

Aerodynamic Impact of Tractor-Trailer in Drafting Configuration

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ABSTRACT

On-highway tractor-trailer vehicles operate in a complex aerodynamic environment that includes influences of surrounding vehicles. Typical aerodynamic analyses and testing of single vehicles on test track, in wind tunnel or in computational fluid dynamics (CFD) do not account for these real world effects. However, it is possible with simulation and on-road testing to evaluate these aerodynamic interactions. CFD and physical testing of multiple vehicle interactions show that traffic interactions can impact the overall drag of leading and trailing vehicles. This paper will discuss results found in evaluating the effects of separation distances on tractor-trailer aerodynamics in on-road and CFD evaluations using a time-accurate Lattice Boltzmann Method based approach and the ramifications for improving real world prediction versus controlled single vehicle testing.

CITATION: Smith, J., Mihelic, R., Gifford, B., and Ellis, M., "Aerodynamic Impact of Tractor-Trailer in Drafting Configuration," *SAE Int. J. Commer. Veh.* 7(2):2014, doi:10.4271/2014-01-2436.

INTRODUCTION

Prediction of aerodynamic drag coefficients by wind tunnel, track and computational fluid dynamics methods are all simulations of a real world environment. Each method can produce results that differ from real world experience, creating confusion and a lack of industry confidence in the maturity of the tools. These differences can occur where the specific analytical and test conditions are not comparable to actual real world situations. These fundamental differences are sometimes not adequately explained or appreciated in presenting predictions. Differences between these simulations, whether physical or virtual, and on road performance can include unsteady wind conditions that can be driven by various factors. One of the key variables generally missing in wind tunnel, track and CFD analyses is the effect of multi-vehicle interactions, which exist in the real world environment.

Multi-vehicle, on-road aerodynamic interactions have been the subject of physical testing and reporting worldwide since at least the 1990's, under the phrase "slipstreaming", "platooning" or "intelligent highway" research [1][2][3][4][5][6][7][8][9][10]. These terms overshadow the fundamental truth, that vehicles share road infrastructure and generally are more likely to be operating in the wake of other vehicles than not. The correct term for this is generally defined as "traffic".

As part of the Department of Energy SuperTruck program that was awarded to Cummins Incorporated and Peterbilt Motors Company, a series of investigations was conducted on the aerodynamic ramifications of traffic [11]. The present investigation will discuss the impact of traffic conditions on aerodynamic drag for typical vehicle separation distances at typical highway speeds. Testing was performed along two Texas highway routes to determine the impact of surrounding traffic conditions to oncoming air flow to a vehicle. The paper includes multi-vehicle on-highway testing and use of multi-vehicle computational fluid dynamics.

TRAFFIC WAKE EFFECTS

Multi-vehicle wake effects have been recognized for decades. Vehicle drafting has been a well-established and popularized racing practice in NASCAR, Formula 1, long distance track & field, and bicycle competitions [12][13][14]. The Federal Aviation Administration has established minimum aircraft spacing requirements due to wake effects that have been well documented at airports [15]. Years of government, industry and academic research into intentional platooning of vehicles has documented that the fuel economy of a vehicle can be improved by being in the wake of a lead vehicle. It should not be a surprise that similar effects occur daily in unintentional traffic conditions and regularly affect the aerodynamic drag and fuel economy of vehicles. Yet there are very few published peer reviewed investigations that attempt to quantify these real world effects.

The complexity of multi-vehicle heavy duty vehicle investigations is challenged by scale. A typical North American tractor, pulling a standard 53 foot van trailer, can be 70 feet in length. Two vehicles with a variable highway separation distance observed in typical traffic conditions exceed 200 feet as illustrated in Figure 1.

