In Depth Cd/Fuel Economy Study Comparing SAE Type II Results with Scale Model Rolling Road and Non-Rolling Road Wind Tunnel Results

Adrian Reynard
and
Tim Jennings
and
Henri Kowalczyk
and
Fritz Marinko
and
Mike Camosy
Auto Research Center, Indianapolis, Indiana

ABSTRACT

The trucking industry is moving into a new era of development brought on by governmental concerns over energy independence as well as the realities of increasing fuel costs. This has renewed interest in optimizing the aerodynamics of Class 8 tractor-trailer trucks. However, many of the large aerodynamic gains have already been developed, for example trailer skirts and boat tails giving fuel economy improvements of approximately 5%. Research continues in order to better understand the aerodynamics of these vehicles and further improve their efficiency. Scale model rolling road testing has been around for several decades. In fact, the earliest rolling road wind tunnel test of a Class-8 truck that the authors are aware of occurred in the late 1980's [1]. In order to define the performance of a heavy duty truck, it has been well established that the use of wind averaged drag coefficients are required. To achieve wind averaged drag coefficients, it is necessary to measure data with a model in yaw for either a static floor or rolling road tunnel. The authors previously published results comparing a generic truck model tested using both a moving ground plane and a static ground plane. This paper builds on the work using a more detailed and modern truck model. The improvements in aerodynamic drag by fitting trailer skirts are discussed. These drag reductions are converted into fuel efficiency improvements and are compared to SAE type II testing. The reader will be able to appreciate the difficulty associated with attempting to correlate wind tunnel results to SAE Type II results.

Some of the issues related to scale model rolling road testing such as Reynolds number dependency and yaw over a rolling road will be explored. Due to the size and nature of heavy duty trucks, cross winds must be taken into account. In addition to track or on-road testing, static tunnels have been the primary experimental tool for developing heavy duty trucks. Using the static floor tunnel method, heavy duty truck models have fixed (non-rotating tires) and are yawed via a turn table mounted in the floor of a tunnel. Multiple studies have been published which illustrate the necessity for rotating the tires in order to achieve improved correlation to real-world results, for examples see [1],[3],[4],[5],[6].

INTRODUCTION

In recent years, the Auto Research Center (ARC) has seen an increased interest in testing of class 8 tractor-trailer aerodynamic characteristics. The ARC has worked with truck, trailer, after-market manufacturers and fleets using scale model, rolling road testing to advance the heavy trucking industry's ability to improve fuel economy and reduce green house gases by improving the aerodynamic efficiency of their vehicles. This testing allows accurate, quick and cost efficient development which is important since over 21 percent of a heavy truck's power requirement is needed to overcome aerodynamic drag, [2].

It is a common belief that a moving ground plane is only required for vehicles that are low to the ground and would not be required for class 8 trucks, however, Sardou [1] found otherwise. He states: "We just wanted to analyse [*sic*] whether or not high speed moving ground plane must be used for truck development. The answer seems to be yes…" [1]). Subsequent research also showed that the interaction between the moving ground plane and the vehicle being tested were very complicated and unpredictable. Research based on different types of vehicles ranging from trains to race cars showed "that it is just impossible to find any kind of correlation between stationary and moving ground results" [3]. These types of findings are consistent with the experience of the authors at the ARC tunnel. Typically passenger cars show a reduction in drag with a moving ground plane [4]. The authors have previously published results [5] that show an increase in drag with a moving ground plane for class 8 tractor trailers. These results are consistent with recently published studies using CFD to study the effects of yaw and a moving ground plane on semi trucks [6]. Clearly the effect of a moving ground on drag coefficients cannot be easily predicted *a priori*.

In order to understand the impact of aerodynamic improvements on the overall efficiency of a truck, it is important to consider the environment in which the truck will be used. When trucks travel in a road environment they will experience a relative wind from various directions depending on the road speed and wind speed, thus it is accepted practice that a drag coefficient should include the effects of yaw. SAE J1252 [7] procedure shows how to compute the wind averaged drag to account for the expected operating conditions in the USA. Results at ARC are usually reported for a speed range of 50 to 75 mph, for this paper the wind averaged drag was computed at the same speed as the SAE type II test that is shown. Figure 1 [8] shows what the probability of yaw angle versus speed is for a truck traveling on a highway. Based on this as well as the SAE1252 procedure for calculating wind averaged drag at greater than 50 mph, it is felt that limiting testing to 9 degrees of yaw is a reasonable time and cost savings measure.

