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SYSTEMATIC APPROACH TO ANALYZING AND REDUCING AERODYNAMIC DRAG OF HEAVY VEHICLES

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This paper presents an approach for reducing aerodynamic drag of heavy vehicles by systematically analyzing trailer components using existing computational tools and moving on to the analyses of integrated tractor-trailers using advanced computational tools. Experimental verification and validation are also an important part of this approach. The project is currently in the development phase while we are in the process of constructing a Multi-Year Program Plan. Projects 1 and 2 as described in this paper are the anticipated project direction. Also included are results from past and current related activities by the project participants which demonstrate the analysis approach.

1.0 Goals, Objectives, and Approach

The project goal is to develop and demonstrate the ability to analyze aerodynamic flow around heavy truck vehicles using existing and advanced computational tools. These tools can be used to reduce aerodynamic drag of heavy truck vehicles and thus improve their fuel efficiency. The effort is divided into two separate but related projects:

Project 1: Simulation of Trailer Components with Existing Computational Tools (near term)

Project 2: Integrated Tractor-Trailer Simulation with Advanced Computational Tools (longer term)
By using *existing* computational tools, Project 1 is a 'near-term' effort for relatively quick development of drag reducing guidelines (Part 1 of Project 1) and the demonstration of a trailer add-on device (Part 2 of Project 1).

The objectives for Part 1 of Project 1 are

1) The identification and prioritization of trailer drag-sources,
2) Guidelines for improving trailer drag by the use of aerodynamic add-ons, trailer contouring, and tractor-trailer gap control, and
3) The establishment of an effective computational approach for designing/analysis of heavy vehicles. This will be based on a summary of benchmarking efforts and results with the computational tools compared to experimental data.

The objectives for Part 2 of Project 1 are

1) A document detailing the design, analyses, and testing (wind tunnel and field testing) of a trailer add-on device used for drag reduction,
2) The demonstration of a trailer add-on device that can reduce vehicle drag and thus, fuel consumption.

The design of a fully-integrated, aerodynamic tractor-trailer, Project 2, is a 'longer-term' project with a research and development component. Project 2 includes the use of *advanced* computational tools, currently in development.

The objectives for Project 2 are

1) A document detailing a multi-level analysis approach for the design of an integrated tractor-trailer system using accurate computational modeling with advanced computational tools and wind tunnel testing, and
2) A computational tool and experimental methods for use by industry, national laboratories, and universities for the aerodynamic modeling of heavy truck vehicles.

The issues related to the design, manufacturing, integration, and use of aerodynamic add-on devices and a fully-integrated tractor-trailer will be addressed with the industry throughout the simulation effort. Acceptance and careful planning of the implementation of aerodynamic guidelines is critical to the success of the entire project. Communications through documentation and meetings with an Advisory Committee of industrial representatives will be part of Projects 1 and 2.

2.0 Background

To determine how the DOE can assist the heavy vehicle industry, the DOE and Lawrence Livermore National Laboratory (LLNL) co-sponsored a Workshop on Heavy Vehicle Aerodynamic Drag in Phoenix, Arizona on January 30-31, 1997. The Workshop succeeded in providing a forum for communication between competitors in the heavy vehicle industry, DOE National Laboratories, other government laboratories, and universities. It
was the general consensus at the Workshop that the trailer design should be the focus of near term efforts, since significant improvements have already been made to tractor designs. Improvements to the trailer would have to include changes to a number of areas including the base region, undercarriage, and tractor-trailer gap. However, even the improvements to the trailer cannot, by themselves, produce the entire 50% drag reduction goal; but it is a starting point. With the limited projected improvements using add-on devices, most of the Workshop participants also agreed that an integrated tractor-trailer design is needed to achieve significant drag reductions.

