

CFD Correlation with Wind-Tunnel for Dry Van Trailer Aerodynamic Devices

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ABSTRACT

The primary purpose of this paper is to correlate the CFD simulations performed using PowerFLOW, a Lattice Boltzmann based method, and wind tunnel tests performed at a wind tunnel facility on 1/8th scaled tractor-trailer models. The correlations include results using an aerodynamic-type tractor paired with several trailer configurations, including a baseline trailer without any aerodynamic devices as well as combinations of trailer side skirts and a tractor-trailer gap flow management device. CFD simulations were performed in a low blockage open road environment at full scale Reynolds number to understand how the different test environments impact total aerodynamic drag values and performance deltas between trailer aerodynamic devices.

There are very limited studies with the Class-8 sleeper tractor and 53ft long trailer comparing wind tunnel test and CFD simulation with and without trailer aerodynamic device. This paper is to fill this gap.

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INTRODUCTION

In 2015, the United States Environmental Protection Agency (EPA) and Department of Transportation's National Highway Traffic Safety Administration (NHTSA) released their proposal for the second phase of regulations to reduce greenhouse gas (GHG) emissions from on-road heavy duty vehicles. This second phase of proposed regulations is similar to the first phase of regulations that went in to effect for 2014 model year heavy duty vehicles in that the proposal continues to push for further reductions in GHG emissions. One difference is that this new proposal takes a more systematic approach to reducing emissions by considering the impact that trailers have on the fuel efficiency, and therefore the emissions. The new proposed regulations will continue to allow manufacturers to evaluate aerodynamic performance of designs using alternative methods such as computational fluid dynamics (CFD) simulations and wind tunnel tests. It is important for the industry to have confidence in these alternative methods.

The newly proposed second phase of the GHG emissions standard for heavy-duty vehicles impacts the trailer in addition to just the tractor standard in GHG phase one [1, 2, 3, 4]. The GHG Phase-2 adds the wind yaw conditions in addition to Phase-1. Due to this, aerodynamic performance requirements for the tractor as well as the trailer have become more stringent. Original equipment manufacturers (OEMs) can choose between both experimental tests, such as coast down testing [5], wind tunnel testing with reduced-scale or full-scale model [6], and SAE Type II testing [7], as well as analytical means such as

CFD to assess aerodynamic performance. Greenhouse Gas Emissions Model (GEM) is used to determine relative fuel economy savings from aerodynamic drag [8, 9, 10]. GEM uses a standard defined trailer for OEM tractor it takes a drag area ($C_D A$) as aerodynamic input, and for trailer OEM's may use a variety of Class-8 sleeper tractors as the front end for trailer fuel economic evaluations.

This paper investigates both the drag coefficient (C_D) and incremental delta C_D correlation of a 1/8th scale wind tunnel model and its corresponding CFD simulation for yaw sweep. The model is evaluated with and without trailer aerodynamic devices, specifically a Tractor-Trailer Gap Fairing (TTGF), and Trailer Skirt (TS). It also compared the impact of the scaled model in wind tunnel environment to the open road (OR) condition for following three different configurations.

- Baseline
- Baseline with TTGF
- Baseline with TTGF along with TS

The effects investigated are:

- Influence of the tunnel geometry
- Influence of adding TTGF
- Influence of adding TTGF and TS
- Influence of open road (OR) condition

PREVIOUS RELEVANT WORK

Horrigan K. et al [11] compared CFD aerodynamic results to 1/5th scale model wind tunnel measurements from the University of Washington Aeronautical Laboratory (UWAL) [12] using Kenworth T2000 tractor and only smaller trailer was used as the scale model. They found overall very good agreement between simulation and experimentally measured drag. And also compared with the open road condition.

Horrigan K. et al [13] investigated CFD simulations of a 1:8-scale Generic Conventional Model (GCM), were conducted using a Lattice-Boltzmann based solver. Comparisons were made to experimental measurements from the NASA Ames 12-Foot Pressure Wind Tunnel [14], including drag coefficients as a function of yaw, static and transient surface pressures, and three-component particle image velocimetry. They found excellent agreement in overall drag prediction as well as local flow results including average static pressure, tractor-trailer gap flow, trailer wake structure, and transient pressure spectra in these regions.