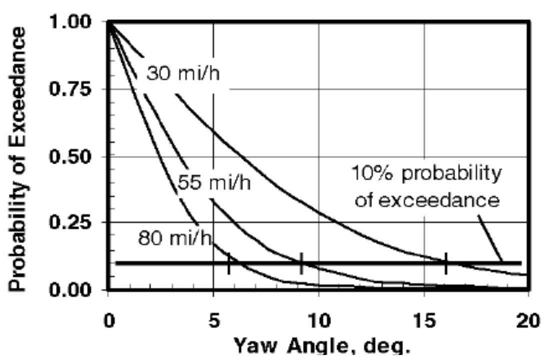

Figure 1 – Probability of exceeding a given yaw angle [8]

A common rule-of-thumb used in the industry is that to achieve a 1% fuel economy increase you must decrease aerodynamic drag by 2% at 60 mph. Table 1 shows this relationship for a few different speeds [9]. It shows the difficulty in achieving meaningful fuel economy through aerodynamic improvements increases at lower speeds. In this paper the authors prefer to use the results from a more refined methodology [10] in order to present the fuel efficiency results to the end users. This is discussed in the data reduction section.

Vehicle Speed (mph)	Aerodynamic Drag Reduction to Increase Fuel Economy 1%
60	2%
40	3%
20	6%

Table 1. [9]

DESCRIPTION OF TEST FACILITY

The ARC tunnel is a scale model rolling road tunnel that tests models of vehicles. The model is mounted to a balance cradle that houses a 6-component load cell balance. The balance cradle is attached to a sting that is attached to a steel beamed structure that is mounted on vibration pads 8 feet underground. This mounting allows for the model to be completely isolated from any building noise. The model's wheels run on top of the rolling belt that has a surface roughness to match the average surface roughness of highways and roads in the US. The belt speed matches the wind speed to +/- 0.01 m/s. The turbulence intensity is .24% and the flow angularity is .24 degrees. Boundary layer velocity is 99.8% freestream at 1.0 mm height at center of the model.

The vehicle model motion system (VMMS) is mounted within the cradle that is mounted inside the model. The VMMS allows the vehicle to automatically yaw, pitch, roll, heave and front wheel steer during a test session. To maintain the road flatness, a multi-suction port system is used throughout the platen. To eliminate any belt edge curl, a pneumatic tensioning system is used to apply constant tension to the belt during a test session. To eliminate the static electricity build up before it gets to the model and effects test repeatability, a static electricity discharge system is utilized.

To minimize the road boundary layer that builds up in wind tunnels, a three stage boundary layer suction system is utilized.

TEST PROCEDURE

PRETEST INSPECTION AND WARM UP

At the beginning of each testing session, the tunnel and its data acquisition systems are run for a minimum of 30 minutes to warm up the facility. The balance and laser systems are warmed up for a minimum of four hours prior to use. The model is inspected for any wheel bearing issues or suspect/damaged parts that could affect testing. The tunnel and road system are inspected. The yaw, heave, roll and pitch position are all measured and maintained.

GENERAL

Each test series began with a static weight tare of the model. Following the static weight tare, a rolling wheel tare was taken for each model position that data was to be recorded. The model position remained the same for all of the runs. The positions were standard road height at yaw equaling 0, 9, 6, 3, 0, -3, -6, -9, 0 degrees. There were three 0 degree points to allow for a "first to last" run match that is used to determine potential belt stretch, or in test model issue. Positive 9 degrees is yawing the truck 9 degrees to the driver's left. All rolling wheel tares were completed with the belt running 50 m/s without any air speed.

Following the rolling wheel tares, the data sampling process took place for all 9 yaw angles listed above. All tests were run at a constant dynamic pressure equivalent to 50 m/s. After the model data samples were measured, the tunnel was shut down and a change was made to the model. Following a model change, the general process would be repeated.