At the Workshop, Eugene Olson of Navistar International Transportation Corporation provided a summary of heavy truck development in the US from the 1930's to present day. An interesting conclusion was that truck design is driven primarily by operator economic issues. Also, since the 1950's engine power has continually increased, allowing larger and boxier trailers to operate. Both circumstances ultimately result from a plentiful supply of inexpensive diesel fuel. The oil embargo of 1973 generated renewed interest in more efficient aerodynamic designs and improvements were made using various add-on aerodynamic devices (e.g., aero-shields, trailer skirts and boattails).

The achievement of reduced fuel consumption hinges upon the availability of trucks having greater aerodynamic efficiency. In the past twenty years, drag coefficients for typical large trucks have decreased by about 30% - from the range $C_D = 0.8-1.0$ to $C_D = 0.5-0.7$. Note that the drag coefficient, $C_D$, is a dimensionless drag force defined as the drag force/ (dynamic pressure x projected area). The tractor aero-shields were the first major drag improvements, and newer truck cabs possess a more aerodynamic shape and an integrated trailer-shield. Economical travel will require even greater efforts to integrate tractor and trailer design in one clean aerodynamic-package.

Figure 1 contains the estimated horsepower associated with aerodynamic drag in comparison to the power required to overcome rolling resistance and to supply needed auxiliary power, plotted as a function of speed. The truck in question is a modern Class 8 tractor-trailer possessing a wind-averaged drag coefficient of $C_D=0.60$, and weighing 80,000 pounds. At a speed of about 50 miles per hour, the horsepower contribution required to overcome aerodynamic drag, and the contribution required to overcome rolling resistance/ auxiliary power are about equal. For higher speeds the aerodynamic contribution becomes progressively more dominant. At 70 miles per hour, overcoming aerodynamic drag repre-
sents about 65% of the total energy expenditure for a typical heavy truck vehicle. Truck cruising speeds in the range of 70-80 miles per hour are not uncommon.

It is conceivable that present day truck drag-coefficients can be reduced from $C_D = 0.5-0.7$ to maybe as low as $C_D = 0.3$, which represents an ambitious goal of approximately 50%. There are several reasons for our confidence in these projected improvements. First, automobiles have undergone comparable improvements, and the cars of today are still not optimum aerodynamic shapes, due to styling considerations. Truck design is more strongly driven by economic considerations. If a near-optimum aerodynamic design that meets payload and functionality requirements and contributes to fuel savings for the operator should become available, it would likely be adopted.

Figure 2 illustrates the overall economic benefit associated with reductions in aerodynamic drag as a function of vehicle speed. The ordinate on the left presents calculations of fuel consumption in gallons per mile traveled for a typical Class 8 tractor-trailer powered by a modern, turbocharged diesel engine operating at a fixed specific fuel consumption, $bsfc=0.34$ #/HP-hr. Five estimates of fuel consumption are shown, corresponding to five values of wind-averaged drag coefficient between $C_D=0.7$ and 0.3. To the right are plotted the total yearly fuel expenditures expressed in billions of gallons based upon the estimate of 60 billion highway miles traveled (per year) in the year 2012 by Class 8 trucks. The 60 billion highway miles is predicted by applying a 30% growth factor to the FHWA annual vehicle-travel estimates for 1992 (Highway Statistics 1992, p 207, US Government Printing Office, SSOP, Washington DC 20402-9328). Reducing the drag coefficient from 0.6 to
0.3 for a typical Class 8 tractor-trailer would result in a total yearly savings of 3 billion gallons of diesel fuel for travel at a present day speed of 60 miles per hour. The mileage improvement is from 6.1 miles per gallon to 8.7 miles per gallon - a 43% savings.

![Graph showing fuel expenditures as a function of travel speed and drag coefficient.]

**FIGURE 2.** Fuel expenditures for a typical Class 8 tractor-trailer as a function of travel speed and drag coefficient.

It should be noted that aerodynamic issues extend beyond the desire for improved fuel economy. They include the assurance of sufficient vehicle stability for safe handling at highway speeds, as well as the minimization of harmful interactions with other vehicles on the roadway. These interactions occur as aerodynamic loads on nearby vehicles, and by means of unwanted splash and spray raised from the roadbed. The attainment of a satisfactory aerodynamic design must include the mitigation of potential buffeting and turbulence loading on nearby vehicles.

