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Test, Evaluation, and Demonstration of Practical Devices/Systems to Reduce Aerodynamic Drag of Tractor/Semitrailer Combination Unit Trucks

FINAL REPORT

April 2007

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i. Preface

This project was a team effort by a significant number of dedicated and talented individuals at four Truck Manufacturers Association (TMA) member companies. These companies are normally fierce competitors. However, for this effort they worked separately, but in unison, to develop and demonstrate that significant fuel saving advances are possible that will contribute not only to their customers' profitability, but more importantly to the nation's goal of energy independence. The work described in this report is the result of the outstanding collective efforts to the following individuals:

Freightliner LLC
Scott Smith
Karla Younessi
Matt Markstaller
Dan Schlesinger
Bhaskar Bhatnagar
Donald Smith
Bruno Banceu

International Truck and Engine Corporation
Ron Schoon
VK Sharma

Mack Trucks Inc.
Mark Kachmarsky
Srikant Ghantae

Volvo Trucks North America
Michael Sorrels
Conal Deedy
Justin Clark
Skip Yeakel

I especially want to single out the extraordinary efforts of Michael D. Laughlin of New West Technologies, Landover, MD, who provided invaluable help in coordinating and integrating the work of the individual contributors. In addition, I would like to express my great appreciation for the excellent work that Charlotte Seigler of Strat@comm in Washington DC did to organize and plan the end-of-project event and make it a great success.

Most of all, this project was the direct result of the vision and dedication of the late Dr. Sidney Diamond, who passed away in 2005 and was sadly not able to see the beneficial results of the aerodynamic work he began with these industrial partners. The entire team appreciates the hard work that Dr. Diamond put into making this project happen, as he did with all his projects at DOE. We thank him for his support, and note that he will be sorely missed.

Robert M. Clarke
President, Truck Manufacturers Association
April, 2007

1. Executive Summary

The objective of this project was to determine aerodynamic drag reduction and fuel economy improvement effects of additions or changes to the configuration of Class 8 tractor-semitrailer systems. The overall approach for the project was to pursue complimentary research paths investigating aerodynamic devices and systems that matched individual manufacturer technical strengths and product development plans. Research focused on the overall effects on combination-unit aerodynamics attributable to: differing rear-view mirror designs; aerodynamic treatments of the tractor trailer gap, trailer side, and trailer wake; trailer aerodynamics, trailer gap enclosure, and trailer gap flow control; and vehicle underside design and management of tractor-trailer air flows. Four major North American truck manufacturers (Freightliner, International, Mack, and Volvo) participated in this project, which was led by the Truck Manufacturers Association.

The project had two distinct research phases. In Phase I, researchers conducted preliminary tests and analyses on a wide range of candidate devices and systems to determine the effectiveness of each device and to identify promising sets of devices for further research. This testing involved both full-size vehicles and scale models in wind tunnels. Computational fluid dynamics analyses were also performed to establish the effects of various devices on overall combination-unit aerodynamics. In Phase II, participants tested the most promising devices they had identified in Phase I, using full-size Class 8 trucks in wind tunnels or in real-world environments. This testing quantified the fuel economy changes and/or aerodynamic drag changes (in terms of a percentage change relative to a similar baseline truck and trailer) that could be anticipated through the use of these devices and systems.

In terms of accomplishments for Phase I, Freightliner completed wind tunnel tests of a current state-of-the-art standard head/mounting mirror system on a full-scale class 8 tractor establishing the effect of the mirror system on aerodynamic drag and flow behavior. This wind tunnel data was correlated with computational fluid dynamics (CFD) modeling. Freightliner also evaluated the aerodynamic characteristics of the truck with mirrors to baseline truck without mirrors. CFD models of airflow around the truck and mirror were constructed, with good correlation between experiment and modeling.

In terms of accomplishments for Phase II, Freightliner concluded that several mirror design parameters (frontal area, shape, alignment, and placement in the flowfield) have significant effects. For instance, the mirror housing should be curved and placed appropriately with respect to the A-pillar and cowl vortex. Mirror mounting structure should have a minimal number of struts, since together they form a complex system with a larger wake. Finally, the mirrors and cab should be designed as one integrated system. With well-designed mirrors, aerodynamic drag can be reduced 2 to 3 percent. Eliminating mirrors altogether would yield a 6 percent improvement. CFD simulations and wind tunnel testing are complementary tools that should be used together to develop vehicles and accessories. These two tools provide repeatable results that eliminate the effects of differing environmental conditions that occur when vehicles are tested on-road.

In Phase I, International completed evaluations of modifications to trailer sides, trailer wake, and tractor-trailer gap through two rounds of one-eighth scale model wind tunnel testing. The first round of scale model testing quantified the effects of a number of vehicle modifications in order to select a subset of these for a second round of scale model testing. Testing of several additional vehicle modifications was also conducted in the second round: these additional modifications were the result of customer input on practical devices. Aerodynamic drag reductions of up to 23 percent were demonstrated in wind tunnel testing using the 1/8 scale models.

In Phase II, International demonstrated an 11.5 percent improvement in fuel economy with the use of Wal-Mart's experimental aerodynamic trailer in full-scale on-road tests, using the SAE J1321 Type II fuel economy test procedure. They partnered with Great Dane Trailers and Wal-Mart to build and test an experimental aero trailer, and developed unique solutions to overcome common objections to trailer skirts and trailer base plates. International also demonstrated fuel economy improvements for tractor-trailer gap devices, including a 2 percent improvement for trailer forebody shape (patent application submitted) and a 1 percent improvement for variable geometry side extenders.

Mack's Phase I accomplishments included completing computational fluid dynamics (CFD) analysis on the effect of trailer gap enclosure, and trailer gap flow control on the truck aerodynamics through the StarCD Software. Several aerodynamic aids (vortex generator, trailer boat tails, etc.) were analyzed through a workshop involving experts from the industry for selecting most promising technologies for further full size vehicle testing. A trailer equipped with a boat tail, side skirts, side strakes and a vortex generator has been acquired for use in Phase II fuel economy tests.

In Phase II, Mack conducted screening tests of combinations of aerodynamic devices (trailer gap enclosure, trailer boat tail, side strakes, side skirts, and vortex generators) to determine the most promising devices for full-scale vehicle fuel economy testing. Mack completed SAE Type II fuel economy tests of various combinations of trailer gap enclosures, side skirts, and boat tails on the TRC test track in Ohio, demonstrating fuel economy benefits of 1 - 8 percent.

In Phase I, Volvo completed computational fluid dynamics analysis of the effect of vehicle underside design and airflow management on truck aerodynamics. They estimated that vehicle underside design is associated with approximately 35 percent of total vehicle drag, and that improvements to underside design, trailer gap manipulation, and trailer bogie improvements could reduce overall drag by approximately 7 percent. Volvo has identified device designs for full-scale on-road testing, using results obtained to date from CFD analysis and scale model testing.

Volvo's Phase II work included completion of SAE Type II fuel economy tests of combinations of add-on aerodynamic devices (smooth under-body device, trailer gap up-flow prevention device, adjustable roof extension and optimized side deflector extensions to effectively shorten the trailer gap, and trailer bogie deflectors) on the TRC test track in Ohio. Fuel economy benefits of between 1 and 2.3 percent were demonstrated.

2. Introduction

Class 8 heavy-duty trucks account for over three-quarters of the total diesel fuel used by commercial trucks (trucks with GVWRs more than 10,000 pounds) in the United States each year. At the highway speeds at which these trucks travel (i.e., 60 mph or greater), aerodynamic drag is a major part of total horsepower needed to move the truck down the highway, Reductions in aerodynamic drag can yield measurable benefits in fuel economy through the use of relatively inexpensive and simple devices. The goal of this project was to examine a number of aerodynamic drag reduction devices and systems and determine their effectiveness in reducing aerodynamic drag of Class 8 tractor/semitrailer combination-units, thus contributing to DOE's goal of reducing transportation petroleum use.

The project team included major heavy truck manufacturers in the United States, along with the management and industry expertise of the Truck Manufacturers Association as the lead investigative organization. The Truck Manufacturers Association (TMA) is the national trade association representing the major North American manufacturers of Class 6-8 trucks (GVWRs over 19,500 lbs). Four major truck manufacturers participated in this project with TMA: Freightliner LLC; International Truck and Engine Corporation; Mack Trucks Inc.; and Volvo Trucks North America, Inc. Together, these manufacturers represent over three-quarters of total Class 8 truck sales in the United States. These four manufacturers pursued complementary research efforts as part of this project.

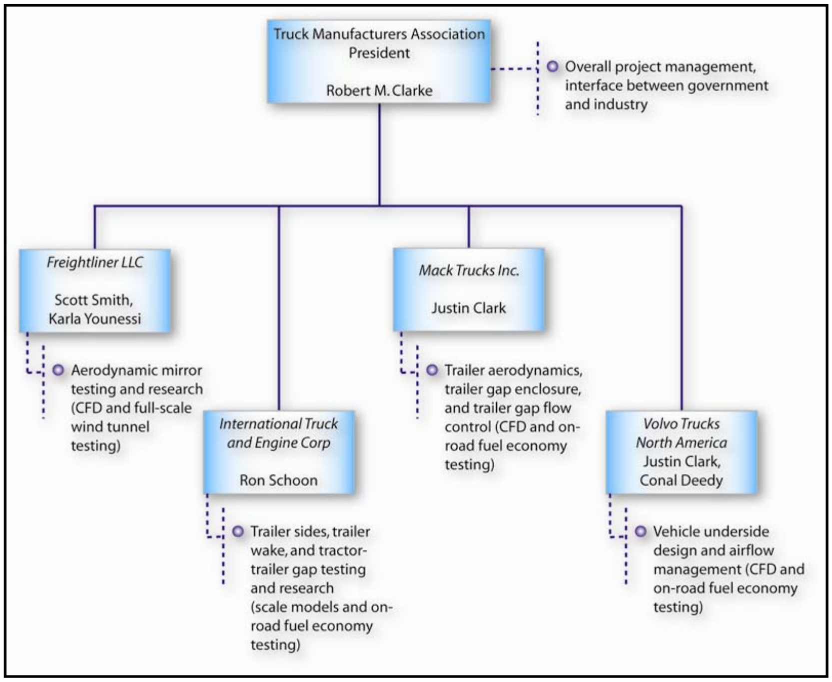


Figure 2-1. Project Roles & Responsibilities

The project work was separated into two phases conducted over a two-year period. In Phase I, candidate aerodynamic devices and systems were screened to focus research and development attention on devices that offered the most potential. This was accomplished using full-size vehicle tests, scale model tests, and computational fluid dynamics analyses. In Phase II, the most promising devices were installed on full-size trucks and their effect on fuel economy was determined, either through on-road testing or full-size wind tunnel testing. All of the manufacturers worked with devices and systems that offer practical solutions to reduce aerodynamic drag, accounting for functionality, durability, cost effectiveness, reliability, and maintainability.

The project team members and their roles and responsibilities are shown in Figure 2-1. Figure 2-2 shows the Phase I and II project schedules for all four projects and associated management activities.

The following pages offer more detailed descriptions of the activities undertaken by the manufacturers under Phase I and II of the project.

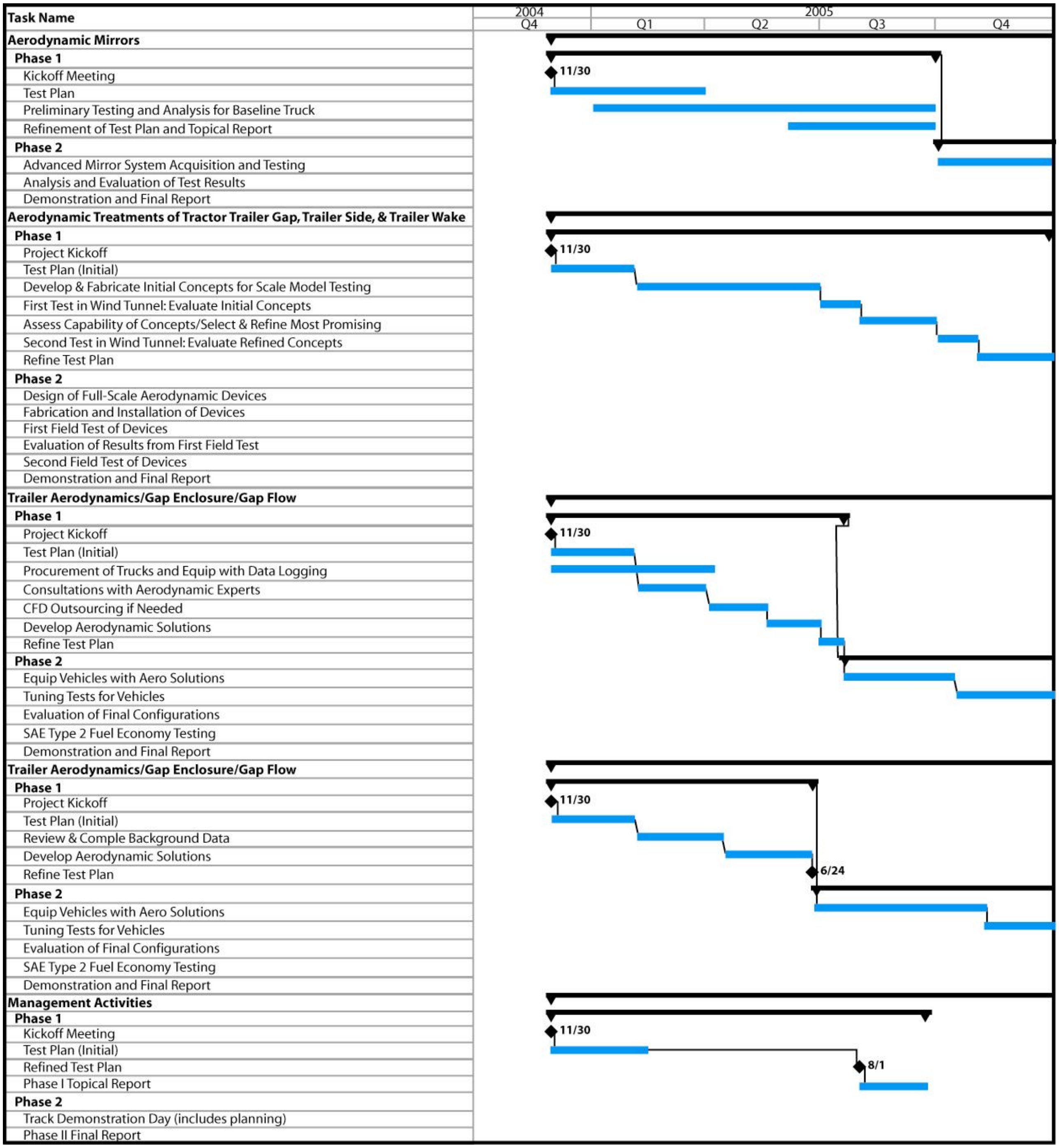
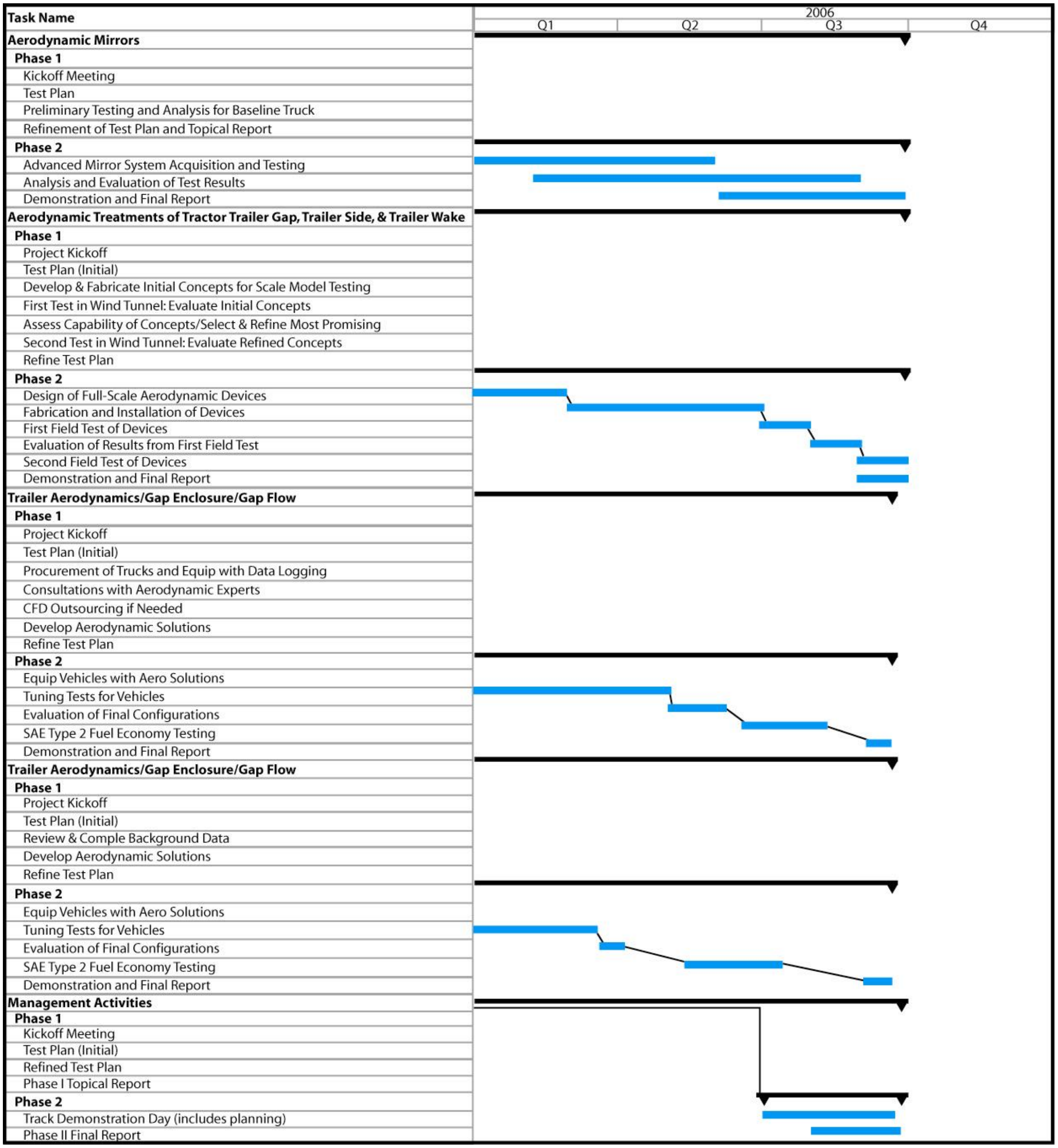


Figure 2-2. Original Project Schedule for Phases I and II



Task Name
Aerodynamic Mirrors
Phase 1
Kickoff Meeting
Test Plan
Preliminary Testing and Analysis for Baseline Truck
Refinement of Test Plan and Topical Report
Phase 2
Advanced Mirror System Acquisition and Testing
Analysis and Evaluation of Test Results
Demonstration and Final Report
Aerodynamic Treatments of Tractor Trailer Gap, Trailer Side, & Trailer Wake
Phase 1
Project Kickoff
Test Plan (Initial)
Develop & Fabricate Initial Concepts for Scale Model Testing
First Test in Wind Tunnel: Evaluate Initial Concepts
Assess Capability of Concepts/Select & Refine Most Promising
Second Test in Wind Tunnel: Evaluate Refined Concepts
Refine Test Plan
Phase 2
Design of Full-Scale Aerodynamic Devices
Fabrication and Installation of Devices
First Field Test of Devices
Evaluation of Results from First Field Test
Second Field Test of Devices
Demonstration and Final Report
Trailer Aerodynamics/Gap Enclosure/Gap Flow
Phase 1
Project Kickoff
Test Plan (Initial)
Procurement of Trucks and Equip with Data Logging
Consultations with Aerodynamic Experts
CFD Outsourcing if Needed
Develop Aerodynamic Solutions
Refine Test Plan
Phase 2
Equip Vehicles with Aero Solutions
Tuning Tests for Vehicles
Evaluation of Final Configurations
SAE Type 2 Fuel Economy Testing
Demonstration and Final Report
Trailer Aerodynamics/Gap Enclosure/Gap Flow
Phase 1
Project Kickoff
Test Plan (Initial)
Review & Comple Background Data
Develop Aerodynamic Solutions
Refine Test Plan
Phase 2
Equip Vehicles with Aero Solutions
Tuning Tests for Vehicles
Evaluation of Final Configurations
SAE Type 2 Fuel Economy Testing
Demonstration and Final Report
Management Activities
Phase 1
Kickoff Meeting
Test Plan (Initial)
Refined Test Plan
Phase I Topical Report
Phase 2
Track Demonstration Day (includes planning)
Phase II Final Report

Figure 2-2. Original Project Schedule for Phases I and II (Continued)

3. Freightliner Project Activities

3.1 Phase I Overview

Freightliner focused on the effect of mirrors and mirror design on truck aerodynamics. The key Phase I activities completed by Freightliner included:

- Established the overall contribution of a current mirror system to the aerodynamic drag of a modern Freightliner truck: the mirror system contributes about 4.5% of the total drag of the vehicle.
- Correlated experimental wind tunnel work with computational fluid dynamics work for this vehicle/mirror combination, both qualitatively (flow field appearance) and quantitatively (contribution of mirrors to overall aerodynamic drag).

3.2 Phase I Activities

Introduction

Freightliner LLC conducted a comprehensive analysis of mirror airflow on a commercial vehicle. The results are available for use by the industry to establish realistic design goals for future mirrors. This supported the U.S. Department of Energy's (DOE) goal of reducing aerodynamic drag to improve fuel economy for heavy-duty vehicles in order to reduce dependence on imported oil and conserve fossil resources for the future.

It has been well recognized within the industry that for every 2 or 3% reduction in aerodynamic drag there is roughly a correlating 1% reduction in fuel consumption. Therefore a targeted decrease of 1% in aerodynamic drag could potentially result in up to a 0.5% decrease in fuel consumption. In 2003, "trucks hauled 9.8 billion tons of freight, or 68.2% of all freight transportation tonnage. To move all these goods, the trucking industry had to consume more than 35 billion gallons of diesel fuel and over 15 billion gallons of gasoline."[1] Thus if a 0.5% reduction in fuel consumption were obtained, that could correspond to energy savings of 175 million gallons of diesel fuel alone annually. In December 2005, the national average for diesel fuel was reported at $2.436[2]. Assuming a 175 million gallon reduction could be achieved, the economic benefit to the U.S. economy attributed to Class 8 vehicles alone could be in excess of $426.3 million. An associated reduction in the amount of diesel exhaust emissions released into the environment would also be realized.

Another accepted premise within the industry is that a mirror contributes approximately 5% aerodynamic drag to the truck. The results of Phase 1 testing produced a 4.5% drag factor in the wind tunnel and a 5.8% drag factor from Computational Fluid Dynamics (CFD) analyses which correlates to this assumption. The explanation for these differences in drag follows in the detailed description of Phase 1 work.

The goal of this project was to understand and quantify the mirrors' drag of an actual full-scale commercial vehicle using current mirror technologies that are commonly in use. This program combined full-scale wind tunnel tests employing a variety of measurements with Computational Fluid Dynamics (CFD) analyses to document the aerodynamics associated with the mirror. Parameters of interest included the overall drag of the mirror and the detailed flow structures near the mirror. The project objectives as follows were comprehensive and technically feasible within the plan.

- Systematically study the detailed physics and aerodynamic drag associated with mirrors on a full-scale class 8 vehicle at Reynolds numbers reflecting highway speeds.
- Measure and present the aerodynamic drag reduction effects of the investigated technologies as a percentage of total vehicle drag. In addition to the numerical values, advanced flow visualization and

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[1] Transport Topics, Daily Updates, 24 August 2005
[2] "Energy Information Administration, U.S. Department of Energy," n.d., <http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp > (12 December 2005)

computational fluid dynamics results will be provided to give a detailed understanding of the flow field physics associated with different types of mirrors.

- Provide information to the industry for development of design goals for future products that minimize the mirror's aerodynamic drag.

Rationale for Proposed Research and Development Program

Very few studies have been conducted testing the mirror airflow. Considerable efforts have been invested in the last decade to study vehicle aerodynamics computationally. Recognizing the limitations of conventional scale model wind tunnel testing, these studies have provided vital information, but they cannot fully capture the impact of airflow that can be measured in a full-scale wind tunnel. This project furthered this work by using full-scale vehicles to obtain results that can be used for optimization of trucks operating today and provide direction for future designs. Based on the results of this project, the information regarding aerodynamic drag of mirrors collected can be shared with other manufacturers. The tractor manufacturers can then manufacture better designs for their own exclusive applications for an even larger benefit to the entire industry.

The domestic heavy-duty commercial vehicle industry has not had an economical full-scale wind tunnel available until Freightliner built the industry's first one in April 2004, so there has not been an opportunity to evaluate and study airflow to this extent. Commercial vehicle companies generally do not have the extensive financial resources available to them to develop this type of facility, as do automobile companies, because their production rates are significantly less. Based on the improvements that have been made to automobiles with the use of wind tunnels, the Freightliner Team fully expects to improve the aerodynamic drag of commercial vehicles by 30% over the next ten years with this facility with the exterior mirrors being a significant portion of that.

Freightliner LLC was pleased to test mirror designs to better quantify drag attributed by each mirror type. The biggest hurdle to overcome for the trucking industry is to arrive at design goals that would be acceptable to both the customer and manufacturer. In order for future designs to be viable, the solution must be cost effective and acceptable to customers. The savings to customers/fleets from less fuel consumption must more than compensate for any additional cost of designs and technologies. For Freightliner, any of the proven technologies would follow a typical commercialization path. Once identified, the selected devices are proven out by testing and through evaluation with installation on customer vehicles. Freightliner works with our suppliers to develop parts to meet product and performance targets. It takes from several months to several years to incorporate a product for sale.

Phase 1 Summary

Phase 1 of this project focused on establishing a baseline from which to compare the effects of aerodynamic drag on different mirrors. A standard mirror was tested along with no mirror on a Freightliner Century Class S/T conventional Class 8 sleeper cab truck with a raised roof. The drag percentage difference was calculated in order to provide useful information without revealing the exact drag of a specific vehicle. Three yaw angles were tested (zero and +/- 6 degrees) when measuring drag and again when the smoke flow visualization was done. Freightliner performed additional unplanned testing on "soiling" also known as water management to study the effects of water accumulation for later comparison to the Phase 2 results.

Prior to beginning the actual wind tunnel work, Freightliner's engineering analysis group performed CFD testing and discussed the best approach to take for simulation and what the extent of the domain, the boundary conditions, the details of the actual simulation approach and set up the modeling software using Freightliner's Century Class S/T tractor. Furthermore, discussions included what type of results the Freightliner team expected to see to make sure the experiment went as planned and to ensure each team member shared the same understanding.

The CFD work complemented the wind tunnel testing and occurred in conjunction with that testing with the brunt of the analysis performed immediately following the wind tunnel testing. This allowed for a flow of information back and forth to adjust models based on the results of the wind tunnel work and to consider modifications to the procedures to better serve the objectives.

Figure 3-1. Freightliner Truck Tested in Wind Tunnel

The correlation work consisted of two components: 1) First, qualitative comparison of wind tunnel test results vs. CFD simulation for streamline patterns, surface pressures, and general flow behavior. CFD plots were created with views of appropriate results data that can be compared to corresponding images captured during the wind tunnel tests. 2) Second, relative drag comparison for CFD vs. wind tunnel tests. The relative increase in overall drag for no mirror vs. with mirror was compared for zero and +/- 6 degrees yaw cases.

<u>Detailed Description of Phase I Work</u>

Tools and Technologies: Wind Tunnel

All wind tunnel testing was conducted in Freightliner's full-scale aerodynamic wind tunnel located in Portland, Oregon. This is the only full-scale wind tunnel of its kind. The tunnel is an open return, closed jet facility specifically designed for aerodynamic development of Class 8 tractors. As such, it incorporates a 3-component under floor balance for measuring tractor loads and a 1-component balance installed in the built-in trailer for measuring trailer drag.

The wind tunnel was developed using extensive CFD modeling. CFD analysis led Freightliner to develop a high quality test section airflow, high quality floor boundary layer, and minimal blockage effect. These factors produce optimal wind tunnel characteristics for heavy vehicles. Like all wind tunnels, Freightliner's main features include the contraction cone, test section, and fans. The contraction cone provides a clean uniform flow in the test section where the vehicle is located and uses ten 72" fans to produce the 60 mph airflow in the test section.

