

Operationally-Practical & Aerodynamically-Robust Heavy Truck Trailer Drag Reduction Technology

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ABSTRACT

A set of five operationally-practical aerodynamic drag reduction devices have been developed for application to the trailer of a tractor-trailer vehicle. The devices have undergone extensive aerodynamic analysis, wind tunnel evaluation, fuel economy assessment and operational testing where they have amassed over 100,000 miles of use. These technologies provide a combined fuel savings of 10% at an average speed of 55 mph. This improvement in fuel economy correlates to an equivalent drag reduction of approximately 25%. Observations and anecdotal evidence from the test activity have shown that the addition of these devices to the trailers has not had a negative impact on operational utility or maintenance procedures and requirements.

INTRODUCTION

The rising cost of fuel is placing a heavy burden on the freight industry where present expenditures for fuel has become the number one operational cost for the industry. Our economy is dependent upon the heavy truck freight industry to move more than 75% of all goods in United States as a result the rising fuel costs are being felt throughout our economy and affecting all of the nations citizens. Immediate action is required to address both the immediate operational cost needs of the freight industry and the long term concerns related to our nations energy, environmental, and economic security (E3S). One technology that is uniquely poised to have an immediate and significant impact in reducing fuel use is the area of ground vehicle aerodynamics. Numerous studies have shown that the application of proven aerodynamic principles to the heavy truck-trailer vehicle can provide up to twenty percent improvement in fuel economy. To achieve both the immediate success urgently needed by the freight industry as well as the long term demands related to the nations E3S demands the aerodynamic solutions must be operationally practical, aerodynamically robust, and satisfy all safety requirements and concerns of the public. It is within this context that the subject study has been conducted.

The primary resistance forces for heavy trucks are drive-train losses, rolling friction, and aerodynamic drag, [1, 2, 3]. However, the rate of increase in aerodynamic drag with increasing vehicle speed is much greater than that for rolling friction such that at approximately 50 mph the force to overcome aerodynamic drag exceeds that required to overcome rolling resistance. The typical design effort has not take into account operational and environmental factors, such as wind disturbances from traffic and weather, that can dominate the aerodynamic drag of tractor-trailer trucks [4, 5, 6, 7] and increase the aerodynamic loading on a vehicle, compared to the ideal case. There are also a number of geometric factors that influence the aerodynamics of tractor-trailer trucks such as flow field in the gap region between the tractor and trailer [8]. The review showed that under ideal conditions a tractor-trailer has a drag coefficient between 0.6 and 0.7 whereas a tractor-trailer truck that does not have aerodynamic shaping and fairings will have a drag coefficient of 0.7 to 0.9.

A review of heavy truck aerodynamics design over the past 20 to 30 years [1, 3, 4, 7 - 9 - 18] show that the trucking community has focused on reducing the aerodynamic drag of the forward facing surfaces of both the tractor and trailer. These efforts have produced reductions in the aerodynamic drag of 30%, for an operating speed of 60 mph, with corresponding improvements in fuel economy approaching 15%. However these improvements have not been consistently realized under operational conditions for the reasons mentioned previously [3, 4, 7, 12, 14, 19, 20, 21]. In an operational environment the unsteady and erratic flow that the vehicle experiences degrades the effectiveness of these aerodynamic devices. An assessment of the aerodynamic drag in an operational environment indicates that the reduction in aerodynamic drag at 60 mph would be closer to 20%, which corresponds to a 10% improvement in fuel economy.

DISCUSSION

The technical challenge of drag reduction requires an understanding of the distribution of the drag between the tractor and trailer, see figure 1. The data used to identify the drag hot spots depicted in figure 1 were obtained from a review of the data contained in references, 2 - 4, 7, 8, 12, 14, 15, and 17 -19. These data show the relative magnitude of the aerodynamic drag force on a tractor-trailer truck under ideal wind conditions. The schematic show that the dominant drag regions on a tractor-trailer truck are the tractor front face, the gap region, the undercarriage, and the trailer base. An audit of the drag on a tractor-trailer truck, with an aerodynamic tractor operating under ideal conditions, indicates that approximately 25% of the aerodynamic drag is attributed to the tractor and 75% is attributed to the trailer. However, during on-road operations the benefit of the tractor mounted aerodynamic fairing devices are not fully realized due to a variety of factors, most notably crosswind effects.