DATA REDUCTION

All force and moment data was measured using an AEROTECH 6 component load cell balance, 124 static pressures and all associated tunnel parameters (ie DC motor information, belt temperature, wind speeds etc.) were recorded using a PI Mistral system. The data was organized through a program called PI AERO which utilizes an ACCESS database. PI AERO was used to display the reduced and raw data into Excel. Using Excel, the data was then summarized for reporting purposes. Once a full test run was completed, the measured drag coefficients for each yaw angle were imported into an Excel sheet that calculated the wind average drag coefficient from 22.3 m/s (50 mph) through 33.5 m/s (75 mph). Each wind averaged drag coefficient was individually compared to its baseline's proper wind averaged drag coefficient and a percentage change calculated. Based on McCallen, et al. [10] we have created a spreadsheet which will convert from percent change of wind averaged drag coefficient to percentage savings of fuel. This percentage change only applies to a theoretical class 8 tractor-trailer, but it gives end users an understanding of the order of magnitude of fuel economy that they can expect, thus allowing them to explore the most economically viable aerodynamic solutions. Figure 2 shows the graph from [10] that the spreadsheet is based on.

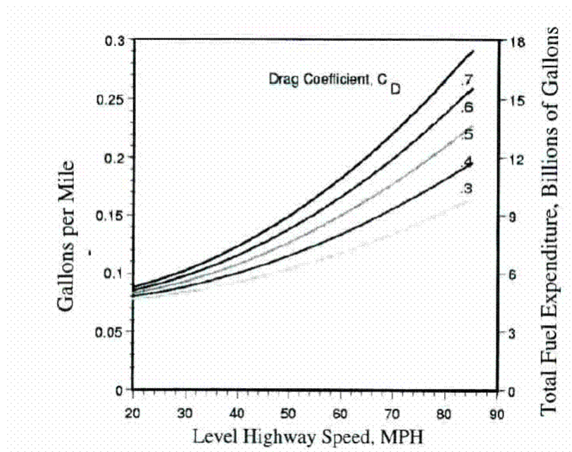

Figure 2 – Fuel consumption for typical Class 8 Truck [10]

A wind speed of 50 m/s, constant dynamic, was used for these investigations using a 1/8 scale mode. A Reynolds number of Re=1.1 Million results from the model's width as characteristic length. SAE J1252 recommended practice recommends that Re_{min} = 0.7 Million. Storms [11] studied Reynolds number effects on various generic configurations and found that for Reynolds numbers ranging from 1.1 Million to 7.0 Million very little change on the wind averaged drag coefficient was measured. In this test our speed sweep showed a minimum of 40 m/s will yield reasonable results for wind averaged drag as seen in Figures 3,4. The appendix shows more detailed graphs of C_d at different yaw angles and Reynolds numbers. Figure 5 shows a comparison of drag coefficient for two different yaw angles at various speeds (Reynolds numbers). It shows that the higher yaw angles have a higher sensitivity to Reynolds number. This yaw angled Reynold's dependency shows that simply listing one minimum Reynolds number to define the testing of Class 8 Trucks is not appropriate and should be treated very carefully to ensure quality data is being recorded.

