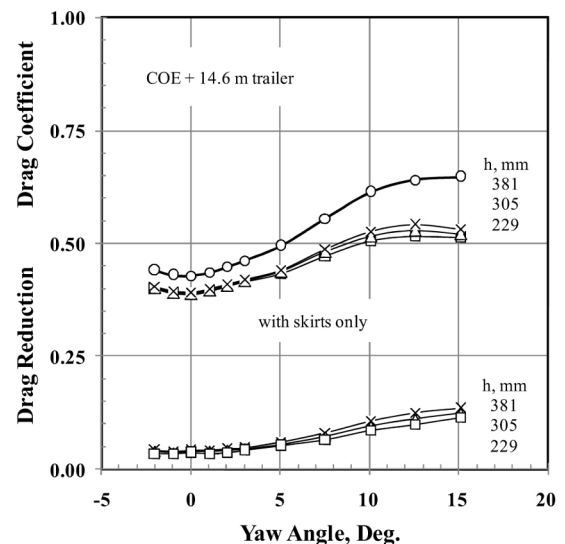
The primary skirt parameter investigated was clearance height above the ground. The measured drag curves for the baseline and the skirt-equipped, tandem-trailer CONV and single-trailer COE trucks are shown in Figure 5 for skirt bottom-edge-to-ground clearances, h , of 229 mm (9 in.), 305 mm (12 in.) and 381 mm (15 in.). The skirts are seen to reduce the aerodynamic drag at all clearance heights and at

all yaw angles. The drag reduction was small at zero yaw angle - the case of no wind or head or tail winds - and increased with increasing yaw angle caused by increasingly strong side winds. The magnitude of the drag reduction increased as the lower edge of the skirt approached the ground because of the greater underbody protection.

The drag magnitudes for the COE model were lower than usually measured. It was thought that this behavior may have been a result of the very simplified tractor model. It was a solid block with no cooling flow or underbody details. Nonetheless, the magnitudes of the measured drag reductions from both skirts and boat-tails were in the range measured in many previous model-scale and full-scale wind tunnel programs at the NRC, as will be discussed later in the paper. The drag coefficients are accurate to ± 0.0005 even though they are quoted to four significant figures.



5 a). conventional tractor with tandem trailers



5b). COE tractor and single trailer

Fig. 5. Drag Reduction Produced by Skirts Alone.

Table 1. Effect of Skirt Clearance on Drag Reduction and on Fuel Savings at 105 km/h for Skirts with Straight Bottom Edges.

Configuration	Skirt Clearance (mm)	$\overline{\Delta C_D}(105)$	Fuel Savings **	
			L/(100 km)	US gal/(100 mi)
CONV + tandem 8.2 m trailers	152	0.0873	4.36	1.85
	229	0.0835	4.17	1.77
	305	0.0779	3.89	1.65
	381	0.0719	3.59	1.53
	457	0.0667	3.33	1.42
	533	0.0596	2.98	1.27
COE +14.6 m trailer	152	0.0604	3.02	1.28
	229	0.0567	2.83	1.20
	305	0.0524	2.62	1.11
	381	0.0488	2.44	1.04
	457	0.0447	2.23	0.95
	533	0.0404	2.02	0.86
COE + 16.2 m trailer	152	0.0565	2.82	1.20
	229	0.0534	2.67	1.14
	305	0.0493	2.46	1.05
	381	0.0453	2.26	0.96
	457	0.0409	2.04	0.87
	533	0.0372	1.86	0.79

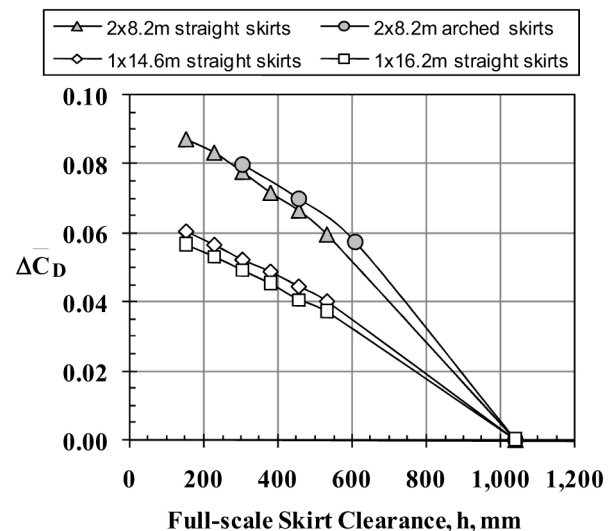
**liters per 100 kilometers.