Finally, it is important to consider constraints imposed by federal laws, city driving, and functionality. In particular, add-on devices must meet design constraints imposed by the US Department of Transportation. Although aerodynamic add-on devices have resulted in fuel savings for the trucking industry, it has sometimes impacted maintenance and operational costs. A study conducted by the Maintenance Council of the American Trucking Association found that tractor mounted aerodynamic devices can cause components to operate at higher temperatures, can cause unwanted debris buildup and corrosion due to retained moisture, can result in reduced visibility, damage at loading docks, poor mounting hardware, increased wind buffeting, reduced access to maintenance items, and increased tractor-trailer weight and brake loads. Similar concerns and additional opera-
tional issues can also exist for trailer add-on devices. In addition, add-on devices must be effective in both up-front costs as well as their life-cycle cost.

Aerodynamic Simulation Utilizing Computational and Experimental Simulation

Flow-Field Modeling: Aircraft versus Heavy Trucks

At present, the aerodynamic design of heavy trucks is based largely upon wind tunnel estimation of forces and moments, and upon qualitative streamline visualization of flow fields. No better methods have been available traditionally, and the designer/aerodynamicists are to be commended for achieving significant design improvements over the past several decades on the basis of limited quantitative information.

The trucking industry has not yet tapped into advanced design approaches using state-of-the-art computational simulations to predict optimum aerodynamic vehicles. Computational analysis tools can reduce the number of prototype tests, cut manufacturing costs, and reduce overall time to market.

Throughout this time, numerical codes have been extensively used in the aircraft industry to aid the design process. Why are they not more utilized for ground vehicles? The reason, we believe, lies with the geometry of the two vehicles (aircraft versus truck) and with the nature of the simplifying approximations which can be justified. Aircraft are more slender than trucks, and flow fields about slender bodies are less complicated. An aircraft’s flow-field has traditionally been divided into an outer, inviscid flow and an inner, boundary-layer flow. The inner, boundary-layer flow is the difficult one to calculate, but the process is simplified by the fact that the boundary layer remains thin and attached for an aircraft. Outer flow calculations then provide information needed to make the boundary-layer calculation. Modern computational techniques do not make this separation explicitly, but their success in modeling aircraft flow-fields is nonetheless related to the slenderness issue.

By contrast, a comparable understanding of the flow field about a large truck (a much more bluff object) is one of the grand challenges in the field of aerodynamics. The flow is strongly three-dimensional, contains significant regions of separated flow, and is unsteady in time. Most numerical schemes presently in use are not well suited to handle unsteady, separated flows, and hence do not provide convincing information for the designer. However, as computer speed and memory capacity improve, the ability to achieve practical calculations for trucks becomes possible. We believe now is the time to start such a computational effort. The next several paragraphs briefly outline a strategy for both computation and experimental verification.

Present and Future Computational Possibilities for Heavy Trucks

In any discussion of computational aerodynamics, it is necessary to distinguish between computer algorithms (or codes) which are sufficiently documented and understood so as to
be available as a design tool, and those procedures or codes which are presently near the forefront of computing research. Into the first category are placed many of the commercially available codes which usually predict a steady time-averaged flow field. In addition, these existing design tools utilize models which have empirically based parameters which are often determined by experiment before parametric design studies can be performed. With the proper experimental validation process, these tools can provide guidance for some general shapes and the complete truck system with some resolution of under-body flow, wheels, mirrors, and gaps between the tractor and trailer. However, these Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) tools may not capture details which are inherently time dependent. In some cases, these unsteady effects are important in refining the truck aerodynamic design and should be included. However, CFD tools more sophisticated than RANS are not developed to the point to be useful for large-scale complex flow-fields and continued research is still needed to advance these tools.