The wind tunnel test section is especially unique in that, through modeling, the wall shapes have been optimized to conform to free streamlines so that the vehicle does not see blockage affects normally associated with a closed duct test section. It is ideally suited for mirror studies due to the excellent airflow characteristics and the full-scale vehicles that it will accommodate with actual underbody and mirror flow.

Tools and Technologies: Computational Fluid Dynamics

The Computational Fluid Dynamics (CFD) code used throughout this study was PowerFLOW™ by EXA Corporation. Selection of this code was driven by computational efficiency and robustness and is Freightliner's standard for exterior aerodynamic CFD studies. This is also one of most commonly used commercially available computational fluid dynamics (CFD) software programs. Detailed digital models of the test vehicle were developed using available CATIA™ data. Post-processing and data analysis were accomplished via PowerVIZ™.

Using the data collected by experiment, computational tools can be validated by comparison so that with confidence, simulations can provide the capability of investigating many different design improvements. Simulations are typically processed with Linux clusters. The validation is best done in stages so that any issues that arise can be systematically dealt with (e.g. boundary conditions, turbulence models, grid refinements). Each approach was evaluated for baseline geometry with multiple grids and time-scales to establish a converged solution for comparison to experiment. This investigation established the required modeling approach and grid discretization to obtain accurate results that can be used with confidence for design.

Tools and Technologies: Test Vehicle

The vehicle used for both the wind tunnel testing and CFD analyses was a Freightliner Century Class model with "aerodynamic" mirrors. This is one of Freightliner's most advanced current production truck designs. Figure 3-1 shows the test vehicle installed in the wind tunnel. Detailed specifications for the truck are presented at the end of this section of the overall report.

Test Methodology: The objective of the Phase I effort was to conduct preliminary full-scale wind tunnel testing and CFD analyses to demonstrate the aerodynamic drag levels and flow physics associated with mirror systems in-use on Class 8 tractors today. Consequently, the vehicle was evaluated with and without mirrors at yaw angles of -6, 0, and +6 degrees. These conditions were maintained for both the experimental and computational portions of the study. In addition, experimental mirror soiling studies were conducted at 0 degrees of yaw. All tests and simulations were conducted at typical highway speeds.

By comparing the overall tractor-trailer drag levels both with and without the mirrors installed, the drag associated with the mirrors was determined. Table 3-1 presents the aerodynamic drag of the baseline mirrors as a percentage of overall tractor-trailer drag.

Table 3-1. Mirror Drag (Percent of Total Vehicle)

	-6 degrees	0 degrees	+6 degrees
Wind Tunnel	3.2%	4.5%	2.4%
CFD	4.0%	5.8%	2.1%

Several items are evident from the data in Table 3-1. First, minor differences exist between the experimental and CFD data. This is fairly typical in the industry. The primary reasons were due to "modeling" differences between the two tools. For example, the experimental setup did not include a moving ground plane, spinning wheels, or a fully developed trailer wake (the drag effect of this last item was estimated). While the CFD model included these items, it did not include every nut, bolt, under hood component, and other small item that exists on the actual truck. The differences described did not appear to cause major variances; the comparison of the results between the two tools is actually quite acceptable. An encouraging result was that the drag level trends for the various yaw angles were mirrored by both tools.

The second item evident in the results was the differences in mirror drag between -6 degrees and +6 degrees yaw. This difference was due to asymmetry of the truck geometry. Each mirror was positioned differently relative to the longitudinal axis of the truck. In addition, under hood and underbody components were positioned off of the central axis. Thus, the differences in mirror drag for the various yaw angles presented in Table 3-1 were acceptable and correct.

The third and most important item evident from the results in Table 3-1 is that mirrors contributed approximately four to five percent of a tractor-trailer's aerodynamic drag. This results in increased fuel usage of about two percent for long-haul applications.

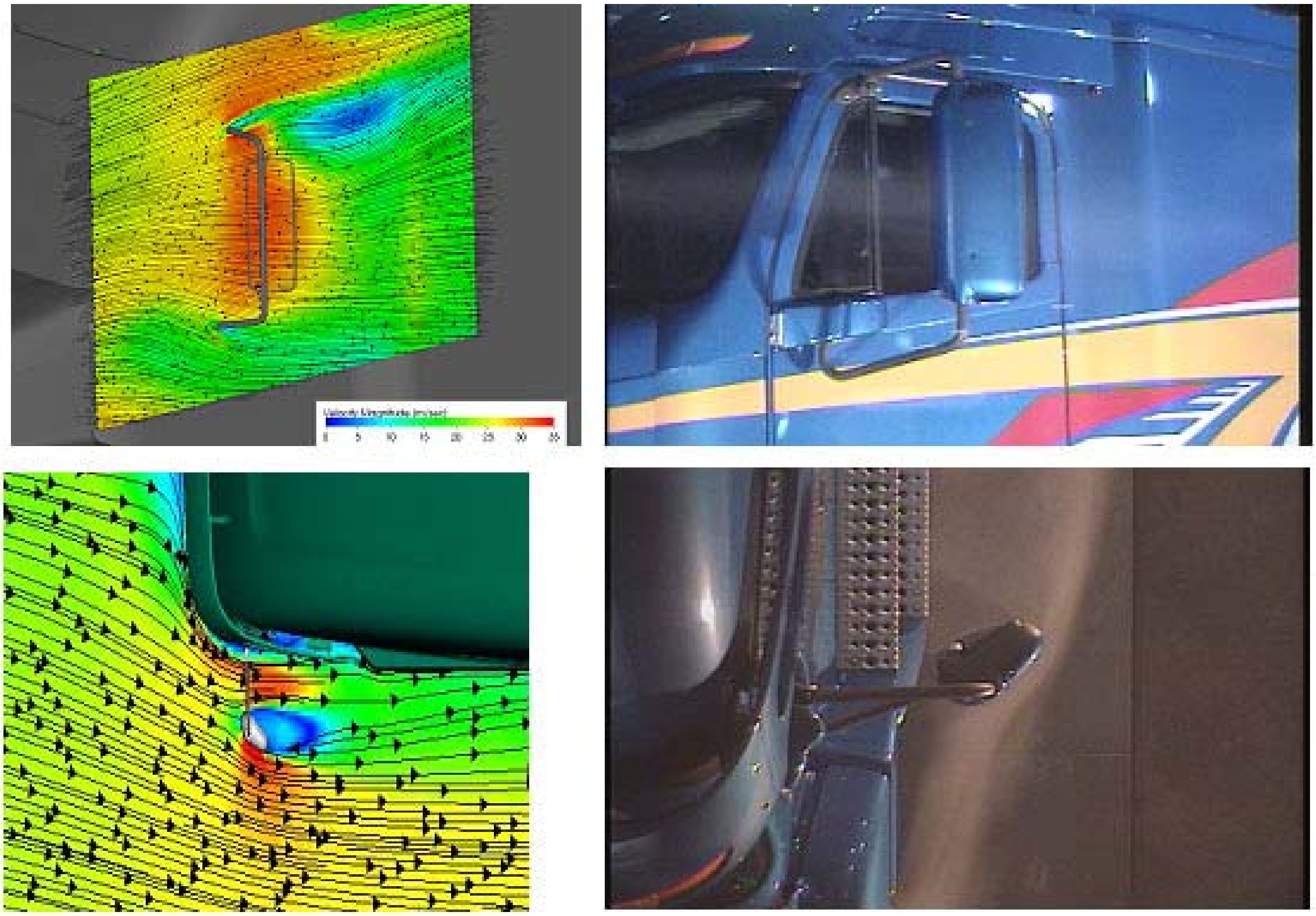


Figure 3-2. Flow Visualization (0 degrees yaw, with mirrors)

Flow Visualization: Figures 3-2 through 3-6 present experimental smoke flow and CFD data images for the mirror region of the truck. Images are presented for all three test conditions (-6, 0, +6 degrees of yaw) with the mirrors installed as well as removed from the truck. Note that the case without mirrors is nearly identical for either -6 or +6 degrees of yaw. These images reveal the mirror wake structures, streamlines, and interaction effects with the a-pillar of the truck.

For the zero yaw case with mirrors, Figure 3-2 shows CFD velocity contours and streamlines on the left with corresponding experimental smoke flow on the right. The images illustrate that the presence of the mirror forces the impinging air to accelerate around both the inboard and outboard surfaces of the mirror housing leaving a wake region immediately downstream of the mirror. Figure 3-3 shows corresponding images for the zero yaw case with the mirrors removed. The flow disturbance due to the presence of the mirror housing no longer exists.

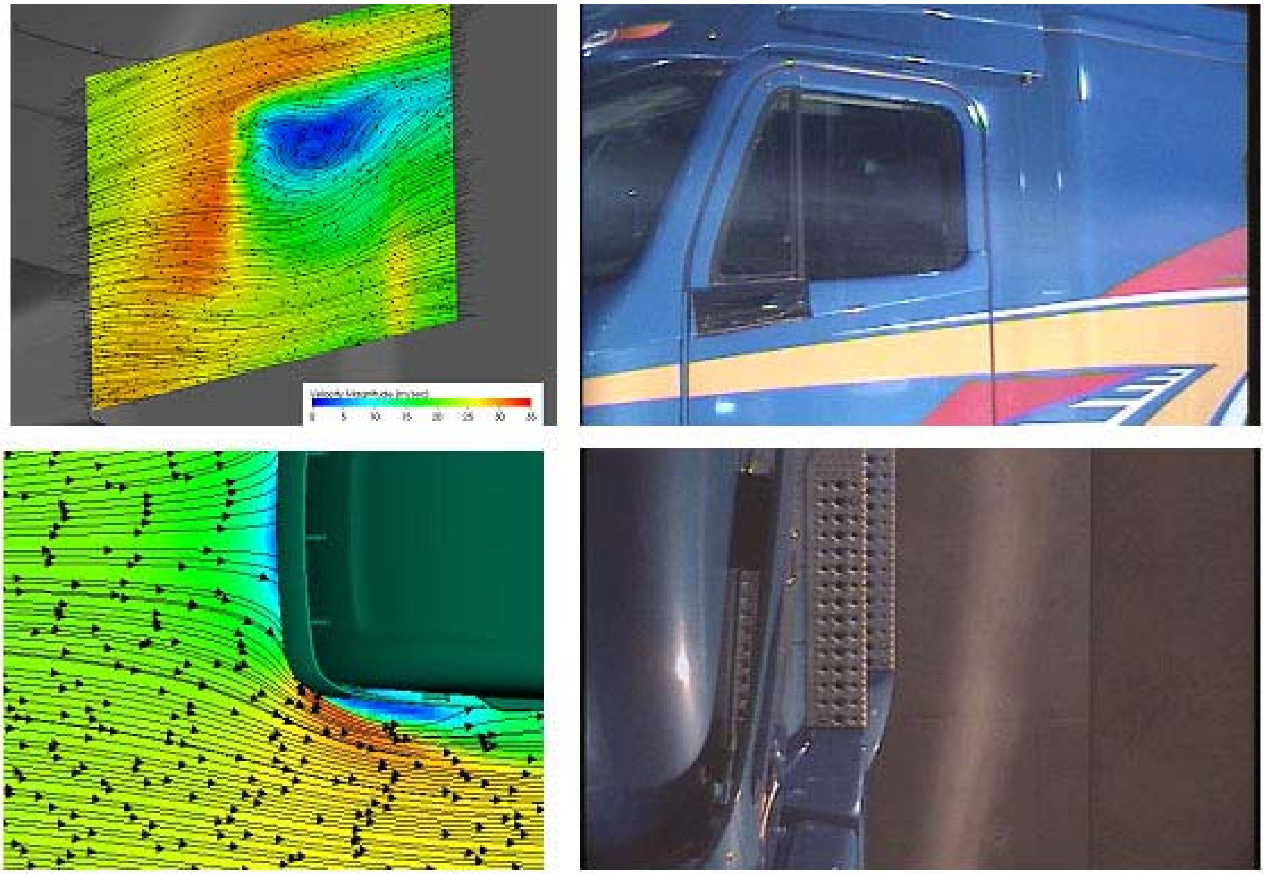


Figure 3-3. Flow Visualization (0 degrees yaw, without mirrors)

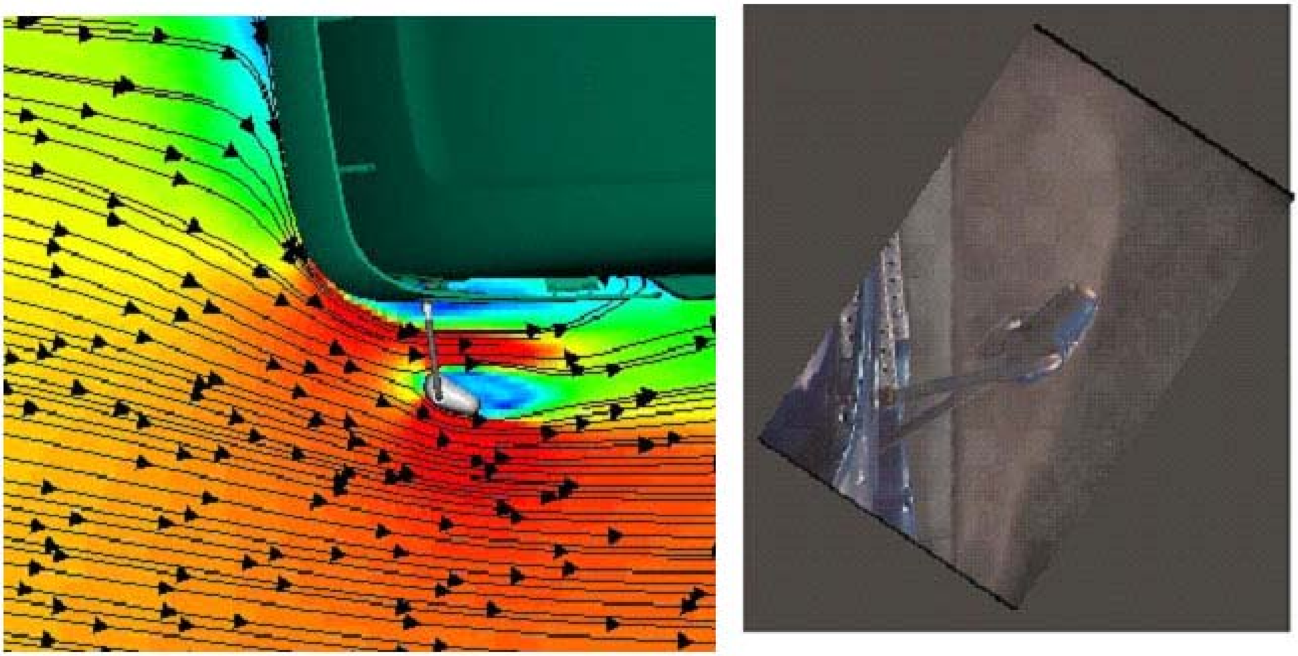


Figure 3-4. Flow Visualization (-6 degrees yaw, with mirrors)

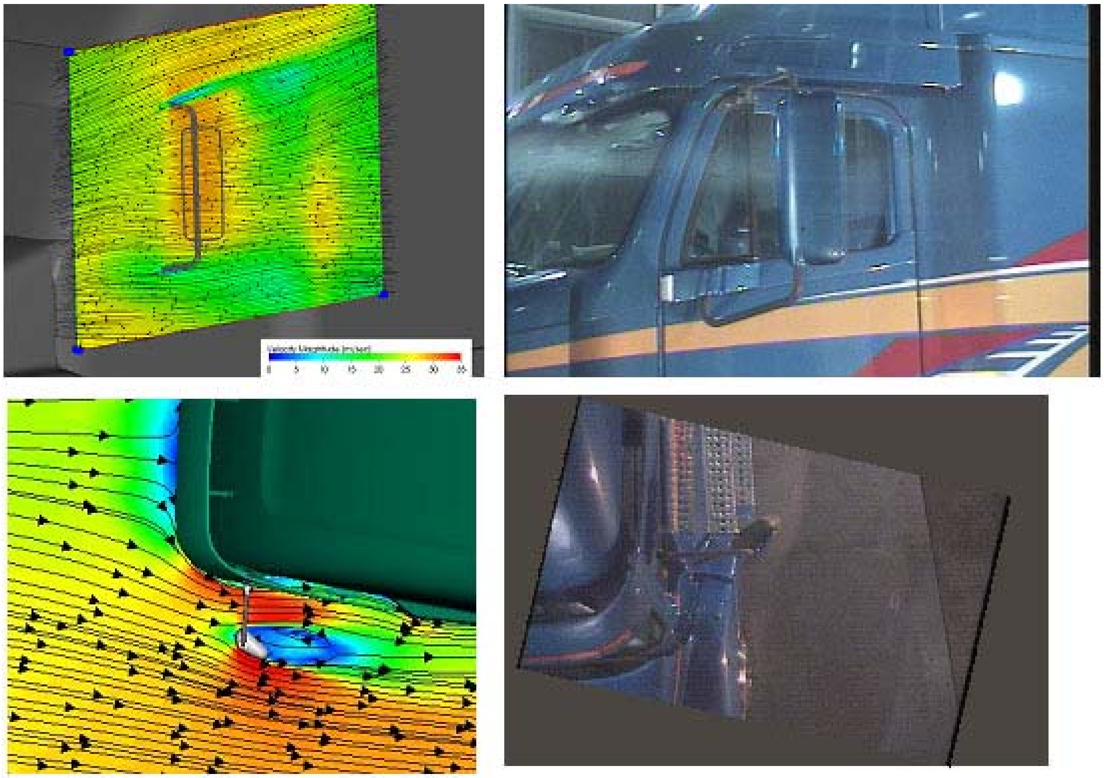


Figure 3-5. Flow Visualization (+6 degrees yaw, with mirrors)

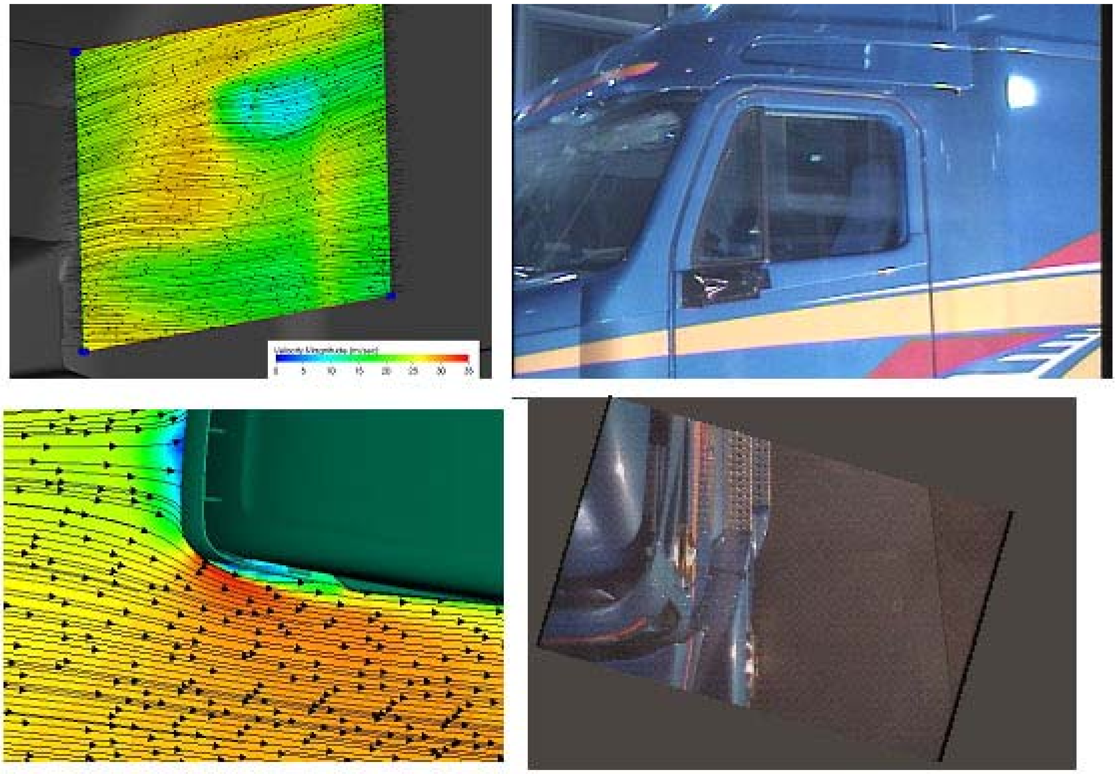


Figure 3-6. Flow Visualization (+6 degrees yaw, without mirrors)

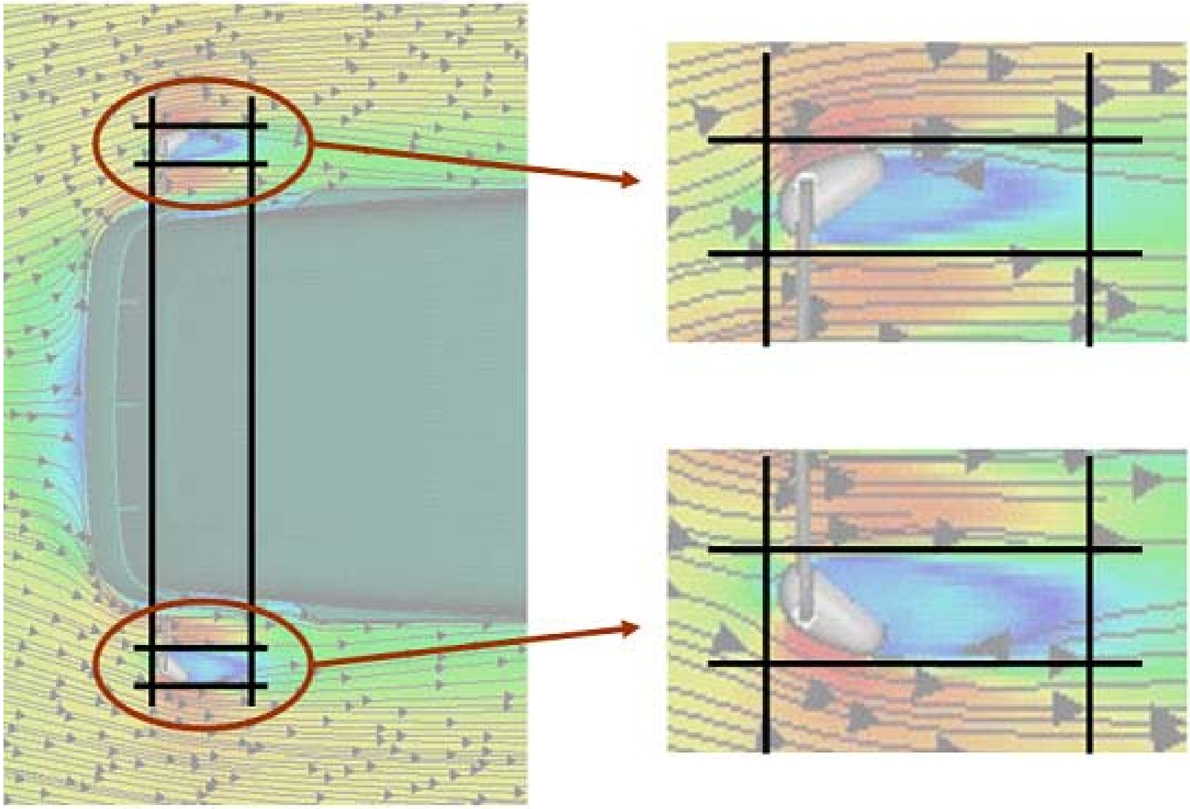


Figure 3-7. Flow Visualization (driver and passenger side mirrors; 0 degrees yaw)

Figure 3-4 shows the flow structure for the -6 degree yaw case in which the driver side mirror is on the windward side of the vehicle. Relative to the zero yaw case, this flow orientation for the driver side mirror results in a reduction in effective projected area of the mirror housing with a corresponding reduction in wake size.

Figure 3-5 shows the +6 degree yaw case. Here the driver side mirror is on the leeward side of the vehicle with a less favorable flow orientation than the -6 degree case, resulting in a larger wake structure behind the mirror.

Figure 3-6 shows the non-zero yaw case with the mirrors removed and the flow disturbance associated with the mirror housing not present.

Figure 3-7 illustrates the asymmetry in both geometry and flow behavior between the driver and passenger side mirrors for the zero yaw case. The less favorable orientation of the driver side mirror results in a larger wake structure.

Comparisons of these images to those of other mirror systems will be accomplished in Phase 2 of the project.

Mirror Soiling: Figure 3-8 presents a photo of the driver's side mirror following Freightliner's proprietary mirror soiling testing. Depicted in the photo is the reflective surface of the mirror showing water droplets deposited during the testing. The water droplets were treated with a fluorescent dye and illuminated by ultraviolet light. Images from mirrors tested in Phase 2 of the project were compared to Figure 3-8.

Phase 1 Conclusions

Freightliner completed all of the wind tunnel testing and CFD analysis for Phase 1 as planned. The following results were gathered from wind tunnel testing alone: 1) Freightliner's current “aerodynamic” mirror contributed approximately 4.5% to total tractor-trailer drag of a Century Class vehicle combination. 2) This increment can degrade fuel economy by as much as 2% for over-the-road applications. 3) Evaluation of streamlines indicated a sizeable wake structure behind the mirror. 4) Soiling studies revealed that water entrained in this wake structure was deposited on the mirror surface.

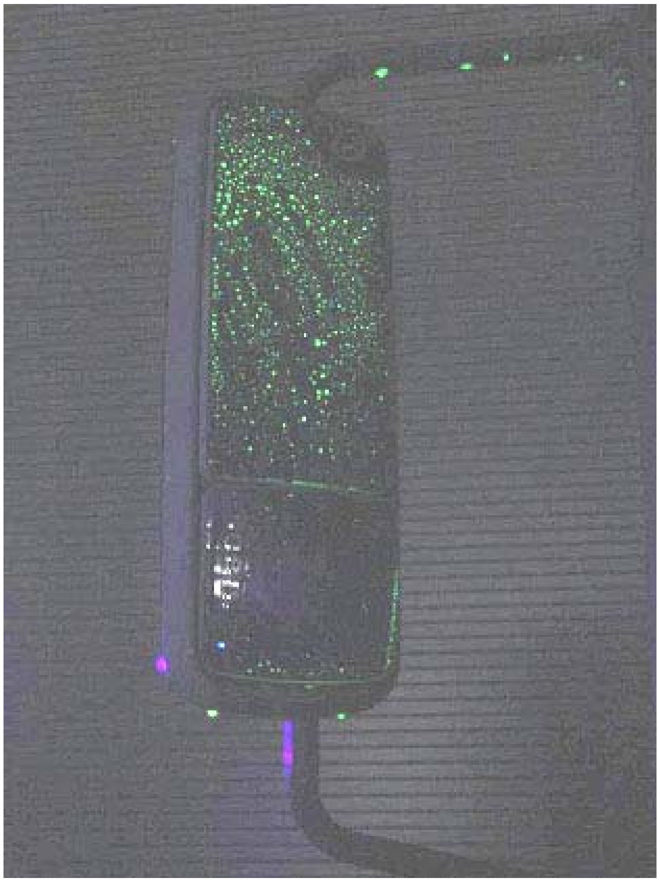


Figure 3-8. Mirror Soiling Results

3.3 Phase II Overview

Freightliner focused on the effect of mirrors and mirror design on truck aerodynamics. The key Phase II conclusions drawn by Freightliner included:

- Several mirror design parameters (frontal area, shape, alignment, and placement in the flowfield) have significant effects. For instance, mirror housing should be curved and placed appropriately with respect to the A-pillar and cowl vortex. Mirror mounting structure should have a minimal number of struts, since together they form a complex system with a larger wake. Finally, the mirrors and cab should be designed as one integrated system. With well-designed mirrors, aerodynamic drag can be reduced 2 to 3 percent. Eliminating mirrors altogether would yield a 6 percent improvement.
- CFD simulations and wind tunnel testing are complementary tools that should be used together to develop vehicles and accessories. These two tools provide repeatable results that eliminate the effects of differing environmental conditions that occur when vehicles are tested on-road. The result of this study is valuable information on mirror system design and placement that can be used by all manufacturers.

3.4 Phase II Activities

Overall Description of Phase II Work

The objective of the Phase II effort was to conduct preliminary full-scale wind tunnel testing and Computational Fluid Dynamics (CFD) analyses on a current production Class 8 tractor with various mirrors installed. The results of this effort demonstrated the aerodynamic drag levels and flow physics associated with mirror systems in-use today. In addition to the stated objectives, Freightliner collected soiling data (from water dispersion on the glass mirror surfaces affecting visibility) as well for comparison purposes.

All of the objectives of Phase II were completed. Both full-scale wind tunnel tests and Computational Fluid Dynamics analyses were conducted on a current-production Freightliner Century Class tractor. The vehicle was evaluated with three mirror systems (and a no mirror configuration for comparison) at three different yaw angles. Aerodynamic drag levels, flow field visualization, and soiling data were generated and collected. These results were combined with those from Phase I for analysis.

