A DISCUSSION OF A HEAVY TRUCK ADVANCED AERODYNAMIC TRAILER SYSTEM

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ABSTRACT

Four simple, low cost aerodynamic drag reduction devices have been developed for application to the trailer of a tractor-trailer truck. Two vortex flow devices have undergone extensive operational fleet testing where they have amassed over 85,000 miles of use. These two vortex flow technologies have shown a combined fuel savings of 8% at an average speed of 47.5 mph. This improvement in fuel economy correlates to an equivalent drag reduction of approximately 20% with a corresponding drag coefficient of 0.45. 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 either the operational utility of the trailers or the maintenance procedures and requirements. Two base mounted devices have been developed to reduce the base drag of trailers. The two base devices have been developed through computational design and wind tunnel testing. Each of these two base mounted devices have been shown to reduce the drag of heavy trucks by more than 8%, which equates to a 4% fuel savings at highway speeds. The estimated combined fuel savings of the vortex flow and base devices is greater than 12%.

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INTRODUCTION

To curb the impact of rising fuel costs the nations heavy truck community is exploring a number of advanced technologies that include aerodynamic drag reduction for both the tractor and the trailer. An assessment of on-road heavy truck energy consumption, for still air conditions, shows that the primary energy loses are due to drive-train, rolling friction, and aerodynamic drag, Hucho, 1988. It is well documented that as vehicle speed is increased the force required to overcome both aerodynamic drag and rolling friction increase, however, the rate of increase in aerodynamic drag with increasing vehicle speed is much greater than that for rolling friction such that at speeds greater than 45 miles per hour aerodynamic drag is the dominant resistance force. The importance of aerodynamics on heavy truck fuel economy is further highlighted by the work of Tyrrell in 1987 that showed operational and environmental factors act to further increase the impact of aerodynamics on heavy truck fuel economy resulting in aerodynamic drag becoming the dominant resistance force for these class of vehicles. These operational and environmental concerns include factors such as vehicle interference, atmospheric effects, and road conditions that must be addressed when developing aerodynamic based fuel economy improvement technologies for heavy vehicles. It is estimated that application of existing aerodynamic innovations to the tractor and trailer will increase the fuel economy by 20 percent. The heavy truck community has been slow to adopt the existing innovations due to their concerns related to operations and maintenance that is driven by device complexity, weight and cost.

DISCUSSION

To understand the technical challenge and economic payoff offered by aerodynamic drag reduction, it is important to understand the distribution of the drag between the tractor and trailer, see figure 1. The data used to develop the drag distributions depicted in figure 1 were obtained from a review of the available historical data, as represented by the data contained in reports by Drollinger, 1987 and Sovran, 1978. The schematic of figure 1 depict the dominant drag regions on a tractor-trailer truck are the tractor front face, tractor-trailer gap, undercarriage/wheels, and trailer base. The data show that under representative operational conditions a crosswind is present and the distribution of aerodynamic drag between the tractor and trailer is 35% tractor and 65% trailer. The drag of the trailer can be further qualified as having equal parts trailer front face drag, trailer base drag, and trailer undercarriage/wheel drag. To address the needs of the trucking community it is critical that aerodynamic drag reduction efforts address vehicle operations, maintenance, safety, weight, cost, stability and handling, braking, splash and spray, and tire wear, Barnard, 1986.

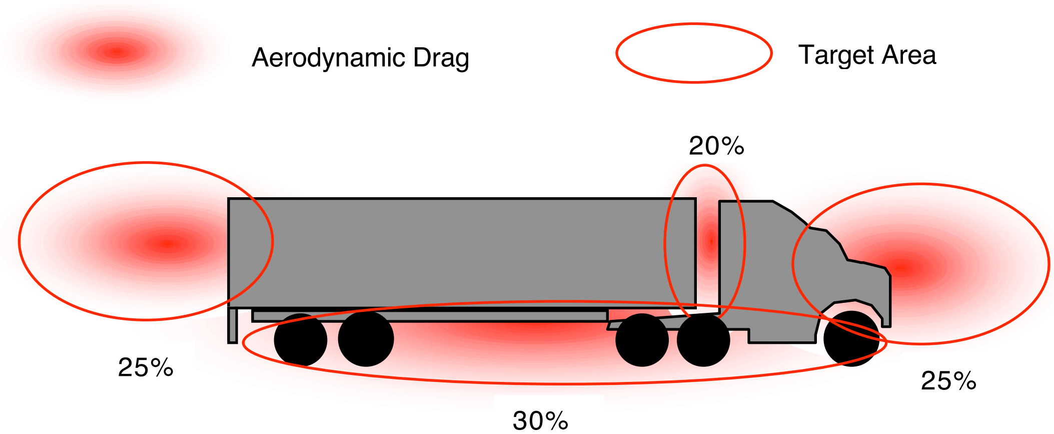


Figure 1. Graphic depicting the distribution of aerodynamic drag for a heavy vehicle tractor-trailer truck.