For a comprehensive calculation of the entire flow-field, a more fundamental approach needs to be considered. One such approach is the large-eddy simulation (LES) technique now under study at many universities and government laboratories. The numerical implementation of LES can be accomplished by finite element methods (FEM), finite difference methods, or Lagrangian approaches termed vortex methods wherein small vorticity elements (or vortices) are directly followed throughout the flow field. The latter procedure is efficient in that only fluid parcels carrying vorticity need be followed, and no computational grid is necessary. All implementations resolve the time dependence of all important large scales of the full three-dimensional flow, and are computationally intensive. Present day computers are not large enough nor fast enough to utilize LES to calculate the flow field around an entire truck. However, time is on the side of these fundamental procedures. As computers inevitably improve in performance, it becomes realistic to think of incorporating these computational tools into a design procedure. An integrated tractor-trailer design that achieves a drag reduction of 50% will require a long-term commitment to computational aerodynamics development. We believe now is the time to begin such a development.

To validate the three-dimensional time-dependent predictions by LES, experimental measurement of the unsteady flow is needed. Commonly, experimental methods only provide steady time-averaged data. There is a significant new computer-based experimental technique which can provide enhanced quantitative flow-field estimation. This is the digital particle image velocimetry (DPIV), or a recent variant termed correlation image velocimetry (CIV). Either one is capable of providing thousands of instantaneous flow vectors in a single flow plane. Such detailed observation of actual flow-fields is also needed for design purposes and for validation of computational solutions. CIV is currently in a development stage, but is progressing in rapid strides. It will be the measurement tool of the coming century, and will be of immense value when it can be utilized routinely by industry.

We should also note that representing the ground motion can be important for computational and experimental simulations. A moving ground plane is a useful device for eliminating the usual ground plane boundary layer in the wind tunnel, but it is not absolutely
necessary. There are other means for controlling boundary layer growth in the wind tunnel.

In summary, existing computational tools with experimental validation can be used in the near term to begin investigating truck design improvements for individual flow areas. While the entire tractor-trailer can be modeled using the RANS CFD approach, it may be possible to model parts of the truck using both RANS and LES approaches. Such areas of study can focus on rear and frontal flows, under-body flows, tractor-trailer and trailer-trailer gaps, under-hood flows, wheel, wheel-well flows, and spray characteristics.

All of these procedures are part of this project. First it is important to identify possible trailer aerodynamic improvements (add-ons, for example) which might be applied in the near term. Second provisions must be made for a significant longer range payoff by the introduction of new tools into the design process. The project strategy for implementation can be summarized as follows:

- Implement RANS calculations and improved RANS calculations where appropriate—particularly in the short term,
- Implement the newer and more computer intensive time resolved procedures (LES) on a longer time scale,
- Develop CIV techniques for use in bluff-body flow-fields, and
- Measure progress by making intercomparisons between RANS and LES calculations and CIV flow field measurements.

### 3.0 Demonstrative Results

The following sections describe example results from past and current related activities by the project participants which demonstrate the project analysis approach. The results of a Ground Transportation System (GTS) research project performed by Sandia National Laboratory is presented in Section 3.1. This project utilized existing computational tools in conjunction with experiments to design a drag reducing boattail. In Section 3.2, an investigation of drag effects due to gap distance between close-following vehicles is presented. This work is a continuing project at the University of Southern California and has implications for gap separation between tractor-trailers, as well as for several trucks traveling in a convoy.

#### 3.1 Demonstration of Trailer Add-On Device

SNL has designed a boattail as part of the Ground Transportation System (GTS) research project. Figure 3 shows the solid model of the GTS tractor-trailer baseline geometry that is similar to the Penske vehicle also shown in the Figure. The 8-foot tangent ogive-type boattail, shown in Figure 4, has good drag reduction benefits in terms of ‘wind-averaged’ drag coefficient. This boattail design has been shown computationally, experimentally, and in field testing to reduce aerodynamic drag by almost 10% for aerodynamically ‘clean’ trac-
tor-trailer systems (savings on actual operational trucks may be less). Figure 5 shows predicted velocity vectors in the base region of the GTS with the boattail.

FIGURE 3. Solid model of the GTS tractor-trailer baseline geometry.