Detailed Description of Phase II Work

Wind Tunnel

All wind tunnel tests were conducted in Freightliner's full-scale aerodynamic wind tunnel located in Portland, Oregon. The tunnel is an open return, closed jet facility specifically designed for aerodynamic development of Class 8 tractors. As such, it incorporates a 3-component underfloor balance for measuring tractor loads and a 1-component balance installed in the built-in trailer for measuring trailer drag.

CFD

The Computational Fluid Dynamics (CFD) code used throughout this study was PowerFLOW™ by EXA Corporation. Selection of this code was driven by computational efficiency and robustness and is Freightliner's standard for exterior aerodynamic CFD studies. Detailed digital models of the test vehicle were developed using available CATIA™ data. Post-processing and data analysis were accomplished via PowerVIZ™.

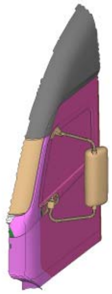
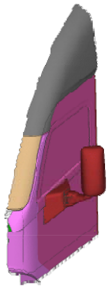
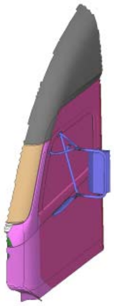
Test Vehicle
The vehicle used for both the wind tunnel testing and CFD analyses was a Freightliner Century Class model outfitted with several different mirrors. Figure 3-9 shows the test vehicle installed in the wind tunnel. Detailed specifications for the truck are presented at the end of Section 3.

Figure 3-9. Freightliner Test Vehicle in Wind Tunnel (-6.0 degrees yaw)

Test Methodology
The objective of the Phase II effort was to build on wind tunnel testing and CFD analyses from Phase I to demonstrate the aerodynamic drag levels and flow physics associated with mirror systems in-use on Class 8 tractors today. Consequently, the vehicle was evaluated with two different mirror systems at yaw angles of -6, 0, and +6 degrees. These conditions were maintained for both the experimental and computational portions of the study. In addition, experimental mirror soiling studies were conducted at 0 degrees of yaw. All tests and simulations were conducted at typical highway speeds. A baseline was established in phase I by testing the Century Class with no mirrors. The standard "aero" mirror on Freightliner's Century Class was also tested in phase I. The mirror systems evaluated in Phase II were "West Coast" style mirrors and a "single post" design.

Aerodynamic Drag
By comparing the overall tractor-trailer drag levels both with and without the mirrors installed, the drag associated with the mirrors was determined. Table 3-2 presents the aerodynamic drag of the baseline mirrors as a percentage of overall tractor-trailer drag.

Table 3-2. Mirror Drag (percent of total vehicle)

Mirror	 "Aero" Mirror	 Single Post	 "West Coast"
-6 degrees	3.4%	4.8%	4.7%
0 degrees	3.8%	5.9%	5.4%
6 degrees	2.1%	2.3%	2.5%

Several items are evident from the data in Table 3-2. First is the difference in mirror drag between -6 degrees and +6 degrees yaw. This difference was due to asymmetry of the truck geometry. Each mirror was positioned differently relative to the longitudinal axis of the truck (Figure 3-10). In addition, underhood and underbody components were positioned off of the central axis. Thus, the differences in mirror drag for the various yaw angles presented in Table 3-2 were acceptable and correct.

The second item evident from the results presented in Table 3-2 is that mirrors contributed approximately two to six percent of a tractor-trailer's overall aerodynamic drag. This results in increased fuel usage of about one to three percent for long-haul applications.

Flow Visualization

Figure 3-10 shows the front isometric view of the three mirrors analyzed in Phase II. The "no mirror" case was the baseline.

CFD & Wind Tunnel analyses were performed on all three mirror designs at 0^0, $+6^0$ and -6^0 yaw cases. However, in this section only the results for the 0^0 yaw cases are provided.

Figures 3-11 through 3-15 show the smoke flow & CFD streamline data images for the mirror regions of the truck. These images reveal the mirror wake structures, streamlines and interaction effects with the a-pillar of the truck.

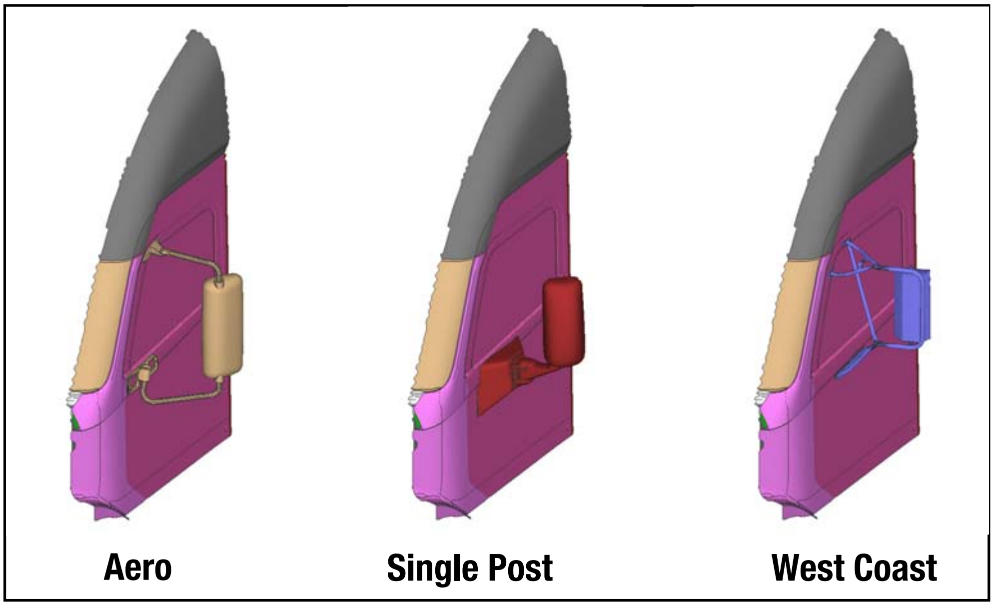


Figure 3-10. Mirror Designs Analyzed in Phase II

Figure 3-11 compares the smoke flow in the wind tunnel tests to the streamline plots generated using CFD. For the zero yaw case in Figure 3-11a, the experimental smoke flow is shown on the left while the corresponding streamline plot is on the right. The images in 3-11a through 3-11d illustrate the following:

1. The presence of the mirror forces the impinging air to accelerate around both the inboard and outboard surfaces of the mirror housing, leaving a wake region immediately downstream of the mirror.
2. Mirror shape plays an important role in the size of the wake and the flow acceleration around the wake. Aero mirrors (Figure 3-11b) have a more aerodynamic shape and the area of the mirror that sees the flow is very small. As a result the wake behind the mirror is small, yielding the least drag among the three designs.
3. The position of the mirror in the flow field is also important. The mirror housing will split the on-coming flow into two parts. The "inside flow" goes between the mirror housing and cab while the "outside flow" goes on the outside of the mirror housing. The Aero mirror (Figure 3-11b) is placed in such a lateral location, that the "outside flow" is the high speed flow. For the West Coast mirrors (Figure 3-11c) and Single Post mirrors (Figure 3-11d), the inside flow is the high speed flow. This high speed flow has no place to relax and eventually causes a larger wake and thus a higher drag for West Coast & Single Post mirror designs.

The adjacent Figure 3-12 shows the iso-surface plot for the four simulation cases at 0^0 yaw angle. As can be seen, the no mirror case has a very clean a-pillar vortex that wraps around the a-pillar of the tractor. The presence of the mirror breaks this a-pillar vortex into two vortices, the a-pillar vortex and the mirror vortex, leading to a larger low velocity region. The larger size of these vortices (or the low velocity regions) leads to a higher drag in the Single Post & West Coast mirror designs.

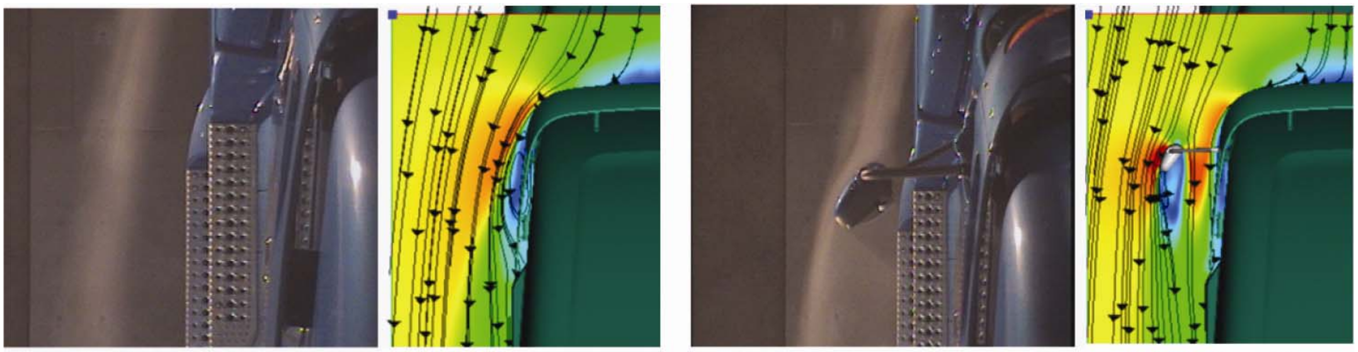


Figure 3-11a. No Mirrors

Figure 3-11b. Aero Mirrors

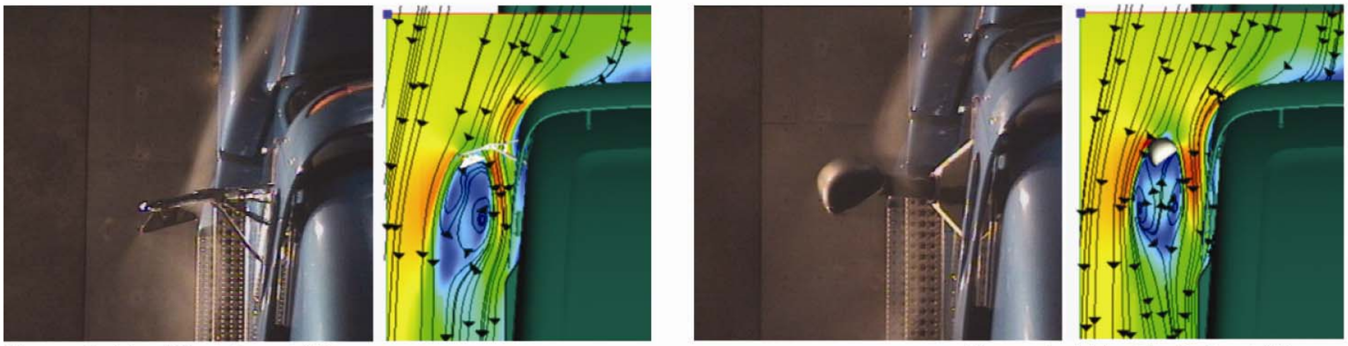


Figure 3-11c. West Coast Mirrors

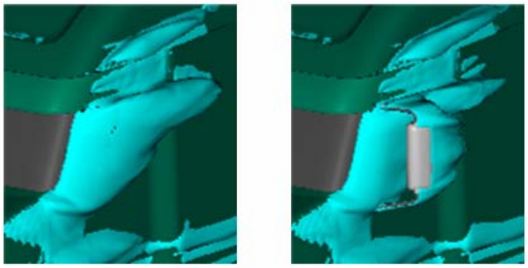
Figure 3-11d. Single Post Mirrors

Figure 3-11. Smoke Flow from Wind Tunnel Testing & Streamlines from CFD at 0° Yaw

Figure 3-13 below shows the velocity section slices for Aero mirrors (Figure 3-13a) and West Coast Mirrors (Figure 3-13b) for the 0^0 yaw simulation. The velocity magnitudes in both cases were set to the same minimum/maximum. The images show that:

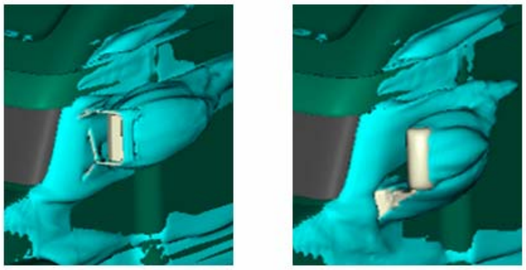
1. The mirror wake for the aero mirrors is smaller than the mirror wake for the west coast mirrors.
2. The mounting structure (tubes) for the west coast mirror also leave a trace (wake) which combines with the mirror housing wake structure.

Based on the ergonomics of the tractor and the driver seat, the driver side & passenger side mirrors have a different orientation. For the truck used in simulations, the angle that the mirror housing makes with the centerline was 4^0 higher on the driver side (Figure 3-14). The effects of this are shown in the velocity plot in Figure 3-15 for the Aero mirror simulation at 0^0 yaw. The mirror wakes between the driver side and passenger sides are substantially different, leading to different drag numbers when simulated for $+6^0$ and -6^0 yaw angles.



No Mirrors

Aero Mirrors



West Coast

Single Post

Figure 3-12. Iso Surfaces for $Cp_{Total} = 0$

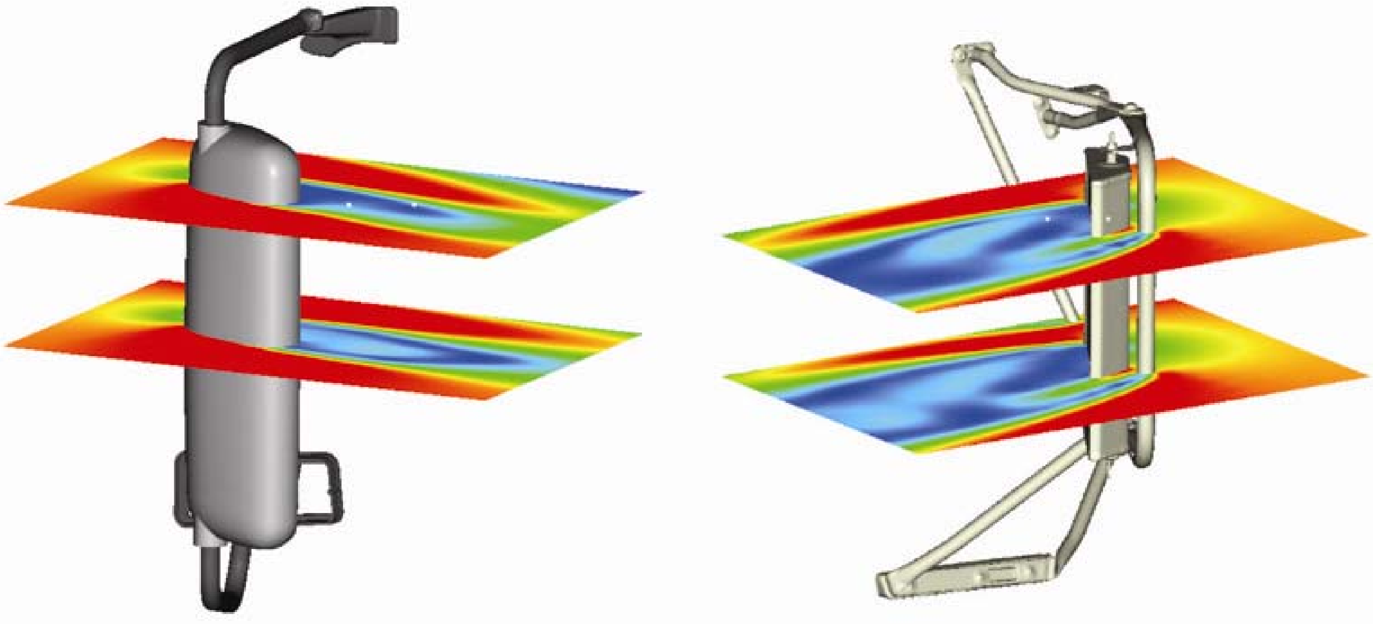


Figure 3-5a. Aero Mirror

Figure 3-5b. West Coast Mirror

Figure 3-13. Velocity Section Slices Taken at the Same 'z' Elevation for 0° Yaw Simulations

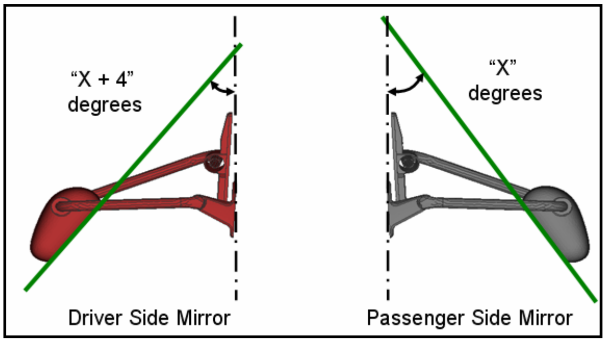


Figure 3-14. Different Orientations between Driver & Passenger Side Mirrors

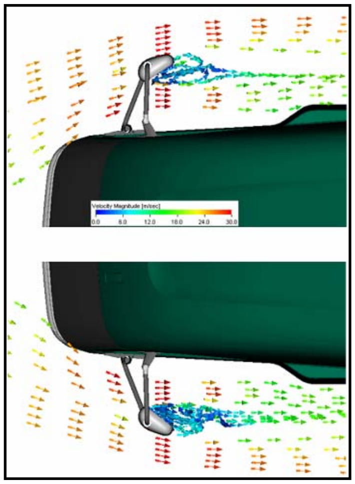


Figure 3-15. Effects of Different Mirror Orientations

Mirror Soiling

Figure 3-16 shows photos of the driver's side mirrors following Freightliner's proprietary mirror soiling testing. The photos depict the reflective surfaces of the mirrors showing water droplets deposited during the tests. The water droplets were treated with a fluorescent dye and illuminated by ultraviolet light.

The images clearly show that the single post mirror shed accumulated water droplets much more effectively than the other two styles of mirrors. Analysis indicated that this was primarily due to the mirror glass

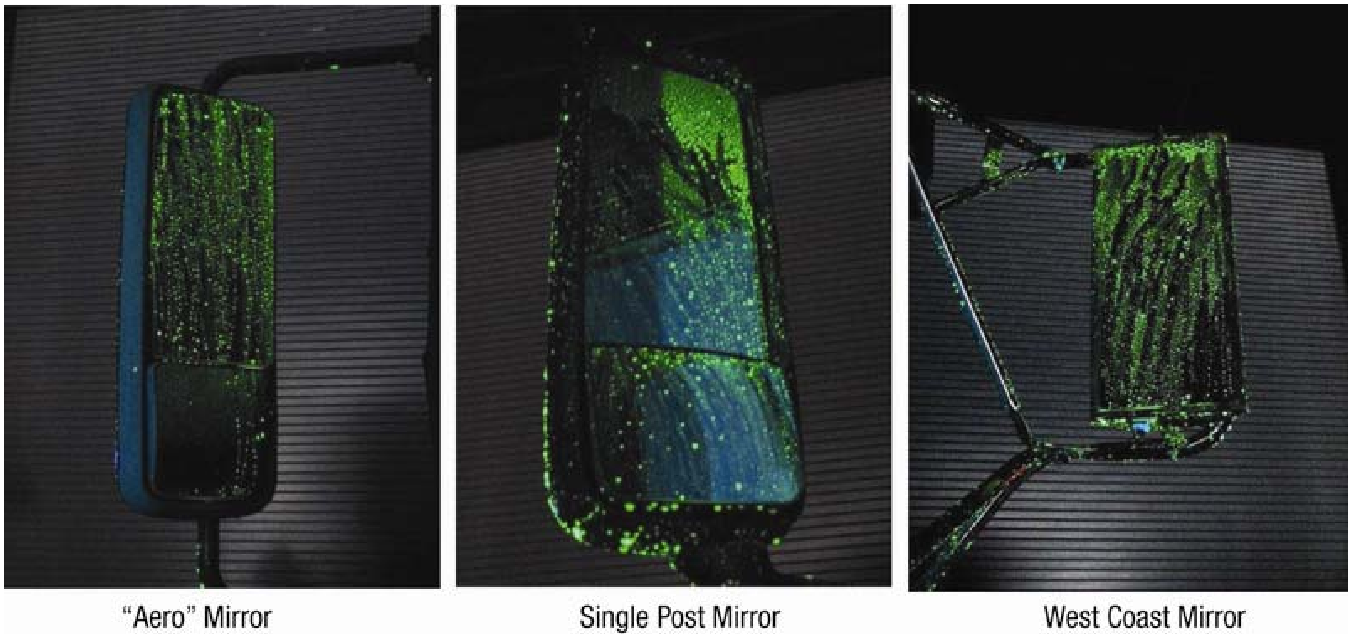


Figure 3-16. Mirror Soiling Results

being recessed into the housing for the single post design. The recess acted to hold vortices that were shed onto the mirror glass, creating a natural "wiping" effect.

Conclusions

To minimize aerodynamic drag on a truck, the mirror and cab should be designed as a system. Mirror effects are seen downstream as far as the trailer. For example, the "Aero" mirror which was designed to fit with the Century Class truck provides the lowest drag percentages. The West Coast mirror, which has the most complex multi-strut mounting system including sharp edges and a rectangular face on the mirror housing, showed results similar to the single post mirror. Even though the single post mirror has fewer struts to cause wakes and a preferable rounded mirror housing, the housing and positioning were not designed to fit with this particular test truck; thus the importance of integrating the mirrors into the vehicle flowfield as one system.

Several mirror design parameters are important: the frontal area, the shape, alignment and placement. Ideally a mirror is designed to fit with a particular cab, and the mirror housing should be curved and placed appropriately with respect to the A-pillar and cowl vortex. The mirror mounting structure should have a minimal number of struts as together they form a complex system with a bigger wake.

There is a potential to reduce drag by 2% to 3% with well-designed mirrors and a potential to reduce drag by +6% by eliminating mirrors. Currently, outside mirrors are necessary on a truck and are an accessory that is in complete control of vehicle manufacturers. This makes the implementation of design improvements practical and immediately achievable.

Finally, Computational Fluid Dynamics (computer modeling) and Experimental Fluid Dynamics (wind tunnel testing) are complimentary tools that work well together in the development of vehicles and accessories. They provide a good check and balance for the types of detailed adjustments that can be made to the vehicle and mirror to achieve optimal results in the reduction of aerodynamic drag. They also provide a relatively quick turn around time that just cannot be achieved in a field test trial.

Freightliner Test Vehicle Data Sheet

Test Number: 2005-015 Wheelbase: 240 inches	Manufacturer: Freightliner Frontal Area: 109.75 ft^2	Model: Century S/T SN#G32852 Max Width: 102 inches

Roof	Truck	Front Axle
Raised	Conventional Sleeper Cab Sleeper Length: 70 inches	Back Number of Axles – 3 Tire Mfg: Michelin Tire Size: 275/80 R22

Options

Front Chassis Fairings Mid Chassis Fairings Rear Chassis Fairings	Side Extenders Angle: 5 (deg)	Main Mirrors

4. International Project Activities

4.1 Phase I Overview

International focused on investigating drag reduction opportunities for three areas within the tractor-trailer system: tractor-trailer gap, trailer side and trailer wake. This approach addressed a major source of aerodynamic drag in a typical class 8 tractor-trailer application. The key Phase I activities completed by International included:

- Demonstrated 23% reduction in aerodynamic drag using trailer skirts, base plates and lengthened side extenders and air fairing; anticipate 11-12% fuel economy improvement at 65mph
- Demonstrated 20%+ drag reduction for several configurations
- Formed partnership with major trailer manufacturer for Phase II—expect to finalize in January 2006
- Demonstrated 30% drag reduction with reduced frontal area trailer plus aero devices

4.2 Phase I Activities

Overall Plan

Multiple devices were developed and evaluated for each area of focus. The most promising concepts were refined and re-evaluated as necessary. Select devices or combinations of devices will be recommended for full-scale on-road evaluation in Phase II.

Tractor-Trailer Gap

Devices were developed that broadly fit into two categories: partial gap closure and total gap closure. Up to four devices were evaluated in each category. These included studying the effects of varying side extender length and shape, installing vertical plates in the gap and investigating trailer forebody shapes.

Trailer Side

Various trailer skirting options were developed and evaluated. The impact of varying skirt shape, fore-aft location and height was considered in addition to a “belly box” which effectively lowers the floor of the trailer between the tractor drive wheels and the trailer wheels.

Trailer Wake

Various configurations of trailer base plates were evaluated. The impact of varying plate length, angle and shape was considered.

Methodology and Model Description

Phase I evaluations were conducted via reduced scale wind tunnel testing. Sub-scale testing is a very efficient and accurate method to conduct trade studies and evaluate alternate shapes. International developed its current generation of industry leading aerodynamic tractors with methods used in this project.

Figure 4-1. Baseline Tractor-Trailer Set-up

Figure 4-2. Baseline Tractor-Trailer Set-up

The tractor used in Phase I testing was a 1/8-scale model of an International 9400 72” Hi-rise Sleeper with a full aerodynamic package. It is shown in Figures 4-1 and 4-2. The tractor model was fully detailed including all pertinent exterior, engine compartment and chassis details. The tractor was paired with fully detailed 1/8-scale van trailer models that included landing gear, exposed structural beams and suspension. Utilizing multiple trailers allowed for the impact of the trailer wake devices to be investigated relative to trailer fineness ratio. During Phase I testing, trailer fineness ratio, l/d, which is defined by the ratio of trailer length divided by effective diameter, varied between 3.7 and 4.8. The baseline van trailer model was 8.5’ wide x 13.5’ tall x 45’ long.

Design Parameters

Throughout the report, non-dimensional parameters are used to characterize aerodynamically relevant geometry in the tractor-trailer system. It is helpful to define the following parameters, illustrated in Figure 4-3.

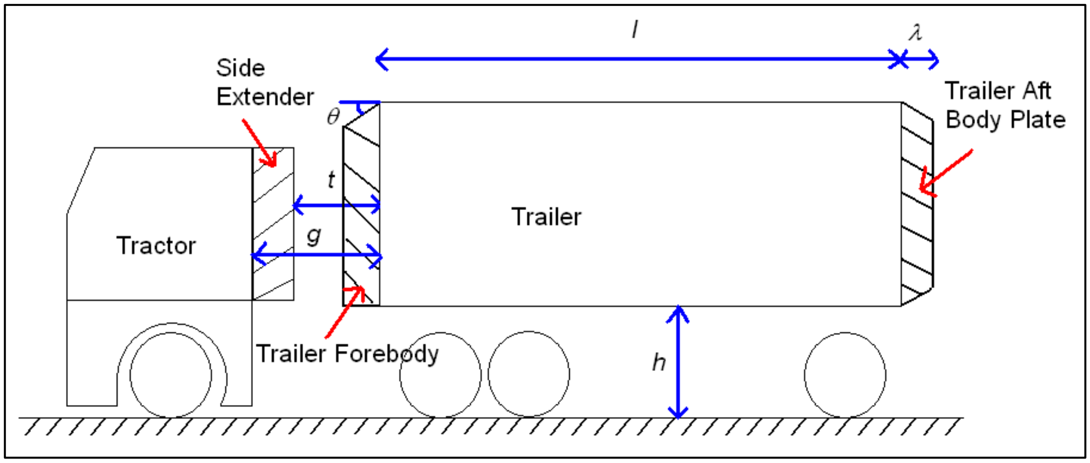


Figure 4-3. Aerodynamically Relevant Geometries of Tractor-Trailer

Trailer Fineness Ratio, l/d: Trailer fineness ratio is defined as the ratio of trailer length divided by effective diameter (l/d). Effective diameter can be calculated by the following equation, given in ref. 1, where A is the projected frontal area of the trailer. The baseline trailer had an l/d = 3.7.

$$d = \sqrt{\frac{4A}{\pi}}$$

Ground Clearance Ratio, h/d: Ground clearance ratio is defined as the ratio of trailer height to ground divided by effective diameter (h/d). The baseline trailer had an h/d = 0.33.

Side Extender Gap Ratio, t/d: Side extender gap ratio is defined as the ratio of the side extender-to-trailer gap divided by effective diameter (t/d). The side extender-to-trailer gap is measured from the trailing edge of the side extender to the front face of the trailer. The baseline tractor-trailer had a t/d = 0.22.

Tractor-Trailer Gap Ratio, g/d: Tractor-trailer gap ratio is defined as the ratio of the tractor-trailer gap divided by effective diameter (g/d). The tractor-trailer gap is measured from the back of cab (lower edge) to the front face of the trailer. The baseline tractor-trailer had a g/d = 0.33.

Trailer Aft Body Length Ratio, λ/l: Trailer aft body length ratio is defined as the length of an aft body treatment device divided by trailer length (λ/l). The baseline trailer had a λ/l = 0 because no aft body device was installed.

