Heavy Vehicle Drag Reduction: Experimental Evaluation and Design

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Sponsored by:

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Collaborators

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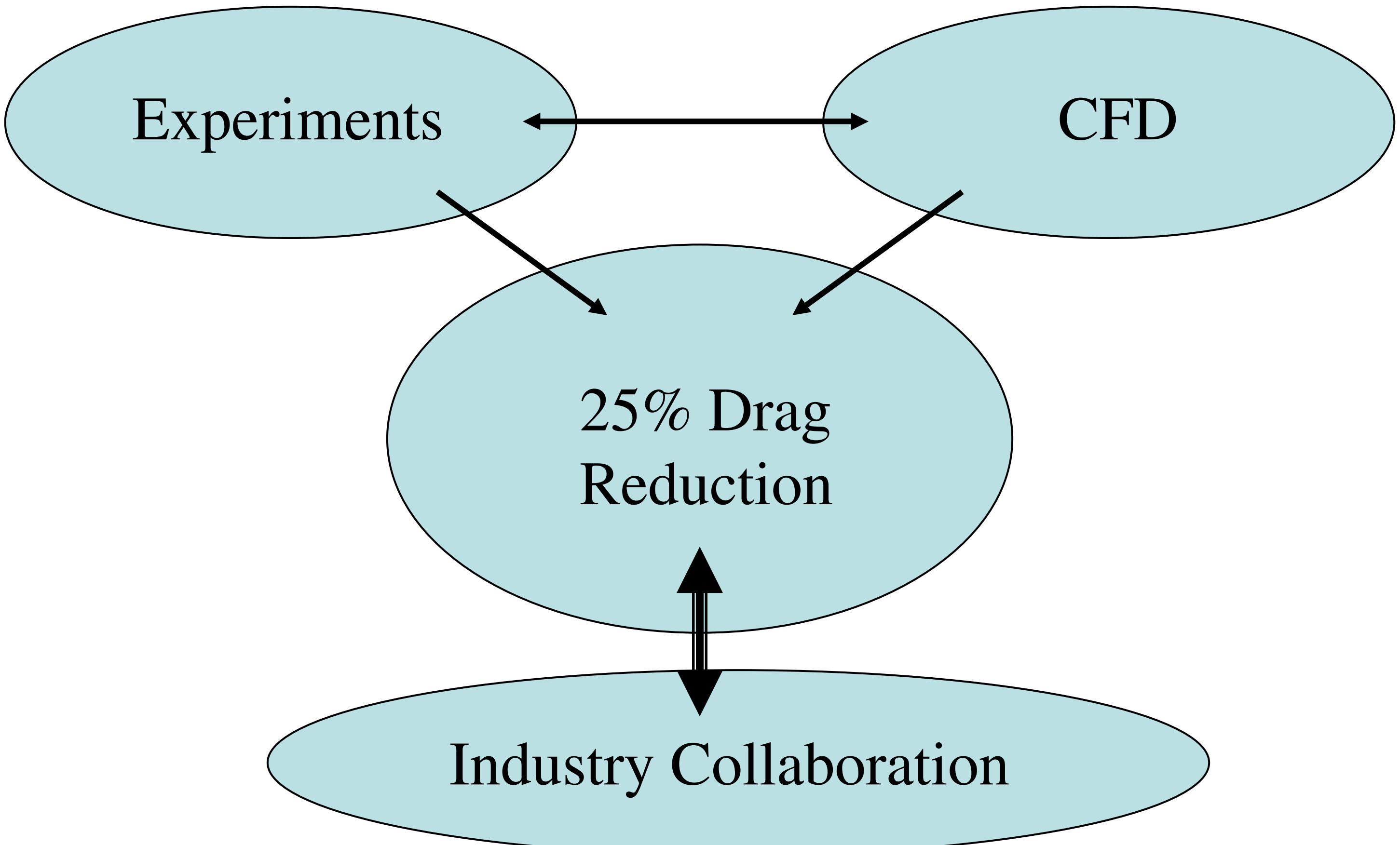
Jason Ortega — University of California Lawrence Livermore National Laboratory

