Reducing Aerodynamic Drag

FOR every mile down the freeway, the average-size American car has to push 5.5 metric tons of air out of its way. That is, quite literally, a drag. Overcoming this aerodynamic drag takes a lot of energy. In fact, at 70 miles (110 kilometers) per hour, the typical highway speed, as much as 65 percent of the fuel the car uses goes to overcoming air resistance.

The numbers are similar for big-rig tractor–trailers, despite their far greater weight, and even higher for high-speed trains. Traveling as fast as 185 miles per hour, high-speed trains may use up to 80 percent of their fuel to overcome drag.

Truck aerodynamics researchers with scale model truck inside the wind tunnel at Ames Research Center, National Aeronautics and Space Administration. Clockwise from top left are James Ross of NASA Ames and Rose McCallen, Kambiz Salari, and Jason Ortega of Livermore.

For more than five years, Livermore has led a Department of Energy project to examine possible ways to make heavy trucks more aerodynamic, reducing air resistance and thus increasing fuel efficiency. Obviously, air resistance cannot be eliminated entirely. But engineers estimate that truck drag coefficients could be reduced by as much as 25 percent over the next 20 years. In the future, such a reduction would save billions of liters of diesel fuel annually, or 12 percent of the fuel used.

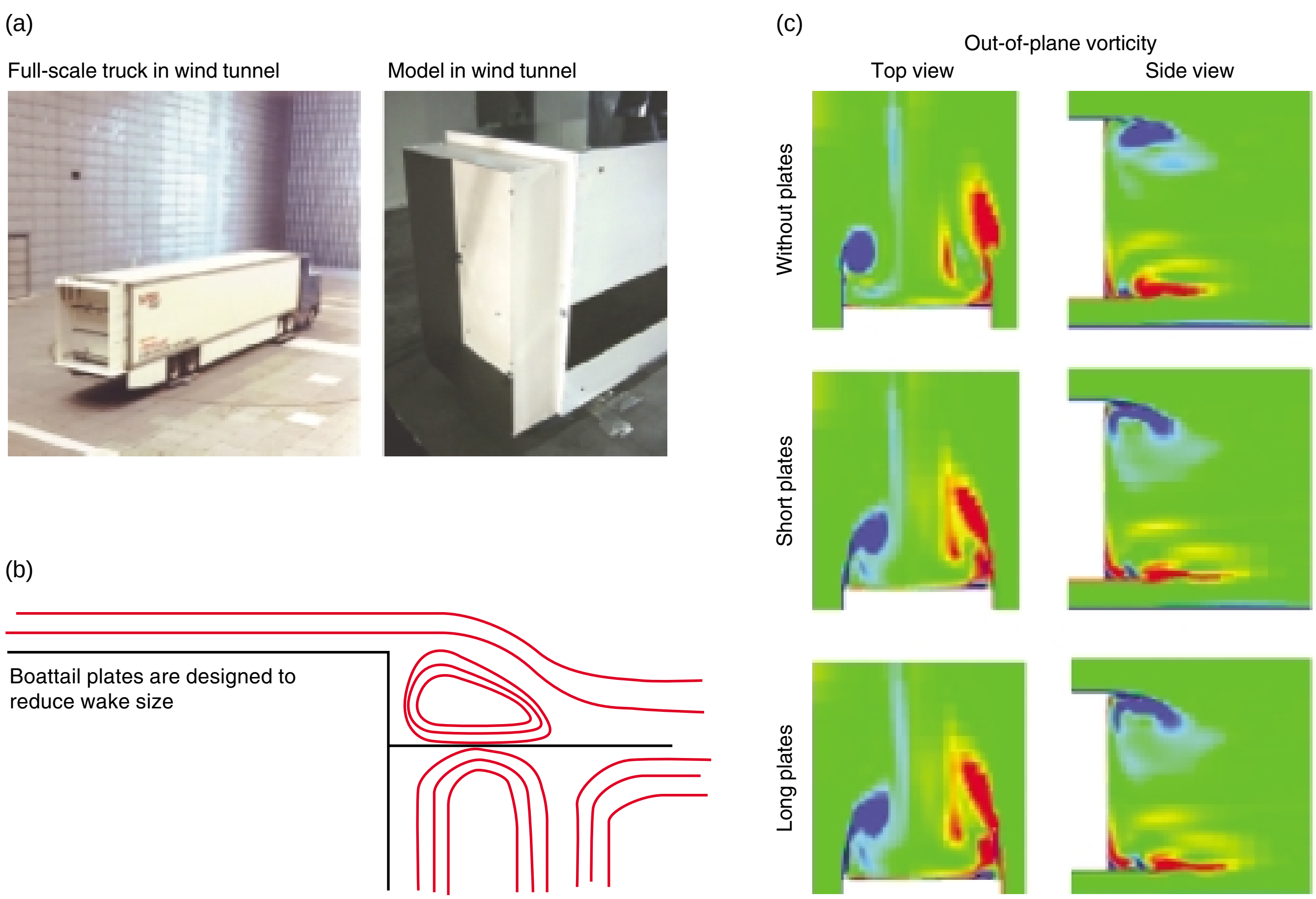
"Our nation's dependence on oil is a national security issue," says project leader Rose McCallen. "Minimizing vehicle aerodynamic drag can significantly reduce this country's dependence on foreign oil."