Facility and Test Procedure

All testing was conducted at Oran W. Nicks Low Speed Wind Tunnel at Texas A&M University. The wind tunnel is the closed circuit, single return type having a rectangular test section 10 feet wide, 7 feet high, and 16 feet long. [ref. 2] Typical test Reynolds number per foot was approximately 1.5×10^6.

All drag coefficient increments quoted in this report are wind averaged at 7 & 55 mph and calculated per the SAE recommended practice J1252 [ref. 3], for heavy truck wind tunnel testing. Wind averaged drag coefficient includes the major effects of the natural wind and is the best measure of "real world" performance, as defined by average, on-road aerodynamic performance over an extended period of time.

Results Summary

The drag reducing impact of each individual device is illustrated in Figure 4-4. These results were analyzed based on both the individual device contribution, as well as the incremental contribution obtained by adding the device in combination with other previously installed devices. The total drag reduction as a result of device combination was not always equal to the sum of individual device's drag contribution.

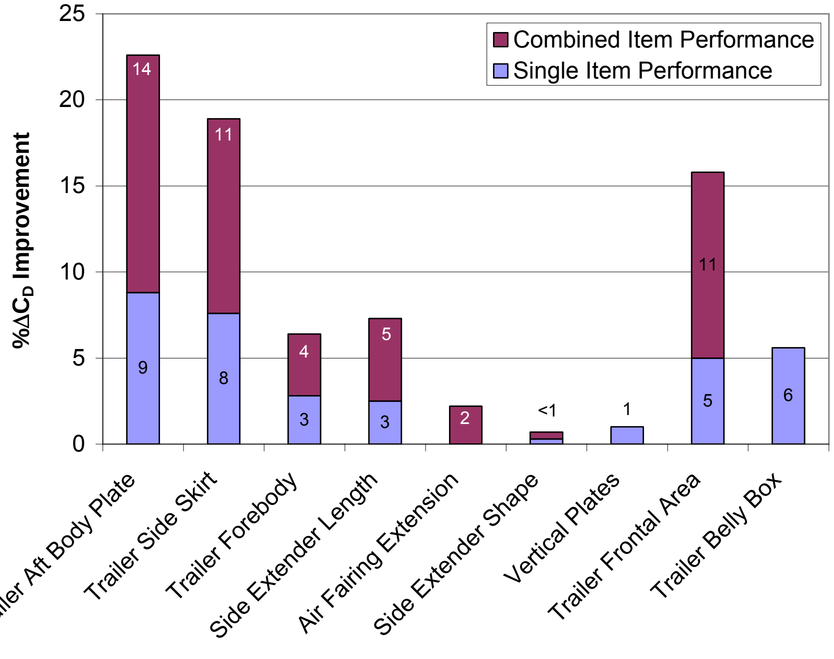


Figure 4-4. Performance Overview of Drag Reduction Devices

The test results showed that the largest drag reductions came from adding trailer aft body plates and trailer skirts. The plates provided a 9 to 14% drag reduction and adding skirts provided an 8 to 11% drag reduction. The results were consistent across the range of trailer fineness ratio evaluated, from 3.7 to 4.8.

Significant drag reductions were also demonstrated by installing trailer forebody shapes (3 to 4%) and modifying side extender shape and length (3 to 5%). A 5-11% reduction in drag was also observed by reducing trailer frontal area. This was run in conjunction with the belly box investigation to ascertain the potential benefit of a far-reaching opportunity; available if trailer geometry changes were considered. It would require fundamental changes to trailer geometry, likely loss of trailer interior volume, and it was not considered a mainstream recommendation.

Table 4-1. Results of Various Side Extender Top Edge Shapes

Side Extender Top Edge Shape	% Change in C_n (Compared to Baseline)
Baseline	--
Slight Curl	0%
Flare Curl	0%
Flat Curl	< -1%
No Curl	0%

Tractor-Trailer Gap

The actual tractor-trailer gap was not varied during the test. It was set at a tractor-trailer gap ratio of g/d = 0.33 which is a typical gap for good fuel economy. For any application, there is a minimum practical tractor-trailer gap which is usually dictated by trailer swing criteria, and sometimes influenced by vehicle weight distribution and owner preference.

The work associated with this report utilized six approaches to reduce tractor-trailer gap drag. They are as follows:

1.) New side extender top edge shapes
2.) Various side extender lengths
3.) New air fairing extension shapes
4.) Various air fairing extension lengths
5.) Various trailer forebody shapes
6.) Various vertical plate configurations

Some of these devices demonstrated significant drag reductions, while others did not. The following paragraphs provide individual results and analysis for each of the six concepts.

Side Extender Top Edge Shape Study: The top edge of the side extender influences the interaction of flows departing the top and sides of the air fairing. Four different shapes were evaluated for the top edge of the side extender as shown in Figure 4-5. The results in Table 4-1 indicate most

Figure 4-5. Side Extender Top Edge Shapes Evaluated

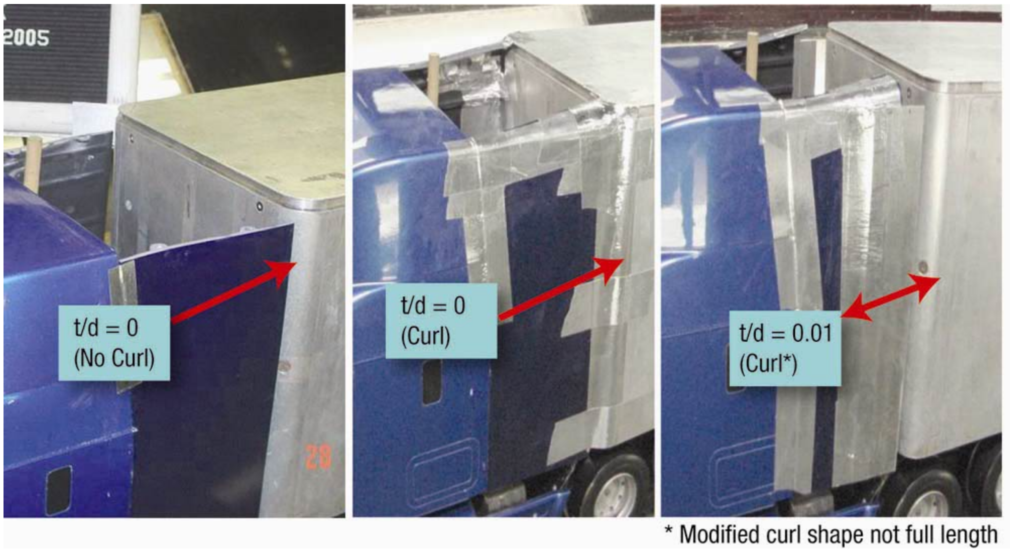
shapes provided no additional drag reduction versus the baseline part.

Table 4-2. Results of Various Gaps Associated with Side Extender Lengths and Top Edge Shapes

	%ΔC_n (Compared to Baseline)	
t/d	**No Curl**	**With Curl**
0	-3%	-4%
0.01	N/A	-2%*
0.03	N/A	-2%*
0.08	-1%	-1%
0.16	-1%	N/A
0.22	0%	-1%
0.27	1%	N/A

* Modified curl shape—not full length

Side Extender Length Trade Study: Significant drag reduction was obtained by lengthening the side extenders. The evaluations were conducted with multiple side extender top edge shapes. The results are shown in Table 4-2 and illustrate up to 4% drag reduction could be obtained if the side extenders were able to completely close the gap (t/d = 0). An additional 1% benefit was possible from optimizing the top edge shape. However, significant operational concerns exist, such as trailer swing, and provide a practical limit to side extender length. It would be a significant challenge to develop a "practical" side extender device that would always maintain the minimum required gap to the trailer face under a variety of operating conditions.



* Modified curl shape not full length

Figure 4-6. Example of Varying Side Extender Top Edge Shape at a Given Side Extender Length

Air Fairing Extension Shape Study: The air fairing extensions were not evaluated as individual devices; the air fairing extensions were evaluated in combination with side extender length concepts. Two air fairing trailing edge shapes were tested, "partial" and "full", as illustrated in Figure 4-7. There were also two trailing edge heights evaluated, "flare" and "flat", also illustrated in Figure 4-7. The air fairing extension shapes did not provide a significant drag reduction, and many provided no drag reduction at all as shown in Table 4-3.

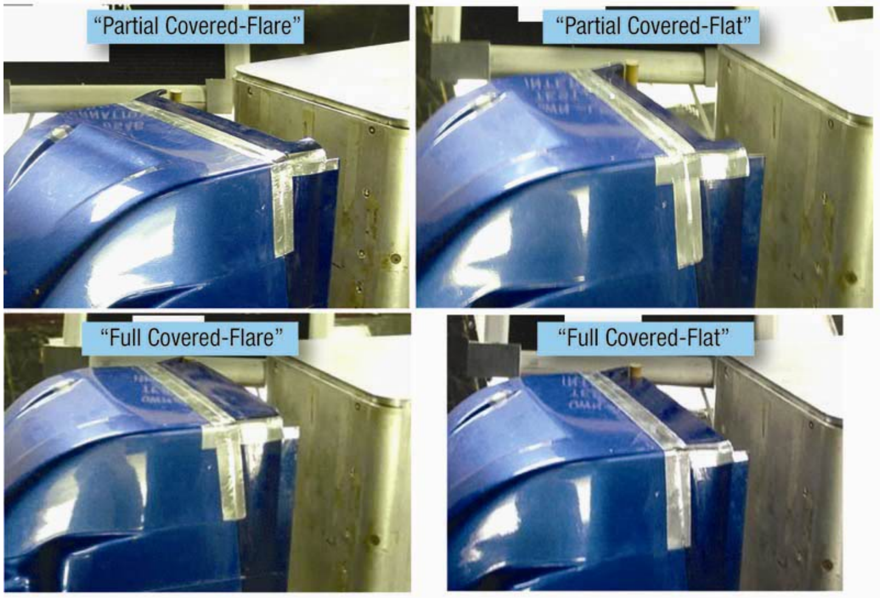


Figure 4-7. Air Fairing Extension Shapes Tested

Air Fairing Length and Shape Trade Study: Air fairing length extensions were evaluated in combination with certain side extender length concepts. The air fairing length extensions were not evaluated as individual devices. Two shape of air fairing extensions were tested, "flat" and "flared". As shown in

Table 4-3. Results of Air Fairing Extension Shapes Tested

Air Fairing Extension Configuration	%ΔC_D (Compared to Baseline)
"Partial Covered - Flare"	0%
"Partial Covered - Flat"	-1%
"Full Covered - Flare"	0%
"Full Covered - Flat"	0%

Table 4-4. Experimental Results of Various Lengths and Shapes Associated with Air Fairing

	%ΔC_D (Compared to no curl configuration)	
t / d	"Full Covered – Flat" Extension	"Full Covered – Flare" Extension
0	-2%	N/A
0.8	-2%	-2%
0.16	-2%	N/A
0.27	0%	1%

Table 4-4, the flat air fairing extension provided a 2% drag reduction over most of the lengths tested, but the flared extension did not consistently provide a drag reduction.

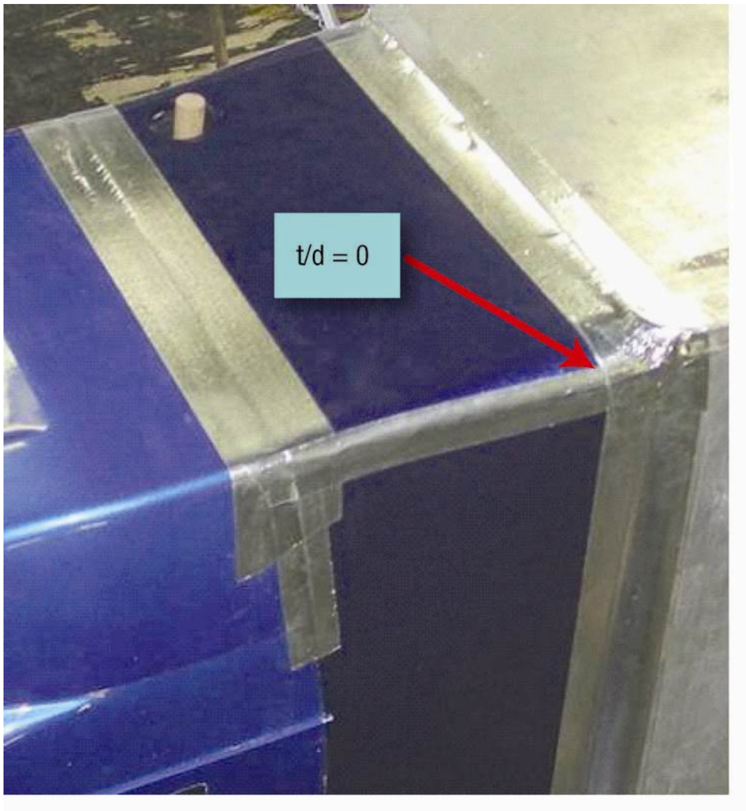


Figure 4-8. Example of "Flat" Air Fairing Length Extension as Tested

Trailer Forebody Study: Shape & Angle: As an alternative to installing devices on the tractor, this section addresses reshaping the trailer forebody to obtain a drag reduction. Note that the tractor-trailer gap remains unchanged and the baseline side extenders remain installed while testing these devices.

Two design parameters, defined by forebody shape and inclination angle, were used to achieve the best performance. Simple illustrations of these definitions are shown in Figures 4-9 and 4-10. Test results showed that up to 3% drag reduction can be achieved using these devices, as shown in Table 4-5.

Vertical Plates: Another approach to reduce the drag associated with flow through the tractor-trailer gap was to use vertical plates to either completely block the gap, or partially block the gap. The partially blocked configurations were intended to deter air from flowing through the gap by creating a tortuous path for the air to navigate.

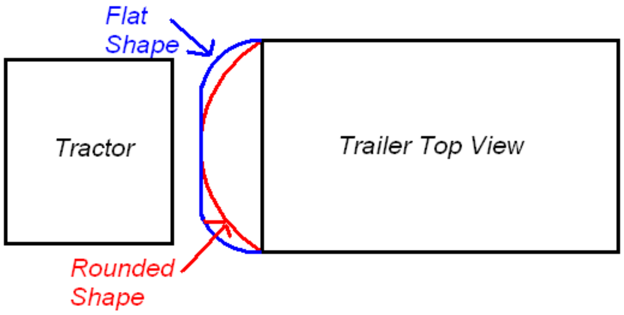


Figure 4-9. Schematic of Trailer Forebody Shape Definition

For the test, plates were mounted to the tractor only, the trailer only, or both tractor and trailer. The configurations evaluated are illustrated in Figure 4-11 and results are tabulated in Table 4-6.

Test results show that these devices provided drag reduction opportunities of only 1% or less. It should be noted that the test was performed with the baseline side extenders installed.

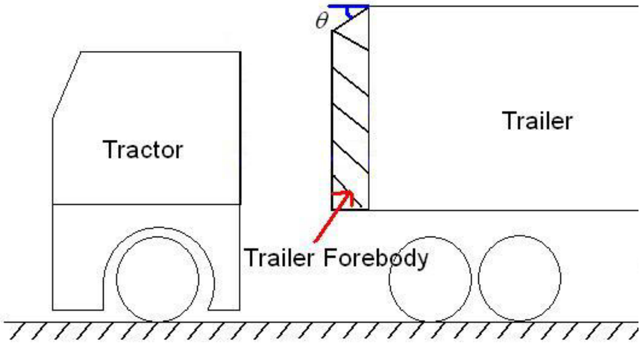


Figure 4-10. Schematic of Trailer Forebody Inclination Angle Definition

Table 4-5. Results of Various Trailer Forebody Shapes and Inclination Angles

Trailer Forebody Inclination Angle θ, deg	%ΔC_D (Compared to Baseline) “Rounded” Shape	“Flat” Shape
0	1%	2%
15	-3%	N/A
30	-2%	-3%
45	-2%	N/A

Table 4-6. Results of Testing with Various Vertical Plate Configurations

Vertical Plates Configuration	%ΔC_D (Compared to Baseline)
Center Plate	0%
Tractor & Trailer Plates	-1%
Trailer Plates	-1%
Tractor Plates	0%

<u>Trailer Side</u>

Various trailer skirt shapes have been evaluated internally at International in the past and more recently by members of the DOE Heavy Truck Aerodynamic Consortium [ref. 4] and National Research Council Canada [ref. 5]. Common objections exist to adding skirts to trailers which include their propensity to accumulate ice and snow and susceptibility to damage.

Phase I development and evaluation in this area focused on collecting trade study data on the performance impact of varying skirt height and shape. That data directly supported the Phase II development and implementation of a solution intended to address common historical objections to skirts. The trailer side drag reduction opportunities investigated were as follows:

1.) Various skirt shapes
2.) Skirt height and trailer height impact
3.) Belly box impact

Skirt Shape Trade Study: Three basic skirt shapes were designed for this test. They were a straight skirt, V-shaped skirt and a U-shaped skirt. The straight skirt is a flat plate extended down from each side of the trailer. The U-shape and V-shape skirts are attached across the trailer underbody. The test results in Table 4-7 show that the straight skirt provided the most drag reduction.

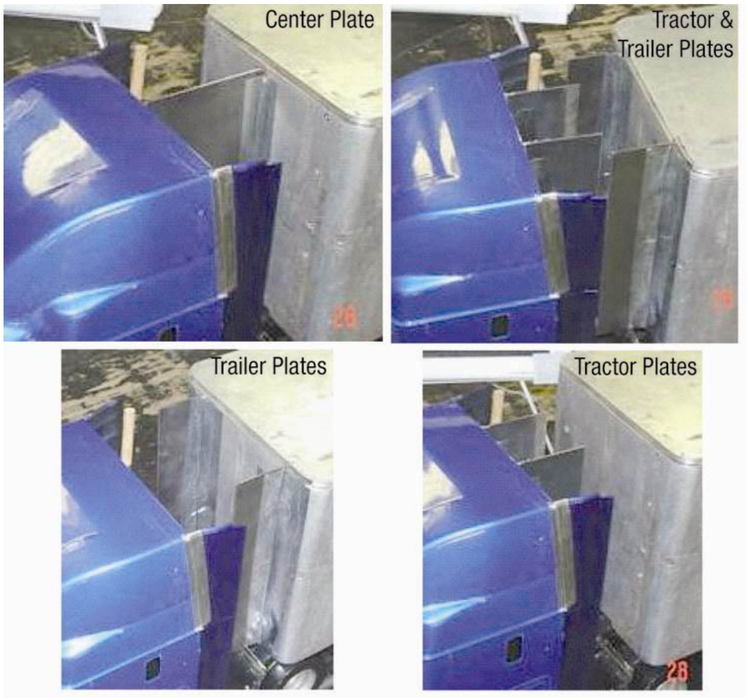


Figure 4-11. Vertical Plate Configurations Evaluated During Test

Table 4-7. Impact of Trailer Side Skirt Shape

Skirt Shape Configuration	%ΔC_D (Compared to Straight Skirt)
Straight	0%
U-Shape	3%
V-Shape	4%

Figure 4-12. Various Side Skirt Shapes Tested in Wind Tunnel

Skirt Height Trade Study and Trailer Height Impact: A trade study on side skirt height was developed to understand the performance impact of raising/lowering skirt height. These data were very important to comprehend in the design of a practical device whose height may be limited by its ability to successfully traverse railroad crossings and egress from submerged loading docks without damage. The test results showed that the closer the skirt edge is to the ground distance (smaller h/d), the greater the drag reduction opportunity. This effect is linear as shown in Figure 4-13. This trend was consistent across the range of trailer fineness ratio evaluated.

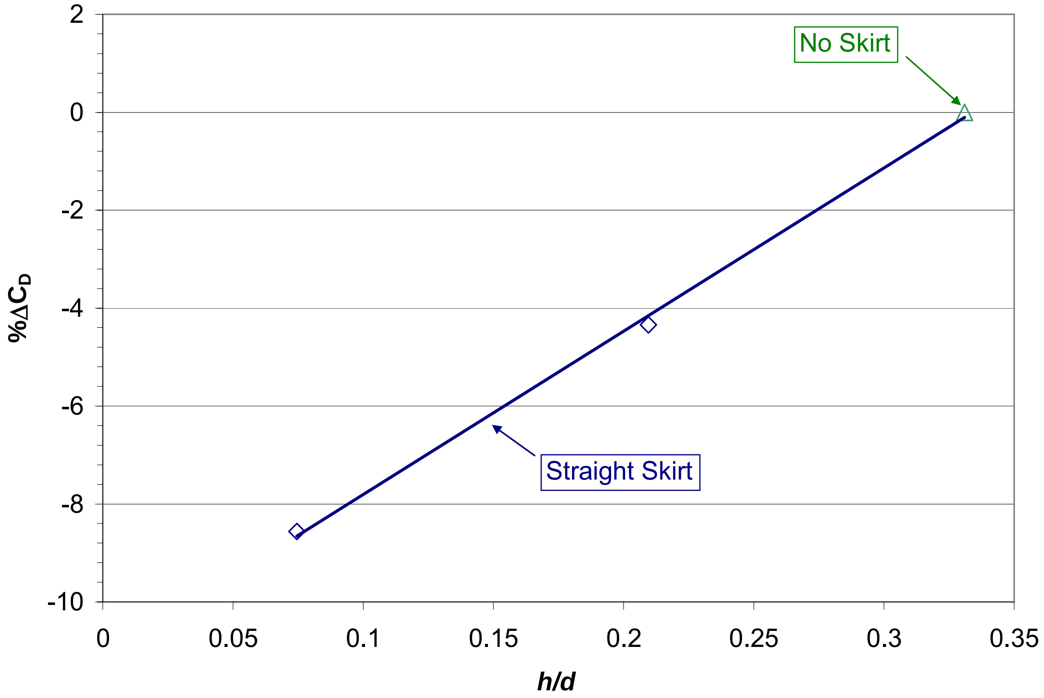


Figure 4-13. Impact of Varying Straight Skirt Height to Ground

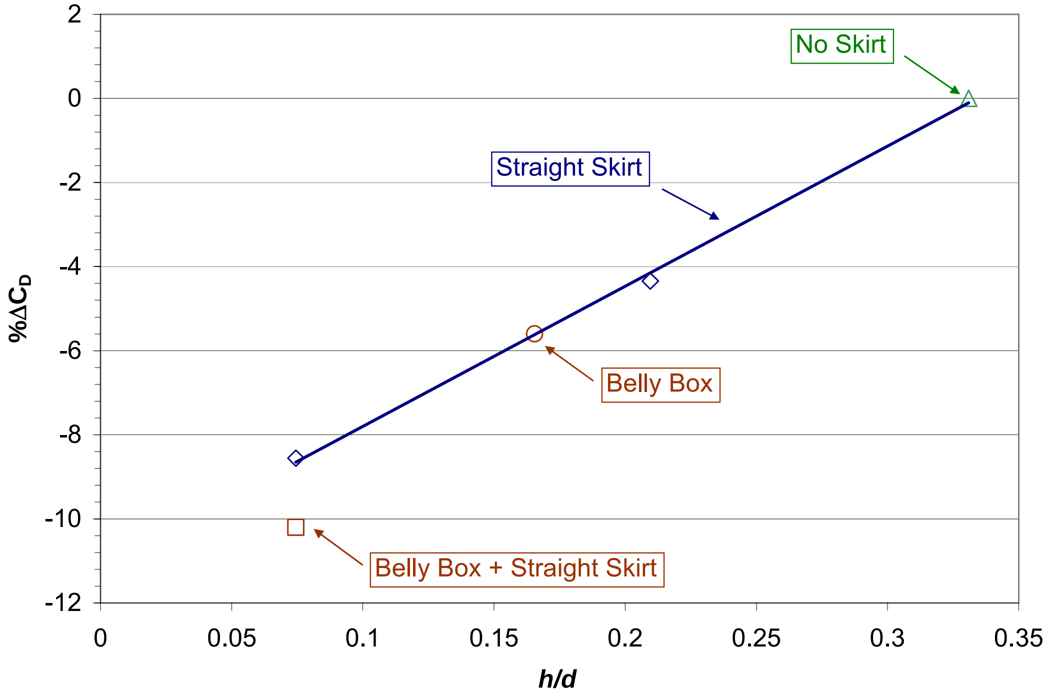


Figure 4-14. Impact of Belly Box versus Varying Straight Skirt Height to Ground

Figure 4-15. Belly Box and Side Skirt Tested

Belly Box Impact: As an alternative to skirting the side of the trailer, a belly box was investigated as a drag reduction device. Typically, a belly box is not an add-on device, but rather an integral part of a "low boy" trailer design. In this design, the structural floor of the trailer was lowered to accommodate more or taller cargo. However, lowering the trailer floor also reduces ground clearance ratio. In this evaluation the belly box was installed on the underside of the existing trailer model. It is important to note that the belly box was completely closed on the bottom and all sides, and did not contain exposed structural members beneath its floor. Test results show the belly box provided equivalent drag reduction to a skirt of the same h/d. If the belly box was supplemented with the addition of a side skirt, the results in Figure 4-14 showed it reduced the drag more than a side skirt alone at the same h/d.

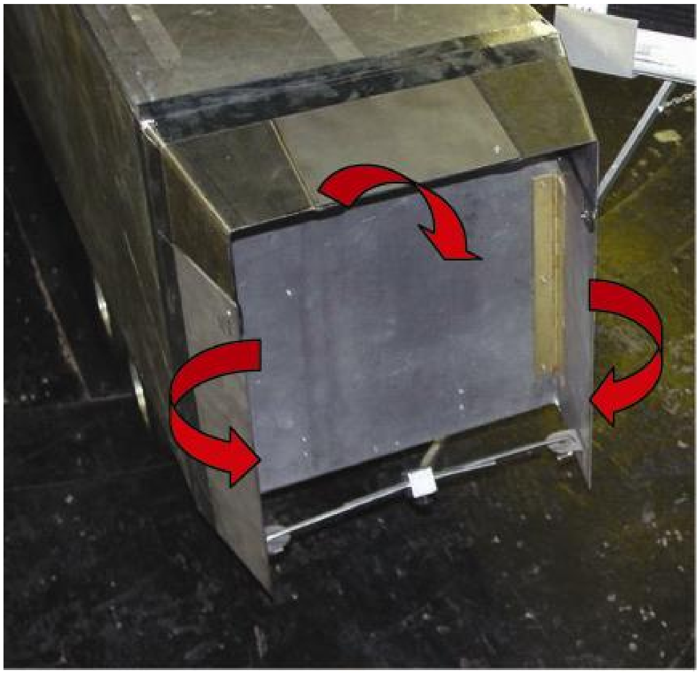


Figure 4-16. Example of Trailer Aft Body Plate Installation

Trailer Wake

As with trailer side skirts, various trailer aft body plates have been evaluated internally at International in the past, and recent data published by National Research Council Canada [ref. 5] and by members of the DOE Heavy Truck Aerodynamic Consortium [ref. 4] concurred that substantial drag reduction can be obtained via this class of aerodynamic add-on devices. There are commercially available devices of this category currently on the market, yet they are not frequently observed on trailers in service. Common objections exist to adding aft body devices to trailers which include a propensity for the device to be damaged during loading dock operations or during low speed maneuvering in a truck stop, for example.

Phase I development and evaluation in this area focused on collecting trade study data on the performance impact of varying plate shape, angle and length. Plates were only evaluated along the sides and top of the trailer. These data will directly support the Phase II development and implementation of a solution intended to address common historical objections to trailer aft body devices. The trailer aft body plate drag opportunities investigated were as follows:

1.) Plate length
2.) Plate Inclination angle
3.) Plate shape

Table 4-8. Impact of Angle Variation on Aft Body Plate Performance

Plate Angle, deg	%ΔC_n for λ/l = 0.02 to 0.07 (Compared to Baseline) Minimum	Maximum
0	N/A	-1%
5	N/A	-6%
10	N/A	-9%
12.5	-7%	-9%
15	-8%	-9%
17.5	-7%	-8%
20	N/A	-8%

Table 4-9. Comparison of Curved versus Straight Aft Body Plates of Fixed Length

Plate Angle, deg	%ΔC_n (Compared to Baseline) Straight	Curved
5	-6%	-7%
12.5	-9%	-8%

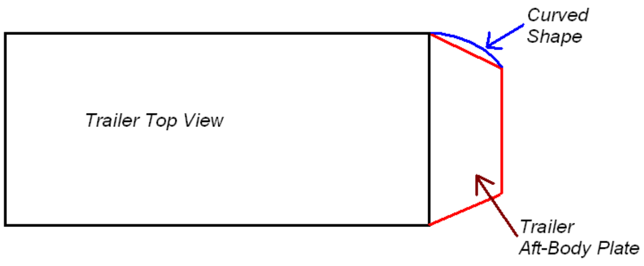


Figure 4-17. Illustration of Typical Straight and Curved Plate Shapes

Trailer Aft Body Plate Length and Angle Study: Table 4-8 shows significant drag reduction can be obtained across a range of plate fineness ratios. At most angles, slightly more drag reduction can be obtained with a higher plate fineness ratio. For a given fineness ratio, λ/l, the drag reduction obtained was fairly insensitive across a reasonable range of angles. Drag reduction of up to 9% was observed for adding the plates alone to a baseline tractor-trailer. The results and trends were valid throughout the range of trailer fineness ratio evaluated.