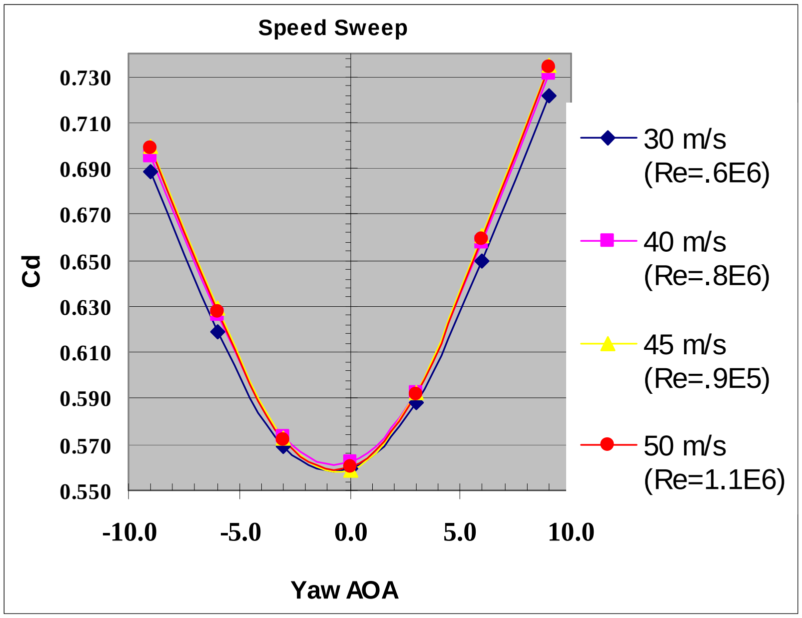

Figure 3 – C_d vs Yaw at various test speeds

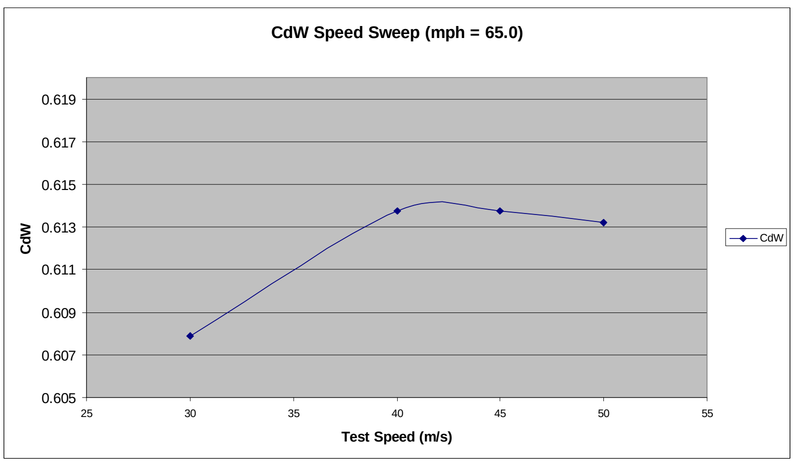

Figure 4 - Wind averaged drag vs Test Speed

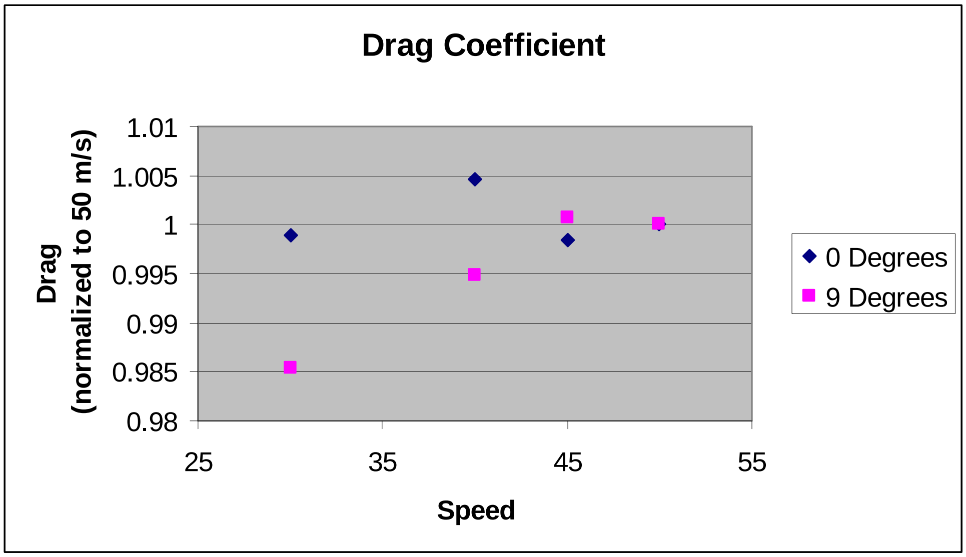

Figure 5 – Drag coefficient normalized to 50 m/s

A source of measured drag that must be accounted for is the drag induced by rolling the wheels with a yaw angle. For much of the testing at ARC, the absolute value of this induced drag is of little interest, since much of the aerodynamic development is geared towards observing changes or deltas in drag coefficients. The observed repeatability of the ARC wind tunnel for this type of testing is +- 0.3%. For this test, however, we were also interested in quantifying the amount of induced mechanical drag that is created by yawing the model over the rolling belt in order to more accurately measure the total aerodynamic drag of the truck to compare to full scale road testing results. We were able to do this by running the model through the yaw sweep without the wind blowing and taring out the rolling drag. The end result is that .54kg (1.2 lbs) is tared out in this initial process versus an overall drag force of 22.68 kg (50 lbs).

DISCUSSION OF TESTING LIMITATIONS

As road and track tests are subject to variations in conditions between runs, the accounting for these variables becomes a large task that does induce errors into their final results. Wind tunnel testing can control a majority of the issues a full scale track test faces, but is also subject to smaller variations. Typically, a full scale track test has an error of 2% (+/-1% in fuel economy). Scale model wind tunnel testing has an error of 0.6% (+/-0.3% in fuel economy). We refer the reader to [12] which has a detailed discussion of some of the difficulties in comparing wind tunnel and on-road testing. Unfortunately the SAE type II test is not designed to give an absolute level of drag so we cannot compare the wind tunnel results directly to SAE type II results. However, we present them here so that the reader can understand the impact aerodynamic changes have on fuel efficiency.

