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Understanding Practical Limits to Heavy Truck Drag Reduction

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Langley Full Scale Tunnel

ABSTRACT

A heavy truck wind tunnel test program is currently underway at the Langley Full Scale Tunnel (LFST). Seven passive drag reducing device configurations have been evaluated on a heavy truck model with the objective of understanding the practical limits to drag reduction achievable on a modern tractor trailer through add-on devices. The configurations tested include side skirts of varying length, a full gap seal, and tapered rear panels. All configurations were evaluated over a nominal 15 degree yaw sweep to establish wind averaged drag coefficients over a broad speed range using SAE J1252. The tests were conducted by first quantifying the benefit of each individual treatment and finally looking at the combined benefit of an ideal fully treated vehicle. Results show a maximum achievable gain in wind averaged drag coefficient (65 mph) of about 31 percent for the modern conventional-cab tractor-trailer.

INTRODUCTION

Fuel costs and environmental pressures continue to promote interest in improving fuel economy in the commercial vehicle transportation sector.[1] Heavy trucks have evolved with most truck manufacturers now offering streamlined models. Conversely, most trailer manufacturers have strived to maintain operational objectives such as a rectangular cross section for the maximum cargo space and a bluff rear end for easy loading access.[2] This has led to the development of commercially available trailer-mounted add-on devices for the purpose of drag reduction.

Some performance claims made by inventors and commercial vendors lack the backing of rigorous testing. In addition, experimental studies fall short by not reporting results with a true uncertainty analysis.

A research program is underway at the Langley Full Scale Tunnel to understand the ideal limits to drag reduction due to add-on technologies used with standard trailer designs and a modern streamlined conventional cab. This work is aimed at contributing to the art by providing a data set with the following attributes:

- Ideal limits to popular device performance
- Modern streamlined tractor design
- Sufficient model detail
- Drag reduction devices representative of many current market offerings
- Virtually no boundary effects over yaw sweep

- Sufficient Reynolds Number
- Minimum interference from support structure
- Overall uncertainty analysis, (not back to back point repeatability)

EVOLUTION OF HEAVY TRUCK DRAG REDUCTION TECHNOLOGIES

The pursuit of low-drag heavy truck designs started in the 1930's. Early efforts at reducing truck drag focused on integrated streamlined cab and trailer designs, a concept now being revisited by major manufacturers. Conversely, the majority of heavy trucks in the current fleet make use of trailers and tractors from independent manufacturers. Over the past 30 years, tractor manufacturers have made great strides in streamlining their product. Initially, add on roof–top flow deflectors were introduced and gradually an overall design philosophy has evolved which integrates the rooftop flow deflector concept, streamlines the side transitions with skirts and cab extensions, may include a front bumper treatment, and provides detail optimization in areas like mirrors and blending fillets.[3] On the other hand until very recently, trailer designs have focused more on optimizing utility and cargo capacity, not aerodynamic drag. One noted exception is the work of Trailmobile where a wind tunnel program led to detail optimization of trailer corner radii and side panels.[4] The technology to provide significant drag savings with add-on devices has been available since at least the 1970's. Recent work has focused on creating devices that are operationally friendly – those that do not restrict access to the cargo doors or gap area or reduce ground clearance drastically. The heavy truck wind tunnel model chosen for this study was originally developed in 2005 to evaluate several new minimally invasive drag reduction devices under the sponsorship of the US Department of Energy.[2] For a fairly recent, concise historical review of commercial vehicle drag reduction, see reference 4.

EXPERIMENT DETAILS

FACILITY - The LFST (formerly the NASA LaRC Full-Scale or NASA 30 by 60) features a large ¾ open-jet test section and large ground board.[5] Full-scale vehicles ranging from conventional cars to Class-8 tractors with shortened trailers can be accommodated. The test section is semi-elliptical in cross section with a width of 18.3 m (60 ft) and a height of 9.1 m (30 ft). The ground board is 13 m wide by 16.0 m long and features a turntable with a diameter of 8.7 m. The overall aerodynamic layout of the facility, showing the double return design, is given in Figure 1. Power is supplied by two 3 MW (4000 HP) electric motors driving two 10.6 m diameter four-bladed fans. For this test the 6-DOF automotive balance was used to measure body-axis vehicle drag, side force, and yawing moment. Ground board boundary layer control was provided through a raised ground board with a suction slot located just upstream of the vehicle.[6] The large ¾ open jet test section of the LFST is ideal for testing the ¼ scale truck model at high yaw angles with negligible boundary effects.