Trailer Aft Body Plate: Curved versus Straight Shape: Trailer aft body plates with curvature were also evaluated along with straight plate shapes. Figure 4-17 illustrates the type of curvature considered. As shown in Table 4-9, the straight and curved plates demonstrated comparable drag reduction. The curved plate provided slightly more drag reduction a low inclination angle, but slightly less drag reduction at a higher inclination angle.

Table 4-10. Phase I Results—Combined Device Performance

	Combinations					
	Tractor Trailer Gap			Trailer Side		Trailer Wake
% ΔC_n (Compared to Baseline)	Side Ext. and Air Fairing Ext. Length	Trailer Fore Body	Vertical Plates	Straight Skirts	Belly Box	Angled Plates
-23	•			•		•
-21		•		•		•
-17				•		•
-21				•	•	•

Combinations of Devices

Various combinations of add-on devices are possible to reduce the drag associated with the tractor-trailer gap, trailer side and trailer wake regions. However, the impact of combining aerodynamic devices is usually not equal to the sum of their individual impacts due to interactions in the flow field. Therefore, it is important to evaluate a certain number of device combinations to ascertain the range of benefits that can be expected from a particular device when it is combined with other concepts. The performance overview chart, Figure 4-4, in the results summary section of this report quantifies the range of performance observed for each device.

It is also important to understand the impact of various device combinations to aid in understanding what flexibility exists in selecting concepts to demonstrate in Phase II of this project. Several combinations of devices obtained drag reductions of greater than 20% compared to the baseline tractor-trailer. The combinations are highlighted in Table 4-10.

Phase I Conclusions

1) Maximum drag reduction of 23% was demonstrated with a combination of lengthened side extender and air fairing, straight skirt, and trailer wake angled plate.

2) Demonstrated drag reductions greater than 20% for other combinations of devices.

3) Demonstrated significant drag reduction for a wide variety of concepts in the three areas of focus: tractor-trailer gap, trailer side and trailer wake.

4) Specific conclusions for the three areas of focus are as follows:
   - Tractor-Trailer Gap
     - Demonstrated 3-5% drag reduction by varying side extender length and shape
     - Demonstrated 2% additional drag reduction possible from extending air fairing
     - Demonstrated 3-4% drag reduction from trailer forebody device
     - Demonstrated only 1% drag reduction for vertical plate(s) in tractor-trailer gap
   - Trailer Side
     - Demonstrated 8-11% drag reduction for straight side skirts (h/d = 0.07)
     - Demonstrated straight skirts provided 3-4% more drag reduction than U or V-shaped skirts of similar ground clearance ratio
     - Belly box provided comparable drag reduction to straight skirts of similar ground clearance ratio
   - Trailer Base Plates
     - Demonstrated 9-14% drag reduction for straight, angled plates on top and sides
     - Angled plate performance was not highly sensitive to trailer fineness ratio and plate angle within a reasonable range
     - Curved plates and straight plates exhibited comparable performance

Recommendations

1) Proceed to Phase II full-scale prototype development and demonstration with at least one concept from each of the three areas of focus: tractor-trailer gap, trailer side and trailer wake.

2) Generate and test (in Phase II) at least two combinations of devices that are anticipated to yield a 10% increase in fuel economy at 65mph due to a corresponding wind averaged drag reduction of 20% as demonstrated in Phase I.

3) Partner with a trailer manufacturer for Phase II development since Phase I development showed a significant amount of drag reduction is possible with trailer-mounted devices. Engaging the knowledge and experience of a trailer manufacturer will increase the robustness of the concepts prototyped in Phase II.

References

1) Mason, W. T. Jr. and Beebe, P. S., “Drag Related Flow Field Characteristics of Trucks and Buses,” Symposium on Aerodynamic Drag Mechanisms of Bluff Bodies and Road Vehicles, September 27-28, 1976; General Motors Research Laboratory, Warren Michigan. New York: Plenum Press; 1978.
2) Oran W. Nicks Low Speed Wind Tunnel Facility Handbook, Texas A&M University.
3) SAE Wind Tunnel Test Procedure for Trucks and Buses, SAE J1252, July 1981, SAE Recommended Practice, 1981.
4) McCallen, R. et al., “DOE’s Effort to Reduce Truck Aerodynamic Drag through Joint Experiments and Computations,” SAE paper No. 2005-01-3511, 2005.
5) Cooper, K. R. and Leuschen, J., “Model and Full-Scale Wind Tunnel Tests of Second-Generation Aerodynamic Fuel Saving Devices for Tractor-Trailers,” SAE paper No. 2005-01-3512, 2005.

4.3 Phase II Overview

International investigated drag reduction opportunities for three areas within the tractor-trailer system: tractor-trailer gap, trailer side and trailer wake. This approach addressed a major source of aerodynamic drag in a typical class 8 tractor-trailer application. The key Phase II accomplishments for International included:

- Demonstrated 11.5% improvement in fuel economy through the use of Wal-Mart's experimental aerodynamic trailer
    - Conducted full-scale on-road tests using the SAE J1321 Type II fuel economy test procedure
    - Partnered with Great Dane Trailers and Wal-Mart to build and test an experimental aero trailer
    - Developed unique solutions to overcome common objections to trailer skirts and trailer base plates
- Demonstrated fuel economy improvements for tractor-trailer gap devices
    - 2% improvement for trailer forebody shape (patent application submitted)
    - 1% improvement for variable geometry side extenders

Phase I Review

Overall Plan

In Phase I, multiple devices were developed and evaluated for each area of focus. The most promising concepts were refined and re-evaluated as necessary. All Phase I evaluations were conducted via 1/8th scale wind tunnel testing.

In Phase II, select devices were further refined to increase robustness and durability, and full-scale prototypes were constructed. All Phase II evaluations were conducted via full scale on road testing.

Phase I -- Approach

Tractor-Trailer Gap
Devices were developed that broadly fit into two categories: partial gap closure and total gap closure. The effects of varying side extender length and shape were studied. Various configurations of vertical plates were installed in the tractor-trailer gap, and different trailer forebody shapes were investigated.

Trailer Side
Various trailer skirting options were developed and evaluated. The impact of varying skirt shape, fore-aft location and height was considered in addition to a "belly box" which effectively lowers the floor of the trailer between the tractor drive wheels and the trailer wheels.

Trailer Wake
Various configurations of trailer base plates were evaluated. The impact of varying plate length, angle and shape was considered.

Phase I -- Methodology and Model Description

Reduced scale wind tunnel tests were conducted in Phase I using a 1/8th-scale model of an International 9400 72" Hi-rise Sleeper with a full aerodynamic package. It is shown in Figures 4-18 and 4-19. The tractor model was fully detailed including all pertinent exterior, engine compartment and chassis details.

Figure 4-18. Baseline Tractor-Trailer Setup

Figure 4-19. Baseline Tractor-Trailer Setup

Phase I -- Results

The drag reducing impact of each individual device is shown in Figure 4-20. These results show both the individual device contribution, as well as the incremental contribution obtained by adding the device in combination with other previously installed devices.

The test results indicated that the largest drag reductions came from adding trailer aft body plates and trailer skirts. The plates provided a 9 to 14 percent drag reduction and adding skirts provided an 8 to 11 percent drag reduction.

Significant drag reductions were also demonstrated by installing trailer forebody shapes (3 to 4 percent) and modifying side extender shape and length (3 to 5 percent). A 5 to 11 percent reduction in drag was also observed by reducing trailer frontal area.

Combinations of Devices

Various combinations of add-on devices further reduce the drag associated with the tractor-trailer gap, trailer side and trailer wake regions. However, the impact of combining aerodynamic devices is usually not equal to the sum of their individual impacts due to interactions in the flow field. Therefore, it is important to evaluate a certain number of device combinations to ascertain the range of benefits that can be expected from a particular device when it is combined with other concepts. The performance overview chart, Figure 4-20, in the Phase I results section of this report quantifies the range of performance observed for each device.

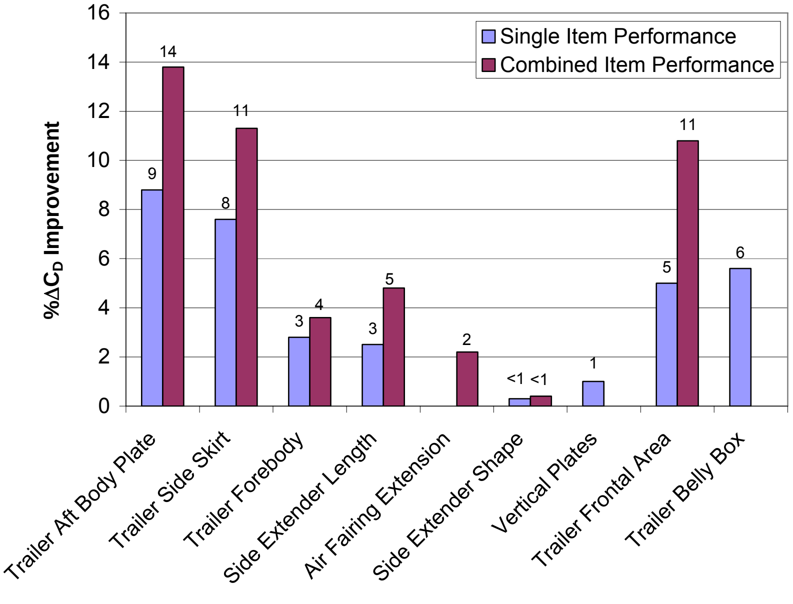


Figure 4-20. Performance Overview of Drag Reduction Devices

It is also important to understand the impact of various device combinations to aid in understanding what flexibility exists in selecting concepts to demonstrate in Phase II of this project. Several combinations of devices obtained drag reductions of greater than 20% compared to the baseline tractor-trailer. The combinations are highlighted in Table 4-11.

Table 4-11. Phase I Results -- Combined Device Performance

	Combinations					
	Tractor Trailer Gap			Trailer Side		Trailer Wake
% C_D (Compared to Baseline)	Side Ext. and Air Fairing Ext. Length	Trailer Fore Body	Vertical Plates	Straight Skirts	Belly Box	Angled Plates
-23	●			●		●
-21		●		●		●
-17				●		●
-21				●	●	●

Phase I Accomplishments

- Demonstrated 23% reduction in aerodynamic drag
  - Utilized trailer skirts, base plates and lengthened side extenders and air fairing
  - Anticipate 11-12% fuel economy improvement at 65mph
- Demonstrated 20%+ drag reduction for several configurations
- Formed partnership with major trailer manufacturer for Phase II--expect to finalize in January 2006
  - Demonstrated 30% drag reduction with reduced frontal area trailer plus aero devices

4.4 Phase II Activities

Phase II Approach

International's Phase II plan was to develop a full-scale prototype of at least one concept from each of the three areas of focus: tractor-trailer gap, trailer side and trailer wake. The prototype development process yielded essentially a "proof-of-concept" hardware set for each concept that could be evaluated on the road for its impact on fuel economy.

Down-selection of concepts from Phase I to Phase II was based not only on performance, but on the additional goal of this program to provide "practical" devices. Decisions on configuration, material selection, control systems (if required), and so forth during the prototype development process will be based on criteria such as cost, weight and complexity, which can all impact reliability and durability.

Since International does not produce dry-van trailers, a trailer manufacturer partner was sought for Phase II effort. The knowledge, expertise and resources of Great Dane Trailers were invaluable in developing truly practical devices.

Additionally, International also sought a motor carrier customer as a partner in the Phase II effort to provide a very valuable "voice of the customer" input in the development and demonstration process.

Phase II Test Methodology and Facilities

In Phase II, full scale on-road tests were conducted on a closed track at a fixed speed of 65mph. This eliminated a number of variables present in on-highway testing, including driver response to varying terrain and accommodations for merging and overtaking traffic.

SAE J1321 Type II Fuel Economy Tests

International followed the procedures outlined in SAE J1321 for Type II fuel economy tests, which employs the use of a control tractor-trailer and the test tractor-trailer. The configuration of the control tractor-trailer was not changed throughout the test. The method also requires multiple runs of each test configuration. To have a valid test, each run must have a very consistent ratio of fuel used between the test vehicle and the control vehicle (t/c ratio). Vehicles must also undergo rigorous inspections, break-in and warm-up procedures. These procedures eliminate common sources of variation in on-road testing.

Phase II fuel economy tests were conducted at the Transportation Research Center (TRC) in East Liberty, Ohio or at the Bosch Automotive Proving Grounds in South Bend, Indiana. The identical tractor was not used in every Phase II test event. However, every test did use a current production International 9000i series tractor, similar in design to the Phase I wind tunnel model illustrated in Figure 4-18. In addition, every test event included a baseline run that was used to calculate the difference in fuel economy attributable to the device(s) tested in that event.

High cubic volume dry-van trailers were used during the test. The baseline trailers were 8.5’ wide x 13.5’ tall x 53’ long.

Phase II Device Selection

Based on the Phase I results, it was clear that significant drag reduction opportunities existed in all three areas being investigated in this study. In addition, it was apparent that using combinations of devices frequently produced results that were greater than the effect of a device, individually.

Customer Considerations

The performance of the devices in Phase I was a very important selection criterion for consideration in Phase II. The customer is going to consider how quickly their investment in a device is returned. It is the performance of the device that will deliver the savings and shorten the return on investment (ROI), making the purchase of the device more attractive to the customer.

However, the customer also considers the likely frequency of repair or replacement for a given device. This judgment varies by customer and is weighted by their experience and factors specific to their operation. If a customer anticipates the money saved in fuel will be offset by frequent device repair or replacement, they will be less likely to purchase that device. Hence, device durability and reliability is very important.

Finally, many customers will be reluctant to add devices that will increase driver workload or add complications to workers at loading docks. These are just some of the factors to be considered in developing a practical device that customers will accept.

Tractor Trailer Gap

Of the five tractor-trailer gap related concepts evaluated in Phase I of this program, two were selected to proceed to Phase II—the variable geometry side extenders and the trailer forebody shape.

As shown in Figure 4-20, the variable geometry side extenders and the trailer forebody shape had the best performance in terms of aerodynamic drag reduction. Each delivered aerodynamic drag reductions of 3-5 percent when tested alone or in combination of other devices. That suggests those devices might obtain a 1-3 percent fuel economy improvement at highway speed.

By contrast, merely changing the side extender shape, or adding vertical plates to the tractor, trailer or both showed improvement of 1 percent or less in aerodynamic drag. Those devices were not carried forward to Phase II because they did not deliver enough performance improvement to merit further consideration at this time.

Finally, the air fairing extension would most likely need to be executed in combination with variable geometry side extenders. It delivered an appreciable performance improvement of 2 percent aerodynamic drag reduction, but it was deemed significantly more difficult to execute than just varying the side extender length alone.

Trailer Side

As described in the Phase I Review section earlier in this report, the primary focus of the trailer side device investigation was into looking at various options for trailer skirting. Skirt size and shape were investigated. In addition, a "belly box" or enclosed lower section of the trailer was examined.

The Phase I report (reference 1) showed that straight side skirts provided the greatest performance improvement as compared to v-shaped or u-shaped skirts, and that the benefit increased linearly as the skirt height to ground decreased. Alternatively, a belly box also showed equivalent performance improvement as a straight side skirt with the same ground clearance. However, adding a belly box and a lower skirt section together gave better performance than a skirt alone for the same height to ground. Therefore, both straight side skirts and belly boxes will be considered in Phase II.

Trailer Wake

The focus of trailer aft body device work was on adding taper to the aft end of the trailer to change the size and shape of the wake downstream of the trailer. The Phase I report (reference 1) showed significant opportunity to reduce drag exists with different taper lengths and angles. The amount of drag reduction demonstrated, combined with the flexibility in choosing taper length and angle, make trailer aft body taper an item to be considered in Phase II.

Phase II Prototype Development

Experimental Aerodynamic Trailer

Two of the Phase I recommendations were accomplished with this trailer. It provided the opportunity to test a combination of devices, and it was the product of teamwork between Great Dane Trailers and International Truck.

International and Great Dane Trailers have a common customer, Wal-Mart, who is very focused on fuel economy improvement. That focused customer was the catalyst in the relationship that led to the construction of the experimental aerodynamic trailer.

Figure 4-21. Wal-Mart Experimental Aerodynamic Trailer

Intellectual property generated during Phase I was shared with Great Dane, and that data facilitated the generation of several experimental trailer concepts with various combinations of aerodynamic drag reduction devices. Wal-Mart opted for the trailer configuration that had the greatest potential for aerodynamic drag reduction and hence fuel economy improvement. The Wal-Mart experimental aerodynamic trailer was designed and constructed without using funding from this program. The experimental aerodynamic trailer is shown in Figure 4-21.

The primary aerodynamic features of the experimental trailer are a tapered aft section, dropped frame and straight side skirts, and an overall height reduction. International also constructed a reduced height air fairing and side extenders for the tractor to match the lower trailer height.

Overall Height Reduction and Drop Frame

The overall height reduction of one foot results in an 8 percent reduction in frontal area. As installed on the tractor, the trailer overall height is 12 feet 6 inches. The trailer overall dimensions are 8.5 feet wide by 12.5 feet tall by 53 feet long.

The load floor of the trailer was dropped 16 inches as compared to the baseline trailer. This dropped frame created a similar aerodynamic configuration, although different depth, as compared to the belly box tested in Phase I. Hence, the dropped frame was expected to provide an aerodynamic benefit.

However, the dropped load floor does require a special variable height suspension to raise the load floor to match standard dock height for loading and unloading cargo. The dropped load floor does help compensate for interior volume lost due to the overall height decrease and the cargo carrying length which was shortened two feet to accommodate the tapered aft section. The interior volume is about 5% less than a baseline 53 foot long trailer.

Trailer Side Skirting

The trailer side skirting was designed to achieve the same height to ground as the smallest h/d (height to ground divided by equivalent diameter) evaluated in Phase I report (reference 1). The h/d ratio is defined in that report as well.

The skirts for the experimental trailer were designed to automatically stow at speeds below 35 mph and deploy at speeds greater than 35 mph to reduce the chance the skirts would be damaged by incidental contact with the ground or other obstacles (e.g. snow bank) during low speed maneuvering,. The skirts are powered by compressed air already provided to the trailer, and are controlled by vehicle speed sensing which is also already available. No driver interaction is required to deploy and stow the skirts in operation. The skirt movement also provides an opportunity to shed any snow and ice that has accreted on the skirts. There are trailer side skirt designs on the market today for trailers, but they are fixed designs.

Figure 4-22 shows the skirts in the stowed position and Figure 4-23 shows the skirts in the deployed position. The skirts stow by folding inboard and up to increase ground clearance.

Because of its moving parts and automated operation, the prototype trailer side skirt design was more complex than fixed skirt designs already on the market. The prototype design would need to undergo significant durability testing and likely require design refinements before it could be released for

Figure 4-22. Side Skirts in Stowed Position

Figure 4-23. Trailer Skirts Deployed on Wal-Mart Experimental Aerodynamic Trailer

production. However, the skirt design does offer a compelling solution to common objections of damage due to curb or ground impact, and the skirt motion gives opportunity to shed snow and ice. Driver workload is not increased since the skirt deploys and stows automatically. Ultimately, the customer will need to judge whether it is a better value than fixed skirt systems already available today.

Trailer Tapered Aft Section

The tapered aft end is structural. That helps minimize the opportunity for damage when contacting a loading dock or backing in at a truck stop or other confined parking area.

Also, the tapered section geometry is fixed, which eliminates the additional effort that would be required by a driver or dock worker to stow and deploy parts. The challenge is to design the taper in a matter that does not adversely impact the ability to load and unload cargo.

Wal-Mart incorporates a roll-up door at the aft end of their trailers. Great Dane identified that it would be possible to add a two foot long section that would not adversely impact the roll-up door open area, if the taper angle was 15 degrees. This yielded a trailer aft body length ratio, λ/l ratio = 0.04. From Table 8 in the reference 1 report from Phase 1, this ratio and angle are anticipated to deliver an 8-9 percent aerodynamic drag reduction. The tapered aft section of the trailer is shown in Figure 4-24.

Figure 4-24. Tapered Aft Section of Trailer (Wal-Mart Experimental Aerodynamic Trailer)

Tractor Trailer Gap

Trailer Forebody Shape

Reducing tractor trailer gap nearly always improves aerodynamic performance. However, a minimum tractor-trailer gap is required for low speed maneuvering. The trailer forebody shapes developed in Phase I were designed to stay within the tractor trailer swing envelope, even when the tractor is at a close gap for good fuel economy.

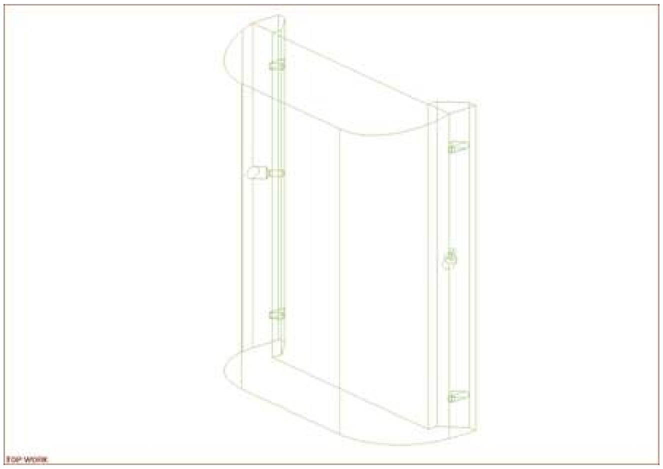


Figure 4-25. 15 degree, Flat Design, Isometric View (Trailer Forebody Device, CAD Image)

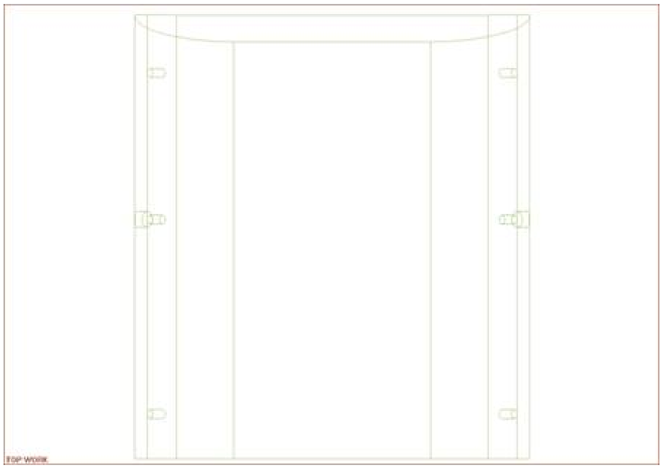


Figure 4-26. 15 degree, Flat Design, Front View (Trailer Forebody Device, CAD Image)

The Phase I test results did show some sensitivity to the inclination angle of the top of the device as compared to the horizontal top of the trailer. Of the parts tested in Phase I the 15 degree inclination angle part performed the best, and that was the angle selected for the prototype parts. It was planned to make two prototype parts, one each of the "rounded" and "flat" shapes tested in Phase I, but due to resource constraints, only the flat 15 degree prototype part was fabricated.

Figure 4-27. 15 degree, Flat Design, Installed on Trailer (Trailer Forebody Device, Prototype Part)

Figure 4-28. 5 degree, Flat Design, Installed on Trailer (Trailer Forebody Device, Prototype Part) Note: Access panel removed in photo

An attractive feature of this design option is that it does not have any moving parts. Since it is a partial gap closure device, it will provide access to the back of cab. The prototype design did consider access panels for installation, maintenance, and it was designed to be lifted into position by overhead crane or forklift.

Figures 4-25 and 4-26 are images of the part based on CAD data, and Figures 4-27 and 4-28 are photos of the prototype part installed on a baseline trailer.

Tractor Side Extenders -- Variable Length

During Phase I development, lengthening the cab-mounted side extenders decreased drag. The more the extenders could be lengthened, the greater the reduction. The maximum reduction occurred when the extenders contacted the front of the trailer.

However, the prototype parts were intentionally designed not to contact the trailer in deployed position to eliminate additional loading on side extender parts. Investigation during full scale part design determined that 4 to 6 inches of clearance was needed to avoid contact during high speed maneuvers when extenders would be deployed.

The variable length extenders were envisioned to automatically stow and deploy with tractor speed, but the actuation was not constructed due to resource constraints. As a result, the prototype required manual operation. The extenders were designed in two sections: a fixed section that mounted to the tractor and a movable section that nests inboard of the fixed section. When stowed, about six inches of the moveable inboard panel extends aft of the fixed outboard panel. The parts were designed to travel approximately 14 inches from fully stowed to fully deployed position.

Figure 4-29 shows the variable length side extenders installed on a production International 9400i tractor. In that image the extenders are fully deployed. Figure 4-30 shows the baseline tractor configuration for the tractor trailer gap device tests.

<u>Phase II Test Results</u>

Experimental Aerodynamic Trailer

The experimental aerodynamic trailer was commissioned by Wal-Mart, and Wal-Mart conducted the initial fuel economy tests on the trailer. Wal-Mart's testing was not funded by this program, and Wal-Mart only

Figure 4-29. Variable Length Side Extenders -- Deployed

Figure 4-30. Baseline Tractor Trailer for Gap Device Tests

shared high-level test results with International, although International was allowed to observe a portion of the testing.

Wal-Mart conducted their fuel economy tests at the Goodyear Proving Grounds in San Angelo, Texas. Wal-Mart demonstrated a 6.7 percent fuel economy improvement for the experimental aerodynamic trailer as compared to a baseline 53 foot long trailer similar to those in their fleet today. These test results were shown at the November 2006 briefing with the U.S. Department of Energy and the coincident public demonstration in Washington D.C. where this trailer was displayed.

International did not conduct a wind tunnel test on the exact configuration chosen for the experimental aero trailer, but the Phase I wind tunnel test results suggest the trailer could achieve a drag reduction of 22-23 percent. This data suggests an 11-12 percent fuel economy improvement might be achievable with this trailer.

There were some unique construction details in the build of this trailer, particularly channels and seams in the tapered aft section, which could have an adverse impact on its fuel economy. International recommended some "tuning" tests be conducted on the aero trailer to determine if greater drag reduction and fuel economy improvement could be obtained from that design.

International conducted the tuning tests in two phases. First, yarn tufts were placed on the areas of concern at the aft end of the trailer and visual observations were made about flow quality at the aft end of the trailer. Then smooth panels were fabricated and installed over the channels and seams and the visual observations were repeated. Figure 4-31 shows yarn tufts on a smooth panel installed on the trailer roof.

Figure 4-31. Yarn tufts on smooth panels covering tapered roof section of trailer

Once satisfactory flow patterns were obtained, rigorous fuel economy tests were conducted. The trailer was tested in the as received and "tuned" configurations. The trailer side skirts were also removed as an incremental run during testing.

These tests were conducted at the Bosch Proving Grounds in South Bend, Indiana. The tests were conducted at a steady state speed of 65mph on a three mile oval track.

Figure 4-32. Test Vehicle (P421) with Baseline Trailer

Figure 4-33. Test Vehicle (P421) with Baseline Trailer

Figure 4-34. Control Vehicle (E463) with Trailer

Figures 4-32 and 4-33 show the tractor and baseline trailer for tuning tests. Figure 4-34 shows the control vehicle which was used for these tests.

Table 4-12 shows the results of International's fuel economy tests with the Wal-Mart experimental aerodynamic trailer. The "as received" trailer demonstrated an 11.5 percent fuel economy improvement over the baseline trailer. A fleet of 6,000 tractors could save $12.4 million a year from reduced fuel costs.

Table 4-12. Fuel Economy Test Results for Experimental Aerodynamic Trailer

Long Haul -- 65mph			
Test ID	**Test Vehicle**	**T/C Ratio**	**% Fuel Economy Improvement versus Baseline***
1	P421 Baseline	1.12	0
2	P421 Wal-Mart, As-Is	0.99	**+11.5**
3	P421 Wal-Mart, No Skirts	1.01	**+9.6**
4	P421 Wal-Mart, Smooth Gutters and Ridges	0.99	**+12.0**

* Accuracy: within +/- 1.0%

Also, it can be seen that installing the trailer side skirts (test ID 2 referenced to test ID 3) provided an increase in fuel economy of +1.9 percent (better). This increment implies only a 4 percent aerodynamic improvement for the skirts, much less than anticipated from the Phase I test results shown in Figure 4-20. The difference is most likely due to the fact that some of the expected skirt height is taken up in the belly box height. Therefore, the incremental part that was removed was much shorter than the skirt parts tested in Phase 1.