The following discussion will present results for an ongoing advanced aerodynamic trailer design activity. The first phase of the effort was initiated in 2002 and was directed at gap and base flow management through the use of vortex flows. Realizing the importance of operational and maintenance concerns to the trucking community this first phase employed operational testing for evaluation of device performance. The second phase of the study was launched in 2004 and has taken a more traditional aerodynamic design approach utilizing computational fluid dynamics and wind tunnel testing to develop the drag reduction technologies. This second phase of the study has focused on base drag reduction. A third phase has been initiated to investigate undercarriage flows. Results for all three phases will be discussed.

Phase I Aerodynamic Design

The objective was to design, develop, and demonstrate aerodynamic devices that improve the fuel economy of tractor-trailer trucks under operational conditions. To ensure the relevance of the innovations it was recognized that vehicle operations, maintenance, safety, weight, and cost must be primary constraints in the design process. A controlling factor in the design activity was the fact that experimental validation would be performed in the context of normal fleet operations which required testing to occur over an extended period of time and under diverse operational conditions. For this operational based test approach fuel economy replaced aerodynamic drag as the figure of merit. The operational testing of the devices also required statistical analysis of the engine performance data to ensure an accurate assessment of the benefit of the aerodynamic device. All of these factors required that the tested devices be designed to perform over a broad range of environmental and operational conditions and the devices could not interfere with fleet operations or require additional maintenance. The tractor-trailer trucks employed in this activity were late model International day cabs with moderate aerodynamic shaping consisting of roof mounted aerodynamic deflectors and side fairings to control the gap flow and the flow over the trailer. The gap dimension was approximately 40.0 inches. The trailers were Great Dane models that were identical in length, height, and width and had roll-up doors on the base. The operational data were obtained with the Cummins Engine INSITE Professional - CELECT Plus data acquisition and analysis system. Because aerodynamic drag reduction could not be quantified, the goal for the Phase I activity was defined as a 15% increase in fuel economy at 60 mph.

The target areas selected for the design activity are the gap region (includes tractor base area and trailer front face) and the trailer base area. 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.

Phase I Design Approach

The aerodynamic design activity produced a number of simple, fixed-geometry, add-on concepts to meet the technical goals established for the activity. These concepts were reviewed with the fleet owner in which a variety of issues were discussed including vehicle operations, maintenance, safety, weight, cost, aerodynamic loads, stability and handling, braking, splash and spray, and tire wear. Based upon these conversations two vortex flow devices were selected for operational testing; cross flow vortex trap device to reduce gap drag and the vortex strake device to reduce base drag.

Gap -Treatment Design

A typical tractor-trailer truck has a gap between the tractor and trailer to allow for articulation of the vehicle during normal operations. As shown in figure 2 the gap allows high velocity air to impact the front face of the trailer resulting in aerodynamic drag. A depiction of the gap flow streamlines present for in the present of crosswind are shown in figure 2.

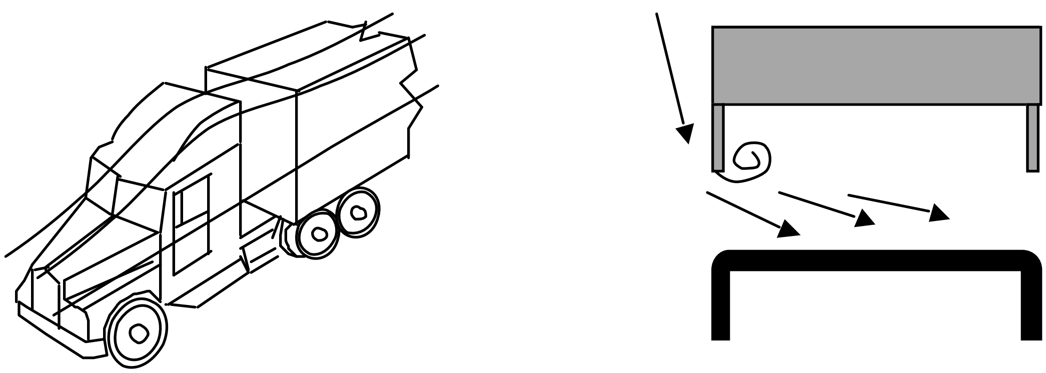


Figure 2. Graphic depicting the gap region and gap flow fields for a typical tractor-trailer truck

This inward turning flow impinges on the trailer front face resulting in an increase in pressure on the trailer front face and subsequent increase in aerodynamic drag. The presence of crosswind flow will tend to increase the flow volume and velocity that enters the gap region and impinges onto the trailer front face. Another detrimental effect of the crosswind flow entering the gap is the flow separation that occurs on the leeward side of the trailer producing a significant side force on the vehicle that may adversely affect the vehicle handling performance.