Bob Englar — Georgia Tech Research Institute

Ross Scheckler — Dynacs Information & Applied Technology

Experimental effort is critical to achieving consortium goal of 25% aerodynamic drag reduction



Experimental Project Objectives

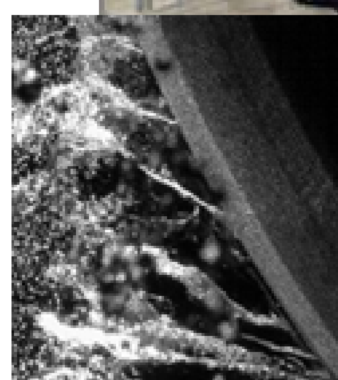
- Improved insight into important flow physics
- CFD validation through high-quality aerodynamics and flow-field data
- Develop and evaluate aerodynamic drag reducing concepts and demonstrate most promising at full scale
- Guidance and technology transfer to industry on aero-testing techniques, particularly Reynolds number
- Improved vehicle aerodynamic integration

Approach: Perform Focused Experiments

- Use appropriate facilities for various stages of development
  - Small-scale wind tunnels for concept screening
  - Large-scale wind tunnels for higher fidelity and Reynolds number effects evaluation
  - "On-road" tests for full demonstration
- Traditional measurements of force & moments plus mean and unsteady pressures
- Use advanced techniques to acquire previously unmeasured flow quantities for physics insight and CFD validation
  - Particle Image Velocimetry (PIV) for flow-field velocity
  - Oil-Film Interferometry for surface skin friction
  - Pressure Sensitive Paint for full-surface pressure distributions

Industry Collaborations

- USC/NorCan/Wabash - evaluation of base flap drag-reduction device in controlled track test
- NASA ARC/Freightliner - aerodynamic design consulting for inlet, diffuser, and wall contouring of new full-scale tunnel in Portland
- GTRI/Volvo/Great Dane - Road and track evaluation of Coanda blowing concept
- USC/Michelin Tires - splash & spray research at USC
- NASA ARC/TMC - presentation on seasonal variation in drag



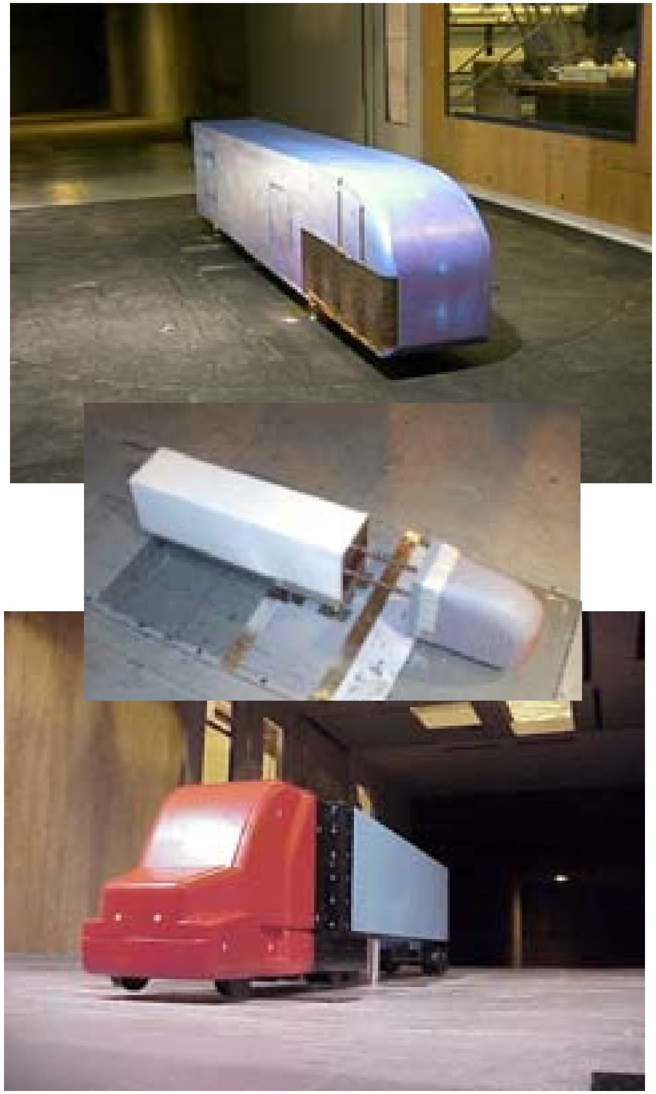
Technical Accomplishments

- **Improved understanding of flow physics**
  - Wake and tractor/trailer gap flows well documented
  - Effects of flow details on overall aerodynamic forces identified

