

Aerodynamic Optimization of Trailer Add-On Devices Fully- and Partially-Skirted Trailer Configurations

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ABSTRACT

As part of the United States Department of Energy's SuperTruck program, Volvo Trucks and its partners were tasked with demonstrating 50% improvement in overall freight efficiency for a tractor-trailer, relative to a best in class 2009 model year truck. This necessitated that significant gains be made in reducing aerodynamic drag of the tractor-trailer system, so trailer side-skirts and a trailer boat-tail were employed. A Lattice-Boltzmann based simulation method was used in conjunction with a Kriging Response Surface optimization process in order to efficiently describe a design space of seven independent parameters relating to boat-tail and side-skirt dimensions, and to find an optimal configuration. Part 1 concerns a fully-skirted tractor-trailer system, and consists of an initial phase of optimization, followed by a mid-project re-evaluation of constraints, and an additional period of optimization. The most influential parameters are identified in achieving significant aerodynamic drag reduction relative to a base configuration. Part 2 uses a similar set of optimization parameters, but finds a fundamentally different drag response to one critical factor, due to a different set of trailer operational constraints using only partial skirting. Results from both portions are supported by physical testing.

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INTRODUCTION

The United States Department of Energy's SuperTruck program made funds available on a cost-sharing basis in order to accelerate the development and deployment of more advanced technology into the heavy trucking industry. The program outlines a goal of improving overall freight efficiency by at least 50% relative to a best in class 2009 model year truck[1]. As one part of achieving this goal, Volvo set a target of 40% aerodynamic drag reduction for their tractor-trailer system, relative to the 2009 VNL 670.

While assisting those companies that decided to take on the challenge, this has also elevated the constant pressure on vehicle manufacturers to make products that meet ever-increasing expectations. Quality, performance, and low cost are in a three-sided battle for resources. One critical aspect of performance is efficiency, which can also impact a consumer's perception of quality. This creates a natural pressure from the marketplace, as customers want the lowest overall cost of operations and ownership, which is partially driven by the fuel economy. Without advances in the technologies or methods employed in the production of these vehicles, substantial improvements in efficiency will come at substantial cost.

Boat-tails and side-skirts on tractor trailers have been studied through physical testing on-road and on-track, in wind-tunnels at partial-scale and full-scale, at least as early as 1982. These studies, conducted at various levels of detail and with various specific goals, have been presented in SAE technical publications on a regular basis since that time [2, 3, 4, 5, 6, 7, 8, 9, 10]. In one particular summary effort in 2009, Landman, Wood, Seay, and Bledsoe estimated an upper bound of 31% on improvement in wind averaged drag coefficient of a contemporary tractor-trailer [11], giving some light to the difficulty of the Department of Energy's proposed task. Vehicle and truck systems have also undergone optimization by various means, and likewise presented in SAE forums; as examples of the variety of works and scope: Jiang, Wu, Tang, Kim, et al simultaneously optimized aerodynamic and aero-acoustic performance on a heavy truck [12]; Lu, Zhang, Liu, Le Loc'h, et al optimized aerodynamic and engine cooling performance on a medium duty truck [13]; Sun, Chang, Fu, Zhao, et al used a response surface method in early-stage development of an SUV [14], and Yang, Zhou, Peng, Li, et al simultaneously optimized a vehicle's aerodynamics and self-soiling characteristics [15]. What is less common is the application of an optimization method in order to efficiently find the combination of values of a subset of influential boat-tail and side-skirt parameters resulting in the lowest aerodynamic drag for a specific fully-detailed semi-truck model, as described below.



This paper will describe details of the original vehicle undergoing study, including the parameters identified for variation, and any design constraints. It will continue by reviewing the analysis approach, including the simulation method, operating conditions, and the optimization process. Last, it will present results from multiple phases of work, including the way in which the optimization process was utilized to enhance the efficiency of the design process - reducing the costs of engineering by employing advanced technologies and shortening the development cycle.

PART 1: DETAILS OF CURRENT STUDY

This optimization study uses a model year 2012 Volvo VNL 670 [16], with a fully detailed underhood and underbody region, in order to achieve the proper flow distribution through, around, over, and beneath the grille openings and bumper. This is configured with a 2012 Great Dane 53' dry van trailer, at a back-of-cab to front-of-trailer gap of 44". The trailer is fully detailed, including rain gutter and trailer door hinges (Figure 2). From this point, a number of off-the-shelf components provided by Freight Wing® are added to the system. A gap reducer is installed on the front face of the trailer, a boat-tail is installed on the rear doors of the trailer, and side-skirt sections are arranged beneath the trailer, extending as far forward and aft as operations allow. The boat-tail is designed to be collapsible via hinges joining several flat sections. The top panel consists of multiple flat sections whose normals are dissimilar when deployed (Figure 2). This configuration is taken as the baseline for this study, as any owner-operator or fleet could purchase these off-the-shelf parts, and achieve similar gains. It is recognized, however, that the gap reducer, side-skirts and boat-tail are designed for widest applicability, and not optimized for any particular tractor-trailer combination. This outlines the primary question that this study aims to answer - how much additional benefit can be realized by optimizing this specific tractor-trailer system, using only side-skirt and boat-tail parameters?

