

Characterization of Aerodynamic Design Spaces for Adjustable Tractor Surfaces

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ABSTRACT

Trailer positioning plays a significant role in the overall aerodynamics of a tractor-trailer combination and varies widely depending on configuration and intended use. In order to minimize aerodynamic drag over a range of trailer positions, adjustable aerodynamic devices may be utilized. For maximum benefit, it is necessary to determine the optimal position of the aerodynamic device for each trailer position. This may be achieved by characterizing a two-dimensional design space consisting of trailer height and tractor-trailer gap length, with aerodynamic drag as the response. CFD simulations carried out using a Lattice-Boltzmann based method were coupled with modeFRONTIER for the creation of multiple Kriging Response Surfaces. Simulations were carried out in multiple phases, allowing for the generation of intermediate response surfaces to estimate predictive error and track response surface convergence. These response surfaces were employed to generate an optimal positioning map for the given aerodynamic device. This methodology was further refined by obtaining positioning maps for multiple tractor configurations.

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INTRODUCTION

Aerodynamic drag reduction on class 8 combination vehicles is a topic of considerable interest as a rising demand for a reduction in fuel consumption is driven by environmental and cost considerations. A 25% reduction in aerodynamic drag results in a 10-15% reduction in fuel consumption for steady travel at highway speeds [1]. Of particular interest is the tractor-trailer gap, which has a significant impact on the overall aerodynamic performance of a class 8 truck.

Many components may be utilized to impact the flow around the tractor-trailer gap region in order to reduce aerodynamic drag. Computation and scale model testing has demonstrated a significant drag reduction by the addition of side extenders and roof extensions [2, 3], and a 3-5% drag reduction by varying side extender length and shape [4]. However, these devices are usually optimized for a specific tractor-trailer gap length and trailer height, and will often show less benefit at larger tractor-trailer gap lengths and trailer heights. In SAE J1321 fuel consumption tests [5] a 10 in. gap increase resulted in a 1.5% increase in fuel consumption, while a gap decrease of 14 in. resulted in a 1.8% decrease in fuel consumption. Similar results have been found for CFD simulations [6].

While reducing the tractor-trailer gap will result in a clear reduction in fuel consumption [6], this is not feasible or possible for all applications. Concerns such as vehicle loading, trailer swing criteria, vehicle weight distribution, packaging of chassis components, and

owner preference will often limit the possible or desired gap reduction. Additionally, variations in both the tractor cab and trailer heights may impact the efficacy of aerodynamic components. The height difference between the trailing edge of the tractor cab and the leading edge of the trailer may vary based on tire diameter, weight, suspension geometry, chassis height, container height, fifth wheel, and other considerations.

Adjustable tractor-mounted aerodynamic devices offer a chance to reduce fuel consumption for a wide range of trailer heights and tractor-trailer gap lengths. As an example, adjustable roof fairings have been demonstrated to provide higher drag reduction for a wide variety of trailer heights [7]. The length, angle, and shapes of the aerodynamic devices which will provide the greatest drag reduction will vary with tractor-trailer gap length. As a result, adjustable devices may offer a solution for a wider range of tractor-trailer heights and gap lengths.

To maximize the benefit of an adjustable device the design space should include the device geometry, device position, and the range of potential vehicle geometry and settings. This can be achieved through the characterization of aerodynamic drag across a suitable design space that spans the complete range of parameters for both the aerodynamic device and the vehicle. This allows for the creation of an aerodynamic performance map for the aerodynamic device that identifies the shape and orientation of the device in the design space.

Optimization studies commonly focus on modifying various vehicle parameters in order to minimize or maximize one or more target variables such as aerodynamic drag, engine cooling airflow or aeroacoustic noise. Examples of such studies include a combined aerodynamic and engine cooling performance optimization on a medium duty truck [8], the early stage aerodynamic optimization of an SUV [9] and a combined aerodynamic and self-soiling optimization on a small van [10]. The typical result obtained from such studies is a particular set of input parameters within the given design space, at which vehicle performance is optimized.

This is in contrast to the current study, which is centered on the characterization of a given design space, for similar vehicle configurations. The end result is a map, indicating the optimal vehicle configuration at any point within the given design space. The main purpose of the paper is to present a characterization method for arbitrary tractor geometry, and then provide some examples of the method in-use from drag coefficient values to the positioning map.

This paper will first present a method for the characterization of the optimal positioning of a generic aerodynamic drag reduction device. Then, it will present an example component, and describe the details of the characterization study performed including the parameter variation, simulation method, and operating conditions. Finally, it will present the results for the given method on two different tractor models.