- **Two detailed databases for CFD validation used by researchers and CFD vendors worldwide**
  - Simplified, Ground Transportation System (GTS)
  - Modified GTS (MGTS)
  - Generic Conventional Model (GCM)

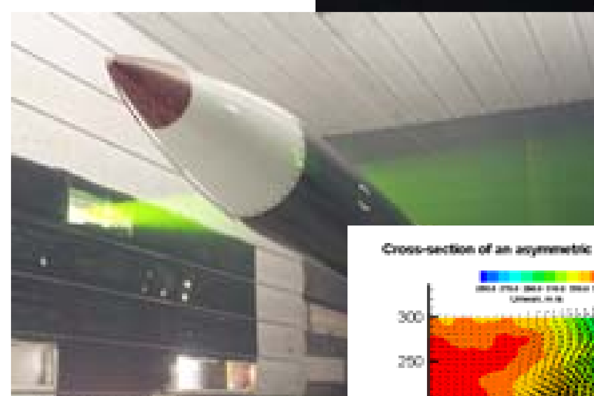
- **Numerous drag-reduction concepts evaluated**
  - Wind-tunnel tests
  - Identified candidates for subsequent road testing
  - All documented - successes and failures

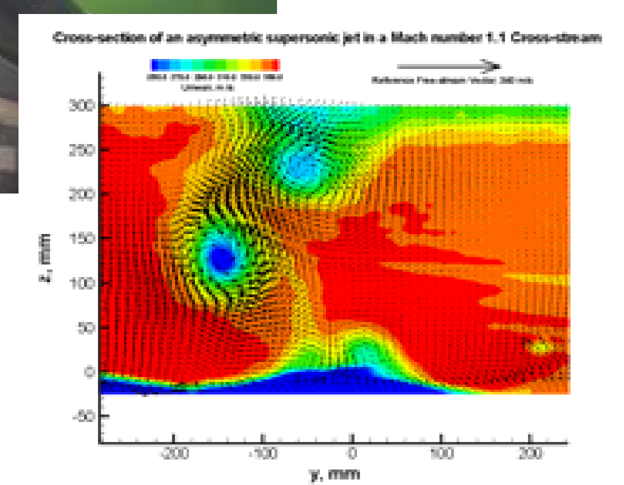
- **Established Re Criteria**
  - Re > 1.5 million (based on width)
  - Re > 50,000 (based on corner radius)



Value Added to NASA and Other Programs

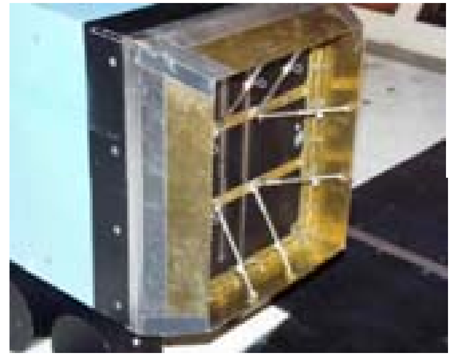
- **Development of large-scale PIV system was accelerated by DOE**
  - Early application of 3-D PIV in a large wind tunnel
  - ***First ever*** application of 3-D PIV in a large pressurized wind tunnel (Ames 12-Foot Pressure Wind Tunnel)
  - Second application in a pressurized wind tunnel was for a Sandia project in the Ames 11-Foot Transonic Wind Tunnel
- **Improved low-speed Pressure Sensitive Paint and Oil-Film Interferometry Skin Friction measurement techniques**