The initial study concerns five parameters, and evaluates their impact on system drag. One parameter adjusts the side-skirt's ground clearance, while the other four parameters concern the boat-tail.

Three of these independently control the angle of the top, side, and bottom panels. The last parameter varies the length of the panels, as measured parallel to the direction of travel. The factors are shown in Figure 3, and were implemented with initial ranges as specified in Table 1. It is expected that these parameters will be critical for defining the tractor trailer's wake structure and determining the system's base drag, but the precise combination of parameter values resulting in the lowest drag cannot be known a priori; the arrangement of upstream components will influence the distribution and characteristics of the flow as it passes onto the boat-tail. While these parameters were primarily chosen for their expected impact on aerodynamic performance, they are furthermore considered excellent candidates for such an optimization exercise, because of their lack of influence on tractor aesthetics and brand identity.



Figure 1. Photograph and side image of the study's baseline Volvo VNL670® with full side-skirt and boat-tail.

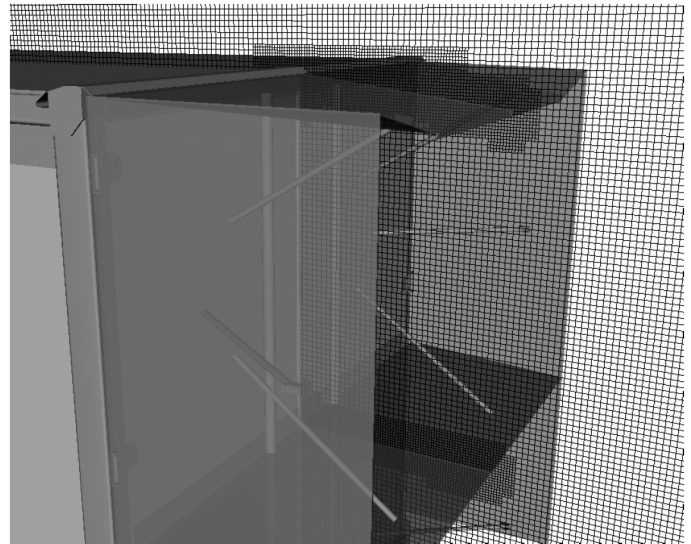


Figure 2. Detail view of boat-tail upper panels, trailer rain-gutter and hinges. A centerline plane shows the volumetric computational grid.

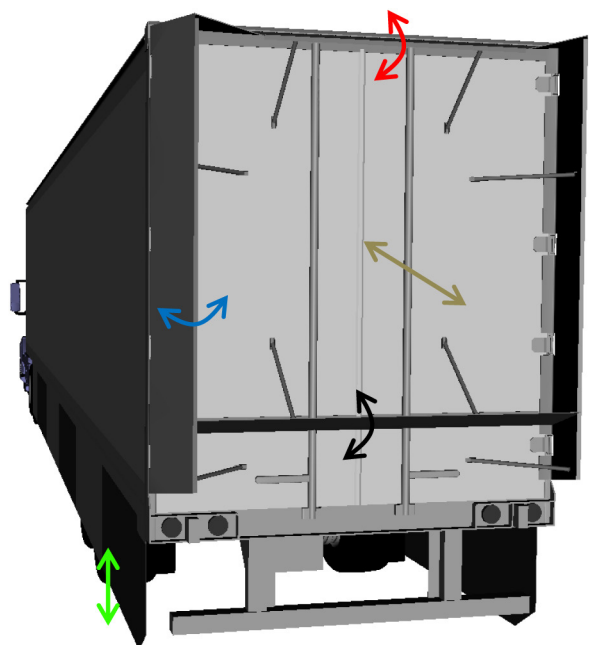


Figure 3. Aft view of tractor trailer, showing detail of boat-tail configuration, and 5 original parameters for optimization.

While modifying curvatures and angles of styled surfaces can yield aerodynamic benefits as well, the optimized shape may depart from brand identity without strict control of the design space. These 5 choices provide significant freedom, opportunity, and no cost in terms of tractor styling or visual impact.