The gap flow design principle is based upon trapped vortex technology in which a region on a vehicle is constructed to capture or trap a vortex that is formed when the incident flow encounters an aerodynamically sharp edge. In the present design activity, a vortex-trap device was designed and located on the forward facing front face of the trailer and is termed the Cross-flow Vortex Trap Device (CVTD). The leading edge of the adjacent surfaces comprising the CVTD were made aerodynamically sharp to ensure the gap cross-flow separates at the CVTD leading edge and generates a vortex that is trapped between adjacent CVTD surfaces. The trapped vortices impart a low pressure on the forward facing surface of the trailer. Shown in figure 3 are a photograph and a sketch of a CVTD installed on the front face of a trailer. The CVTD consists of duplicate, equally spaced, vertically aligned, and adjacent planar surfaces. Each surface of the CVTD extends perpendicular from the surface of the trailer, is 12 inches wide, and extends vertically over a substantial portion of the trailer front face. A sketch of the CVTD induced flow characteristics shows the expected gap flow and CVTD flow characteristics for a minimal, left to right crosswind. As the gap cross flow develops it encounters the leading edge of the furthest windward CVTD surface and separates at the leading edge forming a vortex that is trapped between the furthest windward surface and the adjacent surface, located immediately inboard. The flow separation at the leading edge of the CVTD induces an acceleration of the flow located immediately forward of the CVTD. This induced flow field is accelerated toward the leading edge of the adjacent surface. These flow characteristics are repeated at each subsequent surface, moving from left to right.

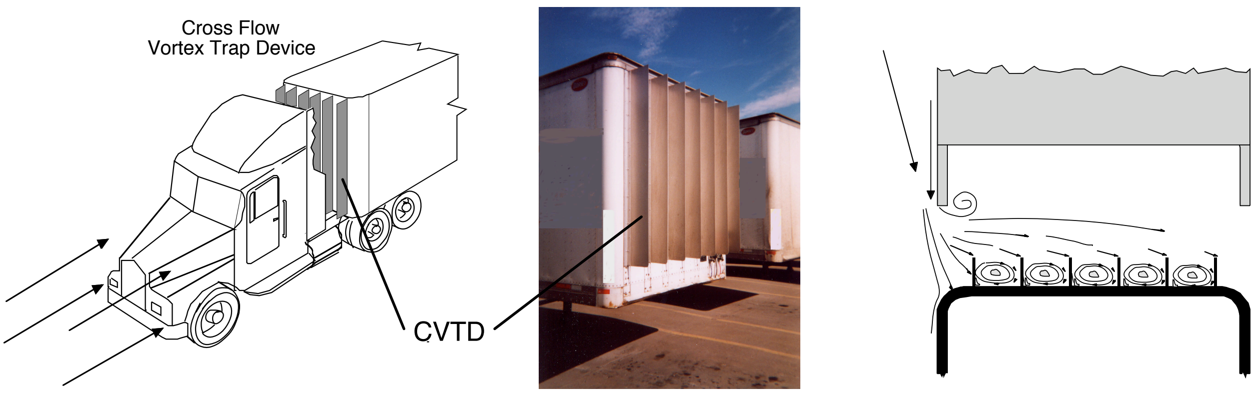


Figure 3. Sketch of the cross flow vortex trap gap treatment device installed on the trailer front face

The velocity of the trapped-vortex is significantly greater than the surrounding flow thereby producing a low pressure on the trailer front face. The pressure loadings on adjacent surfaces of the CVTD are orientated perpendicular to the vehicle axis and thereby they do not contribute the vehicle aerodynamic drag force. The force on the adjacent surfaces are also equal and opposite and do not contribute to the side force on the vehicle. However, the trapped vortices generate low pressures that act on the trailer front face and these pressures generate a force that is aligned with the vehicle longitudinal axis resulting in reduced drag.

Trailer Base Design

Heavy truck trailers come in a variety of types and designs with the most common type trailer being described as a van type which is designed to be light weight load carrying container that is fitted with rear doors to provide efficient loading and unloading of freight. As a result of these operational dominant design requirements the trailer has a very poor aerodynamic shape that may be characterized as a bluff body. The aerodynamic behavior of bluff bodies is dominated by unsteady wake flows that result in high base drag. A graphic of a typical trailer aft end region is shown in figure 4. The aerodynamic design challenge is to control the massively separated and unsteady wake behind the bluff base area in order to reduce the base drag and thereby increase the fuel economy. The schematics of figure 4 show top and side views of the dominant wake flow features behind a tractor-trailer truck.

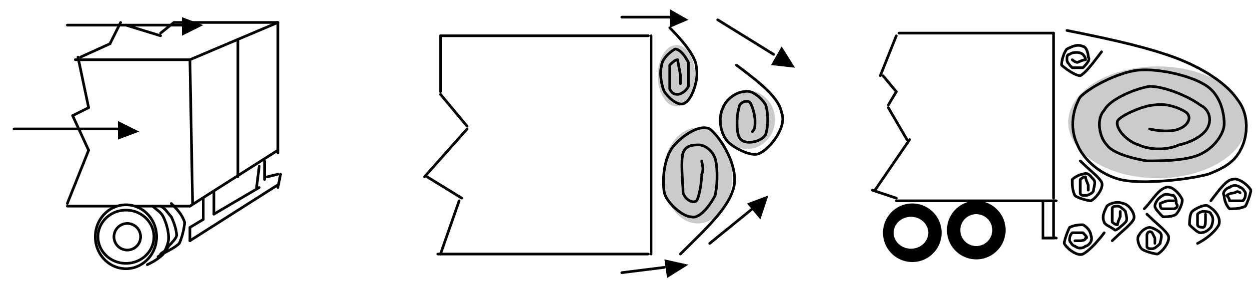


Figure 4. Graphic depicting the trailer bluff base and base flow field of a tractor-trailer truck.