Finally, smoothing out the gutters and ridges in the tapered section of the trailer did not yield a significant improvement as seen by comparing test ID 4 to test ID 2.

International was very rigorous in conducting this test, and the results were repeatable as noted from run to run on the track and in the t/c ratios in Table 4-12 which are all well within 2 percent.

Tractor Trailer Gap

The trailer forebody shape and the variable length side extenders were tested individually. Those results are shown in Table 4-13. The trailer forebody device demonstrated a fuel economy improvement of 2 percent, and the variable length side extenders demonstrated a fuel economy improvement of 1 percent.

These tests were conducted at the Transportation Research Center in East Liberty, Ohio. The tests were conducted at a steady state speed of 65 mph on a seven and a half mile oval track. Figure 4-30 shows the tractor and trailer used for these tests. Figure 4-34 shows the control vehicle which was used for these tests.

Phase I testing suggested even better results were possible if parts were tested in combination with trailer side skirts and trailer wake aft body taper. It was planned to run the devices in combinations, but it did not happen due to resource constraints.

Table 4-13. Fuel Economy Test Results for Tractor Trailer Gap Devices

Long Haul -- 65mph			
Test ID	**Test Vehicle**	**T/C Ratio**	**% Fuel Economy Improvement versus Baseline***
1	S945 Baseline	1.10	0
2	S945 and Trailer Forebody Device	1.06	**+2**
3	S945 and Variable Length Side Extenders	1.08	**+1**

* Accuracy: within +/- 1.0%

International felt the trailer forebody device developed in this program had some unique and non-obvious advantages over trailer "nosecone" type devices on the market today. For example, the wind tunnel data from Phase I showed sensitivity to the inclination angle of the top of the device to the top of the trailer. The 15 degree angle was determined to provide the best performance. International has submitted a patent application for that device.

It should be noted that the trailer forebody device delivered a 2 percent fuel economy improvement while paired with a 9400 tractor with a full aero package (see Figure 4-27). The device may deliver substantially better performance if it is paired with a less aerodynamic trailer.

Conclusions

Significant fuel economy improvements were demonstrated in this program for the devices developed for the tractor trailer gap, trailer side and trailer wake.

An 11.5 percent highway fuel economy improvement was demonstrated with an experimental aerodynamic trailer commissioned by Wal-Mart. That fuel economy savings could translate into an annual savings of 12.4 million gallons and $32.2 million for a fleet with 6,000 tractors.

A 2 percent highway fuel economy improvement was demonstrated for a prototype trailer forebody shape that International is patenting. A 1 percent highway fuel economy improvement was demonstrated for prototype side extenders of variable length.

The Phase II on-road fuel economy test results agreed well with the Phase I reduced scale wind tunnel test results when a 2:1 ratio is applied to translate aerodynamic drag improvements into highway fuel economy improvements. For example, wind averaged drag coefficient improvements of 22 to 23 percent were predicted for the Wal-Mart aerodynamic trailer, while the measured fuel economy improvement was 11.5 percent.

Recommendations

International recently began production of its ProStar aerodynamic tractor. This all-new next generation product has substantially better aerodynamic performance than the 9400i model which it replaced and which was used for these tests.

The Wal-Mart experimental aerodynamic trailer should be tested with a ProStar tractor. It may show even greater potential for fuel economy improvement with a more aerodynamic tractor pulling it.

The aero trailer should also be tested in combination with the trailer forebody shape and the variable side extenders. A test which combined a ProStar tractor, trailer forebody device and experimental aero trailer might yield a 20 percent fuel economy improvement as compared to a baseline 9400i and standard trailer.

International plans to continue participating with Wal-Mart and Great Dane to continue to refine the design of the experimental aero trailer.

Reference

1. Truck Manufacturer's Association Report, "Test, Evaluation, and Demonstration of Practical Devices/Systems to Reduce Aerodynamic Drag of Tractor/Semitrailer Combination Units Trucks, dated March 09, 2006.

5. Mack Project Activities

5.1 Phase I Overview

Mack focused on the effects of trailer aerodynamics, trailer gap enclosure, and trailer gap flow control. The key Phase I activities completed by Mack included:

- Identification of candidate devices for computational fluid dynamics (CFD) studies;
- Initiation of prototype design;
- Installation and testing of data logging equipment;
- Identification of one test tractor, one control tractor, and two trailers for use during tuning tests; and
- Development of workshop to discuss different trailer aero devices available and prioritize for testing based on their estimated fuel savings and practicality.

Figure 5-1. Mack Vision Control Truck for Testing

5.2 Phase I Activities

The purpose of Phase I of the TMA/Mack aerodynamic work was to perform studies on devices to reduce the aerodynamic drag on the trailer and at the tractor and trailer gap. The tractor-trailer enclosure was analyzed using CFD to quantify the reduction in drag coefficient. With a significant improvement in the aerodynamics, the devices would then be designed and prototyped for full scale testing.

In Phase I, Mack also conducted a workshop with experts from the trailer industry and academia who are involved in development of trailer aerodynamic devices. The objective of this activity was to discuss different trailer devices and prioritize these based on fuel savings, simplicity, and practicality. The high priority devices were to be picked to perform full scale testing.

Figure 5-2. Mack Vision Test Truck

The plan used to accomplish the Phase I work was twofold. First, Mack planned to run CFD calculations to analyze the effect of the side enclosures between the tractor and trailer. Second, Mack planned to develop a matrix of available trailer devices in the industry that are capable of yielding high fuel savings, and to

Figure 5-3. Rear of Test Trailer

Figure 5-4. Front of Test Trailer

Table 5-1. Information on Tractors and Trailers to be Tested

Test Tractor (Mack Vision Mid-Rise Tractor)	VIN 1M1AE07Y84N020930
Control Tractor (Mack Vision High-Rise Tractor)	VIN 1M1AE06Y6XW001115
Test Trailer	Number SS045001
Control Trailer	Number 173287

prioritize these devices. Some of these devices were selected to tune and measure the actual fuel savings using SAE Type II fuel economy testing.

For testing the different devices that were identified in Phase I of the project, two tractors and two trailers were identified. The control tractor (shown in Figure 5-1) was a Mack Vision high rise sleeper cab tractor, and the control trailer was a standard 53-foot box trailer. The test tractor was a Mack Vision mid-rise sleeper cab tractor with roof fairings (Figure 5-2) and the test trailer was a Great Dane trailer fitted with four different trailer aerodynamic devices, as shown in Figure 5-3 and Figure 5-4. The four devices fitted to this trailer were a 48 inch boat tail, vortex strakes, side skirts, and a front vortex generator. Table 5-1 provides further information on the two specific tractors and trailers that were used in this project.

Mack employed a 3D computer-aided design package (CATIA, available from IBM and Dassault Systemes) to design new devices for side enclosures and prepare the digital models for computational fluid dynamics analysis. A software tool to model and analyze devices in the computational fluid dynamics arena, (StarCD, developed by CD-Adapco) was used for this phase of the project. CFD calculations were done on the baseline tractor with and without tractor-trailer gap enclosure with a standard trailer. No CFD calculations were done on the trailer devices.

The project team equipped one of the test trucks with the data logging equipment that was used in this project for the Phase II road tests. The project used the EMU-2000 software running on a laptop that is connected to the SAE J1587 databus to capture the engine and vehicle data that was used to determine fuel consumption of the test vehicles. The project team created an analysis tool to take the raw engine and vehicle data and convert it into accurate fuel consumption measurements. An illustration of the data logging equipment is shown in Figure 5-5.

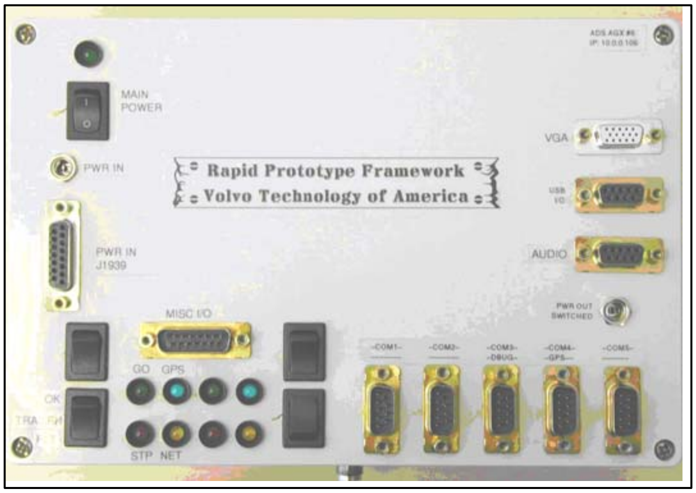


Figure 5-5. Data Logging Equipment Used for Tuning and Type II Testing

All external surfaces of the tractor and trailer were modeled using CATIA V4 computer-aided design software, as illustrated in Figure 5-6. This CAD information was transferred to Star CD (the CFD software package) for further analysis. CFD calculations were done on the baseline tractor and with trailer gap enclosure and a standard 48-foot trailer. As noted above, no CFD calculations were performed on the trailer devices. A plot of surface characteristics around the side extender has been presented as Figure 5-7. The results showed an improvement of 4% in drag at the 0° yaw condition and a 2.5% improvement in drag for the 5° yaw condition for a truck with side enclosure. An overall improvement of 3% in drag coefficient was estimated with this device. A compilation of the information collected is presented in Table 5-2.

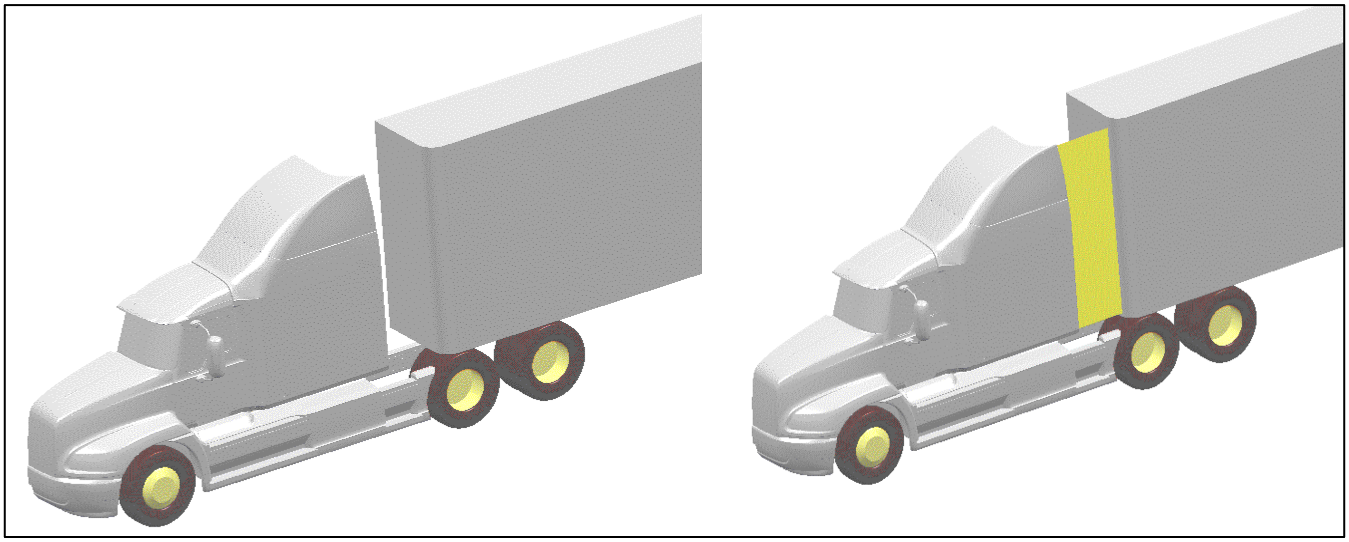


Figure 5-6. Baseline Model With and Without Side Extenders

Table 5-1. Drag Force Improvement with Side Enclosures at Zero Degrees and Five Degrees Yaw Angle

Configuration	Percent Change in Drag Force
Zero degree yaw (baseline)	0%
Zero degree yaw with enclosure	-4%
Five degree yaw (baseline)	0
Five degree yaw with enclosure	-2.5%

A workshop was held on December 14, 2005 in Greensboro, North Carolina with experts in the area of trailer aerodynamic devices. Representatives from the Canadian National Research Center (Kevin Cooper), Clarkson University (Ken Visser and Kevin Grover), Lawrence Livermore National Laboratory (Jason Ortega), Great Dane Trailers (Charlie Fetz), and Solus Inc. (Richard Woods) joined together with the Mack 3P engineers and Volvo Technology engineers to discuss the different devices already installed on the trailer as well as other devices that have shown positive aerodynamic results. Bob Clarke of the Truck Manufacturers Association (TMA) also attended. Bob Englar of Georgia Tech also contributed slides to the workshop, although he was unable to attend.

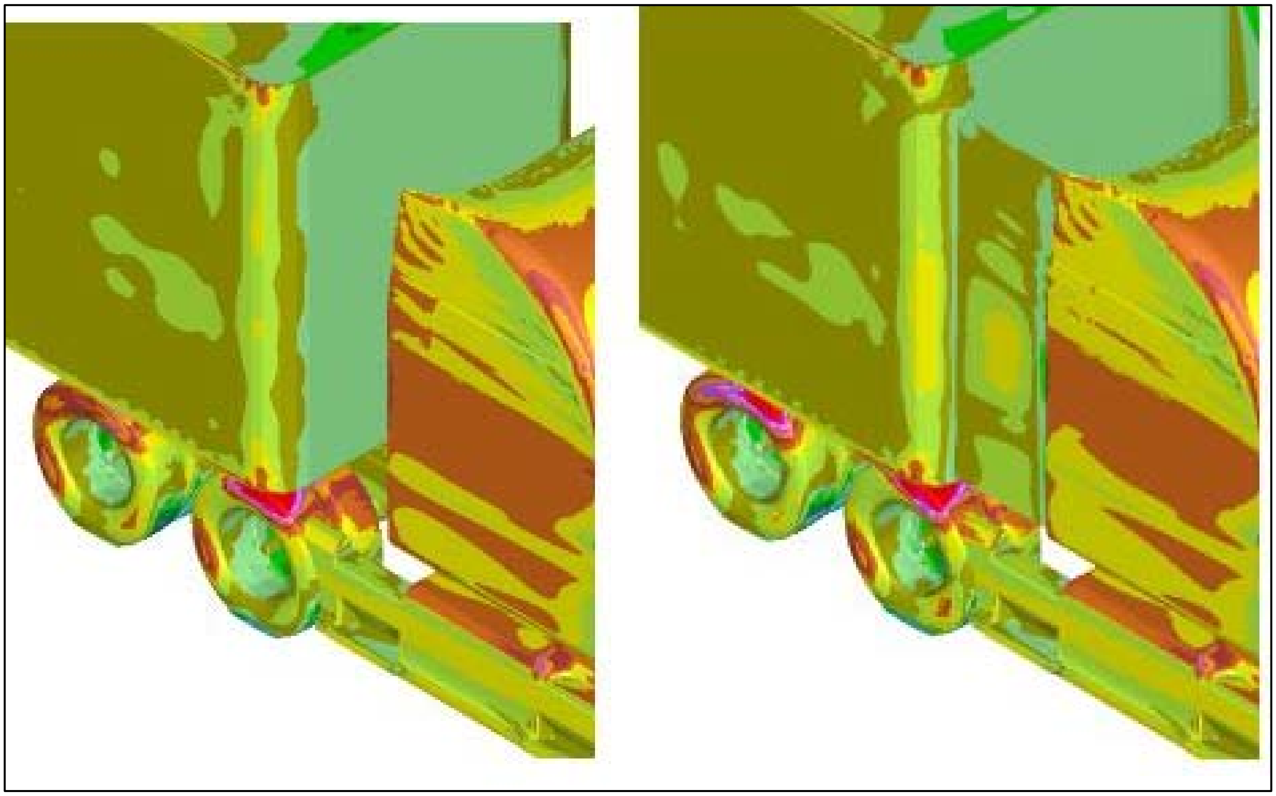


Figure 5-7. Predicted Surface Characteristics with and without Side Extensions for Zero Degrees Yaw

One of the main goals of the workshop was for the Mack team to gain information about different devices and results from testing done by individual groups. Presentations were made by participants on their work in this area. There has been extensive research done in the area of trailer aerodynamic devices, and a number of devices have been studied and tested for their effectiveness. Each of these devices was discussed at the workshop.

At the end of the workshop, the participants listed different aerodynamic devices in a table along with their reported change in drag coefficient. Since there have been different methods and degrees of accuracy used to arrive at the reported results, the workshop team tried to come to consensus on the change in drag coefficient that should be expected. In addition, each device was weighted by priority for testing, potential aerodynamic improvement, and simplicity in regards to installation and cost-competitiveness. Table 5-2 illustrates the overall results of the discussions: note that the highlighted devices have been chosen for Phase II testing. It was also noted in the workshop that the effect of vortex traps in the front of the trailers may be nullified due to the tractor trailer enclosure device.

Phase I of this project determined that adding the tractor-trailer enclosure to the product identified reduced aerodynamic drag by 3%. Adding trailer aerodynamics in combination with tractor trailer enclosure produced an estimated drag reduction of around 15%. In Phase II of this project (described in more detail later in this report), all these devices were installed on the tractor and trailer identified for performing tuning and SAE Type II fuel economy tests to confirm Phase I results.

Table 5-2. Aerodynamic Trailer Device Rankings

			Ranking				
Device	Description	Change in drag force, % range	Priority (1-3)	Aero (1-10)	Practicality (1-10)	Total	Notes
Rear of Trailer							
Boat Tail	***Angled 15°, 7° bottom, 48 inch***	***10-12***	***2***	***8***	***2***	***12***	
	Angled 15°, 7° bottom, 18-24 inch	***12-15***	***3***	***7***	***5***	***15***	
	Angled 15° 20 inch, no bottom	7-9	3	6	6	15	
Norcan	Parallel Box	7-9	2	4	6	12	
Base Flaps	3 sides (Clarkson)	11-14	2	3	6	11	0° yaw
Wake Board	2 vertical plates, 24 inches	8-10	2	3	8	13	
	Air filled	0	-	-	-	-	
Inflatable bubble		11-14	1	7	1	9	*EPA report
Side of Trailer							
Side Skirts	Full skirts	12-15	2	7	4	13	
	Mid skirts	***8-11***	***3***	***6***	***8***	***17***	
	Short skirts	4-5	-	2	9	11	
Belly Box	Box under trailer	4-6	2	2	7	11	
Short Wedge		0	-	-	-	-	
Long Wedge		4-5	1	3	4	8	
Curved Belly		-	-	-	-	-	
Vortex strake		***3-5***	***3***	***4***	***9***	***16***	
Front of Trailer							
Vortex Stabilizer	25 inch, to height of trailer	9-12	-	6	7	13	Attaches to front of trailer
Vortex Trap	***Solus***	***8-10***	***-***	***5***	***7***	***12***	
Side Xtenders	10 inch	3-5	-	-	-	-	
Side Xtenders	20 inch	5-7	-	-	-	-	
Side Xtenders	30 inch	6-8	-	-	-	-	

Note: Devices in bold italics will be investigated in Phase II

5.3 Phase II Overview

Mack focused on the effects of trailer aerodynamics, trailer gap enclosure, and trailer gap flow control. The key Phase II activities completed by Mack were:

- Tuning tests of combinations of aerodynamic devices (trailer gap enclosure, trailer boat tail, side strakes, side skirts, and vortex generators) to identify the most promising devices.
- SAE Type II fuel economy tests of various combinations of trailer gap enclosures, side skirts, and boat tails: fuel economy benefits of 1 - 8 percent were demonstrated.
- Development of a prototype side enclosure concept for folding and deployment of these extenders when not in use.

Phase I Review

In Phase I, Mack analyzed various tractor-trailer gap enclosures, using CFD, to quantify potential reductions in overall tractor-trailer drag coefficient. A CFD analysis was conducted on the Mack cab with a standard 48’ trailer (Figure 5-8) and a tractor to trailer enclosure. The result of the analysis on the tractor to trailer enclosure showed a projected fuel economy improvement of 2%.

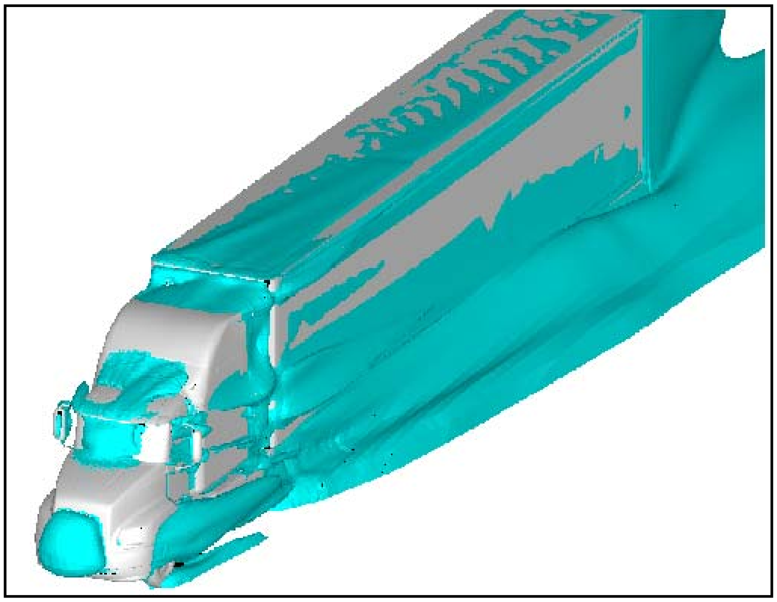


Figure 5-8. CFD Model of Mack Tractor and Trailer Used for Analysis of Side Enclosure

In Phase I, Mack conducted a workshop with experts in the field of aerodynamics and also those working with trailer aerodynamic devices. The objective of this workshop was to list all the available devices that have been developed in the industry and to prioritize them in terms of their potential for improving fuel economy and being practical to use. The list of these devices and their ordering is shown in Table 5-2.

5.4 Phase II Activities

5.4.1. Phase II Objectives

a. Purpose

In phase II of this project, all the various trailer aerodynamic devices were evaluated in tuning tests. A few of these devices were selected for final SAE Type II tests at the Transportation Research Center. Based on these tests, recommendations were made relative to the use of different devices in the tractor to trailer gap as well as various devices that were fitted to the trailer (e.g. boat tails and side skirts).

b. Test Objects

Boat Tail: A boat tail treats the wake and minimizes the effects of the base pressure behind the trailer. A 4′ and 2′ boat tail were evaluated in tuning tests. (See Figure 5-9.)

Side Skirts: Side skirts prevent air flow from interacting with the under side of the trailer and the trailer axles and wheels. They minimize a significant aerodynamic load on the complete vehicle. Side skirts are very effective in side wind conditions. (See Figure 5-10.)

Figure 5-9. 4-Foot Boat Tail

Figure 5-10. Side Skirts

Vortex Traps: Vortex traps generate a local vortex to increase the pressure on the front of the trailer. (See Figure 5-11.)

Strakes: Strakes generate vortex and reduce the effect of wake on the back of the trailer. (See Figure 5-12).

Side Enclosure: The trailer gap is a significant contributor to the aerodynamic drag on a combination vehicle. A side enclosure eliminates the aerodynamic effects of trailer gap especially in side wind conditions where the gap is most influential. (See Figure 5-13.)

Figure 5-11. Vortex Traps

Figure 5-12. Strakes

Figure 5-13. Side Enclosure

5.4.2. Analysis and result

a. Method

The test phase of this project involved two sub-phases, a screening phase using tuning tests to select devices or concepts for more detailed evaluation, and subsequent SAE Type II fuel economy tests on a closed circuit track.

b. Performed Tests (Tuning Tests)

Overview

The intent of this sub-phase was to understand the relative effectiveness of combinations of devices and concepts that were selected in Phase I. The results were used to:

1) Define a narrower selection of combinations to be tested in the next test sub-phase and
2) Determine which of the two vehicles would be used as the test vehicle in next test sub-phase

Note that the results of these tuning tests were not interpreted as an indicator of actual changes in fuel consumption to expect during the SAE Type II testing.

Vehicle Configurations

During this phase of testing, each vehicle was tested in a baseline configuration (with no studied devices or concepts) with the same test trailer. The Mack Mid Rise tractor was then tested with the complete matrix of iterations below. The trailer was unloaded during the tuning tests to make the fuel measures more sensitive to the aerodynamic changes that would differentiate one test run from another.

Table 5-3 shows the test matrix that was defined. The matrix was defined considering how concepts were combined in the analytical results from the tractor-trailer gap enclosure and the various devices that were picked from the workshop.

Test Equipment

Table 5-3. Configurations Tested on the Mack Mid-Rise During Tuning Tests

Test Number / Device Description	0	1	2	3	4
Boat Tail 48"		●			●
Boat Tail 18"			●		
Vortex Trap					●
Side Skirts				●	●
Strakes	●	●	●	●	●

● Devices Included in the Test

In this project, Mack and Volvo conducted separate but highly coordinated test efforts that used the same measurement approach. The information on test equipment, test environment, and local test routes and procedures are common to both projects and are described below.

Multiple parameters were logged from the vehicle's data bus in order to calculate the average miles per gallon (mpg) for a given run. These parameters were logged by a data logging device using the J1939 data bus and a GPS device. The parameters logged were: date, time, road speed, engine speed, instantaneous fuel economy, latitude, longitude, GPS speed, and heading. Road and engine speed measurements were used to verify that the vehicle maintained a consistent speed throughout the test. The instantaneous fuel economy measurement indicated the mpg at that given moment in time. Latitude and longitude measurements enabled more consistent start and stop point determinations. Since the route was a loop, it forced the driver to exit and enter the highway at designated starting and stopping points to guarantee that the tractor would travel at the desired speed for the entire distance. This provided the most consistent and accurate information.

Once the test iteration was completed, the data was extracted from the data logging device and imported into an Excel spreadsheet. Using the designated GPS start and stop point, the large list of data was disaggregated into the six individual test runs. The average of all the instantaneous fuel economy readings was then determined.

Environment

The most important factor in performing tuning tests is consistency. To accomplish this, the following parameters must be met:

- Outside temperature > 55°
- Average wind speed < 15 mph
- Average wind gusts < 20 mph
- No precipitation falling (roads need to be dry if precipitation has fallen before test iteration starts)

A weather station that reported an updated condition approximately every 15 minutes was within about a mile from the test route. Once a test run was completed, the station's website was visited to gather and note the weather conditions. The following conditions were logged for each test run:

- Temperature
- Dew Point
- Pressure
- Wind (direction)
- Wind Speed
- Wind Gusts
- Humidity

Climate effects were estimated and applied to the results of the tuning test by compensating for differences in air density that result from differences in atmospheric pressure, temperature and humidity.

The aerodynamic drag force on the vehicle is given by:

$$F = \tfrac{1}{2} \rho V^2 A\, Cd$$

In this equation, ρ is air density, V is the vehicle velocity, A is the frontal area of the vehicle, and Cd is the coefficient of drag. The difference in drag force between two runs due to changes in any parameter (in this case air density, ρ) is then given by:

$$\Delta F_{\text{air density}} = \frac{F_{\text{baseline}} - F_{\text{iteration}} \text{ x } 100}{F_{\text{baseline}}}$$

Therefore, if air density (ρ) is all that changes (and V, A and Cd are unchanged), the percentage difference in force between two runs due to changes in air density is given by:

$$\% \, \Delta F_{\text{air density}} = \frac{\rho_{\text{baseline}} - \rho_{\text{iteration}} \text{ x } 100}{\rho_{\text{baseline}}}$$

If it is assumed that the relationship between aerodynamic measures of Cd and fuel economy is that a 2% change in drag equates to ~ 1% change in fuel consumption, then the change in fuel consumption due to climate changes in air density is given by:

$$\% \, \Delta \text{Fuel}_{\text{air density}} = \frac{\% \, \Delta F_{\text{air density}}}{2}$$

This difference was then applied to the results comparing the changes in fuel consumption between the baseline and test iteration for each vehicle tested.