APPROACH

DESCRIPTION OF TEST VEHICLE

The test vehicle used was a 1/8 scale tractor and trailer. The tractor was a Navistar Prostar sleeper. The tractor was created by scanning a full size tractor and building a scale model. The trailer was a 53 foot Wabash trailer and was built with data provided by Wabash. The model had articulating suspension. It also included pressure taps that were not used for this test. Any part of the tractor/trailer that touched the air was accurately represented in this model. This model also included internal flow modeling from the tractor grill into the radiator and then into the engine bay. The bogey was adjustable for multiple positions. Pictures of the model used are shown on the following pages.

Navistar Prostar Sleeper Tractor & Wabash Trailer

Navistar Prostar Sleeper Tractor

Front of Wabash 53' Trailer

Tractor/Trailer Starting Configuration Gap

Wabash Trailer Landing Gear

Rear Door & Bumper of Wabash Trailer

Starting Bogey Position was California

TRUCK SPECIFICATION

- 2008 International Pro-Star Sleeper Premium 6x4
- 270” Wheelbase
- Full Height Roof Fairing
- Vertical Exhaust
- Full Aero Side Mirrors
- Hood Mounted Mirrors
- Full Length Fuel Tank Covers
- Full Length Fuel Tank Skirts
- Factory Cab Extenders

TRAILER SPECIFICATION

- 2008 Wabash 53’ Dura Plate Dry Van
- 102” Wide
- Swing Doors
- 36” King Pin
- Hendrickson Air Ride Suspension
- 13.6’ Height with 1” Taper
- Sliding Bogey Set to California Position

CONFIGURATIONS TESTED

1. Ridge Corp 32” Greenwing Trailer Skirt
2. Ridge Corp 36” Greenwing Trailer Skirt
3. Ridge Corp 36” Greenwing Trailer Skirt integral struts
4. Wabash Trailer Skirt

To compare to all SAE Type II tests for these components, the component’s baseline used during the SAE Type II test was also independently established. Non-rolling road and non-rolling wheel, NRRNRW, data were measured at varying yaw angles to deliver a wind averaged Cd value. The same process was used to measure rolling road with rolling wheel, RRRW, Cd values.

RESULTS

The authors were interested in determining the effects on drag of testing trailer skirts on a fully detailed 1/8 scale class 8 tractor trailer model in a moving ground plane tunnel. The following table shows the difference in wind averaged drag coefficient for both moving plane and fixed floor conditions. It is interesting to note that for these cases the road on condition results in more drag, but it is not simply a small offset. Also, notice the difference between the road on and road off cases for the two baselines A and B. Baseline A resulted in 1.28% more drag with moving ground plane and baseline B resulted in 3.22% more drag with moving ground plane. The only difference between these two cases was a 9" full scale difference in tractor to trailer gap and the mud flaps were moved to the trailer bumpers. Clearly the interaction of the truck and ground plane road is a complex one.

Wind Averaged Drag Coefficient at 60 mph			
	Road On	Road off	% Difference
Baseline A	0.623	0.615	1.28%
Configuration 1	0.563	0.554	1.60%
Configuration 2	0.557	0.545	2.15%
Configuration 3	0.554	0.542	2.17%
Baseline B	0.683	0.661	3.22%
Configuration 4	0.620	0.595	4.03%

The next table shows the change in drag from the baseline configuration. The results here are interesting because the fixed floor testing shows a greater difference between the configuration and the baseline. Thus the static floor testing tends to be overly optimistic in predicting aerodynamic improvements for these tests.

Wind Averaged Drag Coefficient at 60 mph			% Difference to baseline	
	Road On	Road off	Road On	Road Off
Baseline A	0.623	0.615		
Configuration 1	0.563	0.554	-9.63%	-9.92%
Configuration 2	0.557	0.545	-10.59%	-11.38%
Configuration 3	0.554	0.542	-11.08%	-11.87%
Baseline B	0.683	0.661		
Configuration 4	0.620	0.595	-9.22%	-9.98%

The next table shows the fuel economy improvements gained by installing the different aerodynamic devices. Here we can see that the SAE Type II testing and the wind tunnel testing are in general agreement. Also we can see that the fixed ground plane testing overestimated the fuel savings compared to rolling road. For three configurations both rolling road and fixed ground plan tests overestimated the fuel savings and for one configuration both underestimated the savings comparing to SAE Type II testing. We should add here that other aerodynamic devices (aside from trailer skirts) yields a similar mix of the SAE Type II testing both over and underpredicting wind tunnel results based on the tractor/trailer starting configuration. Aside from the tractor/trailer baseline sensitivity, the authors also note that significant discrepancies with respects to SAE Type II ambient testing conditions were identified. It is believed that these ambient condition discrepancies play a very large roll in making comparisons to wind tunnel data difficult.