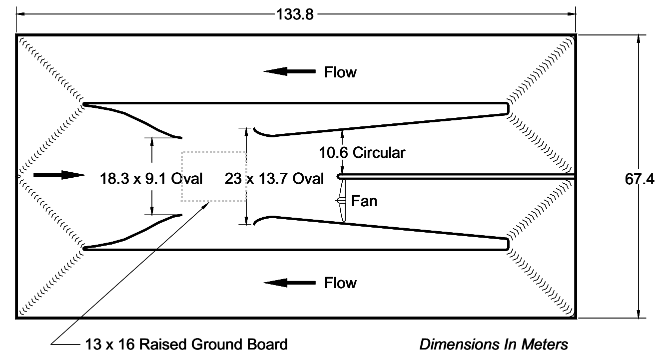


Figure 1 The Langley Full Scale Tunnel Plan View

MODEL – The SOLUS and ODU Representative Heavy Truck (SORHT) model is a ¼ scale, class 8, heavy truck model with overall proportions derived from the DOE Generalized Conventional Model (GCM), but with the addition of tires and axles, trailer structural underbody elements, landing gear, mud flaps, and other details.[7] The cab contours were chosen as representative of current streamlined commercial models. A picture of the model in the test section is shown in figure 2 and a dimensioned drawing is included in the appendix. It should be noted that the model was tested without mirrors. The model was positioned on the balance such that the ground board boundary layer control slot was located approximately 0.23 m upstream of the cab bumper as shown in figure 3. Roughness elements were positioned on the trailer sides to force transition in order to match the full-size turbulent boundary layer character at the trailer base.

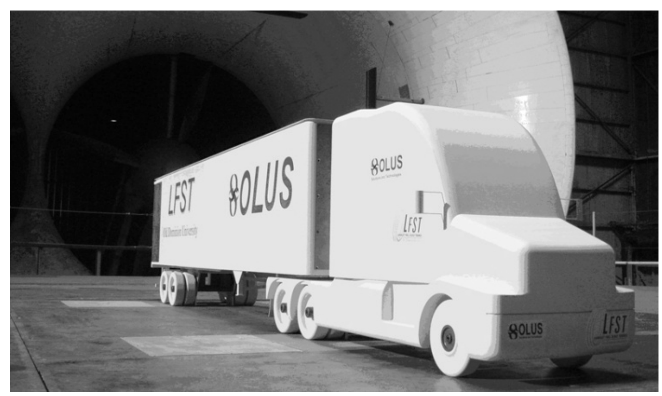


Figure 2 SORHT Wind Tunnel Model

DRAG REDUCTION DEVICES – all the devices chosen for this test have been shown in the literature to be practical add-on devices with many variants available commercially. The configurations were chosen to characterize, as well as bracket the practical through ideal potential of the devices, both individually and working in concert as a full treatment. Figure 4 summarizes the tested configurations where the baseline model is the unmodified SORHT model and the shaded areas illustrate the devices.

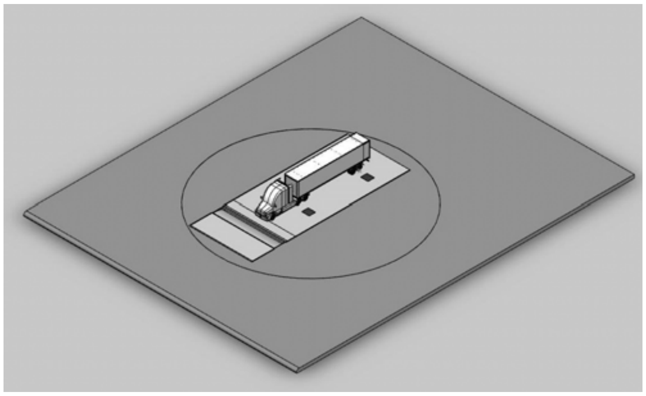


Figure 3 Model Location on Ground Board Showing Turntable and Boundary Layer Control Slot