The top view shows that the wake is comprised of different shape and size vortex structures 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. To improve the base flow characteristics and reduce the aerodynamic drag of the vehicle the Vortex Strake Device (VSD) was developed. As shown in figure 5, the VSD is attached to or integrated into the side and top surfaces of the trailer near the vehicle trailing edge. A photograph of the VSD installed on the test trailer is shown in figure 5. The VSD consists of duplicate, equally spaced and aligned, adjacent planar panels on each side of the trailer. In addition, four duplicate panels were located on the top surface of the trailer in a chevron pattern. Each panel, comprising the VSD, was 36 inches long and 2 inches in width. Each VSD panel, on the sides of the vehicle, was inclined 30°, leading edge up. Each VSD panel, on the roof of the vehicle, was inclined 30°, leading edge inboard.

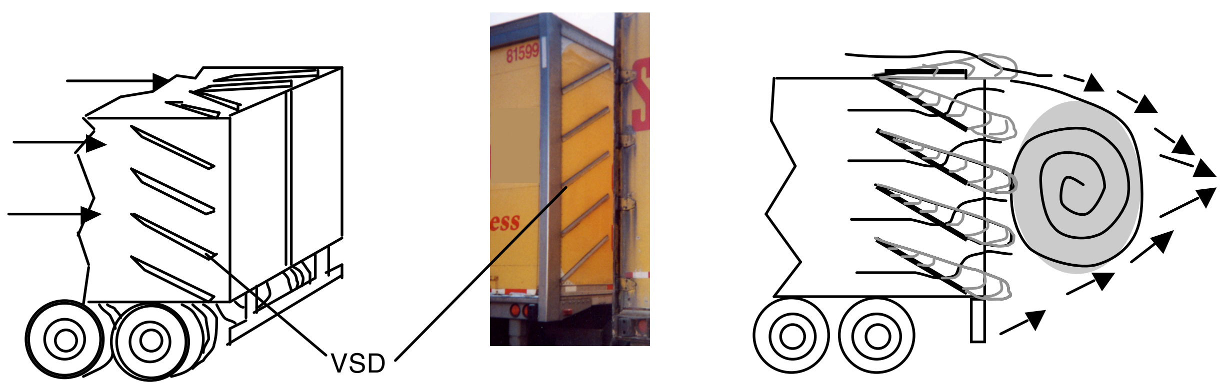


Figure 5. Sketch of the vortex strake trailer base device installed on the aft portion of the trailer

A sketch of the VSD induced flow characteristics are depicted in figure 5. The sketch shows the expected VSD flow characteristics for all free-stream flow conditions. The VSD generates a limited number of large vortex structures on the side and top exterior surfaces of a trailer to energize the flow exiting the trailing edge 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. To maximize the ability of each of the VSD panels to generate a coherent vortex structure, the panels are aligned in planes or surfaces that are perpendicular to the surface of the vehicle. The vortices generated by the VSD are symmetrically orientated about the centerline of the trailer. The subject vortices have a preferred angular velocity and direction that enhances the mixing of the trailer undercarriage flow with the bluff-base wake flow**.** 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 VSD and thus, the aerodynamic drag reduction benefit, increase with increasing flow velocity.

Phase I Operational Testing

The intent of the operational test program was to minimize the large number of factors that influence fuel economy, such as type and geometry of the tractors and trailers, the operational routes, the loads carried by the vehicles, operator behavior, fuel quality, tire quality, rolling friction, and environmental concerns to name a few. Of greater importance to the fleet owner was the impact on operations and maintenance requirements.

The test program included the operation of matching baseline trailer (i.e., no device installed) for each of the experimental trailers. Each of the baseline and experimental trailer pairs were pulled over the same route. Another variable considered in the test activity was the effect that the style/model of the tractor had on the results. The fleet owner had three different style/model tractors that were integrated in to the test activity. However, due to the concern of impacting fleet operation the organization and management of these variables was at the discretion of the fleet owner. The fleet owner minimized fuel related factors by ensuring that each tractor received fuel from the fleet owners fuel supply system and by using the same fuel fill procedures for all test data runs. To minimize the affect of tires the fleet owner ensured that each tractor and trailer involved in the test had similar tire types and tread depth. The collection and delivery of the engine / tractor performance data was the responsibility of the fleet owner. The fleet owner relied upon the Cummins engine INSITE professional CELECT Plus data acquisition and analysis software. The data were to be collected on a daily basis and provided to the engineering team for analysis.

Summary of Operational Testing

Operational performance data have been obtained on tractor-trailer trucks fitted with two aerodynamic drag reduction technologies. The data collection period extended from July 2001 to March 2003. The testing was performed in which duplicate trailers were operated with and without the aerodynamic drag reduction technologies. Each matched set of trailers was operated over a limited number of routes. To evaluate the impact of variation in tractors, each baseline trailer and experimental trailer, comprising the matched set, was pulled by each of the three tractor types operated by the fleet.

Listed below is a summary of the data obtained.