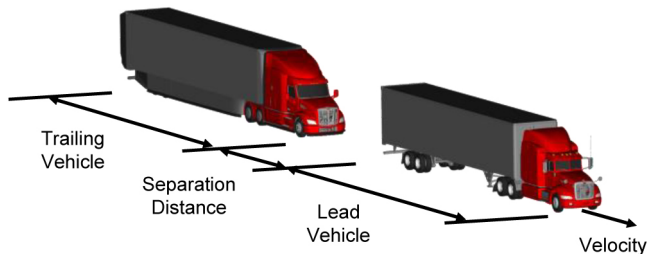


Figure 1. Traffic Modeling

Wind tunnel facilities capable of investigating multiple vehicles with varying separation distances in full scale do not exist. Two of the largest tunnels, the Canadian National Research Center NRC (23.9m test section length) and the U.S. NASA Ames National Full-Scale Aerodynamics Complex NFAC (50.3m section), have test section lengths capable of only a single tractor and trailer [16][17]. These tunnels may be capable of multi-vehicle testing at model scales sufficient to minimize Reynolds number effects [18]. Scale wind tunnels such as Auto Research Center ARC (5.75 m working length), Haas Windshear (7 m max model length), or Monash University's 1.4MW (9.9m test section length), have test section lengths that would require such small scale for the tractor-trailer vehicles that Reynold's number effects would bring the predictions into question [17][18][19][20]. The SAE Windtunnel test protocols for predicting aerodynamic drag such as SAE J1252 are focused on single vehicle testing [21].

Track testing of multiple heavy duty vehicles has been conducted in Sweden, Japan and the U.S., among others, as part of platooning potential research [6][7][8][9][10]. However the established SAE aerodynamic test protocols such as SAE J1263 and SAE J2263 for coastdown tests are tailored to single vehicle testing[22][23]. There are currently no vetted SAE multi-vehicle track test protocols for aerodynamic drag.

On-highway test protocols exist, such as SAE J1321 Type II, SAE J1526 Type III and TMC RP1109 Type IV fuel economy test methods[24][25][26]. As these tests can occur over long distances on public highways, traffic effects are inherently imbedded in the results. Control of surrounding traffic can be done with adequate use of closed test sections or blocking vehicles, but this is rare and could be counter-productive. Results from preventing traffic during testing would be biased from expected real world performance due to omission of the traffic.

Computational fluid dynamics methodology can attempt to simulate these multi-vehicle wake interactions. In CFD evaluations, vehicles can be modeled with extreme geometric accuracy in full scale, with varying separation distances and yaw angles. Additional factors such as moving ground planes, surface roughness, rotating tires, etc. can improve environmental modeling to more closely match the real world [27]. These more involved analyses are limited practically only by computing capacity and time.

DOE SUPERTRUCK PROGRAM

The Department of Energy SuperTruck program for the Peterbilt/Cummins team challenged industry to develop near production ready technologies for attaining 50% improvement in freight efficiency over a representative road test cycle and 68% for a typical 24-hour single driver operation relative to a Model Year 2009 representative baseline vehicle [11]. These aggressive goals required a systems approach to the vehicle design, with complementary contributions from many systems. The significant goal from aerodynamics was a 48% reduction in wind-averaged aerodynamic drag, as determined from CFD analysis in a single vehicle virtual wind tunnel.

Validation of the system level performance for the road test cycle was accomplished through on-highway, two vehicle modified SAE Type III tests, over a predefined 499 km (310 mile) course as reported in business confidential information (CBI) SuperTruck status reports to the Department of Energy. Validation of the 24-hour cycle test was done with a combination of SAE Type III tests over a predefined 805 km (500 mile) course and overnight static hotel segments. Per the program requirements, vehicles were operated at 65,000 pounds gross vehicle weight (29 tonnes), which is one representative operating point typical in U.S. industry [28][29].

During testing of the first prototype Peterbilt Demo 1 SuperTruck, the on-highway fuel economy results were found to be better than predictions from summing the contributions of the interacting systems [30]. The evaluation suggested that the aerodynamic contributions were exceeding predictions, primarily from uncontrolled ambient conditions that include weather conditions and traffic that were omitted from the original CFD evaluations.

The relative magnitude of the weather effects were fairly well understood from various source documents on wind and temperature effects [31][32][33][34]. The magnitude of traffic effects on drag prediction was not as well understood. An on-highway test was developed by Peterbilt engineers and described below, using the two SuperTruck tractor-trailer units on a straight, relatively flat stretch of divided highway operating at posted highway speeds. This testing characterized potential magnitudes of air flow changes due to separation distances. An additional blocking vehicle was employed to eliminate random interactions from other vehicles.