All of the factors discussed above as well as numerous other issues should be viewed as constraints in the design of aerodynamic technologies that are directed at improving the fuel economy of tractor-trailer trucks. Additionally, design activities directed at improving the fuel efficiency of these vehicles must address vehicle operations, maintenance, safety, weight, and cost. Other vehicle performance factors that must also be addressed are aerodynamic loads, stability and handling, braking, splash and spray, and tire wear [2 - 7, 12, 19, 20].

AERODYNAMIC DESIGN

The objective of the present activity is to design, develop, and demonstrate aerodynamic devices that would improve the fuel economy of tractor-trailer vehicles under operational conditions. A further objective was to develop novel technologies and concepts that would address many of the limitations associated with existing devices on the market. The design activity was initiated with an extensive literature review to determine the target vehicle type for the study and to identify the numerous devices and technologies that have been previously developed, see figure 2. Based upon this initial review the heavy truck with van trailer was selected as the baseline vehicle. It was also determined that the technology development process should consider the design requirements for other trailer types such as tank and flat bed.

To ensure relevance of the design activity vehicle operations, maintenance, safety, weight, and cost would be primary constraints in the design. Additional vehicle performance factors addressed in the design activity were aerodynamic loads, stability and handling, braking, splash and spray, and tire wear.

A primary objective of the design activity was to develop a suite of technologies that would work together to not only increase fuel economy but to also improve vehicle safety. Shown in figure 2 are the three selected trailer target areas for the design activity and the individual drag reduction goals for each target area is set at 5%. The design target areas are the gap region (includes tractor base area and trailer front face), the trailer base area, and the trailer undercarriage. To achieve the fuel economy goal, the aerodynamic drag of the vehicle would have to be reduced 30% at 60 mph. This drag reduction goal corresponds to a reduction in the tractor-trailer truck drag coefficient from 0.70 to a value of 0.50.

Design Approach

A knowledge based [25] design approach was used in which existing data sets were analyzed, computational fluid dynamic (CFD) analysis was conducted, wind tunnel testing was performed, operational on-road testing and on-road fuel economy testing was executed in accordance with industry standards. The first phase of the design approach relied upon existing published data and the experience and knowledge of the author. A few noteworthy publications; the work on trapped vortices [26 - 30], the work on boat tails [11, 14, 15, 31 - 35], the work on gap flows [10, 16, 36], the computational analysis detailing flow fields [20, 36 - 39], and reports providing design guidelines [3, 13, 14, 17, 18, 40]. This analysis identified several opportunities to explore the application of vortex flow technologies to the gap, undercarriage, and base areas of the vehicle.

The knowledge based design effort generated numerous simple, fixed geometry devices that did not interfere with the operation and maintenance of the vehicles. Feedback from equipment manufacturers, fleets and owner-operator of the tractor-trailer vehicles was considered on a variety of issues including vehicle operations, maintenance, safety, weight, cost, aerodynamic loads, stability and handling, braking, splash and spray, and tire wear. Based upon the analysis and industry feedback five devices were selected for further development and testing. The selected devices were; vortex trap (VT), mini-skirt (MS), vortex strake (VS), wake board (WB), and frame extension (FX). The VT device mounts to the trailer front face to reduce gap drag. The MS devices mounts to the trailer underside to reduce undercarriage drag and drag of the trailer rear wheel/bogie system. To reduce base drag three devices were developed; VS, WB, and FX. The VS device mounts to the trailer side and top surfaces and can be used on either a rollup door or swing door trailer. The WB and FX devices mount to the trailer base where the WB devices is designed for swing door trailers and the FX devices is designed for roll-up door trailers. An expanded description of each device is provided in the following five sections.