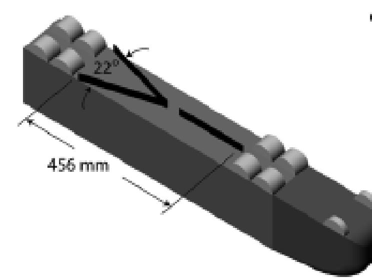


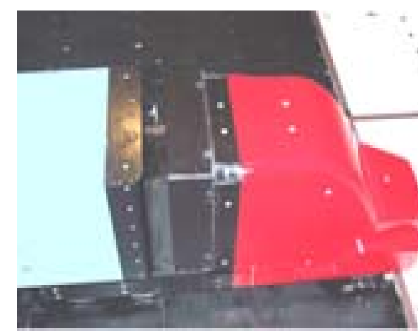
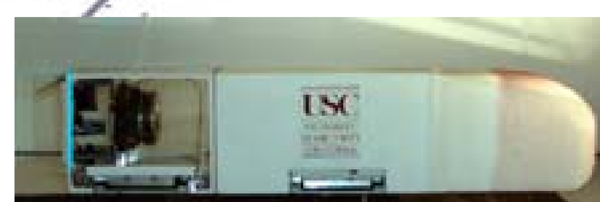


Drag-Reduction Concepts Studied

- **Trailer base**
  - **Base flaps**
  - **Boat tail plates**
  - **Rounded base corners**
  - **Coanda blowing**
  - **Unsteady blowing(synthetic jet)**
  - **Trailer-mounted vortex generators**
  - **“Winglets”**
  - **Curved base flaps**
- **Underbody flow**
  - **Belly box**
  - **Skirts - side and wedge**
- **Gap-flow control**
  - **Side/top extenders (std. practice)**
  - **Splitter plate**

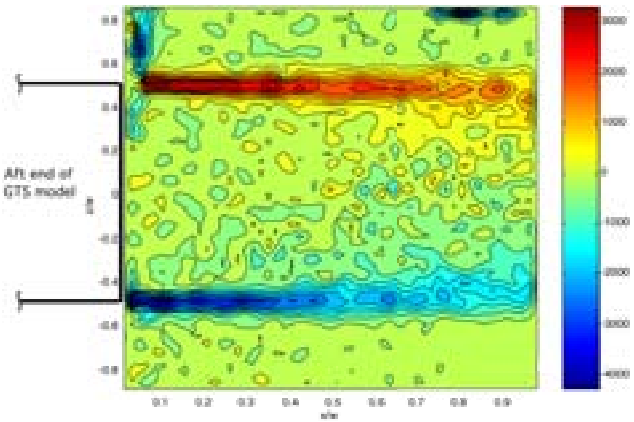


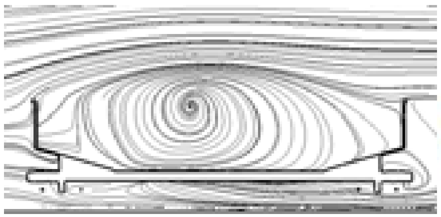



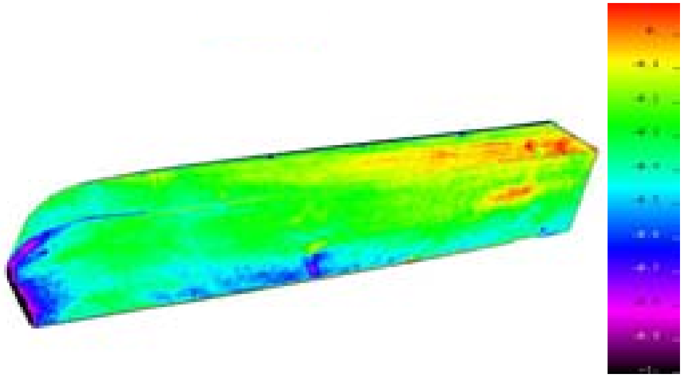




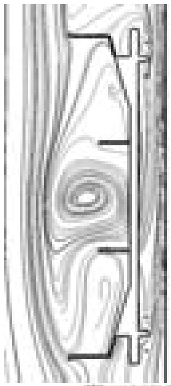
Road Testing

- Base flaps
  - ~4% lower fuel use in track experiment (collaboration between USC, NorCan, and Wabash)
  - On-road evaluation done by NorCan/DFS showed over 6% fuel savings (0.5 mpg improvement with base flaps over 116,000 km test)
- Coanda blowing
  - Excellent collaboration between GTRI, Volvo, and Great Dane
  - ~ 4% lower fuel use (including passive effect of rounding base corners)
  - System complexity reduces likelihood of adoption