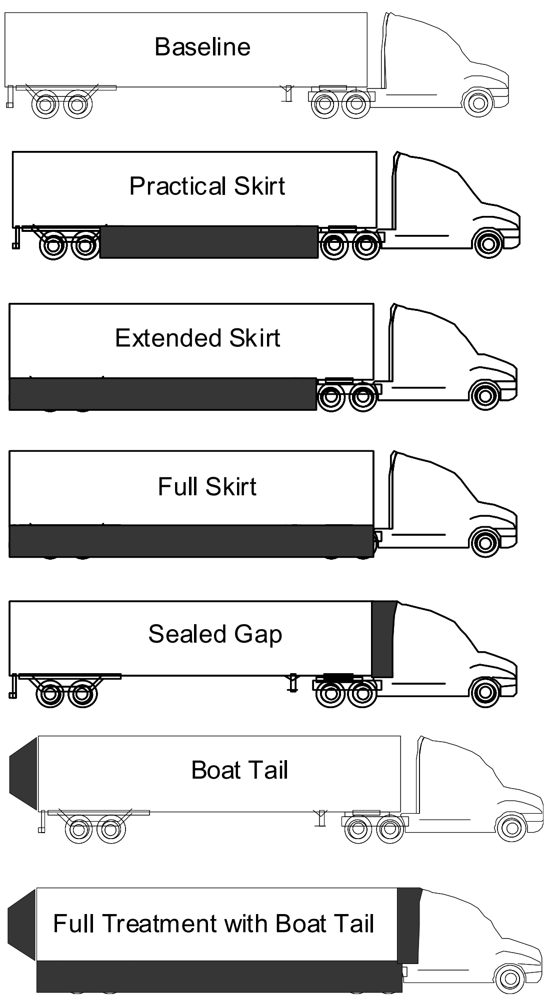


Figure 4 Test Configurations

Practical Skirt - The practical skirt represents many of the commercially available trailer skirts in that it fits between the cab rear wheels and the trailer wheels. The ground clearance was adjusted to approximately 8 mm (on the model), an impractical height, but one that would indicate the ideal limit to potential performance gains.

Extended Skirt – The extended skirt explores the potential of covering the trailer wheels. Again, the ground clearance was adjusted to approximately 8 mm.

Full Skirt – The full skirt explores the potential of covering both the trailer and rear tractor wheels. Again, the ground clearance was approximately 8 mm. This skirt is the least operationally practical but provides the upper bound in performance particularly when used with other devices in the fully treated case.

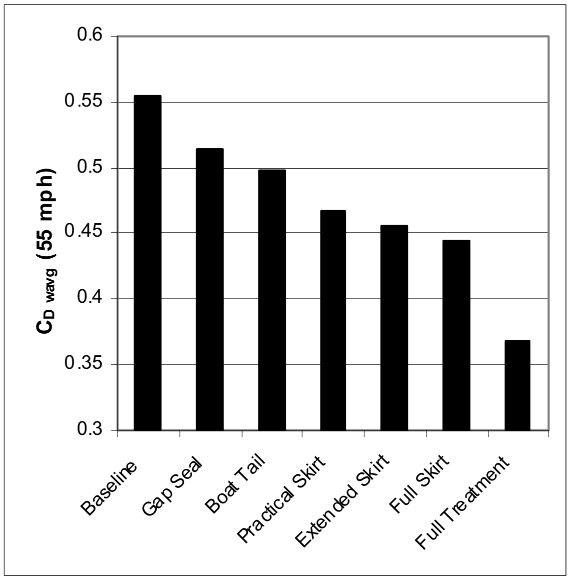
Sealed Gap – The detrimental effects of gap flows are well known. Many current gap treatments strive to prevent as much cross flow as possible. In order to seek the ideal, the gap was completely blocked and formed to smoothly transition the cab to trailer gap. All seams were taped to ensure a seal. A picture of the sealed gap filler is included in the appendix.