Local Test Routes and Procedures

The trucks were run on a local highway during times that traffic was minimal in order to allow for maintaining a constant speed and complete a run without interference from other vehicles. A 5-mile stretch of flat and straight highway was used to perform the tests. In addition to controlling for weather conditions, the following driving and setup parameters were followed to maintain consistency between test runs:

- Air conditioning turned off
- Windows rolled up
- Trailer gap set as close to 50" as possible (± 4")
- Driving speed = 65 mph

A test run was the equivalent of one full loop of the route which included one run on the northbound side and one run on the southbound side of the highway. At least six test runs were completed for an iteration. If the test tractor was slowed by other vehicles, passed another tractor or large vehicle, or was passed by another tractor or large vehicle, that test run was considered invalid and did not count toward the six required for a complete iteration. The driver was responsible for noting the time of the occurrence in order for that data to be eliminated from the list once the data is retrieved.

In order to determine the impact of the changes being tested, a baseline test run must be completed. The baseline was run using the test tractor before any modifications were made. After completing the baseline, any number of test runs may be performed. By comparing the average mpg of the baseline to that of the individual test runs, it was possible to determine which test configuration produced the most improvement.

Tuning Test Results

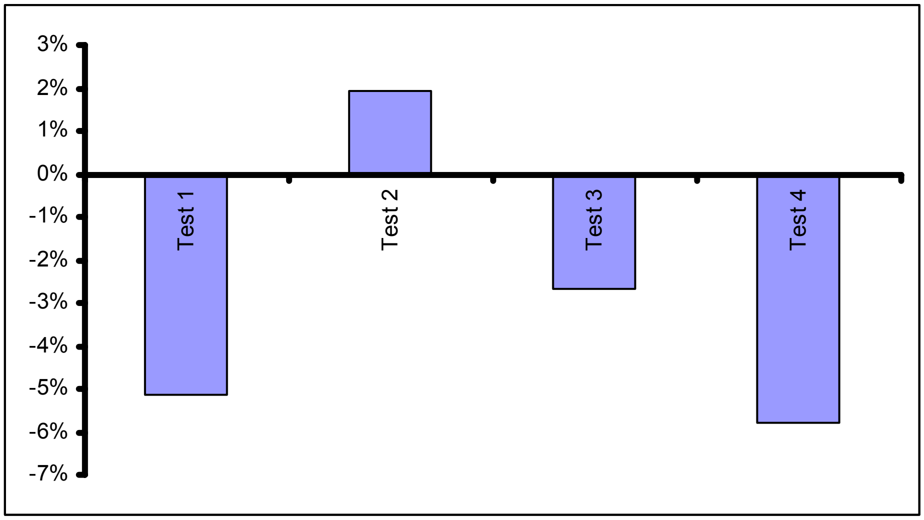


Figure 5-14. Tuning Test Results

As Figure 5-14 shows, the initial screening of different combination of trucks showed that there was a significant benefit for using a boat tail and the side skirts on the trailer (Test 1, around 5%). Test 2 with a different vendor 2-foot boat tail showed that there was no significant fuel savings benefit. Test 3 shows that the trailer skirt demonstrated about a 2.5% fuel benefit in the initial tuning. The results showed no significant improvement from the use of strakes. The vortex traps were not considered into the final list of devices for the Type II tests because the effect of the traps will be nullified by the benefit of the side enclosure.

Table 5-4. Test and Device Combination for SAE Type II Tests

Test Number Device Description	1	2	3	4	5
Boat Tail 4 Foot	●		●		
Boat Tail 2 Foot		●			
Side Enclosure	●	●	●	●	●
Side Skirts	●	●		●	

● Devices Included in the Test

c. Full-Scale Tests (SAE Type II Tests)

Overview

During this sub-phase of testing, differences in fuel economy associated with changes in aerodynamic combinations were measured according to TMC/ASE Fuel Consumption In-Service Test Procedure Type II. This work was contracted to the Transportation Research Center in East Liberty, Ohio. A complete description of this procedure used can be found in SAE Recommended Practice J1321. The SAE Type II test procedure provided a controlled test environment when testing fuel economy on full scale trucks. The principal disadvantage compared to real world testing was that testing is conducted on an essentially flat gradient facility. Therefore, the baseline fuel consumption was represented by a relatively flat driving cycle. Another disadvantage was that the procedure sets no limits on wind speed or direction. The results presented here indicated the percentage changes in fuel consumption for the applied devices and concepts.

Figure 5-15. Baseline Mack Mid Rise

Vehicle Preparations

The Mack High Rise was the control vehicle, while the Mack Mid Rise was the test vehicle. Both vehicles pulled 53’ Great Dane trailers. The test and control vehicles were prepared as follows:

- Steer, drive and trailer axles were aligned
- Tractor and trailer axle bearing and brake adjustments were checked
- GPS units were installed
- 5th wheel positions were adjusted and fixed at a pre-chosen trailer gap length of 1.27 meters
- Trailer axle bogies were positioned at a point 1/3 of their travel behind the forward-most point

- Trailers were loaded to a GVW of 65000 pounds +/- 50 pounds
- Gravimetric fuel systems with quick-disconnect couplers were installed
- Tires were set to consistent cold pressures
- A/C compressors were disabled

Vehicle Configurations

Based on the results of the tuning tests, the matrix of vehicle configurations shown in Table 5-4 was tested according to the SAE Type II procedures.

Figures 5-15 through 5-20 show the actual tested configurations on the Mack Mid Rise.

Figure 5-16. Test 1 – Side Enclosure, 4 Foot Boat Tail, and Side Skirts

Figure 5-17. Test 2 – Side Enclosure, 2 Foot Boat Tail, and Side Skirts

Figure 5-18. Test 3 – Side Enclosure and 4 Foot Boat Tail

Figure 5-19. Test 4 – Side Enclosure and Side Skirts

Figure 5-20. Test 5 – Side Enclosure

Type II Test Procedures: Vehicle Procedures

As noted above, Mack and Volvo conducted separate but highly coordinated test efforts that used the same measurement approach. The Type II test procedures and data reduction equations are common to both projects and are described below.

The SAE Type II test procedure specified the use of test vehicles and control vehicles. The test vehicle was tested in its baseline configuration and was then retested with various aerodynamic test configurations. The control vehicle remained unchanged during all of the test segments. Any measured variation in fuel consumption on the control vehicle during a given test segment was used to correct the results of the test vehicle for that segment. This compensated for any environmental changes that affect fuel economy. For example, if the test vehicle measured a -3% change in fuel consumption and the control vehicle measured a -0.5% change, then the -0.5% change is subtracted from the -3% test vehicle result to yield a -2.5% test vehicle result.

The test matrix consisted of a baseline test and four iterations of aerodynamic changes. Each complete test segment consisted of at least three runs on the facility; the results of three runs were used to compute an average result. The furthest outlier(s) of all the runs in a segment were discarded. One driver was randomly chosen for each truck and trailer combination and that same driver drove the same vehicle for all test segments. This was done to minimize the effects of driver variability on fuel economy. The vehicles were accelerated to a cruise speed of 65 mph at which point that speed was maintained in top gear with cruise control. Each of the test segments consisted of at least three runs. Each run consisted of six laps for a total distance of 45 miles on the 7.5 miles test track.

The Type II procedure did not specify weather limits but does require recording the weather data. This information was recorded by a local weather station.

Prior to each test segment, the vehicles were inspected and prepared:

- Tire pressures were checked and balanced as needed
- Mirrors adjusted consistently
- Headlamps were turned on and set to low beam
- Heater blowers were set to low speed with A/C turned off
- All other electrical loads were turned off
- The vehicles were warmed up to operating temperatures
- During driver breaks, the test crews drove the trucks to maintain operating temperatures.

Type II Test Procedures: Fuel and Data Acquisition Procedures

Fuel consumption for each vehicle in each test was measured in pounds by weighing portable fuel tanks immediately before and after each test run. The tanks are weighed using a portable triple-beam balance accurate to within 0.01 pound resolution. Successive test runs were made until the following criteria were met:

- The spread of three T/C ratios did not exceed 2% of the highest of the three
- The run times of each truck (control and test) over the same three runs did not exceed +/- 0.5%

With these criteria met for three runs in each segment, the test segment was deemed complete.

Data Reduction

The result of each test segment for the test vehicle was reported as a ratio of the weight of fuel consumed by the test vehicle divided by the weight of fuel consumed by the control vehicle. This ratio is called the

Test/Control or T/C ratio. The percentage of fuel saved in a test segment compared to the baseline is given as:

$$\frac{\text{Average baseline T/C} - \text{Average test T/C}}{\text{Average baseline T/C}} \quad \text{x } 100\%$$

Type II Test Results

An 8.01% improvement in fuel consumption was observed in test 1 for the combination of side enclosure, 4' boat tail, and side skirts. Test 2, consisting of side enclosure, 2' boat tail, and side skirts, showed a fuel improvement of around 7.8%. The other test results are displayed in Figure 5-21.

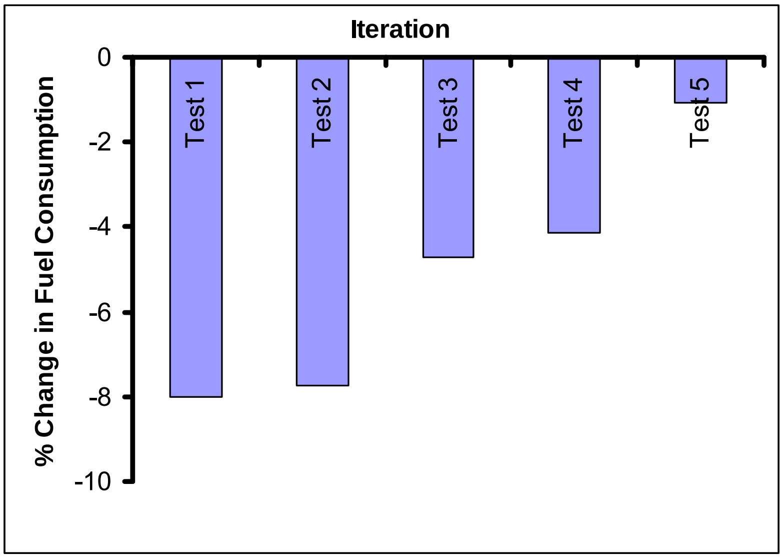


Figure 5-21. SAE Type II Test Results

Type II Test Conclusions

Tuning tests have been conducted for different trailer devices and the fuel savings for each of the combinations have been recorded. Based on these results, two trailer devices were further tested using the SAE Type II test. The side enclosure was selected for Type II testing based on the CFD analysis. The combination of a 4 foot boat tail, side enclosure, and trailer skirts showed a fuel improvement of 8.01%. However, the test was also conducted on a combination with a 2 foot boat tail, side enclosure, and trailer skirts and demonstrated a fuel improvement of 7.75%. This result shows that there was a potential for using a 2' boat tail which can improve the fuel economy significantly. Also, the combination of side skirts and the side enclosure showed a fuel improvement of 4.14%. In addition, the tuning tests and the SAE type II test demonstrated a correlation between those test procedures, enabling further reliable testing and estimation of fuel economy on other devices without investing in full SAE Type II test.

d. Side Enclosure Concept

A simple side extender with no fold back and stow away mechanism was used for the SAE Type II test. Many patents and ideas have been registered for different concepts for devices that can closed the tractor and trailer gap while still able to be stowed when not required. However, these devices have not been commercialized. In this project, Mack examined several practical concepts for the tractor and trailer side enclosure. A new device was prototyped to demonstrate a potential concept to be commercialized. Figure 5-22 shows the prototype of the concept

Figure 5-22. Side Enclosure Concept

folded position on the right hand side and deployed on the left hand side of the truck.

5.4.3. Conclusions and Recommendations

Phase II testing of various devices for closing the tractor and trailer gap and for improving trailer aerodynamics have shown that there are practical solutions available that can be installed and still produce significant aerodynamic benefit.

Additional work needs to be done to study the combined effect of and interaction between devices both on the tractor and the trailer. Also, SAE Type II tests do not consider the side wind load condition, and many of the devices studied (e.g., side enclosures) are more effective in side winds. Additional tests thus need to be conducted to refine fuel consumption savings estimates under these conditions. In addition to the above, further studies can be conducted in partnership with trailer and fleet customers in the industry to test devices in the field and record information on in-use fuel savings.

6. Volvo Project Activities

6.1 Phase I Overview

Volvo focused on the effects of vehicle underside design and tractor-trailer airflow management on vehicle aerodynamic drag. The key Phase I activities completed by Volvo included:

- Completed analysis of the contribution of vehicle underside design to total drag: approximately 35% of total vehicle drag results from the underside of the tractor and trailer.
- Analyzed several modifications to the vehicle underside and trailer gap to reduce overall vehicle drag: 5-6% reductions have been estimated as a cumulative result based on incremental results of underside concepts.
- Additionally, an incremental 2-4% improvement has been shown experimentally by employing simple optimized devices which shorten the effective trailer gap, depending on vehicle specification.

Figure 6-1. Volvo VN-Series Truck

6.2 Phase I Activities

The purpose of Phase I of the TMA/Volvo aerodynamic work was to perform initial screening of candidate devices with the purpose of reducing the effect of vehicle underside design on truck aerodynamics and management of tractor-trailer air flows. The screening was to be performed through computational fluid dynamics (CFD) studies in order to qualitatively evaluate air flow under the vehicle and determine its effect on the complete vehicle drag, and to evaluate the most promising candidate aerodynamic enhancements to be pursued in later studies. Once the candidate devices that produced the best results for managing underside air flow were identified, prototype designs were to be developed for use in Phase II to equip test tractors and trailers for tuning tests. During this phase, these tractors were to be equipped with data logging equipment.

In Phase I, Volvo performed CFD work outside of this project. Results from that work were used to recommend devices to use for this project and to support follow-up CFD analysis for concept optimization. Initial prototype design work was performed for these devices. In addition, the data logging equipment that will be used in the tuning tests was identified.

The project team has equipped one of the test trucks with the data logging equipment that was used in this project for the Phase II road tests. The project used the EMU-2000 software running on a laptop that was connected to the SAE J1587 databus to capture the engine and vehicle data that was used to determine fuel consumption of the test vehicles. The project team created an analysis tool to take the raw engine and vehicle data and convert it into accurate fuel consumption measurements.

The test object for the CFD calculations was a Volvo VNL 620 with roof deflector, chassis fairings and cab side deflectors. The vehicle ride height represented the most common specification on the product. The trailer represented a 48 foot, 102″ wide container with 13′-6″ ground to roof clearance and 10″ rounded leading edge corners. A photo of an actual truck similar to the modeled truck is illustrated in Figure 6-1.

The analysis was made using a commercially available CFD code, Star CD. It employed an 18 million cell model with a high resolution exterior and under hood grid scheme. The under hood airflow was included since it can have an influence on the underside airflow. Rolling road and wheels were employed in the open road simulation.

The results were extracted as an average from within the fluctuations of the converged solution.

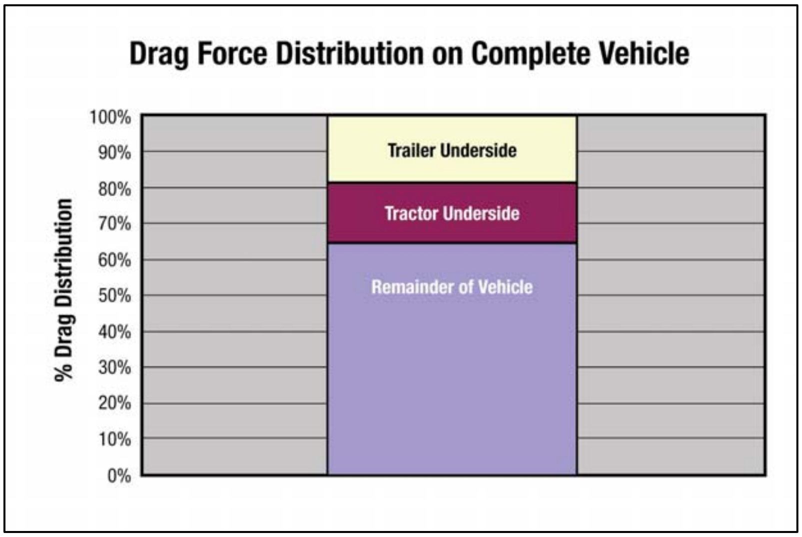


Figure 6-2. Drag Force Distribution on Complete Vehicle

The following iterations were defined and analyzed:

- Baseline
- Baseline with underside geometry (Concept 1)
- Baseline with underside geometry (Concept 2)
- Baseline with underside geometry (Concept 2) and trailer gap manipulation
- Baseline with Concept 3 underside geometry and trailer gap manipulation
- Incremental effect of a trailer bogie deflector

The analysis predicted that 16% of the complete vehicle drag was produced on the underside of the tractor and 19% was a result of the trailer underside. Therefore, roughly 35% of the total vehicle drag was associated with the complete vehicle underside, as shown in the graph in Figure 6-2.

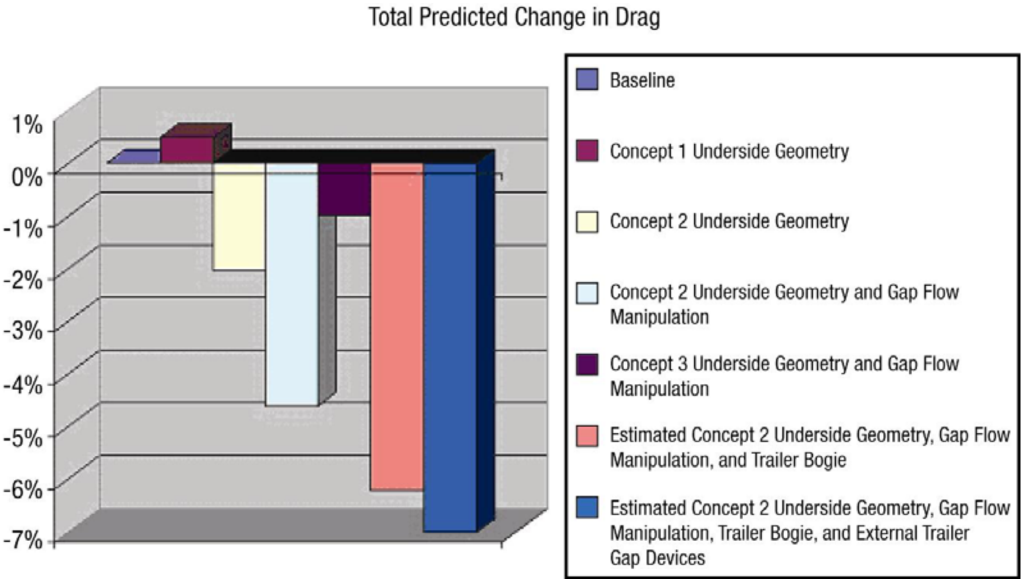


Figure 6-3. Total Potential Change in Vehicle Drag

Table 6-1 summarizes the potential benefits from the work performed to date for the various vehicle concepts, while Figure 6-3 presents the estimated cumulative effects of these improvements. The underside concepts analyzed were combinations of added underside geometries on the middle and rear ends of the underside. Concept 2 was a system of geometries on only the front end of the underside. Concept 3 was a combination of geometries on the front and rear ends of the underside.

Table 6-1. Drag Reduction Results To Date

Analyzed or Measured Vehicle Configuration	Change in Drag (Percent) versus Baseline
Baseline	--
Baseline with underside geometry (Concept 1)	+0.5
Baseline with underside geometry (Concept 2)	-2.0
Baseline with underside geometry (Concept 2) and trailer gap manipulation	-4.6
Baseline with optimized underside (Concept 3) and trailer gap manipulation	-1.0
Incremental effects of external trailer gap devices (adjustable roof extender and optimized side deflector extensions)	-2.5
Incremental effect of adding trailer bogie deflector	-1.6

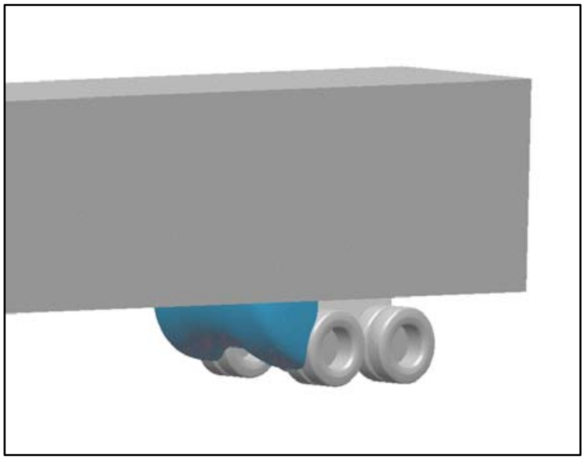


Figure 6-5. Trailer Bogie

The results indicated that Concept 2 was the best opportunity to address the underside. But even then, the opportunity seems to be rather small. Volvo considered this to be an indicator of the efficiency and optimization of the existing vehicle geometry.

Figure 6-4 illustrates flow characteristics on the underside of the vehicle with several of the underside conditions.

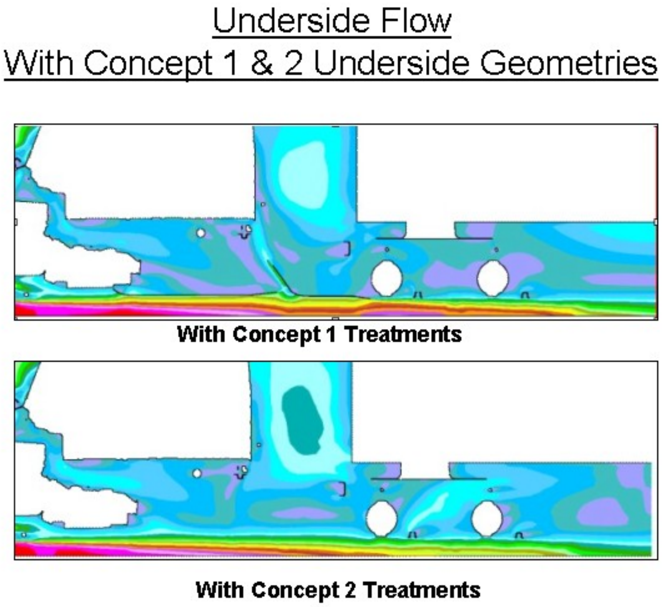


Figure 6-4. Underside Flow

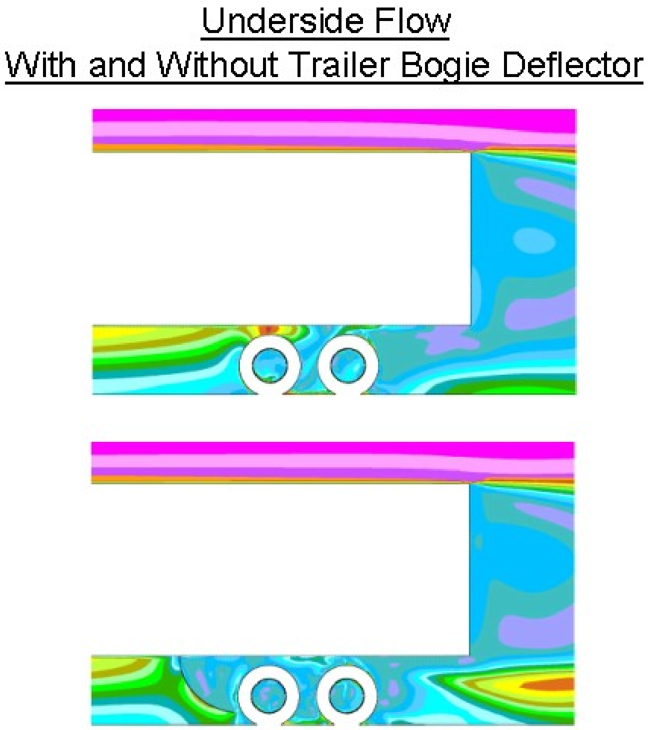


Figure 6-6. Underside Flow

Further, Volvo has seen in previous ½ scale wind tunnel tests that there is an interaction between the underside flow and the trailer gap. Volvo identified a potential improvement of 1% by manipulating the flow of air between the underside and the gap. This potential was related to the opportunity for retuning the setting of adjustable aerodynamic devices in the gap. But it should be noted that the ½ scale testing did not include the influence of underside airflow with a rolling road or spinning wheels.

However, the CFD analysis including representation of a rolling road and spinning wheels predicted an incremental 2% improvement by manipulating the air flow between the underside and the trailer gap, independent of the adjustable feature. The predicted cumulative result of employing the Concept 2 underside geometry and manipulating the gap flow was shown to be a drag reduction of 4.6%.

Finally, Volvo studied the benefits of improving the underside geometry of the trailer. Volvo proposed an air deflector that would improve the effective shape of the bogie (wheels and axles), as shown in Figure 6-5. The combined result of the devices will not necessarily be additive. Therefore, Volvo estimated a total cumulative benefit employing the Concept 2 underside geometry, manipulating the gap flow, and adding a trailer bogie deflector to be as much as around a 5-6% reduction in drag. Figure 6-6 shows flow characteristics around the trailer bogie with and without the deflector.

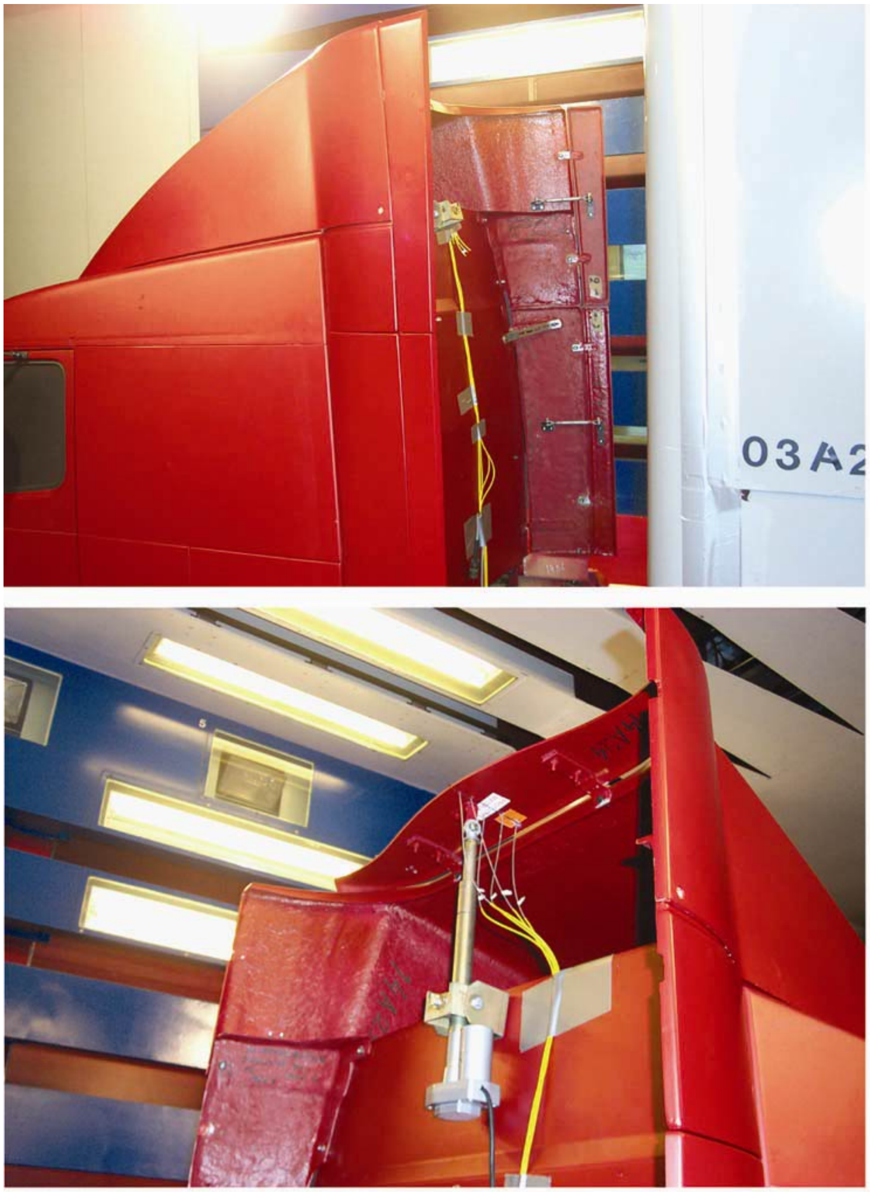


Figure 6-7. Sample Trailer Gap Flow Controls: Side Deflector Extensions (Top) and Roof Extenders (Bottom)

Additionally, there are simple devices on the market that can further reduce drag on the vehicle in areas related to the trailer gap. Volvo provided several add-on devices to further manipulate the airflow within or across the trailer gap (similar to those shown in Figure 6-7). These devices have been shown outside of activities related to this program to collectively reduce the complete vehicle drag by 2% - 4% on ½ scale wind tunnel tests depending on certain applicable vehicle configurations. With the configurations of trailer gap and height that Volvo plans to use for the full-scale demonstration, Volvo estimated performance will be in the lower to middle range of this 2-4% result.