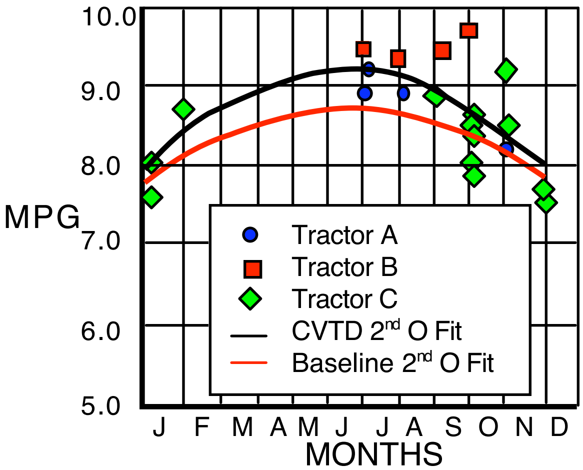
Baseline Trailer Trips	86
Baseline Trailer Miles	97165

Baseline Trailer Avg. Speed	47.8
Experimental Trailer Trips	69
Experimental Trailer Miles	85329
Experimental Trailer Avg. Speed	47.4

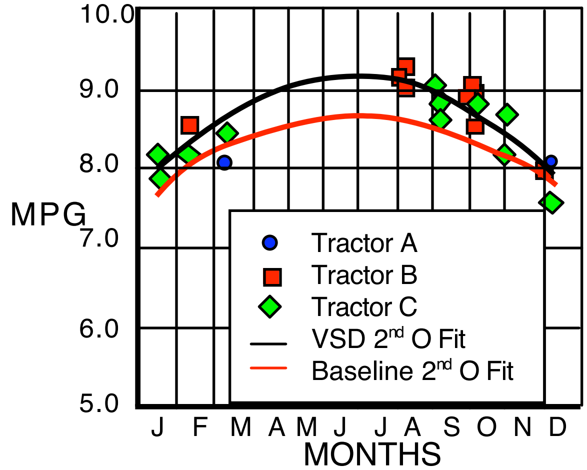
The average speed of each data set was approximately 47.5 miles per hour.

As discussed previously, there are a large number of factors that influence the fuel economy of tractor-trailer trucks. In the present operational test it was recognized that aerodynamics, engine and drive train, environment, tires, and operations may each influence the fuel economy by more than 10%. It was further recognized that it is not possible to control or even document a significant number of these factors. As a result, it was determined that the only means available to account for the known variability in the data was to increase the number of data points by extending the test period. The extended test period resulted in an increase in the influence of environmental factors on the data obtained with the primary affect being the yearly temperature variation. A review of data from the National Oceanographic and Atmospheric Administration (NOAA) revealed that the yearly temperature variation in the geographical location of the truck operations was greater than 50°. It is estimated that the 50° variation in temperature could influence the data by more than 6%.

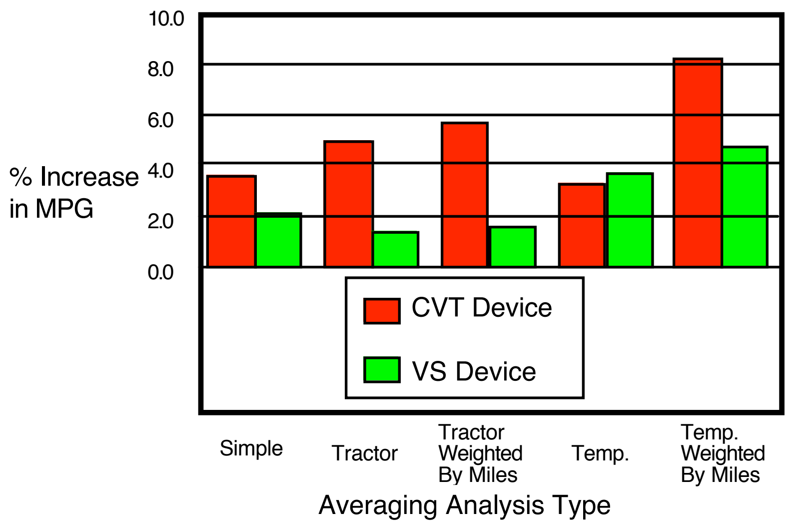
Presented in figure 6 are the operational data obtained for the baseline trailers and the trailers with the two aerodynamic devices installed. The least squares curve fit through the baseline trailer data is presented as the red line in both figures 6a and 6b. The data obtained for the two aerodynamic drag reduction devices are presented in figure 6a and 6b. The fuel economy data of figure 6 is plotted against the month of the year, varying from January to December. As noted previously the average temperature variation in the region of the Untied States where testing was performed was greater than 50°F between winter months and summer months. Also presented in figure 6a and 6b are data for each of the three tractor types used in the test program. A review of the data in figure 6 show that the largest data scatter in a single month, for a given tractor, is less than 10% and the average scatter for a given tractor is less than 5%. The 5% scatter in the data for a single tractor is equivalent to that seen in previously published operational data sets. The data of figure 6 show that the most consistent and largest variation in the data is due to temperature, as indicated by Month. The curve fit of figures 6a and 6b show a consistent 12% variation between winter and summer months. To determine the improvement in fuel economy offered by each device the data of figure 6a and 6b were analyzed and the results are presented in figure 6c. The bar chart of figures 6c reflect a number of analysis results which included; 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. The data of figure 6c show that all averaging schemes show that both devices provide positive improvements in fuel economy with the CVTD varying from 3 to 8 percent and the VSD varying from 1 to 5 percent. Perhaps the most accurate measure of the benefit of each device is determined by the approach which is an average based upon temperature weighted by miles, right side of figure 6c. This analysis would accurately account for the variation in temperature and operational miles associate with a single data point.



a. CVT Device



b. VS Device



c. Percent change in fuel economy

Figure 6. Plot of the trip fuel economy for each drag reduction device as a function of the time of year.