Gap: Vortex Trap Device

The vortex trap (VT) device was developed to reduce aerodynamic drag associated with flow in the gap region, for both no crosswind and crosswind flow conditions. Depicted in figure 3 is a sketch of a six surface VT installed on the front face of a trailer.

The VT consists of equally spaced, vertically aligned, and adjacent planar surfaces. Each surface of the VT extends forward perpendicular from the front face of trailer. Each planar surface extends vertically over a substantial height of the trailer front face. The leading edge of the forward projected surfaces are aerodynamically sharp to ensure that the gap flow will separate at the leading edge of each adjacent surface and generate a vortex that is trapped between adjacent surfaces comprising the VT. Each trapped vortex imparts a low pressure on the forward facing surface of the trailer.

Undercarriage: Mini-Skirt Device

The mini-skirt (MS) device was developed to provide a large ground clearance without sacrificing drag reduction of the trailer undercarriage, rear bogie, and rear wheel set. Shown in figure 4 is a sketch of the MS device. The MS is a two panel skirt device that mounts to the trailer undercarriage. The device is located laterally near the two outside edges of the trailer and positioned longitudinally between the trailer rear wheels and the landing gear. The two-panel design makes use of vortex flow and upwash flow to control and capture flow entering the undercarriage of a trailer. The outer panel generates a vortex that turns the incoming flow upward where the inner panel captures the vortex induced upwash field and redirects the captured flow streamwise. Compared to flow blocking based single panel skirts, the flow control employed by the two panel MS device allows for greater ground clearance without a loss in drag reduction performance.

Base: Devices

The wake flow behind a tractor-trailer truck is comprised of multiple eddys that vary in direction of rotation. These rotational structures result from the low energy flow passing along the sides and top of the trailer that separates at the trailing edge of the trailer and spills into the trailer base area. This base area flow interacts with the low energy flow exiting from under the trailer resulting in an even greater unsteady flow environment. The technical challenge is to control the massively separated and unsteady wake behind the bluff base area. In addition, the base drag reduction concepts must be applicable to a variety of base door types (e.g. roll-up and swing open).

To improve the base flow characteristics and reduce the aerodynamic drag of a trailer three aerodynamic devices were designed and tested.

Base: Vortex Strake Device

The first of the three devices is the Vortex Strake (VS). As shown in figure 5, the VS is attached to or integrated into the side and top surfaces of the trailer near the vehicle trailing edge. The VS consists of multiple, equally spaced and aligned, adjacent planar panels on each side of the trailer and four duplicate panels were located on the top surface of the trailer.

The VS generates a limited number of large vortex structures on the side and top exterior surfaces of a trailer. These vortex structures energize the flow exiting the trailing edge of the side and top exterior surfaces of the trailer, thereby increasing the ability of the flow on the trailer side and trailer top exterior surfaces to expand into the base region and provide drag reduction, increased fuel economy and improved operational performance. The result is a stable bluff-base wake flow and a high pressure that acts on the base surface of the trailer. The strength of the vortices formed by the VS and thus the aerodynamic drag reduction benefit, increase with increasing flow velocity.

Base: Wake Board Device

Shown in figure 6 is a sketch of the wake board (WB) device. The WB device was developed to reduce the base drag of swing door trailers while satisfying the operational needs of the industry. The WB consists of a vertical panel located laterally near the outside edge of each rear swing door. Each panel of the WB device extends vertically over the height of each door and extends aft perpendicularly from the door surface.

Aerodynamic drag reduction is accomplished by the creation of a virtual boattail surface. The virtual boattail results from the capture of the low energy boundary layer flow in the aft facing step defined by the corner region between the WB panel outward facing surface and the portion of the rear door surface outboard of the WB panel. This captured boundary layer evolves into a trapped vortex structure that forms the virtual boattail surface.