Table 1. Initial study parameters and ranges

Parameter Description	Parameter Range
Boat-tail Top Angle	7° → 35°
Boat-tail Side Angle	0° → 19°
Boat-tail Bottom Angle	0° → 18°
Boat-tail Overall Length	18" → 32"
Side-skirt Ground Clearance	4" → 7"

PART 1: ANALYSIS APPROACH

The aerodynamic simulations are conducted with Exa's PowerFLOW simulation software. It utilizes a Lattice Boltzmann method (LBM), and a simulation process that automatically generates its Cartesian volume grid of variable resolution. More thorough descriptions of the numerical functions involved in the LBM method, as well as turbulence modeling and grid resolution specifics have been presented in the past by Heineke, Beedy, Horrigan, and Sengupta [17].

Simulation setup is consistent with SAE International Standard J2966 [18], in order to best approximate ideal on-road conditions. The model is situated in a computational domain with blockage less than 1%, walls and ceiling represented with frictionless boundary conditions, and the floor as a no-slip boundary, moving at a speed consistent with the free-stream velocity. Tires are given rotating boundary conditions, consistent with the sliding floor. Free-stream velocity is defined at 65 mph, such that the Reynolds number is consistent with the operating condition of interest. Simulations are conducted with flow both body-aligned, and at a 5 degree yaw condition, and the objective function for the optimization studies is to minimize the average of the drag values obtained from these two yaw angles. This strategy is utilized in place of a more thorough yaw sweep, as it typically provides a conservative estimate of real-world impact, and assists in maintaining a rapid pace of development.

The optimization process uses a Kriging Response Surface model, and is described thoroughly by Sun, Chang, Fu, Zhao, et.al in 2014 [14], or alongside additional response surface methods by Jones [19]. The intention in this study is to characterize the design space adequately enough to find optimal configuration(s) with the least cost. This is not always straightforward, due to the balance between computational costs and engineering & labor costs. For example, evaluating all points in a full-factorial Design of Experiments of 5 parameters with just 5 levels each, the labor costs from engineering and decision-making may be quite low, but the computational cost of more than 3000 simulations would be very high. Further, a great deal of data would be amassed in areas of the design space that hold little interest if the goal is to find the best performing

configurations. Thus, the process begins with analysis of a small set of simulations in order to get an initial characterization of the design space. Latin Hypercube Sampling is used to define the initial sets of parameter values. In this process, the initial set of simulations are distributed in the n-dimensional space in such a way to maximize their separation. A consequence of this arrangement is a minimized average distance between any point in the design space, and one evaluated point. The Kriging Response Surface model will fit these evaluated points, and based upon assumptions for general behavior and range of influence, the model predicts responses in between these points. Predictions will vary from the actual response based on distance from evaluated points, and of course the level of activity in the actual response; this is called predictive error. Based on the response surface's predicted values for the objective, as well as its estimated uncertainty at these locations, the optimization process then assists in choosing design configurations during what is called adaptive sampling, which can be weighted to either eliminate the greatest amount of uncertainty, or find the points of best performance. The last phase is to select one or more specific points from the design space, which are expected to be the optima, and eliminate any predictive error by simulating these configurations.

This process still offers great flexibility to accommodate various combinations of constraints on time or computational resources. While it may be computationally most efficient to conduct a very small initial characterization and follow this with adaptive sampling sets of 1 configuration each, one may decide it is more desirable to run larger adaptive sampling sets, using parallel processing to reduce the project's calendar time duration.

PART 1: RESULTS

Initial Characterization

The quantity of simulations for the initial characterization was set at 11; parameters and results are outlined in Table 2. This is more than the minimum required points to garner information regarding nonlinearity of the parameter responses in the 5-D space, but given availability of computational resources, a more densely populated initial characterization is helpful in more rapidly guiding adaptive sampling process toward areas of interest.

Table 2. Description of and results for initial characterization.

	Run ID	Top Angle [deg]	Sides Angle [deg]	Bottom Angle [deg]	Length [inches]	Skirt Height [inches]	%Δ AVE CD
Initial Characterization	run01	14.0	14.1	14.5	23.3	8.3	0.0%
	run02	29.7	14.1	13.8	19.0	7.5	1.1%
	run03	23.1	5.3	6.3	30.7	5.8	-4.1%
	run04	19.8	1.6	1.6	27.1	7.8	0.9%
	run05	7.3	11.6	4.2	31.5	7.0	-4.3%
	run06	17.6	11.2	5.1	21.2	5.9	-0.5%
	run07	12.9	8.7	7.8	25.1	6.4	-4.0%
	run08	16.9	5.0	9.9	28.8	5.3	-5.0%
	run09	20.6	3.8	2.8	22.2	6.5	-1.5%
	run10	16.5	3.9	16.7	18.2	8.1	-0.4%
	run11	25.7	12.6	0.7	24.3	7.2	-1.6%