There are very limited studies with the Class-8 sleeper tractor and 53ft long trailer comparing wind tunnel test and CFD simulation with and without trailer aerodynamic device. This paper is to fill this gap.

METHODOLOGY

Scaled Down Rolling Road Wind Tunnel

Wind tunnel tests were performed on a 1/8th scale long sleeper with a standard 53-foot dry-box trailer in rolling road wind tunnel at the Auto Research Center (ARC) [15-16]. The representative baseline wind tunnel trailer model is shown in Figure 1, for confidentiality reason tractor image is not shown anywhere in this paper. The tractor is a standard Class-8 sleeper cab with fully detailed underbody components, such as engine, transmission, heat exchangers side tank, heat exchangers core (were modelled as perforated vertical flat plates which matches the velocity ratio in the heat exchanger), fan (were replaced by circular anemometer) and fan shroud, steer axle and tandem drive axle with tires, after treatment system, battery box, air tank, fuel tank, exhaust pipe, quarter fender, drive wheel mud flap, deck plate and stair case in the tractor to trailer gap. Tractor main and hood mounted auxiliary mirrors, chassis skirt, side extender and roof extender were also included. Measured wheel base for the scaled model is 28.0 inch, tractor to trailer gap is 5.6 inch, trailer height 2.0 inch taller than the tractor. For the confidentiality reason we could not able to provide the other dimensional details for the tractor, trailer and trailer aero devices.

The approximate boundary layer (BL) thickness at the test section is 1mm, turbulence intensity (TI) is 0.24% and the flow angularity is 0.24° [16]. Wind off rolling wheel tares were performed at 40% belt speed. The model was tested at a speed of 50 m/s (which corresponds to Reynolds number (Re) of 1.1M based on width of the tractor as characteristic length), for the complete yaw sweep of -9° to 9°. Rotating tire and moving floor (floor is not yawed with the vehicle)

were modelled, blockage ratio (defined by ratio of vehicle front projected area to tunnel nozzle exit area) of the model were 3.6% and 7.3% at 0° and ±9° yaw condition respectively which is within recommended blockage ratio as per the SAE J1252 [6] for open jet wind tunnel. Forces and moments were measured using an Aerotech 6-axis force measurement balance mounted to the trailer through a mounting sting. The model was tested in three different configurations, and evaluated over the full yaw sweep.

- Baseline
- Baseline with TTGF
- Baseline with TTGF along with TS



Figure 1. Baseline wind tunnel trailer

CFD Simulation Approach

CFD simulations were performed using the commercially available software, which uses the Boltzmann Equation to solve for the flow field [17]. It can be shown rigorously that the Lattice Boltzmann formulation is equivalent to solving the time dependent compressible Navier-Stokes Equation [18] and that the formulation imposes fluid boundary conditions on solid surfaces [19]. A review of the fundamentals of the Lattice Boltzmann Method can be found in [20].

CFD tool uses the Very Large Eddy Simulation (VLES) turbulence model to solve the resolvable scale flow scale and modeling the sub-grid scale using RNG k-epsilon; further details on turbulence modeling are available in [21]. Reference [22] provides a review of the LBM simulation approach using this turbulence model, and describes capabilities for aerodynamics, thermal, and aero-acoustics applications for production vehicle development. Examples of published validation studies including full-detailed production vehicles using this simulation approach are shown in [23, 24, 25, 26, 27]. Several examples of validations studies using wind-tunnel data from scale-model vehicles are shown in [28, 29, 30, 31].

For the full-scale model the computational grid for the simulations was established using nested regions of refinement of a Cartesian grid, with a finest cell size of 6.0 mm in critical areas, and 12.0 mm cells around the entire tractor according to the recommended best practices procedures for heavy truck Lattice Boltzmann aerodynamics

simulations SAE J2966 [32]. For the case of the scaled model the grids are scaled down accordingly. The CFD model was evaluated in three different configurations, the same as it was in the wind tunnel test.

- Baseline
- Baseline with TTGF
- Baseline with TTGF along with TS

There were two CFD simulation environments used in this study.