Base: Frame Extension Device

Shown in figure 7 is a sketch of the frame extension (FX) device. The FX device was developed to reduce the base drag of rollup door trailers while satisfying the operational needs of the industry. The FX attaches to the trailer base and consists of a vertical panel located laterally near each outside edge of the trailer, a vertical panel located near the top edge of the trailer and a lower structural surface that is in plane with the floor of the trailer. Each of the two vertical panels of the FX device extends vertically over the height of the trailer base and extends aft perpendicularly from the trailer base surface.

The top and bottom panels of the FX device extend horizontally over the width of the trailer base and extend aft perpendicularly from the trailer base surface.

Aerodynamic drag reduction is accomplished by the creation of a virtual boattail surface. The virtual boattail results from the capture of the low energy boundary layer flow in the aft facing step defined by the corner region between the FX side and top panel outward facing surface and the portion of the rear base surface outboard and above of the side and top FX panels, respectively. This captured boundary layer evolves into a trapped vortex structure that forms the virtual boattail surface

AERODYNAMIC ASSESSMENT

Multiple aerodynamic assessment methods were employed to refine the aerodynamic and operational performance of each device. These methods include operational testing (OPT), computational fluid dynamics (CFD), wind tunnel testing (WTT), and fuel economy testing (FET) as described below.

Operational Testing (OPT)

The OPT activity had two objectives; 1) to obtain fuel economy data and 2) to collect operational and maintenance information. At the time of the OPT activity only the VT and VS devices were available for evaluation.

To obtain a statistically significant body of data the operational testing occurred over a two year period. The tractors used were late model International [22] tractors with moderate aerodynamic shaping consisting of roof mounted aerodynamic fairings and side fairings. The gap dimension was approximately 40.0 inches. The trailers were 53 foot roll-up door Great Dane [23] models Operational fuel economy data was obtained with the Cummins Engine INSITE Professional - CELECT Plus data acquisition and analysis system [24]. The baseline and experimental trailers were alternately pulled by the same tractor. Each of the baseline and experimental trailer pairs were pulled over similar routes. Each tractor received fuel from the same fuel supply and used the same fuel fill procedures. To minimize the affect of tires each tractor and had similar tire types and tread depth.

Listed below is a summary of the data obtained.

Total Trips	232
Total Miles	253600
Baseline Trailer Trips	135
Baseline Trailer Miles	143207
Experimental Trailer Trips	97
Experimental Trailer Miles	110393
Available Trips	155
Available Miles	182494
Baseline Trailer Trips	86
Baseline Trailer Miles	97165
Baseline Trailer Avg. Speed	47.8
Experimental Trailer Trips	69
Experimental Trailer Miles	85329
Experimental Trailer Avg. Speed	47.4

The average speed of each data set was approximately 47.5 miles per hour.

A summary of the operational data is presented in figure 8 for five separate averaging schemes. The fuel economy improvement values presented are; arithmetic mean average, average based upon tractor, average based upon tractor and weighted by miles, average based upon temperature, and average based upon temperature weighted by miles. The purpose of weighting the data by miles is to ensure that a low mileage data point did not have equal weight as a high mileage data point. Note, the figure shows positive increases in fuel economy for all averaging approaches. The data show that the VT has the largest fuel economy improvement followed by the VS. The combined increase in fuel economy for the VT and VS devices varied from 5% to 12%.

Anecdotal information collected during the two year operational testing indicated that the VT and VS devices did not impact operations or add maintenance to the vehicle. This information provided a validation of the design approach and helped guide the refinement of all five devices to ensure that they were operational practical and aerodynamically robust.

Computational Fluid Dynamics (CFD)

Drawing on the initial success and lessons learned from the OPT activity the design process was directed at refining the aerodynamic performance of the five devices. The initial design efforts made use of CFD analysis to improve the understanding of the vehicle aerodynamic and fluid dynamic characteristics. The CFD analysis effort was also used to design the wind tunnel test heavy truck model and to select the design variables for each of the five devices.