Note: 1.0 US gallon = 3.7854 liters and 1.0L/(100 km) = 0.4251 US gal/(100 mi).

Table 1 summarizes the wind-averaged drag coefficient reductions and predicted fuel savings at 105 km/h as a function of skirt clearance for all three truck configurations. A positive sign indicates a reduction in drag or fuel consumption. The drag reductions in the table reflect the drag curves of Figure 5 and show an almost linear trend with skirt clearance over the range of clearances tested, with a slope of -0.073 m^{-1} . Thus, each increase in clearance of 0.10 m would lead to a decrease in the drag reduction from the skirt of $\Delta \overline{C_D} = -0.0073$. Ground clearances as low as 305 mm to 381 mm would seem practical to implement as they are in the range found in moving vans. Smaller clearances might be practical with a flexible lower extension. The shaded rows highlight the clearance chosen for the production skirts.

The effect of skirt clearance can be seen in Figure 6 for both straight-bottom-edged and arched-bottom-edge skirts on the tandem trailers and for straight-bottom edged skirts for the two single trailer lengths. The skirts were arched so that the center of the skirt was 152 mm higher than either end. The skirt clearance was measured at the skirt center. The arched skirt is shown to provide a small additional drag reduction.

Since not all trailers in a fleet may have skirts, it was of interest to look at the effect of fitting skirts to either the front or the rear trailer alone. The results of doing so are summarized in Table 2 for the CONV truck, in comparison with the 48 ft. and 53 ft. single trailers on the COE truck. Clearly, the majority of the drag reduction occurs when the skirts are fitted to the front trailer. This is important

**Fig. 6. Effect of Skirt Ground Clearance on Wind-Averaged-Drag Reduction.**

operationally since it indicates that skirt-equipped trailers should be positioned first whenever possible in a tandem configuration. Further, it offers the opportunity of obtaining 75% of the drag reduction with skirts only on the front trailer. Thus, buying skirts for half the tandem trailers would be cost effective, at least to start, assuming that the skirt equipped trailer could be positioned first most of the time. It is also apparent that the drag reduction from skirts with tandem trailers is greater than with single trailers. This might be expected because the tandem trailers have two trailer bogies to protect.

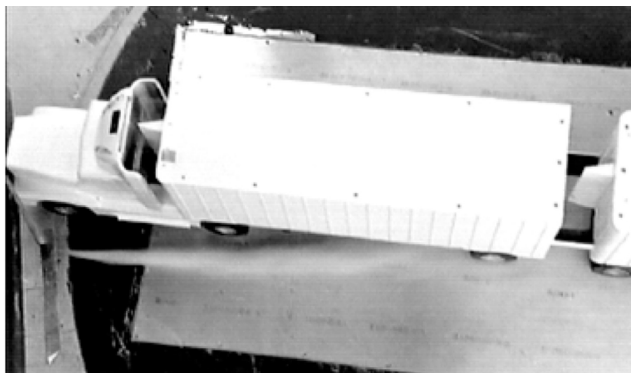
The front/rear skirt combinations were only tested at the lowest clearance. It is expected that the same fractional drag reductions would be found at the other skirt clearances. That is, at any skirt clearance, the use of front skirts alone would decrease the drag reduction to 75% of that for both sets, while use of rear skirts alone would decrease the drag reduction to 40% of that due to both sets. It is expected that the difference between skirts on the front or the rear trailers would diminish with longer trailers due to reduced aerodynamic interaction of the front pair of skirts with the more distant rear trailer bogies.

It is not understood why skirts produced a smaller drag reduction for the 53 ft. trailer than the 48 ft. trailer. This behavior was consistent at all skirt clearances. It is also intriguing that the sum of the drag reductions from the front and the rear skirts alone is greater than that with both sets in place. This may result from the fact that the front skirt provides some protection to the rear trailer at the smaller yaw angles.