Device Tested	SAE Type II	WT (rolling road)	WT (non-rolling road)
Configuration 1	4.0%	4.8%	4.97%
Configuration 2	5.2%	5.31%	5.69%
Configuration 3	5.1%	5.54%	5.94%
Configuration 4	5.6%	4.62%	4.99%

Table 2 – Summary of Results

Figure 6 shows the difference in drag between moving ground plane and static floor conditions of four configurations. It is interesting to note that the delta is not a simple offset but instead varies throughout the yaw range. This has important implications since a truck traveling on a highway will be influenced by significant cross wind components. What is especially interesting is the change in yaw dependence between the two baseline cases. For Baseline A we see a hysteresis effect throughout the yaw range that is not present for Baseline B.

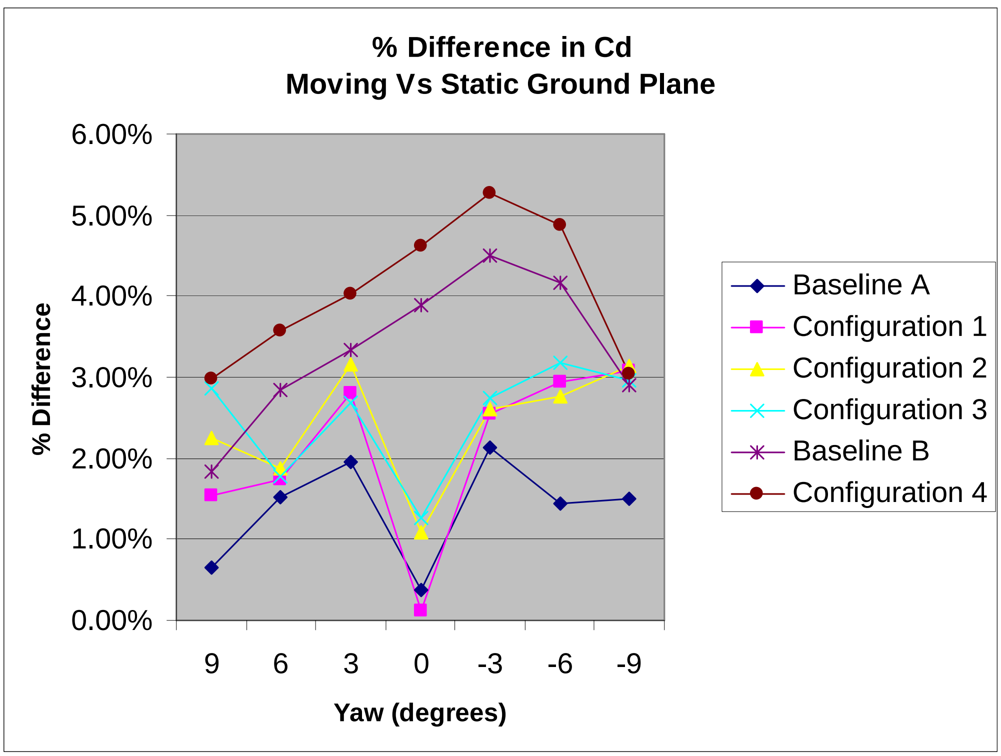

Figure 6

Another example of this asymmetry in relation to yaw angle is the percent difference in drag coefficient versus yaw angle show in figure 7. This is interesting because it highlights a potential difficulty in correlating wind tunnel testing to road testing. When computing the wind averaged drag coefficient, the yaw dependence is subsumed into a single drag coefficient which assumes the wind direction is somewhat evenly distributed around 360 degrees. However, it is very likely that a single over the road test such as an SAE type II test, will have wind coming from only a single direction or at most a single quadrant, this could skew the results and make it difficult to correlate to these types of tests.