CHARACTERIZATION METHOD

The first step in characterizing the performance of a given adjustable aerodynamic device is determining and suitably parameterizing the design space. This consists of bounding the possible positions for the surrounding vehicle geometry and the aerodynamic device over a continuous range or a discrete set of positions and identifying the various independent parameters needed to completely describe these geometry changes. Aerodynamic drag evaluations are then carried out for each position of the adjustable device, at the minima, maxima, and midpoint of each parameter range. The vehicle drag coefficients from these evaluations are used to create a response surface for each position of the aerodynamic device through the Kriging algorithm, resulting in predicted drag values for all intermediate points in the design space. The Kriging Response Surface model is described in greater detail in [10] and [11].

This distribution of points for drag evaluations spans the entire design space and hence minimizes error in the resultant response surfaces by eliminating the use of extrapolation during response surface creation. The uniform spacing between evaluation points also ensures that each position of the aerodynamic device is evaluated over the same set of trailer positions, preventing biasing in the response surface. A sample distribution is shown in Figure 1 for a design space consisting of two independent parameters.

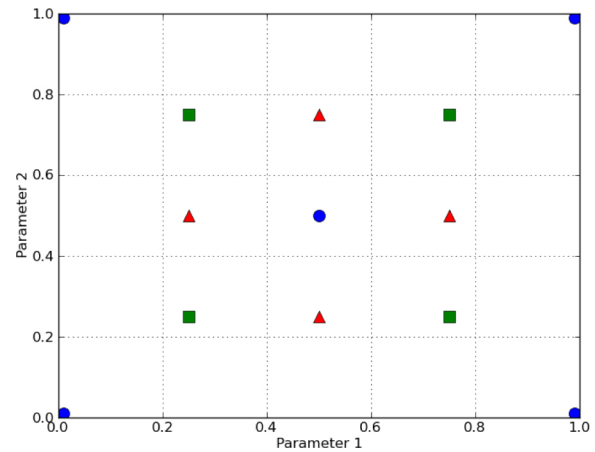


Figure 1. A sample evaluation distribution map for a two parameter design space with blue circles representing the initial batch of evaluations, green squares representing a possible second set and red triangles indicating a potential third set of uniformly spaced evaluations.

Further aerodynamic drag evaluations are then carried out for each position of the adjustable device at trailer positions corresponding to the midpoints between the center of the design space and each extreme bound. These added evaluations serve to refine the response surface by increasing the number of interpolation points for the Kriging algorithm, while continuing to maintain uniform spacing between points. Such a distribution can be readily extended to any number of independent parameters. An example using three parameters is shown in Figure 2.

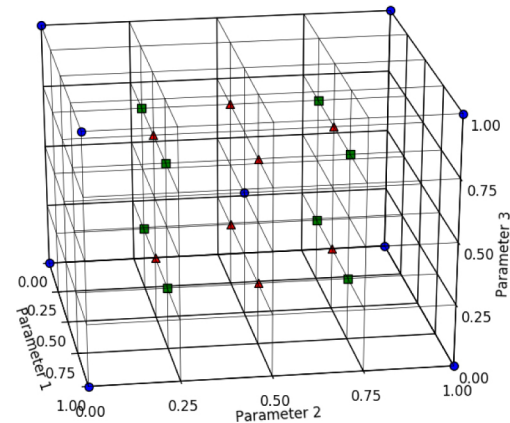


Figure 2. A sample evaluation distribution map for a three parameter design space with blue circles representing the initial batch of evaluations, green squares representing a possible second set and red triangles indicating a potential third set of uniformly spaced evaluations.

The convergence of the response surfaces as more aerodynamic drag data is added is tracked by calculating the mean absolute error of the response surfaces at various intermediate stages. The mean absolute error of a response surface is defined as the actual average value of the difference between calculated and predicted drag at the corresponding location in the design space [12]. This recursive bisection process is repeated at successive positions corresponding to the midpoints between previous positions. This may be repeated, each successive iteration refining the response surface, until the desired resolution is achieved.

The resolution of the final, refined response surfaces can be verified by carrying out drag evaluations at additional points within the design space for each position of the aerodynamic device and comparing the resultant drag coefficient with that predicted by the corresponding response surfaces.

The resultant refined response surfaces are then intersected with each other to yield the final aerodynamic performance map for the adjustable device. This map indicates the position of the adjustable device that reduces the aerodynamic drag for any given value of trailer height and tractor-trailer gap length within the previously established bounds for the specified operational vehicle condition.

Tractor mounted aerodynamic devices primarily reduce drag by deflecting the airflow as it leaves the tractor to create smoother flow above and around the tractor-trailer gap. These changes in the airflow propagate down the length of the trailer and can interact with trailer mounted aerodynamic devices. They can also influence the low pressure wake region created by the trailer through interaction with underbody airflow and hence affect trailer base pressure drag. These effects have been observed in multiple studies as seen in [13, 14]. Aerodynamic drag evaluations for tractor mounted adjustable devices may benefit from utilizing front drag values to create the various response surfaces. The front drag is defined as the cumulative drag on the vehicle from the front of the tractor to the midpoint of the trailer.