Boat Tail – The open boat tail treatment (or base flaps) was constructed of thin sheet metal which formed a 15 degree tapered rear with an open cavity, extending 0.15 m aft of the baseline trailer model.

TEST PROCEDURE AND DATA REDUCTION

Test Conditions and Drag Measurement - All configurations were tested at a nominal dynamic pressure of 10 psf over a yaw sweep of +/- 15 degrees. The nominal Reynolds number based on trailer width (Re_w) was 1.26×10^6, felt to be adequate to avoid scaling issues.[8,9] The zero yaw case was repeated for each configuration, and two of the configurations were chosen at random to be run as complete replicates for uncertainty estimates. A PC based data acquisition system with a 16-bit A/D samples both automotive balance load cell forces, as well as a differential pressure transducer dedicated to dynamic pressure measurement. The drag force measurement and wind tunnel dynamic pressure calibration was conducted as specified in the SAE J1252 recommended practice. Detailed data for each configuration yaw sweep is presented in the summary plot of the appendix.

Response Model - A cubic spline was fit to each configuration yaw sweep to allow interpolation between the recorded yaw values and those required for calculation of wind averaged drag coefficients at various highway speeds.[10] Wind averaged drag coefficients calculated using SAE J1252 with a chosen highway speed of 55 and 65 mph are presented (in rank order) in figure 5. Individual device drag increments are



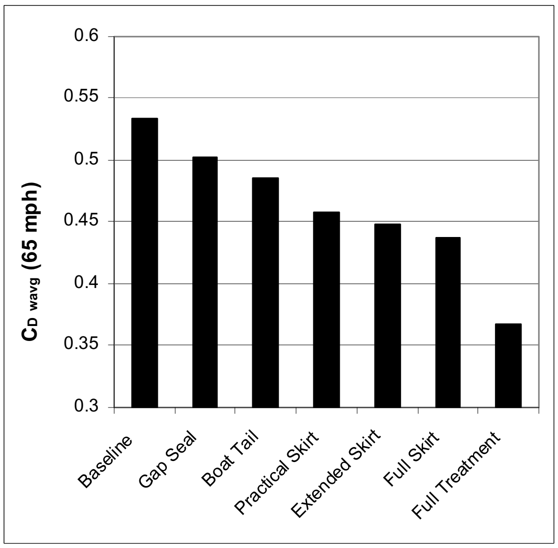


Figure 5 Wind Averaged Drag Coefficients

presented in table 1. A sample spline fit is included in the appendix.

Uncertainty Analysis - An uncertainty estimate (U) for an individual drag coefficient measurement was obtained by combining bias (B) and *true* precision (P) errors .[11]

(1) $$U^2 = B^2 + P^2$$

The precision error is the random error component that is best obtained by the replication of measurements of the desired response. In this experiment two pairs of replicate runs were performed allowing a sum of squares of differences to be computed between the pairs. A true replicate requires that a given configuration run is conducted, subsequent runs follow which require changes in the geometry (preferably in random order), and then the replicated run is conducted later in the test program. This insures that the precision estimate includes the error associated with removing and replacing the devices on the model.[12] Many authors use repeat runs (no geometry change) for precision estimation which by nature results in lower precision estimates. The replicate based precision measurement is then an honest estimate of the true uncertainty associated with not only measuring the flow conditions and forces, but also the ability to control the model geometry. Measured drag coefficients from two replicate runs were used to provide an estimate of the variance. Using the two pairs of runs, the variance may be pooled to give a single value representative of the entire test.