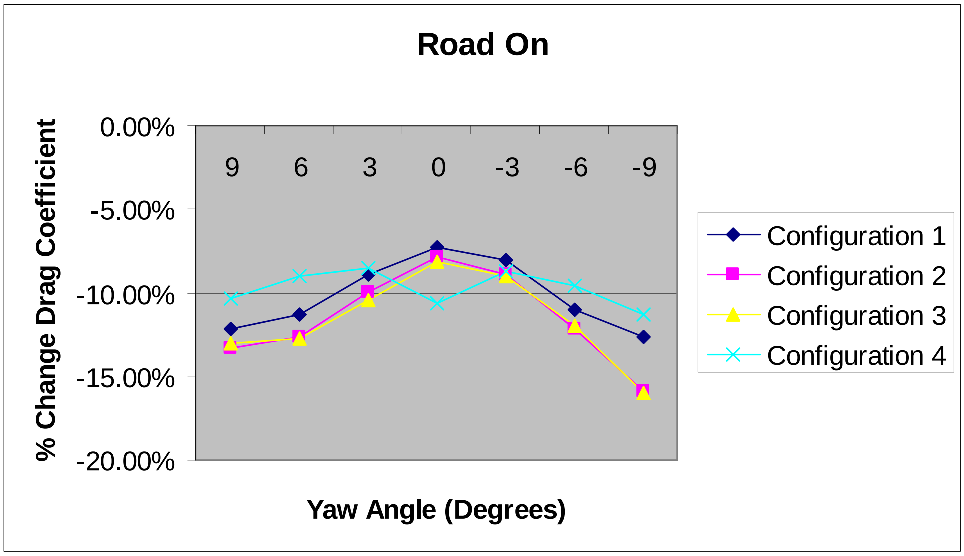

Figure 7

CONCLUSIONS

Because wind averaged drag coefficients are calculated based on wind tunnel testing and take into account the average of all cross flows a tractor/trailer could see (over 360 degrees), wind tunnel comparisons to SAE Type II testing could be skewed since during a typical SAE Type II test the tractor/trailer is most likely not seeing the average estimated cross flows acting over 360 degrees, but more likely acting from one direction or quadrant.

The interaction between the tractor/trailer and the ground plane is complex and it is difficult to estimate the impact of the rolling road on the aerodynamic drag. It must be tested for each case of interest.

For the cases studied, the static ground plane tends to overestimate aerodynamic improvements compared to the rolling road testing.

Depending on the tractor/trailer configuration, a hysteresis effect can be measured throughout the yaw range. Trailer skirts do not change this hysteresis effect, but simply will offset it.

Tractor/Trailer combinations have a Reynolds dependency that is a function of yaw angle (or cross wind). This yaw angled Reynold's dependency shows that simply listing one minimum Reynolds number to define the testing of Class 8 Trucks is not appropriate and should be treated very carefully to ensure quality data is being recorded.

FUTURE WORK

The authors are currently working to improve correlation between the wind averaged drag coefficient and on the road testing. As a part of this, the authors plan to improve on the correlation between aerodynamic drag and fuel economy.

This paper dealt with a limited subset of aerodynamic devices available. Further work will compare boat tails, trailer leading edge add-on devices, as well as comparing the position of mud flaps, bogeys and the tractor to trailer gap.

Further work is currently being carried out by the authors using CFD to understand the yawed flow conditions. This work will explore the Reynolds number effects on yawed flow and tractor to trailer gap, as well as understanding the localized angled flow around the rolling wheels.

Understanding why certain tractor/trailer configurations have a hysteresis effect over a standard yaw range could provide clues towards improving overall vehicle stability.