1. The scaled wind tunnel model for the full yaw sweep of -9° to $+9^\circ$, except $\pm 3^\circ$.
2. Open-Road (OR) - The simulation domain was an idealized domain with negligible (0.05%) blockage representing the OR. Tested at 0° , 2° and 6° yaw condition

In the scaled wind tunnel model environment [Figure 2], the wind tunnel facility was modelled as per the SAE J2966 [32]. We have replicated WT facility from the measured dimensional data and/or photo images to create the CAD of the facility. Here the wind tunnel setup starting from the settling chamber, contraction section, test section with same length and width of the moving belt, plenum and wind tunnel collector wall followed by diffuser with all the breather were modeled along with the test vehicle. Rolling road boundary condition was applied at the tunnel center belt and rotating tire also modelled. The ground clearance is matched as with the test wheel scrubbing is modelled as like in the WT test. The vehicle is placed at the same location on the belt as in WT test and the rolling road is not yawed with the model. Not modelled were the closed circuit in the tunnel, fan, and distributed suction in front of the rolling belt which is replaced by frictionless wall. Mass flow rate inlet and pressure outlet boundary condition were applied. The mass flow rate at inlet applied based on the test section speed corresponds to 50m/s (which corresponds to Reynolds number (Re) of 1.1M). Simulation condition as low turbulence intensity (0.3%) free stream flow. Cooling flow were modeled as like in the WT test by matching the velocity ratio in the heat exchanger.

Here we have used similar tractor and trailer model in CFD and matched the WT test vehicle dimensions from the measurement. Boundary layer (BL) on the floor in the CFD WT simulations were matched as per the WT test (1mm). Boundary layer on the vehicle is unknown for the WT test and turbulent boundary layer for the CFD simulation.

For the OR environment, the same vehicle geometry used for the CFD wind tunnel simulation [Figure 3, 4, 5] was scaled up to full scale size, and the corresponding on-road simulation boundary conditions such as vehicle speed (65mph, full scale Re of 5M), moving ground, and rotating tires were applied. Similar turbulence intensity as in scale model was used, but with a 0.05% blockage environment representative of an ideal open road environment as per SAE J2966 [32], so that the extents of the flow domain do not impact the vehicle. The vehicle and moving floor is yawed about the freestream direction, simulation done at three different yaw angles 0° , 2° and 6° .

Figure 3 shows the CFD baseline simulation trailer, it uses the same exact CAD from the WT test. Figure 4 shows the baseline with TTGF configuration and Figure 5 shows the baseline with TTGF and TS.

All simulations were performed from an initial flow field obtained from a coarse-grid simulation in order to reduce initial transient oscillations. All simulations were run transient and time-accurate, until forces were stabilized and averaged forces were converged. Analysis of the transient forces was used to determine the end of the initial transient and the amount of time required for averaging. The results are reported for the time-averaged flow field, averaged over 10 seconds of physical time.

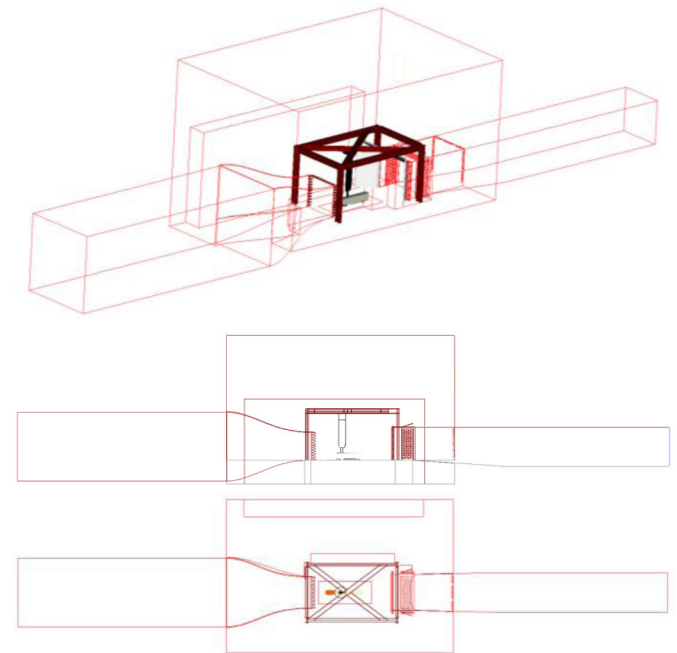


Figure 2. Representative scaled CFD model in wind tunnel



Figure 3. Baseline trailer

RESULTS & DISCUSSION

Experimental Result

The wind tunnel testing was performed at yaw sweep from -9° to $+9^\circ$ yaw. Table 1 shows the wind tunnel test results. Here, the drag coefficient (C_D) values are normalized (C_{Dn}) based on the 0° yaw baseline wind tunnel test value. We assumed that the dynamic pressure correction was applied in the wind tunnel test data but not have information about the dynamic pressure calculation method, here the C_{Dn} (normalized drag coefficient) are presented as it is received from the wind tunnel test, i.e. no correction was applied after that. We also don't have any information about the uncertainty of the wind tunnel test.