Current predictions are that at present rates of consumption, world energy demand will begin to exceed energy available from all sources by the year 2050. Reducing consumption is just one approach to meeting this challenge head on.

After the first oil crisis in the early 1970s, trucking companies adopted a shield that curves up over the top of the trailer to reduce drag. But two major components of drag on a heavy truck remain: the gap between the tractor and the trailer and low pressure in the trailer's wake. Friction losses—the air shear resistance on the trailer–tractor sides—contribute 10 to 20 percent to the total vehicle drag.

"Trucks are much more complicated than cars and planes, which are integrated and streamlined," notes McCallen. "Not only do trucks come in two parts, with a gap in between, but the trailer has to be a big unstreamlined box to maximize cargo space."

As if the aerodynamic situation weren't complicated enough, tractors and trailers are built by different companies. "It would be wonderful to be able to manufacture a single unit," she adds, "but it just isn't going to happen."



Large-eddy simulations of the back end of a trailer with boattail plates. (a) The full-scale truck and the scale model, (b) diagram of the flow field of boattail plates, and (c) simulations of a truncated vehicle (showing just the back end of the trailer) with and without boattail plates. Red and blue indicate counterrotating vortices. The flow is from left to right in the side view.

An Aerodynamic Partnership

Responding to the complex physics problem of truck aerodynamics is a consortium of Livermore, Sandia, and Argonne national laboratories, University of Southern California (USC), California Institute of Technology (Caltech), National Aeronautics and Space Administration Ames Research Center (NASA Ames), and Georgia Tech Research Institute (GTRI), under the leadership of McCallen in Livermore's Energy Technology and Security Program. The DOE Energy Efficiency and Renewable Energy, Office of FreedomCAR & Vehicle Technologies (CAR stands for Cooperative Automotive Research), is supporting the consortium's effort. Four tractor manufacturers have joined the partnership as well: AB Volvo, which owns Mack Trucks, Inc.; International Truck and Engine Corporation; Freightliner Limited; and Paccar Inc., which manufactures both Kenworth and Peterbilt trucks.

The aerodynamic design of heavy trucks is currently based on performance estimates derived from wind tunnel, track, and road experiments. Now, with the availability of powerful supercomputers, scientists can begin to simulate complex tractor–trailer air flows. The trick is to make the simulations reliable and thus predictive. The simulations must also run efficiently, with quick turnaround times. Only then will they be useful for designers of heavy tractors and trailers.

The simulations must be able to accurately portray the complex interaction between a vehicle's many different surfaces and the air striking or moving past it. The air flow around the front end of the tractor is complicated by the bumper, head lamps, hood, mirrors, and any other trim that the driver has chosen to add. The contribution to drag from the gap flow between the tractor and the trailer and behind the trailer has already been noted. Air also flows along the underbody of the truck and in the wheel wells. Computational fluid dynamics, McCallen's area of expertise, is the tool of choice on this project.

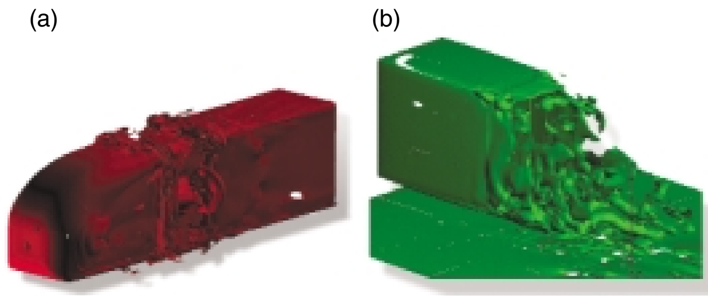
As computer simulations of various parts of a truck's air flow are being performed by Caltech and the Lawrence Livermore, Sandia, and Argonne national laboratories, companion wind tunnel experiments using models of tractor–trailers are under way at NASA Ames, USC, and GTRI. Livermore, USC, and GTRI are also developing devices that can be attached to tractors or trailers that reduce aerodynamic drag.