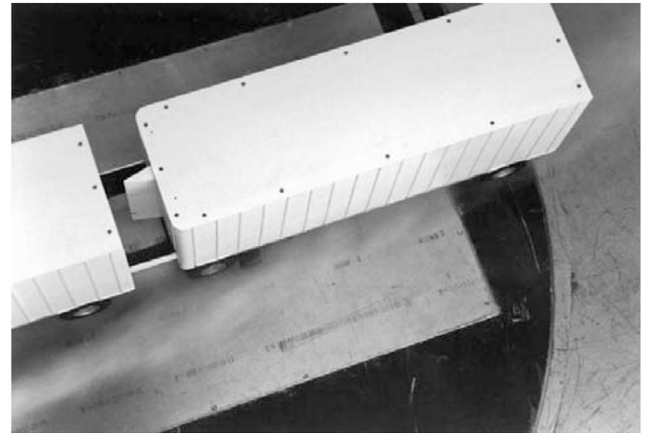
Table 2. Drag Reductions and Predicted Fuel Savings from Skirts at 105 km/h - 305 mm Skirt Clearance.

Configuration	Modification	ΔC_D (105)	Fuel Savings	
			L/(100 km)	US gal/(100 mi)
CONV + tandem 8.2 m trailers	Skirts on both trailers	0.0779	3.89	1.65
	Skirts on front trailer	0.0587	2.93	1.25
	Skirts on rear trailer	0.0311	1.55	0.66
COE + 14.6 m trailer	Skirts	0.0524	2.62	1.11
COE + 16.2 m trailer	Skirts	0.0493	2.46	1.05

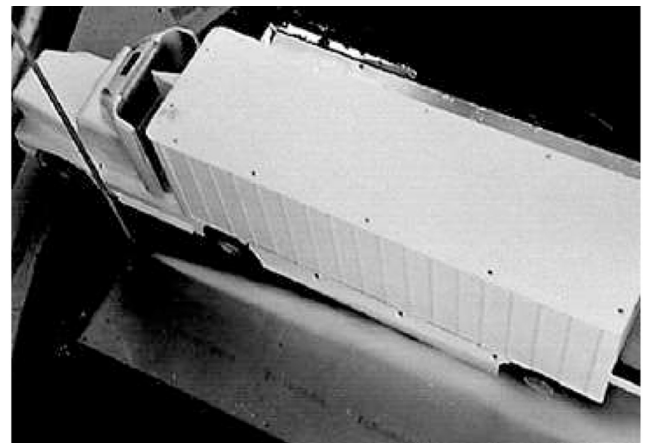
Figure 7 shows a smoke stream used to illuminate the differences in the underbody flows with and without skirts. The flow curves under the standard front and rear trailers, 7a) and 7b), striking the trailer bogies, whereas skirts are seen to deflect the flow along the side of the trailer and away from the underbody and trailer bogies, 7c).



7a). standard front tandem trailer - flow curves under the trailer and impinges on the trailer bogies



7b). standard rear tandem trailer - flow curves under the trailer and impinges on the trailer bogies



7c). skirt-equipped trailer - the skirt removes the cross-flow

Fig. 7. Smoke Visualization of the Under-Trailer flows.

Rear Boat-tail Panels

Rear boat-tail panels fitted to the sides and the tops of the single and tandem trailers (triple boat-tail panels) were found to provide a nearly constant drag reduction with yaw angle, as seen in Figure 8. The boat-tails fitted to the tandem trailers were set at different angles on the front and rear trailers. The rear-trailer boat-tails were set at 15° while the front-trailer boat-tails were set at 0° for reasons given in the discussion of the data presented in the following table, Table 3.

The reductions in wind-averaged drag coefficient and the predicted reductions in fuel consumption are summarized for both truck configurations in Table 3. The table indicates that the boat-tail panels on the tandem trailers provide 56% of the drag reduction measured for 305-mm-clearance skirts on the tandem trailers and that the boat-tail panels on the single trailer provide 100% of the drag reduction measured with 305-mm-clearance skirts on the single trailer. The fuel savings for both trucks were in the same proportions.