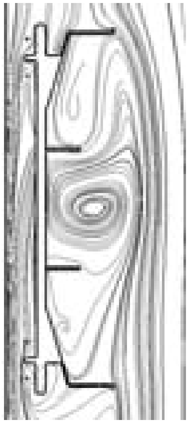


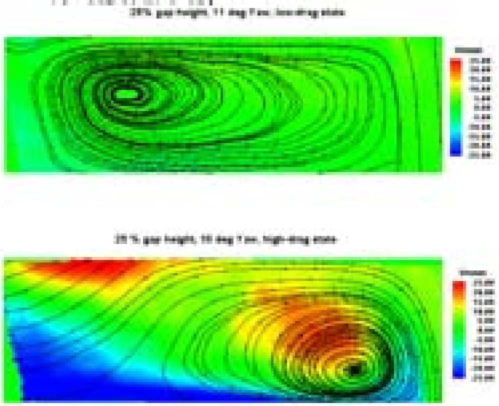


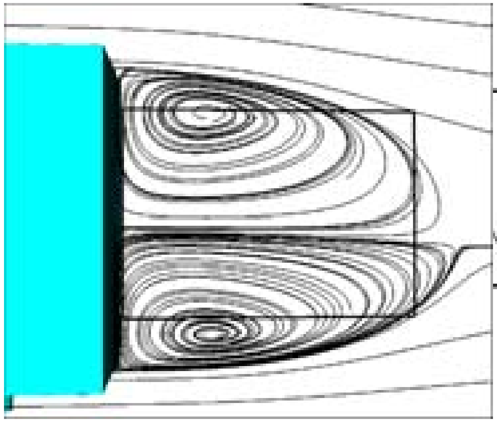


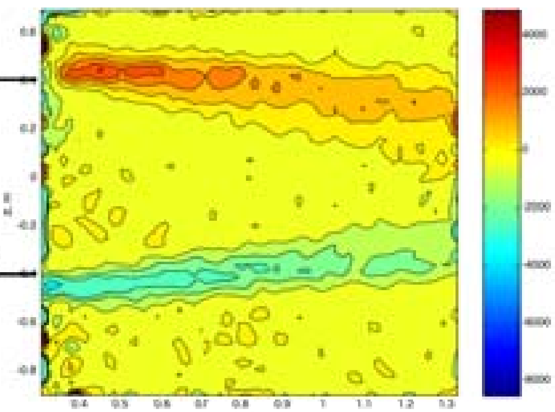


Flow Physics





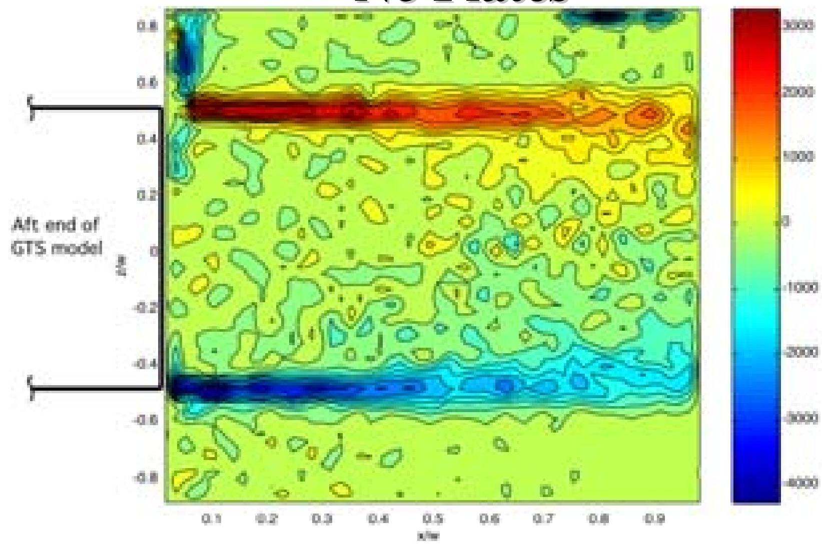




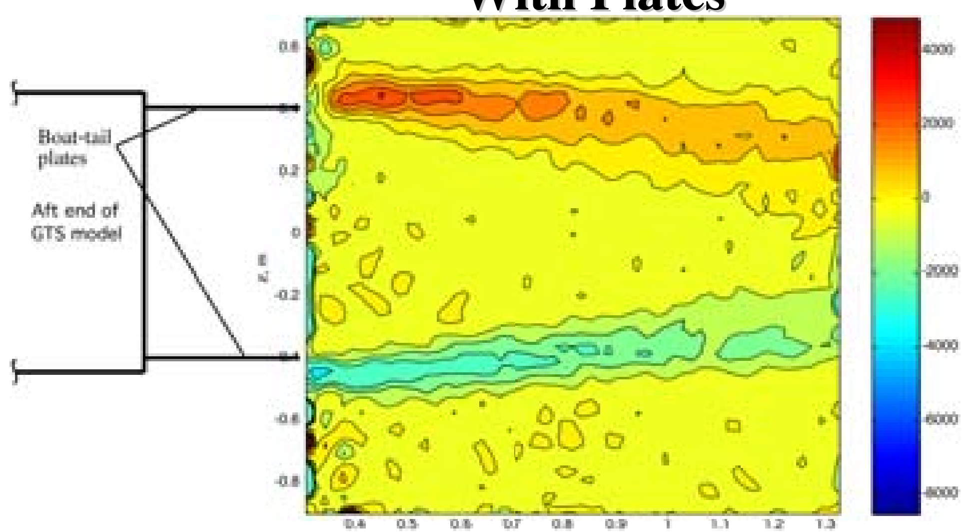
Effect of Boat-Tail Plates

- Boat-tail plates cause wake to close more quickly (measured vorticity contours shown)
- Also stabilizes the wake, reducing the lateral oscillations
- Wind-averaged drag reduction of 0.06 due to plates