Phase II Aerodynamic Design

Phase II design activities are directed at developing base mounted devices to reduce trailer base drag. A sub-objective of the phase II design effort was to develop simple, low cost devices that would take advantage of the VSD technology to provide significant levels of drag reduction. It is well known the aerodynamic community that the most effective means to reduce the drag of a bluff body is to control the wake flow and increase the base pressures, this is best accomplished by reshaping the base area or by adding devices to the base area that reshape the wake flow. A further objective was to design, develop, and demonstrate aerodynamic devices that improve the fuel economy of tractor-trailer trucks under operational conditions. To ensure the relevance of the innovations it was recognized that vehicle operations, maintenance, safety, weight, and cost must be primary constraints in the design process. All of these factors required that the tested devices be designed to perform over a broad range of environmental and operational conditions and the devices could not interfere with fleet operations or require additional maintenance.

Unlike the phase I effort the phase II study would make use of computational fluid dynamics (CFD) and wind tunnel (WT) testing to evaluate the subject innovations. The tractor-trailer truck model employed in this activity was a 25% scale generic long haul tractor concept with state-of-the-art aerodynamic shaping consisting of a full aerodynamic package to control the gap flow and the flow over the trailer. The gap dimension was approximately 10.0 inches. The trailer model geometry was developed jointly with Great Dane and included detailed representation of the undercarriage and wheels. The Phase II design goal was defined as a 15% reduction in aerodynamic drag at 60 mph. The target area selected for the design activity was the trailer base area.

Phase II Design Approach

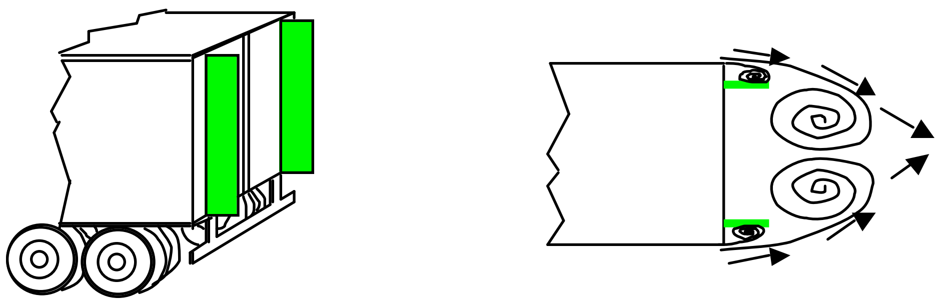
Van type trailers fitted with either swing doors or a roll-up door dominate the U.S. trailer fleet. The focus of this effort was to develop two simple cost effective base-mounted trailer drag reduction innovations that are consistent with both swing and roll-up door type trailers. The aerodynamic design activity focused on developing simple, low-eight, low-cost, fixed-geometry, add-on concepts to meet the technical goals established for the activity. These design criteria for the concepts were reviewed with several fleet owners and trailer manufacturers in which a variety of issues were discussed including vehicle operations, maintenance, safety, weight, cost, aerodynamic loads, stability and handling, braking, splash and spray, and tire wear. Based upon these conversations one swing door concept and one roll-up door concept were selected for wind tunnel testing. The swing door concept is termed the wake board (WB) device and the roll-up door concept is termed the frame extension (FX) device.

WB Design

The challenge was to develop simple, low cost, drag reduction innovation that work with the existing structure and shape of swing door door systems such that the new device would not interfere with normal operations or add maintenance requirements. As discussed previously the aerodynamic design challenge is to control the massively separated and unsteady wake behind the bluff base area in order to reduce the base drag and thereby increase the fuel economy. The trailing wake is comprised of different shape and size vortex structures 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.

To improve the base flow characteristics and reduce the aerodynamic drag of swing door trailers the Wake Board (WB) device was developed. As shown in figure 7, the WB is comprised of two vertical panels that attach to the rear swing doors near the outside edge. The WB consists of two duplicate planar panels on each side of the trailer base where the full scale dimensions of each panel is 100 inches long and 24 inches in width.

A sketch of the WB induced flow characteristics for all free-stream flow conditions are depicted in figure 7. The WB innovation captures the flow exiting the trailing side edge of the trailer and forms a virtual boattail surface thereby increasing the ability of the flow on the trailer side exterior surfaces to expand into the base region thereby resulting in drag reduction, increased fuel economy and improved operational performance. To maximize the ability of each of the WB panels to generate the virtual boattail and to not carry a device drag penalty, the panels are aligned in planes or surfaces that are perpendicular to the surface of the vehicle. The result is a stable bluff-base wake flow and a high pressure that acts on the base surface of the trailer.