Air Flow in Action

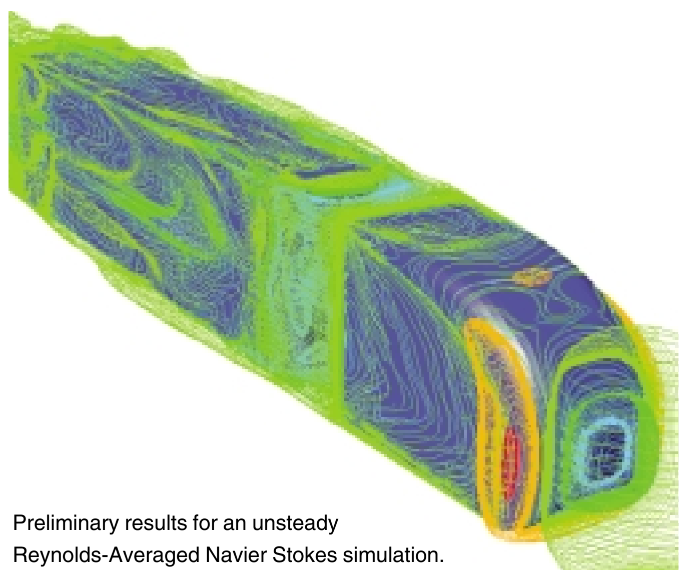
Complex turbulent flows—whether in the explosion of a nuclear weapon or in the wake of a heavy tractor–trailer—are particularly challenging problems in fluid dynamics. Livermore has been working to simulate turbulence for decades, first for weapons design and more recently for stewardship of the nation's nuclear stockpile. For this project, Livermore's focus is again on turbulence, this time in the trailer's wake. Engineer Kambiz Salari is leading the Livermore effort.

Salari's team first developed a simplified three-dimensional (3D) form representing the typical tractor–trailer combinations, a geometry that is now being used by other researchers around the world. With this form, Salari and his team are using large-eddy simulations (LES) to model what happens at the back end of the trailer.

Some of their simulations have included boattail plates attached to the back of the trailer to reduce the wake. The



Models using large-eddy simulation software show air flow in (a) the tractor–trailer gap and (b) the trailer's wake.



Preliminary results for an unsteady Reynolds-Averaged Navier Stokes simulation. The truck model used is the cab-over design. Air flow in the gap between the tractor and the trailer and in the trailer's wake are visible. This simulation methodology more accurately models wake and hence total drag than steady Reynolds-Averaged Navier Stokes methods.

figure on p. 26 shows “snapshots” of the flow field with short and long boattail plates and without these plates. (The plates were designed by a private firm not involved in the partnership.) The simulations with the plates indicate a reduction in the trailer wake, which is consistent with wind tunnel experiments at NASA Ames.

The consortium recently obtained the first 3D particle image velocimetry (PIV) results in a large production wind tunnel. Three-dimensional PIV techniques being developed at NASA Ames use laser beams to measure the velocity and direction of air flow in a series of planes. Two-dimensional PIV is far more common, and experiments usually take place in small research wind tunnels. But NASA Ames is home to a 2-meter by 3-meter wind tunnel, where the first 3D PIV images were obtained using a one-eighth scale model. More recently, experiments were run in a 3.5-meter pressurized wind tunnel at NASA Ames.

The pressurized tunnel is capable of simulating the air flow at realistic highway speeds. Because the wind tunnel is housed in a pressure vessel, the PIV experiments in the vessel are controlled remotely to avoid blowdown (pressure release) of the vessel when the laser or cameras are repositioned; obviously, no one can be in the tunnel during an experiment.

Engineer Jason Ortega, a member of Salari’s team, has been developing new devices that show promise for reducing aerodynamic drag. Detailed tests incorporating these devices started this spring at one of the wind tunnels at NASA Ames.

Sandia has been using steady Reynolds-Averaged Navier Stokes (RANS) models to simulate air flow around a heavy tractor–trailer. But researchers are finding that steady RANS models, which are routinely used to simulate fluid dynamics and are computationally efficient, do not accurately predict tractor–trailer wake or low-pressure region. So Livermore is developing hybrid techniques that combine LES and unsteady RANS turbulence models, resulting in more accurate, predictive simulations. Drag estimates must be correct before solutions can be found.

A World of Interest

Outside interest in the partnership’s work was evident in the large turnout for a December 2002 conference in Monterey, California, on “The Aerodynamics of Heavy Vehicles: Trucks, Buses, and Trains.” DOE and the United Engineering Foundation sponsored this conference that brought together researchers in aerodynamics from national laboratories, universities, and corporations around the world. Interest was so high that a similar conference is planned for 2004. Saving energy is important—reducing drag on heavy vehicles is one way to do it.

—Katie Walter

Key Words: aerodynamics, computational fluid dynamics, heavy trucks, large-eddy simulations (LES), Reynolds-Averaged Navier Stokes (RANS) models.

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