Physical Testing

A challenge was how to measure the wake effects on the trailing vehicle without modifying the vehicle with additional instrumentation that could bias results. Peterbilt engineers observed that the engine fan was effectively operating as a simple flow meter as it free-wheeled with the clutch disengaged. Instrumentation was added to the fan to measure the rotational speed, which augmented the continuous data recording. In flat, on-highway operation, the cooling fan is generally not needed, with cooling provided solely by ram air.

The Model Year 2009 baseline Peterbilt Model 386 vehicle, pulling a standard 53 foot Utility DX4000 Van Trailer, was selected as the lead vehicle. The trailing vehicle was a Peterbilt Model 587 based tractor, pulling the Peterbilt modified Demo 1 SuperTrailer as shown in Figure 2. Both had production engines and cooling systems. The 587 tractor-trailer system is a more aerodynamic configuration, with added aerodynamic features such as tractor-trailer gap closeouts, trailer skirts, and tractor bogey aerodynamic shields. The two vehicles were operated with vehicle spacing reducing from multiple vehicle lengths down to 10 feet. Multiple tests were conducted in opposite directions on the divided highway.



Lead Vehicle

Trailing Vehicle

Figure 2. Separation Distance Test Vehicles

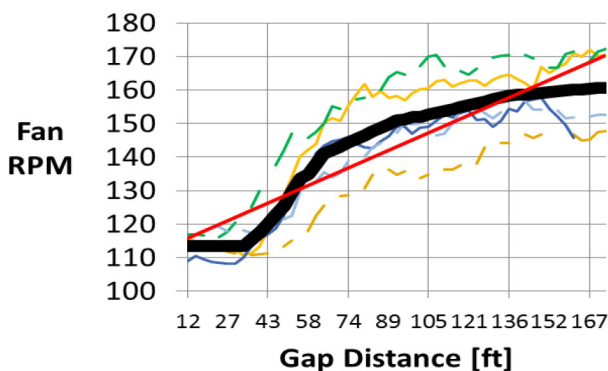


Figure 3. Two Truck Trailing Fan RPM vs Gap Spacing

This physical testing established that the free-wheeling fan RPM reduced as separation distances decreased. Fan speed was measured using a Banner SM312LV optical sensor. The validity of the optical sensor was checked when the fan was engaged. The results from the optical sensor showed the engaged fan speed within 1% of the engine speed multiplied by the known fan pulley ratio of the engine driven fan. Figure 3

shows in the bold black line the cumulative free-wheeling fan rotational speed on average for several test runs, and a linear approximation of the trend in the red line.

Subsequent review of on-road testing in a 310 mile on-highway test runs and evaluations on an alternate commercial 400 mile run from a warehouse in Irving, Texas to a Laredo, Texas terminal showed that free-wheel fan speeds could document the presence of multi-vehicle interactions. An rpm change threshold was set from open free stream on-road conditions. The full route data was then parsed. Figure 4 shows that significant rpm reductions due to surrounding traffic conditions occurred between 37% and 53% of the travel.



Route	Irving To Laredo	Denton to Vernon
In Wake Effects	37%	53%
In Free Stream	63%	47%



Figure 4. Two Route Traffic Type Wake Percentage

In this testing, full vehicle aerodynamic data was not collected either through fuel economy measurements or other means. However, recent SAE Type 2 fuel economy testing has shown that running tractor-trailer combinations in proximity can achieve fuel economy savings through aerodynamic effects on both the leading and trailing vehicle [3].

Having substantiated that wake vehicle interactions were occurring with sufficient frequency and magnitude to bias predictions, a detailed CFD investigation was initiated.

Multi-Vehicle Drag CFD Evaluations

Simulations using PowerFLOW, a computational fluid dynamics software based on the Lattice-Boltzmann Method, were used to evaluate the aerodynamic drag impact on leading and trailing tractor-trailer configurations in a drafting configuration at various trailing distances. PowerFLOW is an inherently transient solver that utilizes a Very Large Eddy Simulation technique where the large anisotropic levels of turbulence are calculated on the computational grid while the small isotropic