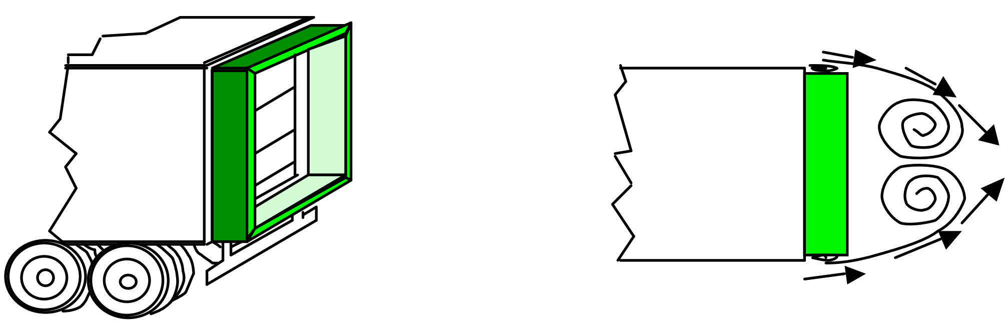


a. Sketch of Wake Board b. Sketch of flow features on Wake Board and in trailer wake

Figure 7. Sketch of Wake Board device and the resulting wake flow characteristics

FX Design

To improve the base flow characteristics and reduce the aerodynamic drag of roll-up door trailers the Frame extension (FX) device was developed. As shown in figure 8, the FX is an aft extension of the existing perimeter door frame. The outer surface of the FX innovation is recessed inward from the trailer side and top surfaces resulting in a small aft facing step at the trailer trailing edge. The FX device extends aft 24 inches, full scale.



a. Sketch of Frame Extension b. Sketch of flow features on Frame Extension and in trailer wake

Figure 8. Sketch of Frame Extension device and the resulting wake flow characteristics

Depicted in figure 8 is a sketch of the FX induced flow characteristics, for all free-stream flow conditions. The FX innovation provides drag reduction, increased fuel economy and improved operational performance by; 1) increasing the depth of the existing minimal depth cavity present on existing roll-up door trailers and 2) capturing the flow exiting the trailing side and top edge surfaces of the trailer and forms a virtual boattail surface thereby increasing the ability of the flow on the trailer side exterior surfaces to expand into the base region. To maximize the ability of the FX to generate the virtual boattail and to not carry a device drag penalty, the four sides are aligned in planes or surfaces that are perpendicular to the surface of the vehicle. The result is a stable bluff-base wake flow and a high pressure that acts on the base surface of the trailer.

Phase II Device Assessment

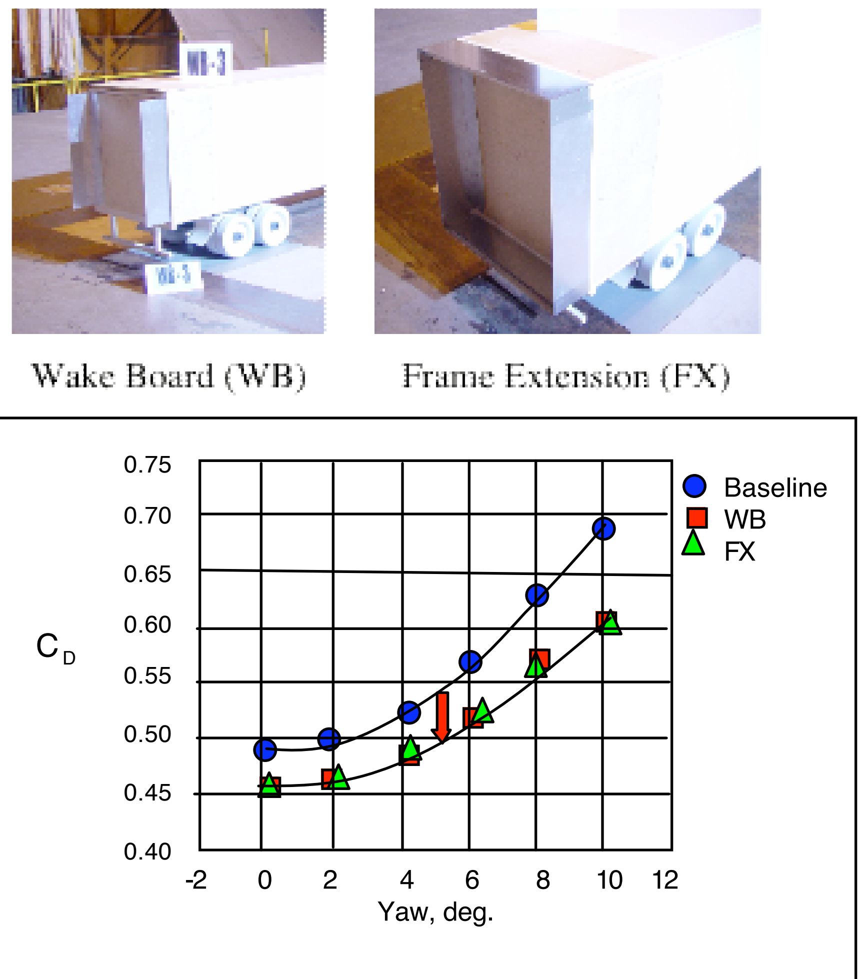
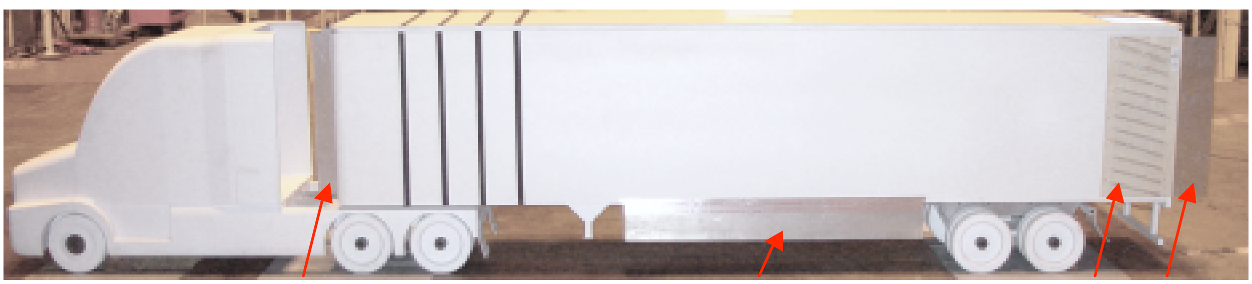