FIGURE 4. Surface grid for computations with 8-foot boattail.
3.2 Wind Tunnel Observations and Field Tests Predict the Drag of Two Close-Following Vehicles

Wind tunnel test results predict that two ground vehicles (minivan models in the tests), following one another closely, would both experience a reduction in drag. In fact, at short spacings—say less than about 0.4 vehicle lengths—the forward vehicle is shown to experience a smaller drag than the trail vehicle. This counter-intuitive result has prevailed even when the model vehicles have been positioned in back-to-back, front-to-front, or in reversed orientations. Such changes are easily accomplished in the wind tunnel. Figure 6 is a photograph of the two model vehicles mounted on specially designed wind tunnel ground plane. The surface of the ground plane has been partially removed to reveal the underplane stepper motor-controlled support system.
As a supporting demonstration, full-scale field tests were recently conducted to separately measure the drag of each vehicle in a close-following geometry. The two vehicles—Windstar vans in this case—are connected by means of a towbar instrumented to measure force. In an acceleration, or pull-up phase, the forward vehicle tows the trail vehicle to a speed of approximately 85 MPH. In a deceleration, or coast-down phase, the trail vehicle brakes modestly to slow both vehicles. Figure 7 shows the two vehicles on the dry lakebed at El Mirage during pull-up/coast-down tests. The drag coefficients for the full-scale tests are shown in figure 8 in comparison to the wind tunnel results. The drag coefficients are plotted for each vehicle as a fraction of the drag of an isolated vehicle, as a function of vehicle spacing—from bumpers touching to a separation of about one vehicle length. Most importantly, the wind tunnel and full-scale experiments both predict a region of short separations for which the drag of the lead vehicle is less than the drag of the trail vehicle. Furthermore the magnitudes of the drag coefficients, estimated from wind tunnel and full scale, agree to within estimated errors in this region. The two experiments disagree somewhat on where the crossover takes place—the wind tunnel result places the crossover at about 0.4 vehicle lengths, and the full scale result is approximately 0.5 vehicle lengths.
FIGURE 7. Photograph of two vehicles during full-scale field tests.

FIGURE 8. Comparison of full-scale and wind-tunnel tests.

More recent wind tunnel experiments have explored the back-to-back vehicle geometry in more detail. At short spacings, this particular geometry is very sensitive to small changes in spacing. At a certain spacing—approximately 0.15 vehicle lengths—the drag on the trail
vehicle increases by a factor of about 1.7, while the drag of the lead vehicle remains roughly constant. The average drag is thus increased by about 1.35, or 35 percent.

These results have implications for large tractor-trailer combinations including those hauling second trailers. There may be certain gap separations for which the drag increases significantly, and these separations are to be avoided. More accurate geometric models of tractor-trailer gaps are needed, of course, to make reliable predictions for trucks.

4.0 Future Plans

The first priority for fiscal year 1998 is to finalize a Multi-Year Program Plan (MYPP). A Technical Subcommittee with the following members has prime responsibility for constructing the MYPP and will directly work with industry in the MYPP development:

DOE National Labs  Rose McCallen (LLNL) - committee chair
  Walter Rutledge (Sandia National Lab)

Universities  Fred Browand (University of Southern California)
  Anthony Leonard (Caltech)

This Technical Subcommittee consists of those individuals who will be directly involved in the analysis of aerodynamic components and the integrated system. They will visit several of the industrial representatives at their design and manufacturing sites to better assess the current practices.

An Advisory Committee will also be formed to help define and develop the MYPP. Meetings of the Advisory Committee will provide a forum for communication between competitors in the heavy vehicle trucking industry, DOE National Laboratories, other government laboratories, and universities with the ultimate goal to develop a MYPP acceptable to all. This Advisory Committee will suggest not only short-term changes and improvements, but also long-term approaches and designs. In addition to actual suggestions for design improvements, the Advisory Committee will also assess current aerodynamic analysis capabilities (both computational and experimental) and make recommendations for future US research and development relevant to this technology area.

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