No Plates

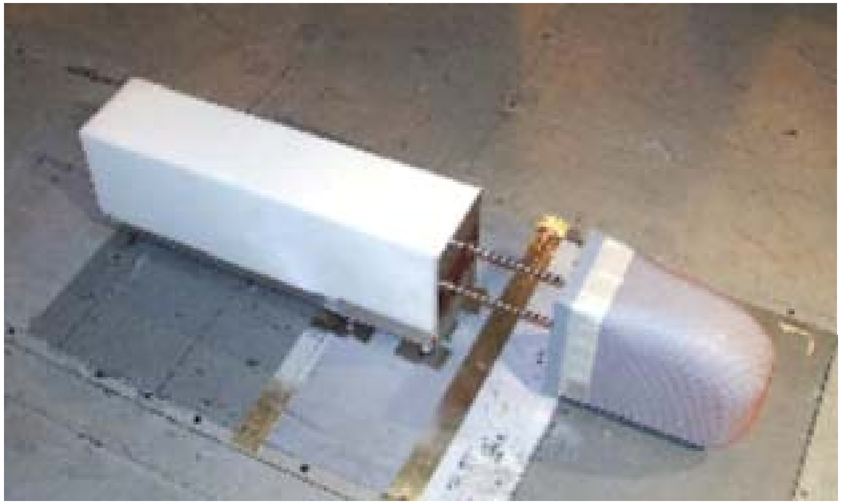


With Plates



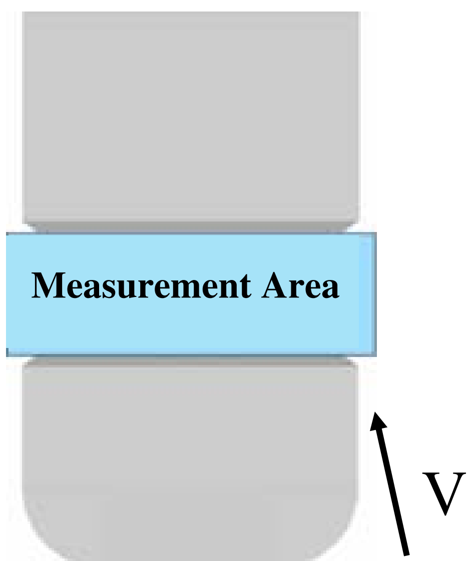
Gap flow studies
Modified GTS Geometry

- **Modified geometry studied at USC (increased corner radius and added tractor-trailer gap)**
  - Documented minimum corner radius criterion to eliminate separation ($Re_{radius} > 50{,}000$)
- **Identified flow patterns in tractor/trailer gap and their effect on drag**
- **Documented effect of gap distance on the flow/drag behavior of a tractor-trailer**



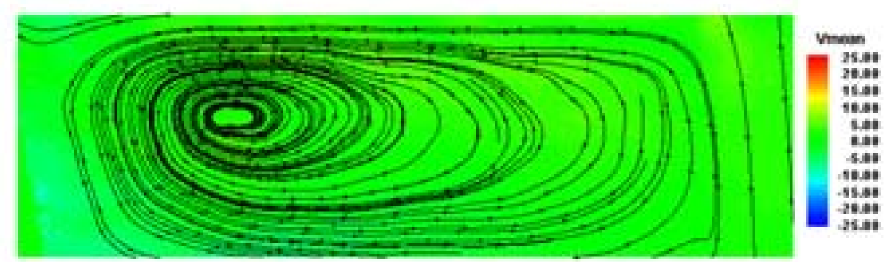
Understanding of Gap Flow Field

Flow field for a typical gap - at ~10° yaw shows 2 different flow patterns - resulting in either low or high drag