Figure 9. Plot of the measured drag reduction for the wake board and frame extension devices.

The WB and FX devices were refined through computational analysis and wind tunnel testing. The device assessment activity focused on the development of base mounted devices that would be applicable to both swing door and roll-up door trailers. This computational and experimental effort resulted in the development of the Wake Board (WB) device for swing doors and the Frame Extension (FX) device for roll-up doors. A photograph of each device installed on the 1/4 scale heavy truck model installed in the NASA Langley Full Scale Tunnel (LFST) is depicted in figure 9. The wind tunnel data show that both base mounted devices provide 8% drag reduction that correlates to a 4% fuel savings at highway speeds. The data for the vortex flow devices from the phase I effort and the WB and FX base mounted devices show that a combined a fuel savings of 12% may be achieved for both a roll-up and swing door van type trailers.

Phase III Aerodynamic Design

A Phase III design activity has recently been initiated to explore advanced aerodynamic technologies to reduce trailer undercarriage drag. As mentioned previously there are three major drag zones on a trailer; the front face, the rear base, and the undercarriage/wheels. The phase I activity focused on the trailer face and rear base and the phase II effort further addressed the rear base drag. The combined drag reduction of phase I and phase II innovations have been shown to exceed 20 percent providing more than 10 percent improvement in fuel economy. It is estimated that a properly designed trailer skirt will control the undercarriage flow and provide another 5 percent improvement in fuel economy. The primary challenges in skirt design are related to road clearance, weight, and driver access to the undercarriage. Preliminary wind tunnel test results for a mini-skirt concept have demonstrated a 10 percent drag reduction with road clearance that exceeds 20 inches, full scale. The combined improvement in fuel economy from the phase I, II ad III studies are projected to exceed 15 percent. A photograph of the 1/4 scale wind tunnel model with the phase I, II, and III devices installed is shown in figure 10. On road fuel economy testing of the subject devices are scheduled for the May - June of 2006.



CFVT Mini-Skirt VSD WB

Figure 9. Photograph of 1/4 scale SO RHT wind tunnel model with CFVT, VSD, WB, and Mini-Skirt innovations installed.

CONCLUDING REMARKS

Reported herein is a review of an ongoing tractor–trailer truck fuel economy improvement activity. The subject activity is an aerodynamic drag reduction effort in which low cost, simple, geometric devices have been designed and validated through operational testing and wind tunnel testing. To date, five aerodynamic drag reduction devices have been developed for application to the trailer of a tractor-trailer truck. The two vortex flow devices have undergone extensive operational testing where they have amassed over 85,000 miles of use. These technologies have shown a combined fuel savings of approximately 8% at an average speed of 47.5 mph. This improvement in fuel economy correlates to an equivalent drag reduction of approximately 20% with a corresponding drag coefficient of 0.45.   Note, the aerodynamic drag reduction and associated fuel savings also result in a measurable reduction in exhaust emissions that is equivalent to the percent reduction in fuel usage. Observations from the test activity have shown that the addition of these devices to the trailers has not had a negative impact on either the operational utility of the trailers or the maintenance procedures and requirements. Anecdotal evidence indicates that these devices have not altered any of the vehicle driving and handling characteristics.

Two base mounted devices have been developed to reduce the base drag of trailers. The two base devices have been developed through computational design and wind tunnel testing. Each of the two base mounted devices have been shown to reduce the drag of heavy trucks by more than 8%, which equates to a 4% fuel savings at highway speeds. Preliminary wind tunnel test results for a mini-skirt concept have demonstrated a 10 percent drag reduction with road clearance that exceeds 20 inches, full scale. The estimated combined fuel savings of the vortex flow, base mounted, and undercarriage devices is projected to be greater than 15%.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

A	maximum cross sectional area of tractor-trailer vehicle, ft^2
C_D	drag coefficient, D/AQ
d	equivalent diameter based upon A, ft.
D	aerodynamic drag force, lbs.
G	gap between tractor and trailer, ft.
HP	horsepower
mpg	miles per gallon
mph	miles per hour
psf	pounds per square foot
Q	dynamic pressure, psf
V	vehicle speed, mph