These devices were optimized to improve performance on vehicles with trailer gaps longer than would be considered ideal from an aerodynamic point of view. Both reduce the effective length of the trailer gap. Figure 6-8 illustrates how the shape of the side deflector extensions has been optimized to provide the maximum reduction in drag possible at 0 and wind average yaw angles. The adjustable roof extender was also optimized to provide maximized performance at various trailer gaps and heights. Figure 6-9 illustrates how there is an optimized setting for a given gap length (shown in green). It shows that for a given tested gap length, there is an optimal setting position which maximizes the effectiveness of the extender. Additionally, what is not shown is that even though there is an optimal setting at a given gap length, the drag is always lower than if the roof extender were removed on these vehicles which have these exceptionally long gaps.

Because the cumulative result was again likely not additive, Volvo estimated a total result of employing the Concept 2 underside geometry, manipulating the gap flow, adding a trailer bogie deflector and trailer gap add-ons to be a drag reduction of around 6-7%.

The total cumulative effect of these devices was only an estimated prediction. Volvo did not analyze the combination of underside geometry changes and add-on devices external to the trailer gap.

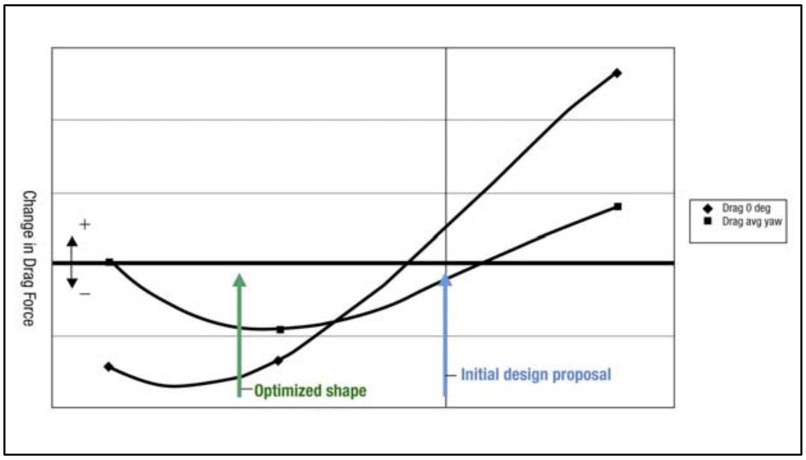


Figure 6-8. Optimized Side Deflector

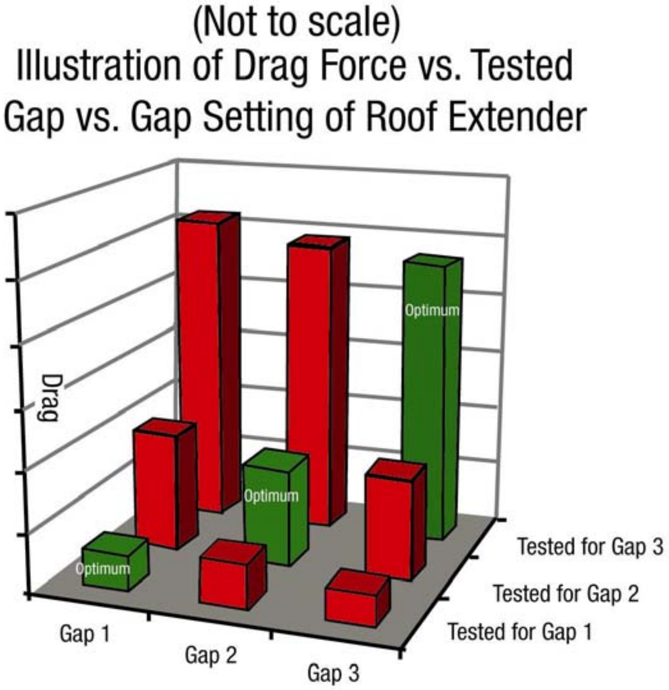


Figure 6-9. Drag Force vs. Tested Gap vs. Gap Setting of Roof Extender

6.3 Phase II Overview

Volvo focused on the effects of vehicle underside design and tractor-trailer airflow management on vehicle aerodynamic drag. The key Phase II activities completed by Volvo included:

- SAE Type II fuel economy tests of combinations of add-on aerodynamic devices (smooth under-body device, trailer gap up-flow prevention device, adjustable roof extension and optimized side deflector extensions to effectively shorten the trailer gap, and trailer bogie deflectors). Fuel economy benefits of 1 to 2.3 percent were demonstrated in track testing.

<u>Phase I Review</u>

Volvo utilized information from CFD analyses that were made outside of this project as a reference to understand the aerodynamic circumstances under the vehicle. It was found that 35% of the vehicle drag is derived from forces on the underside of the tractor and the trailer, with approximately 16% coming from the tractor underside and 19% coming from the trailer underside.

Various solutions to provide a smooth underside concept were then analyzed, as shown in Figure 6-10. It was concluded that with an efficient solution to address underside airflow at the front of the vehicle, little gain can be realized by adding additional and more complex underside devices downstream of the vehicle front.

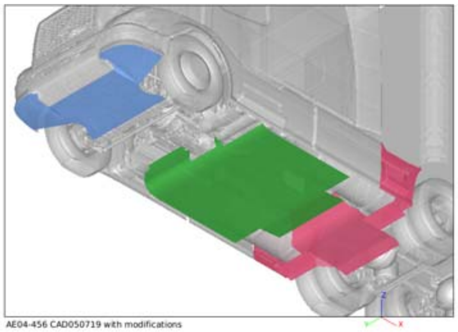


Figure 6-10. Rendering of Concepts Studied by CFD Analysis of the Vehicle Underside

The benefits of preventing air under the vehicle from flowing up into the trailer gap were also analyzed. The results indicated that this concept, in combination with the smooth forward underside, could yield a 4.6% reduction in overall drag. Figure 6-11 shows several examples of results from this analytical effort.

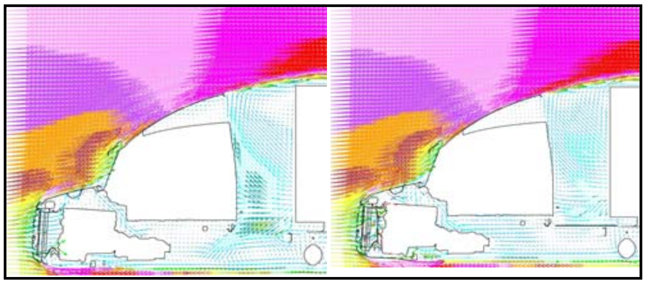


Figure 6-11. CFD Analysis of the Vehicle Underside and Deck Plate Closure

The benefits of coupling these concepts with other concepts that were in the process of being industrialized by Volvo were also considered. Roof and side deflector extensions are devices which effectively reduce the length of the gap between the cab and the trailer. Much work has been done in the academic, government and industry sector to understand and communicate the significance of minimizing the trailer gap to reduce overall drag in a complete tractor-trailer combination vehicle. Although this concept is not completely new, Volvo's solutions are unique in ways that are discussed herein.

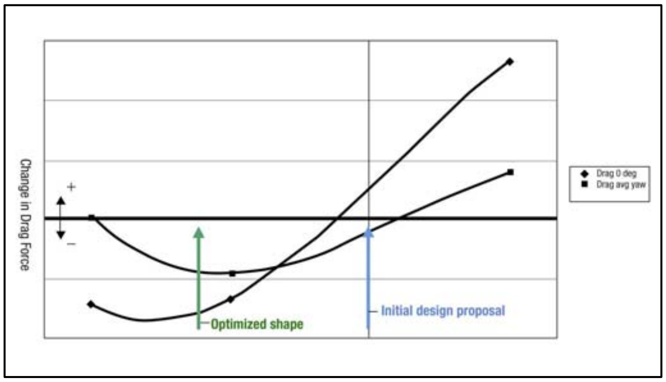


Figure 6-12. Results of Optimizing the Cab Side Deflector Extensions in the Wind Tunnel

The shape of the Volvo cab side deflector extensions were optimized to provide the maximum performance possible. The shape or the extenders matches the complex shape of the cab side deflectors to which they mount. Compared to simple flat

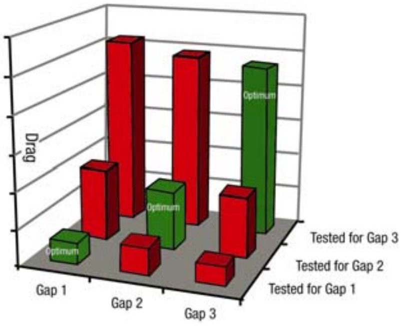


Figure 6-13. The green columns show the lowest achievable drag when the extension is set at the gap which is run

extensions, which degraded vehicle performance, these formed devices provided the greatest reduction of drag possible in an optimized design as illustrated in Figure 6-12.

Volvo's patented adjustable roof extension enables a customer to optimize the airflow across the top of the trailer gap in a wide variety of applications and combinations. Longer-than-ideal trailer gaps cause the air flow coming from the roof of the tractor cab to over-shoot the trailer. This device effectively adapts the shape of the tractor cab roof to accommodate various longer-than-ideal trailer positions and heights by pulling the airflow back to the appropriate re-attachment point on the trailer. By choosing from several pre-determined positions which were based on extensive wind tunnel development and optimization, the user can set the extension at the appropriate position based on the measured trailer gap and relative height of the trailer and tractor. Properly adjusted, these devices provide a maximum possible drag reduction as shown in Figure 6-13.

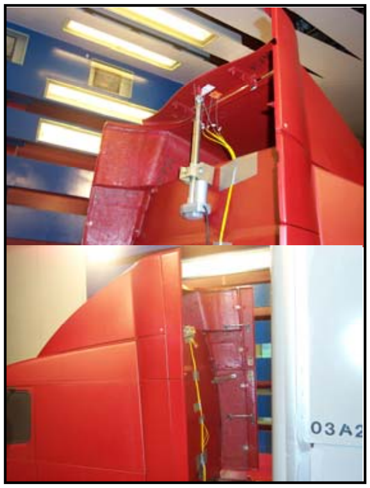


Figure 6-14. Half-Scale Wind Tunnel Testing of the Side Deflector and Adjustable Roof Extensions

Both of these devices were previously developed and optimized based on Volvo's ½ scale wind tunnel test program, the foundation of which is a ½ scale model (Figure 6-14) of the VN product with a highly detailed exterior and chassis and a semi-detailed under hood. These side deflector and adjustable roof extender devices have been proven to contribute a 2-4% cumulative drag reduction in scale model testing depending on specific vehicle configuration.

Figure 6-15. CFD Analysis of Proposed Trailer Bogie Deflector

Finally, CFD analyses indicated that an air deflector device to improve the air flow performance around the trailer bogie (Figure 6-15) could yield a potential drag improvement of approximately 1.5%.

6.4 Phase II Activities

6.4.1. Phase II Objectives

a. Test Objects

Based on results and recommendations of Phase I, the following test objects were prototyped for subsequent testing in Phase II.

Smooth bumper underside fascia: This device mounts to the underside of the bumper and extends to the front axle. It covers the entire underside of the engine compartment. The same bumper and fascia was used on all three test vehicles during the test iterations. (See Figure 6-16.)

Figure 6-16. Underside Fascia

Figure 6-17. Deck Plate

Tractor deck plate enclosure: This device is a simple flat panel that mounted across the frame rail to completely block the flow of air from under the vehicle up into the trailer gap. Small filler pieces were used as needed on each vehicle to fill in remaining openings between the frame rails, such as just forward of the fifth wheel. (See Figure 6-17.)

Volvo's side deflector extensions and patented adjustable roof extender: The side and roof extensions are features that Volvo offers to its customers. Side deflector extensions were fitted to each test vehicle. The components were unique to each vehicle since the roof and side deflector systems are shaped differently on each side of the vehicle and on each VN model. (See Figure 6-18.)

Figure 6-18. Side Deflector Extensions and Adjustable Roof Extender

Figure 6-19. Two Different Trailer Bogie Concepts Studied in Phase II

Trailer bogie deflector: These devices were acquired from a private developer in Montreal, Quebec, Canada. One covered the leading set of wheels on the trailer and the other did not cover the wheels at all. Each had a slightly different shape across the face of the part. One of these parts had been previously tested in the NRC wind tunnel. (See Figure 6-19.)

b. Test Trucks

The following vehicles were utilized during the various sub-phases of testing and are shown in Figure 6-20.

- Volvo VN 670 (Vehicle ID 338931): This vehicle was tested in the tuning test phase and was the test vehicle in the SAE Type II tests.
- Volvo VN 780 (Vehicle ID 350893): This vehicle was tested in the tuning test phase.
- Volvo VN 630 (Vehicle ID 6311 Advantage Truck Leasing): This vehicle was tested in the tuning test phase and was the control vehicle in the SAE Type II tests.

Figure 6-20. Test Objects

6.4.2. Analysis and Result

a. Method

The test phase of this project involved two sub-phases. The first sub-phase was a screening phase where tuning tests were performed to screen and compare combinations of selected devices or concepts prior to defining a test plan for the next more detailed and thorough sub-phase. This second sub-phase involved SAE Type II fuel economy tests on a closed circuit track.

b. Performed Tests (Tuning Tests)

Overview

The intent of this sub-phase was to understand the relative effectiveness of combinations of devices and concepts that were selected in Phase I. The results were used to:

1) Define a narrower selection of combinations to be tested in the next test sub-phase and
2) Determine which of the three vehicles would be used as the test vehicle in next test sub-phase

Note that the results of these tuning tests were not interpreted as an indicator of actual changes in fuel consumption to expect during the SAE Type II testing.

Vehicle Configurations

During this phase of testing, each of the three test vehicles was tested in a baseline configuration (with no studied devices or concepts) with the same test trailer. The VN 670 was then tested with the complete matrix of iterations shown in Table 6-2. The best combination of these was then run on each of the other two vehicles with the devices and concepts adapted specifically to each tractor as necessary. Adaptation was only necessary, for example, to accommodate a larger deck plate area on one truck compared to another. Otherwise, the concepts were identical on each truck.

Table 6-2. Configurations Tested on the VN 670 (Volvo Tuning Tests)

Test ID / Devices	Baseline 670	Test 2 670	Test 3 670	Test 4 670	Test 5 670	Test 6 670	Test 7 670	Test 8 670	Test 3 780	Test 3 630
Gap Extension Devices		●	●			●			●	●
Deck Closure		●	●	●	●	●			●	●
Smooth Underside			●	●	●	●			●	●
Bogie Deflector 1					●	●	●			
Bogie Deflector 2								●		

● Devices Included in the Test

The trailer was unloaded during the tuning tests to make the fuel measures more sensitive to the aerodynamic changes that would differentiate one test from another.

The test matrix shown in Table 6-2 was defined considering how concepts were combined in the analytical stages in Phase I and in consideration of how devices and concepts might be offered or marketed to potential customers. For example, gap related devices were tested in Test 2 where the side/roof extensions coupled with the deck closure were combined. Similarly, the bumper underside flow device was coupled with the deck closure in Test 4. Test 3 looked at all tractor related devices while tractor and trailer underside devices were combined in Test 5. Test 6 provided an evaluation of all devices in combination. Finally, the two bogie deflectors were compared without any other changes to understand their relative performance in Test 7 and 8.

Test Equipment, Environment, and Local Test Routes and Procedures

As noted above, Mack and Volvo conducted separate but highly coordinated test efforts that used the same measurement approach. The information on test equipment, test environment, and local test routes and procedures are common to both projects and are described in Mack's Phase II efforts (Section 5.4.2).

Tuning Test Results

The initial screening of all proposed combinations was made on the VN 670. The results of this effort on the initial VN 670 tests are shown in Figure 6-21 and indicated that the most effective combinations of devices is Iteration 3 (all added tractor devices) with Iteration 4 (deck closure and smooth underside) and Iteration 6 (all tractor devices plus trailer deflector) and Iteration 8 (bogie deflector 2) being the next most effective.

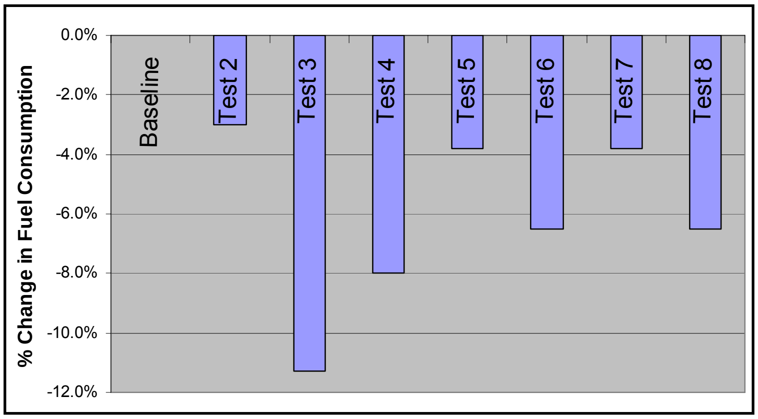


Figure 6-21. Tuning Test Results for the VN 670

Again, it is important to point out that this phase of screening was not a well controlled procedure with no reference vehicle to level influences unrelated to the aerodynamic changes made (with the exception of compensating for air density changes). The results were only used as "order of magnitude" indicators to aid in down-selecting combinations for the Type II testing.

The intent of this phase was to determine a relative effectiveness between combinations and to identify which truck was showing the greatest sensitivity to these changes. The purpose for identifying this sensitivity was not to draw conclusions regarding relative effectiveness of devices on one truck versus another, but rather to know that the relative conclusions being made were based on the best sensitivity available among the test vehicles.

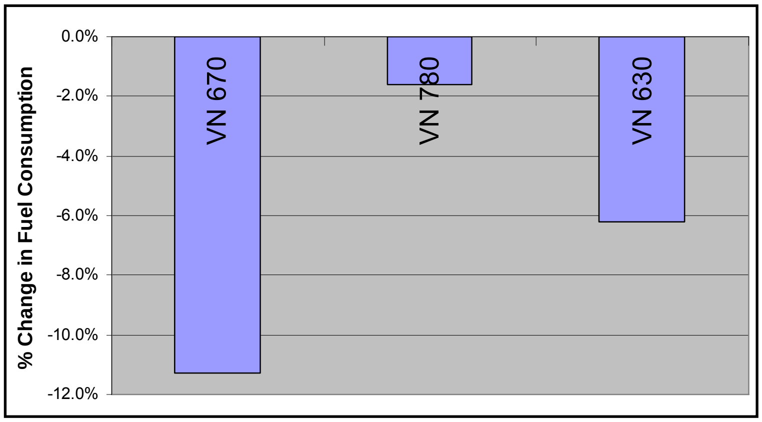


Figure 6-22. Tuning Test Results for Iteration 3 on All Vehicles

Since Iteration 3 was the combination to which the 670 was most sensitive, Iteration 3 was then tested on each of the other two test vehicles, the results of which are shown below together with the results of the VN 670 in Figure 6-22.

Table 6-3. Recommended Type II Test Matrix as Result of Tuning Tests

Test ID Devices	Baseline 670	Test 2 670	Test 3 670	Test 4 670	Test 5 670
Gap Extension Devices		●	●		●
Deck Closure		●	●	●	●
Smooth Underside		●	●	●	
Bogie Deflector 2		●			

● Devices Included in the Test

Tuning Test Conclusions

Since the 670 was shown to be the most sensitive to the changes, it was decided that this vehicle would be the test vehicle for the next phase of tests. The intent was to determine the relative effectiveness of all the devices on the vehicle that showed the greatest sensitivity in the tuning test procedure.

Further, based on the tuning test results, the second bogie deflector showed the greatest improvement in fuel consumption compared to the first and was therefore recommended for SAE Type II testing. The combinations shown in Table 6-3 were recommended for Type II fuel economy tests.

c. Full-Scale Tests (SAE Type II Tests)

Overview

During this sub-phase of testing, differences in fuel economy associated with changes in aerodynamic combinations were measured according to TMC/SAE Fuel Consumption In-Service Test Procedure Type II. This work was contracted to the Transportation Research Center in East Liberty, Ohio. A complete description of the procedure used can be found in SAE Recommended Practice J1321.

The SAE Type II test procedure provided a controlled test environment when fuel economy testing full scale trucks. The principal disadvantage compared to real world testing was that testing is conducted on an essentially flat gradient facility. Therefore, the baseline fuel consumption was represented by a relatively flat driving cycle. Another disadvantage was that the procedure sets no limits on wind speed or direction. Even though a control vehicle was used to identify and compensate for these influences, some of the tested devices were highly effective with high side wind components. The results presented herein indicate the percentage changes in fuel consumption for the applied devices and concepts.

Vehicle Preparations

The VN 630 was the control vehicle, while the VN 670 was the test vehicle. Both vehicles pulled 53’ Great Dane trailers. The test and control vehicles were prepared as follows:

- Steer, drive and trailer axles were aligned
- Tractor and trailer axle bearing and brake adjustments were checked
- GPS units were installed
- 5th wheel positions were adjusted and fixed at a pre-chosen trailer gap length of 1.27 meters
- Trailer axle bogies were positioned at a point 1/3 of their travel behind the forward-most point
- Trailers were loaded to a GVW of 65000 pounds +/- 50 pounds
- Gravimetric fuel systems with quick-disconnect couplers were installed
- Tires were set to consistent cold pressures
- A/C compressors were disabled

Vehicles

Figure 6-23 through Figure 6-28 show the actual tested configurations on the VN 670.

Figure 6-23. Control Vehicle VN 630

Figure 6-24. Baseline VN 670

Figure 6-25. Test 2 VN 670 – Total Combination of Tractor and Trailer Mounted Devices

Figure 6-26. Test 3 VN 670 –All Tractor Devices

Figure 6-27. Test 4 VN 670 – Gap Devices and Deck Closure

Figure 6-28. Test 5 VN 670 – Gap Devices and Deck Closure

Type II Test Procedures: Vehicle Procedures/Fuel and Data Acquisition Procedures/Data Reduction

As noted above, Mack and Volvo conducted separate but highly coordinated test efforts that used the same measurement approach. The Type II test procedures and data reduction equations are common to both projects and are described in the Mack Phase II section above.

Type II Test Results

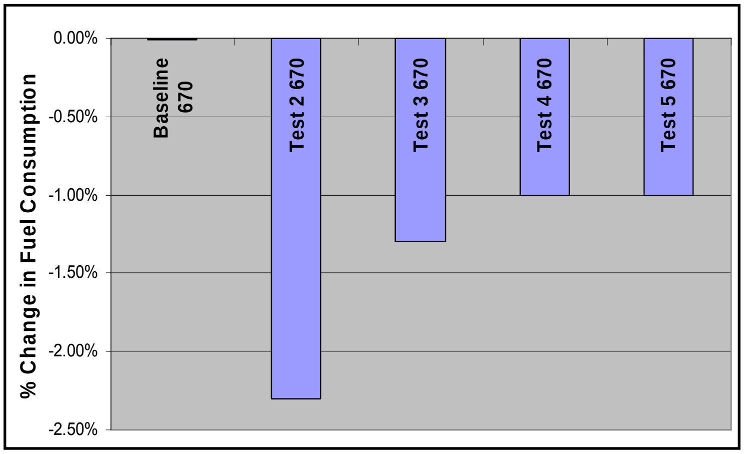


Figure 6-29. SAE Type II Test Results

A 2.3% improvement in fuel consumption was observed for the combination of all tractor devices plus the trailer bogie deflector, Test 2. All of the devices on the tractor, Test 3 (excluding the trailer deflector), yielded a 1.3% improvement in fuel consumption. The combinations of the smooth underside plus deck closure, Test 4, and the combinations of deck closure plus gap extension devices, Test 5, each yielded a respective 1% improvement in fuel consumption. These results are shown in Figure 6-29.

Figure 6-30 shows the results of the tuning tests and SAE Type II tests, comparing the iterations that were run in each test phase. It can be seen that the orders of magnitude differ greatly, but the relative trends are consistent.

Type II Test Conclusions

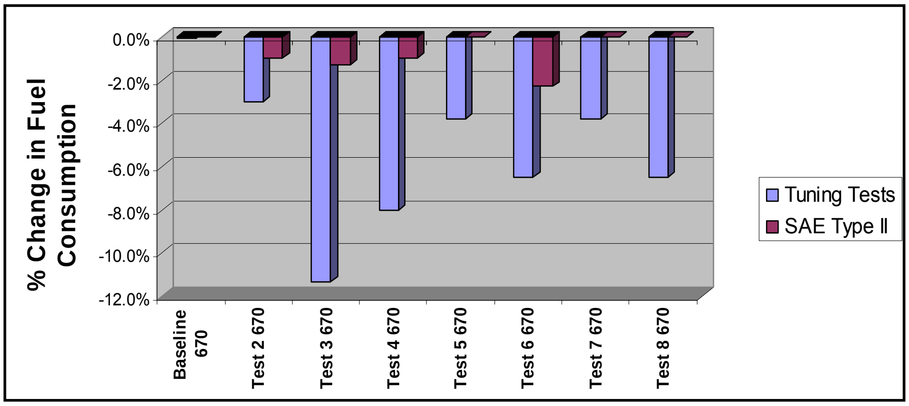


Figure 6-30. Changes in Fuel Consumption During Tuning and SAE Type II Tests

The tuning test methods employed during this phase of the project proved useful in comparing aerodynamic changes on a given vehicle for the purpose of observing relative effectiveness, however this methodology was not useful when comparing similar changes between vehicles. The method also did not yield comparable absolute fuel consumption results compared to those obtained using the SAE Type II test procedures.

The SAE Type II tests confirmed the trends observed in the tuning tests and illustrated the potential fuel savings benefit of the aerodynamic technologies studied in this program.

6.4.3. Conclusions and Recommendations

The second phase of the project proved the technologies investigated by Volvo can be integrated into tractor and trailer combinations to yield modest, but significant improvements in fuel consumption.

Complementary projects by other OEM's yielded higher potential savings with larger and more complex devices and concepts. The intent of the Volvo portion of the program was to complement these more complex designs with significantly effective, but simpler approaches.

Collectively, the efforts of all the participants demonstrated that there are opportunities for improving aerodynamic drag on heavy vehicles. However, the program also demonstrated that significant detailed engineering analysis, testing and tailored design work is necessary to achieve these additional gains, since today's modern tractor designs already perform well in this regard. Nothwithstanding, this program has significantly contributed to the Department of Energy's goal of demonstrating the benefits of technologies that are not currently in the market place and in helping to educate the market as to their potential value.

7. Project Conclusions

In Phase I, potential aerodynamic drag reductions of up to 20% have been identified through various modifications to the truck tractor and trailer system. Contributions of mirror systems to total aerodynamic drag of the truck tractor and trailer system have been identified. Issues of practicality, manufacturability, and serviceability have been considered in the choice of aerodynamic aids and the basic design of such aids.

In real-world track testing for Phase II, fuel economy improvements of up to 11.5 percent have been demonstrated through various modifications to the truck tractor and trailer system. Contributions of mirror systems to total aerodynamic drag of the truck tractor and trailer system have been identified. Issues of practicality, manufacturability, and serviceability have been considered in the choice of aerodynamic aids and their basic design.

On November 13, 2006 the four participating manufacturers presented an oral briefing of the results on their work to DOE officials in Washington, DC. On November 14, all four manufacturers displayed the trucks and trailers they used in the Phase I and II research outside the DOE Forrestal Building, for the benefit of DOE and other agency management, as well as for DOE staff and the general public. Speakers at this event included: Robert M. Clarke (President, Truck Manufacturers Association), Patrick Charbonneau (Vice President of Government Relations for International Truck and Engine Corporation), David Rodgers (DAS for Technology Development for DOE EERE), and Congressman David Hobson from Ohio. Photos from the day's event are shown on the next page.

There was great interest from the Congressman and the DOE staff in the technologies displayed. The group spent a significant amount of time discussing the achievements of each OEM with the technical representatives in attendance. The OEMs participating in the event developed press releases within their own public relations organizations describing their achievements, and the event received coverage from Transport Topics and other trade press. The photos on the next page illustrate the trucks and technologies that were displayed at the event.

CFD Velocity Profiles (Freightliner)

International/Wal-Mart/Great Dane Trailer

Freightliner Display Truck

Mack Demonstration Truck

International ProStar Aero Tractor

Trailer Boat Tail (Mack)

Volvo Underbody Concept

Volvo Trailer with Bogie Deflector

Dignitaries at Event (from left): Pat Charbonneau (International); Congressman Dave Hobson; David Rodgers (DOE); Robert Clarke (TMA)