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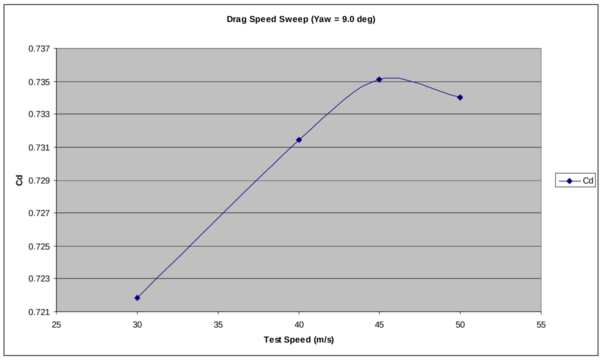
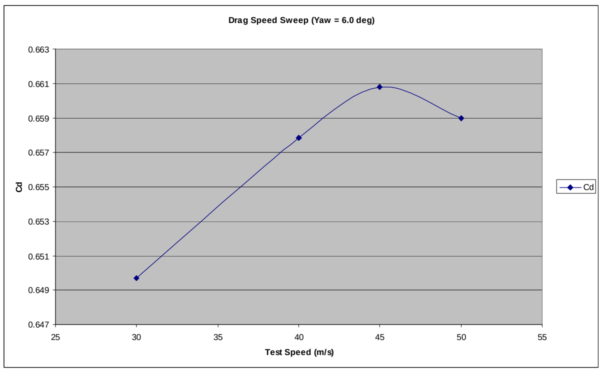
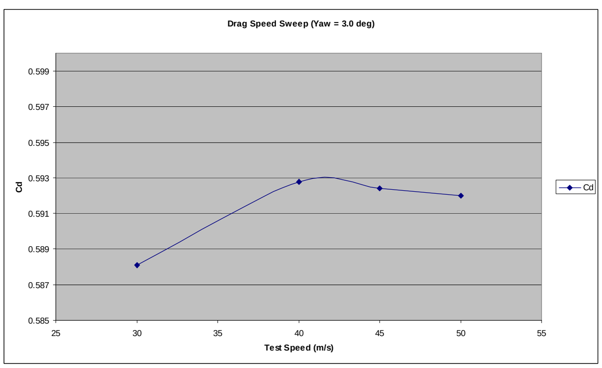
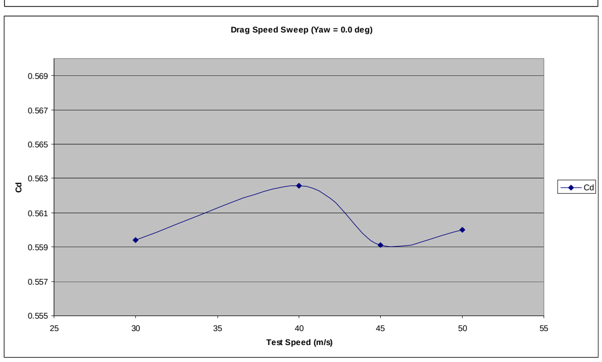
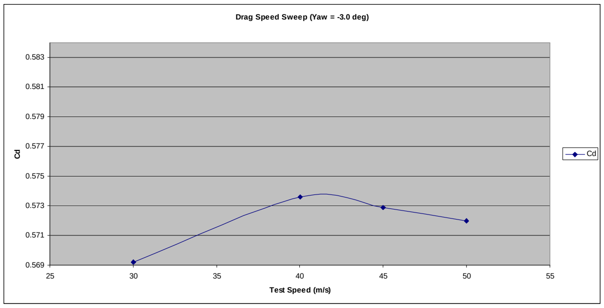
APPENDIX A – REYNOLDS NUMBER SWEEP RESULTS

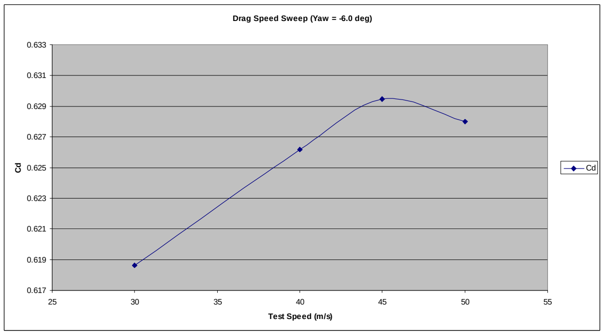









Drag Speed Sweep (Yaw = -3.0 deg)
Cd
Test Speed (m/s)
Cd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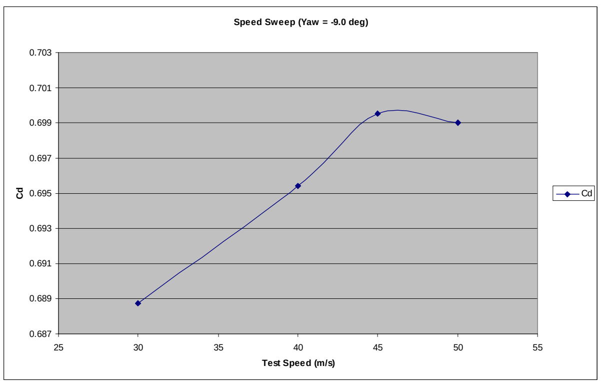
Cd
Test Speed (m/s)
Cd


Speed Sweep (Yaw = -9.0 deg)
Cd
Test Speed (m/s)
Cd