To calculate the variance (S^2) associated with a pair of replicate runs, form the quotient of the root sum square of differences for the *n* runs over the degrees of freedom (number of runs less one):[12]

(2) $$S^2 = \frac{\sum_{i=1}^{n} (C_{D1_i} - C_{D2_i})^2}{n-1}$$

In equation 2, C_{D1} represents a drag coefficient value at the i*th* yaw angle from the initial run and C_{D2} the replicate at the same yaw angle. Set point error between the points may be adjusted out by using a fitted response function such as the cubic spline. To pool the variances of two pairs of replicate runs, use the number of degrees of freedom as weights:[13]

(3) $$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$$

The precision, P for a single measurement of the mean drag coefficient is found by including a coverage factor for the desired confidence level (t statistic) with the estimate of the standard deviation.[11,13] There were a total of N=30 replicated values from two configurations

Configuration	$C_{dwavg\,(65)}$	$\Delta C_{Dwavg\,(65)}$	% Change
Baseline	0.534	0	0.0
Gap Seal	0.503	0.031	5.8
Boat Tail	0.485	0.049	9.2
Practical Skirt	0.458	0.076	14.2
Extended Skirt	0.448	0.086	16.1
Full Skirt	0.437	0.097	18.2
Full Treatment	0.367	0.167	31.3

Configuration	$C_{dwavg\,(55)}$	$\Delta C_{Dwavg\,(55)}$	% Change
Baseline	0.554	0	0.0
Gap Seal	0.515	0.039	7.0
Boat Tail	0.497	0.057	10.3
Practical Skirt	0.467	0.087	15.7
Extended Skirt	0.457	0.097	17.5
Full Skirt	0.444	0.11	19.9
Full Treatment	0.369	0.185	33.4

Table 1 Component Drag Reductions from Baseline

which were pooled for the variance estimate. For a 95% confidence interval, the precision may be expressed as:

$$(4)\quad P = \frac{2S_p}{\sqrt{N}}$$

The bias error in this experiment is the systematic error due to the instrumentation. The bias estimates can be found through the data reduction equation used to calculate the drag coefficient. If D is the measured drag force, q the measured dynamic pressure, and A the vehicle frontal area then C_D is

$$(5)\quad C_D = \frac{D}{qA}$$

Using the method of reference 11, holding frontal area constant , the bias may be expressed as

$$(6)\quad B^2 = \left[\frac{\partial C_D}{\partial D} B_D\right]^2 + \left[\frac{\partial C_D}{\partial q} B_q\right]^2$$

Performing the partial differentiations:

$$(7)\quad B^2 = \left[\frac{1}{qA} B_D\right]^2 + \left[\frac{-D}{q^2 A} B_q\right]^2$$

Over the range $0.3 < C_D < 0.6$, the estimated uncertainty in obtaining a mean value for drag coefficient at a single yaw value is +/- 0.002 with 95% confidence.

DISCUSSION OF RESULTS

In reviewing the yaw sweeps of appendix figure A4, it can be seen that the overall trend in the drag response with yaw for each of the devices compares favorably to that shown in references 3,4, and 8. As the cross flows through the gap and under the trailer are progressively blocked by longer skirting, the rate of drag increase with yaw decreases. In the limit, the fully treated truck (body axis) drag is relatively insensitive to yaw changes.

Incremental gains due to individual treatments from the current study are given for two vehicle highway speeds in table 1 and figure 5. The boat tail shows a wind averaged drag coefficient reduction of 10.3% versus the baseline for a reference speed of 55 mph. Table 2 summarizes comparisons of boat tail treatments of a similar device length to trailer length ratio. Both ideal and contemporary truck-trailer geometries have been published in the recent literature. The work of Storms, 2001 highlights the ideal gain where the vehicle is streamlined and free of gaps and protuberences.[14] Storms, 2004 data is from measurements on a model with more detail, namely a gap and protruding wheels and shows that the gains will diminish as the upstream flow is disturbed.[9] Schoon's results were generated

Reference Source	$\Delta C_{D\ wavg}$ (55)	$\Delta C_{D\ wavg}$ (65)
Schoon, 2007	~8.5%	
Cooper, 2003		6%
Storms, 2001	20.0%	
Storms, 2004	~15 %	
Leuschen, 2006 (Transtex 3 panel)		~9.5%
Current Study	10.3%	9.20%

Table 2 Comparisons of Boat Tail Drag Reduction, Increment from Baseline

from a detailed scale model and Leuschen tested a full scale truck, both with drag increments in line with the findings of the current study.[15,16]