For the baseline, the C_{Dn} varies from 1.000 to 1.304 for 0° to $\pm 9^\circ$ yaw conditions. $C_{D_{WAn}}$ (normalized wind average drag as per SAE J1252 [6] based on 65mph vehicle speed with 7mph wind speed) is 1.091. For the baseline w/ TTGF, the C_{Dn} varies from 0.994 to 1.246 for 0° to $\pm 9^\circ$ yaw conditions, $C_{D_{WAn}}$ is 1.073. For the baseline w/ TTGF and TS, the C_{Dn} varies from 0.873 to 1.055 for 0° to $\pm 9^\circ$ yaw conditions and $C_{D_{WAn}}$ is 0.947.

The data clearly shows that adding the TTGF improved the wind averaged drag coefficient by 1.6% and adding the TS in addition to the TTGF improves the wind averaged drag coefficient by 13.1% over the baseline.

Figure 6 shows that the drag coefficient polar are slightly asymmetric between the positive and negative yaw angles for all the test configurations. This may be due to the difference in blockage to the sides of the model in the plenum (one side is 25% more room than the other side) and/or some extent of the test vehicle upper body and underhood components. A more parabolic drag profile (more steep increase of drag wrt yaw) is seen for the baseline configurations as well as the baseline with TTGF only. As the trailer becomes more aerodynamic by adding the TTGF with the TS, the drag polar increases more gradually (less slope).

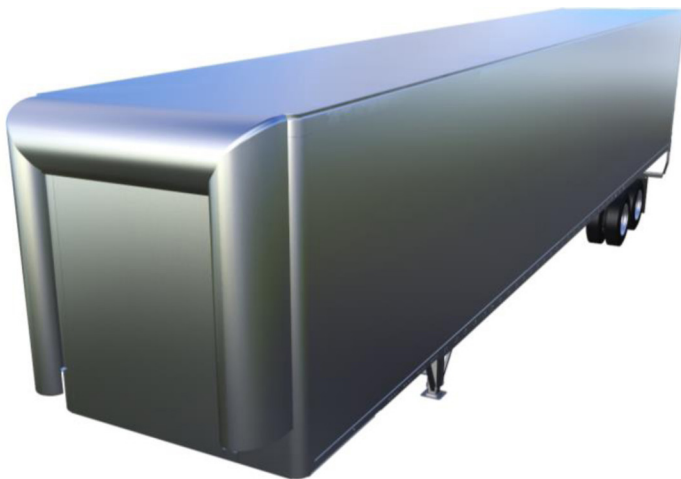


Figure 4. Baseline trailer w/ TTGF



Figure 5. Baseline trailer w/ TTGF and TS

Table 1. Summary of aerodynamic data for the WT test (All C_D values are normalized wrt Baseline 0° yaw wind tunnel result; Delta = (x-Baseline)/Baseline)

Yaw ($^\circ$)	C _{Dn} 1/8th Scale Wind Tunnel Test				
	Baseline	TTGF	TTGF +TS	Delta C _{Dn} %	
				TTGF	TTGF +TS
-9	1.261	1.225	1.029	-2.8%	-18.4%
-6	1.127	1.105	0.967	-1.9%	-14.2%
-3	1.028	1.017	0.901	-1.0%	-12.3%
-1	1.001	0.991	0.876	-1.0%	-12.4%
0	1.000	0.994	0.873	-0.6%	-12.7%
1	1.007	0.997	0.884	-1.0%	-12.2%
3	1.050	1.034	0.923	-1.5%	-12.1%
6	1.167	1.139	0.998	-2.4%	-14.5%
9	1.304	1.246	1.055	-4.5%	-19.1%
C _{D_{WAn}}	1.091	1.073	0.947	-1.6%	-13.1%