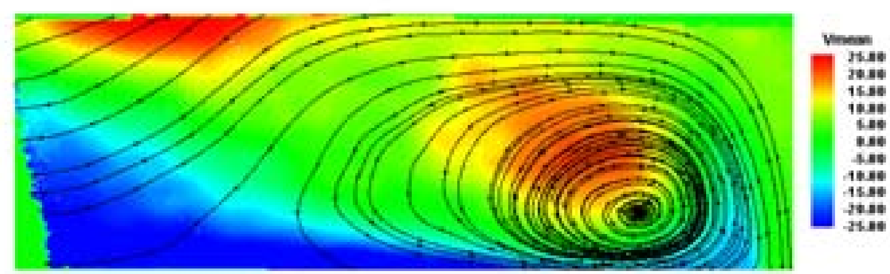
Low drag

25% gap height, 11 deg Yaw, low-drag state

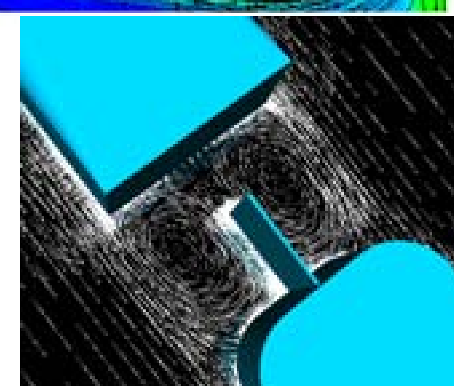


High drag

25 % gap height, 10 deg Yaw, high-drag state



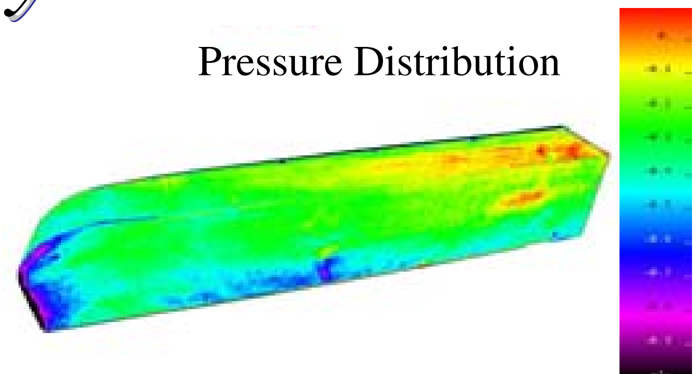
Led to splitter plate concept

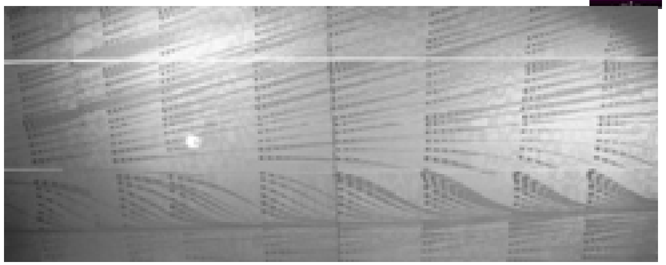


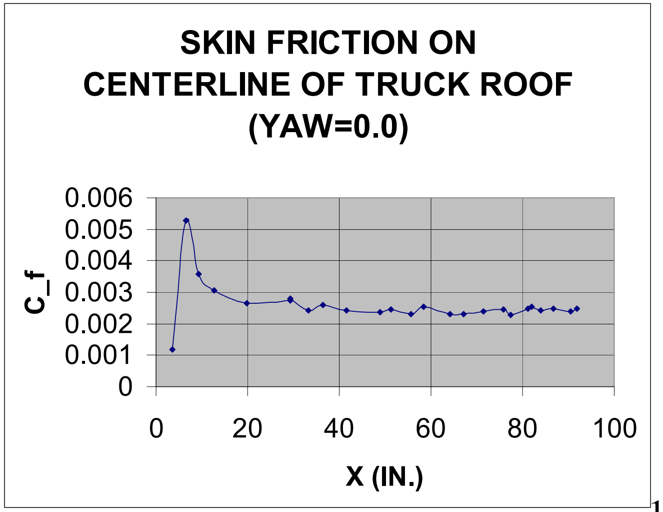
CFD Validation Data
GTS Geometry

- Baseline flow field documented