The skirts chosen for this study were meant to reveal the maximum potential for a skirt of a given (longitudinal) length. The ground clearance was kept at the minimum possible for reliable drag measurements. In the work of Schoon, 2007, a parametric height study is performed on a trailer skirt using a trailer geometry identical to that of the SORHT model, together with a tractor of modern conventional (versus cab-over)cab design. Overplotting the results of the current studies' practical skirt using the references non-dimensional notation as shown in figure 6, a curve may be fitted to describe the trends toward an ideal limit to this treatment.[15] The non-linear nature of the response has been shown in light trucks and cars as the skirt height approaches a completely blocked state.[3]

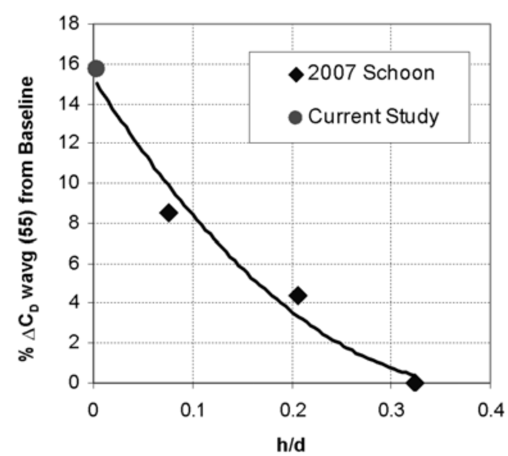


Figure 6 Drag Reduction vs. Non-dimensional Skirt Height

The gap seal device fully blocks and seals the gap, fairing the cab extensions into the trailer sides and cab roof into the trailer roof (see appendix for photo). The 7% drag reduction (55 mph) as expected is appreciably higher than published results for devices that failed to seal the gap such as the single panel described in reference 8. Schoon describes a fully closed gap treatment, composed of several separate panels with gains of 5 %.[15] The result of the current study is then felt to represent an upper limit in achievable drag reduction by faired gap seals used with modern conventional cab designs. Comparisons are presented in table 3.

Reference Source	$\Delta C_{D\ wavg}$ (55)	$\Delta C_{D\ wavg}$ (65)
Schoon, 2007	5.0%	
Cooper, 2003		4.0%
Current Study	7%	5.8%

Table 3 Comparisons of Gap Seal Drag Reduction, Increment from Baseline

Reference Source	$C_{D\ wavg}$ (55)	$C_{D\ wavg}$ (65)
Cooper, 2003 (NRC)		0.54
Storms, 2001	0.225	
McCallen (Ed.), 2002		0.189
Current Study	0.369	0.367

Table 4 Comparisons of Overall Drag for Fully Treated Geometries

Finally the fully treated vehicle of this study is compared to other similar studies. Comparisons are difficult to make between different facilities and model geometries but nevertheless are of interest. Table 4 is a compilation of absolute wind averaged drag coefficients for several fully treated designs. In reference 8, Cooper's 2nd generation NRC truck had similar treatments to the SORHT model with the exception of exposed trailer wheels, slightly higher ground clearances and an older conventional cab body contour. The current study suggests further savings are possible with a modern faired cab shape and covered wheelsets. In reference 4 the University of Maryland Trailmobile study is described where an all-around skirt (no bumper) was fitted with an extremely low ground clearance. A faired and filled plug sealed the gap and an impractically long boat tail graced the rear end. In addition, the frontal area used was the overall height by overall width, further lowering the drag coefficient. Storms simplified GTS model is included here for comparisons to an ideal model geometry with representative overall dimensions.[14]

CONCLUSION

It is perhaps dissappointing to those new to heavy truck aerodynamics to discover that the technology to substantially improve the fuel economy of tractor-trailers has been around for quite some time. Increasing fuel prices and new environmental pressures have led government and industry to once again pursue drag reduction technologies. It is the hope of the authors that the work presented here may add to the prior art by helping to define the upper limits to drag reduction technologies possible with current generation conventional cab tractors and trailers. These limits may be used to judge new device performance claims where proper testing has not yet been reported.