DETAILS OF EXAMPLE IMPLEMENTATION

Adjustable Roof Extension

The parameterization method was applied to a specific case on two different class 8 tractor-trailer configurations. The aerodynamic device investigated is an aerodynamic trim tab concept. The tab concept, depicted in figure 3, is designed to guide the flow leaving the trailing edge of the tractor roof as it transitions to the top of the trailer. The tab concept is depicted in US Patent 6991281 [15]. The extension is mounted at the rear of the roof of the vehicle, and can be adjusted into various positions. A decal is utilized to instruct the operator of the optimal trim tab positioning (Figure 4) [16].

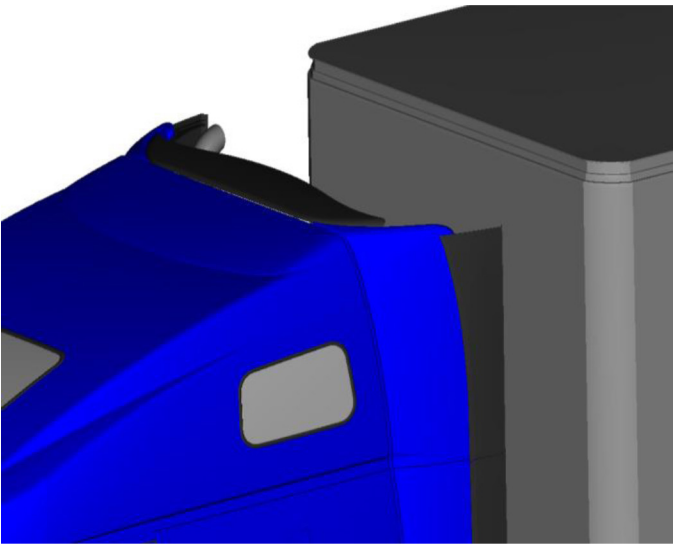


Figure 3. Image of the installed aerodynamic trim tab device.

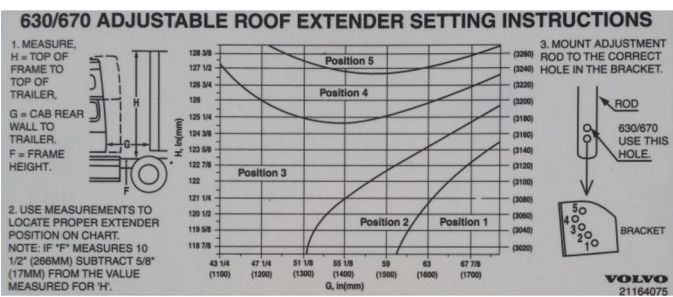


Figure 4. Image of the Volvo VNL670 adjustable roof extender (trim tab) positioning decal [16].

Parameter Description/Range

The trim tab positioning study has three parameters as noted in Table 1, and evaluates their impact on the front drag. There are five discrete trim tab positions in order of increasing height as noted in Table 2, which are defined by which bracket hole the trim tab rod is attached to (see Figure 4). The second parameter is the length of the tractor-trailer gap, measured from the maximum x-position of the tractor cab rear wall to the front surface of the trailer. The final parameter is the height of the leading edge of the trailer from the top of the frame-rail

Table 1. Parameter description and ranges for the trim tab positioning study.

Parameter Description	Parameter Range
Trim Tab Position	1, 2, 3, 4, and 5
Tractor-Trailer Gap	44.00 in. → 64.00 in.
Trailer Front Height Above Frame Rail	118.50 in. → 128.75 in.

Table 2. Trim tab trailing edge center vertical height difference as a percentage of the total difference between position one and position five.

Trim Tab Position	Percent of Total Height Difference Between Position 1 and Position 5
1	0
2	25 %
3	50 %
4	75 %
5	100 %

Analysis Approach

The vehicle drag coefficient values are obtained through computational simulations conducted using PowerFLOW [17], a Lattice-Boltzmann-based simulation tool. Full descriptions of the numerical processes have been given previously by Heineke, Beedy, Horrigan, and Sengupta [18]. The simulation setup is consistent with the SAE International surface vehicle recommended practice J2966 [19] to approximate on-road conditions. The full-scale model with a fully detailed under hood and underbody is simulated with a computational domain with less than 1% blockage, with frictionless boundary conditions on the ceiling and the walls. The floor is modeled with a no-slip boundary condition moving with a speed equivalent to the free-stream velocity of 65 mph. The vehicle is situated at a 4.5 degree yaw angle. The trailer is a generic 53' dry van trailer. The trailer tires have a rotating boundary condition consistent with a