The importance of including an uncertainty analysis with any experimental result can not be overemphasized, particularly if presenting results where the "signal to noise ratio" may be high, such as operational road testing. As trucks adopt more of the "large gain" devices and researchers strive for the last few percent drag reduction possible, it is imperative that we understand and report the associated uncertainty.

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APPENDIX

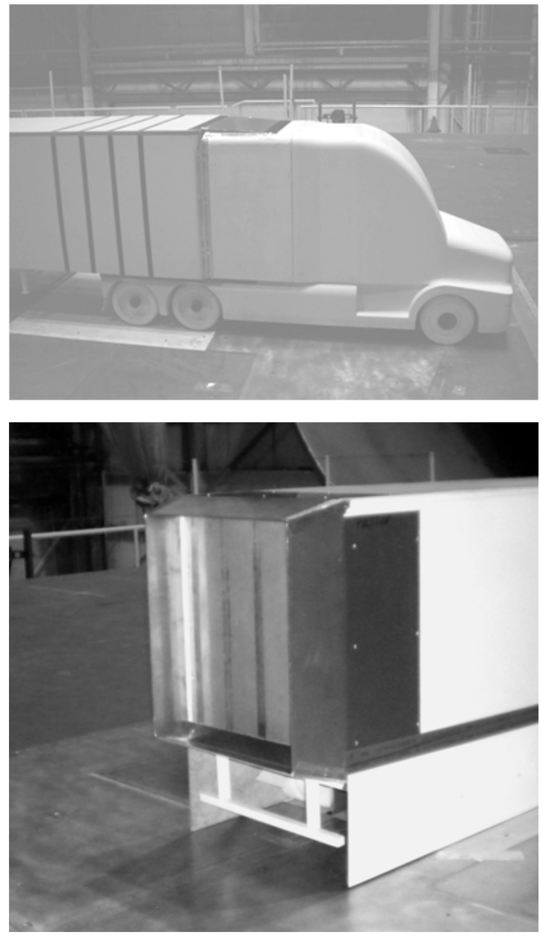

Figure A2 Gap Seal and Boat Tail Treatments

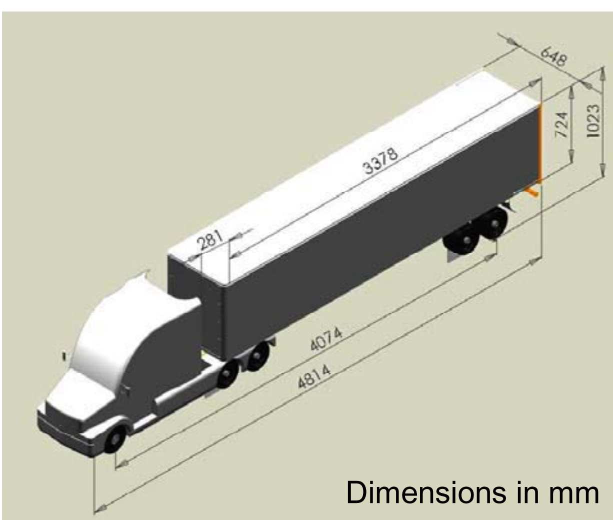

Figure A1 SORHT Model Details

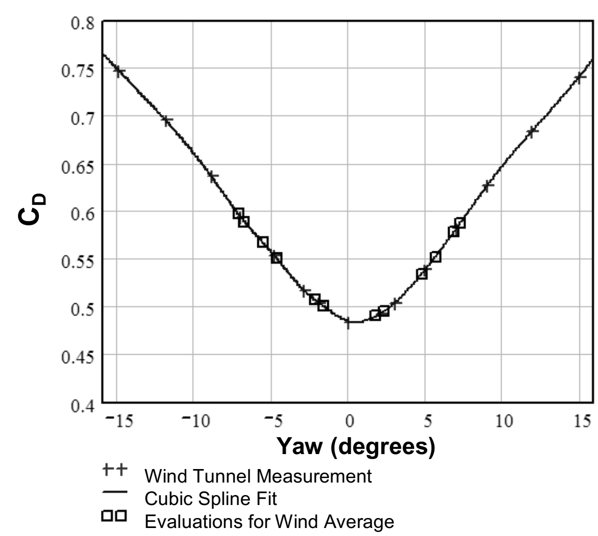

Figure A3 Sample Cubic Spline Fit

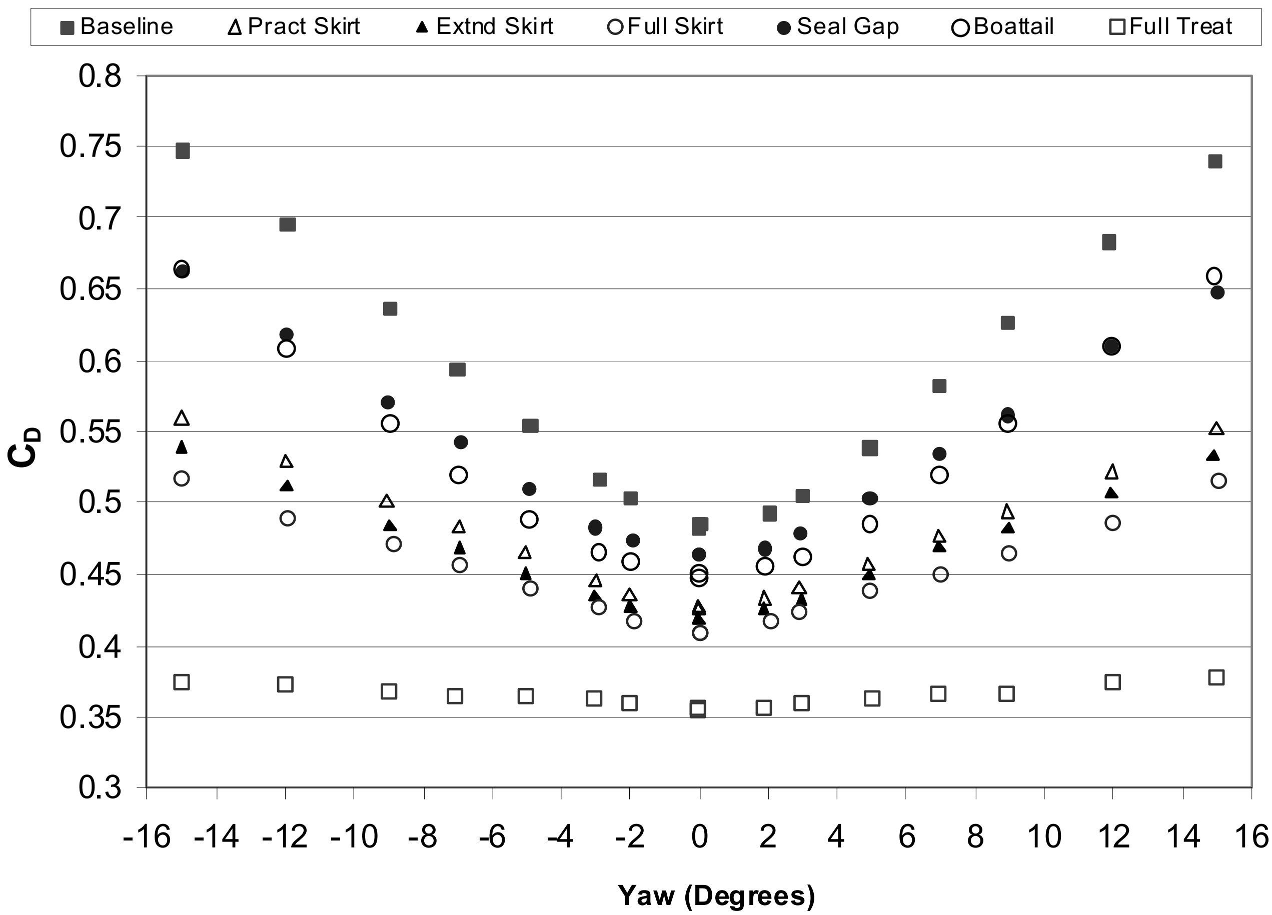

Figure A4 Detailed Configuration Yaw Sweep Data Summary

Appendix Concluded