  - Detailed pressure distribution using Pressure Sensitive Paint
  - Skin friction measurement
  - Details of flow separation around front corner documented using surface hot films and oil-flow visualization
  - Three-component velocity measurements in wake
- Effect of boat tail plates documented
  - Drag change
  - Effect on pressure distribution
  - Effect on wake structure and dynamics

Pressure Distribution



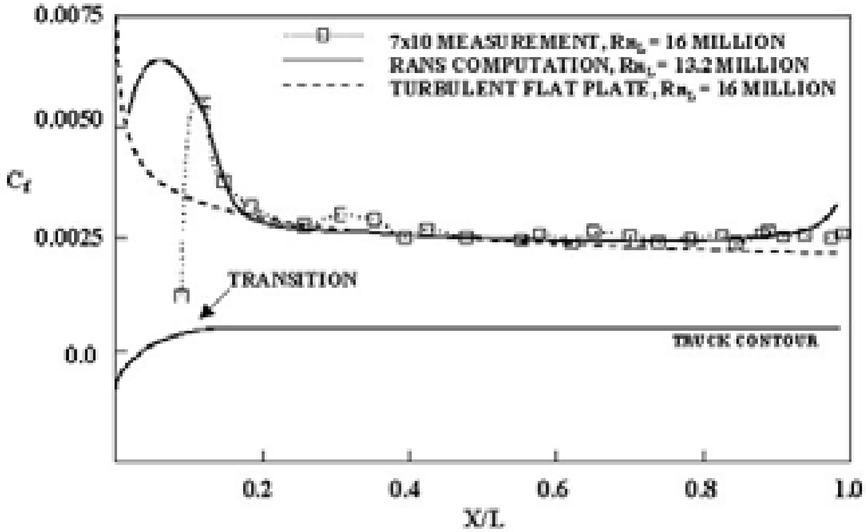


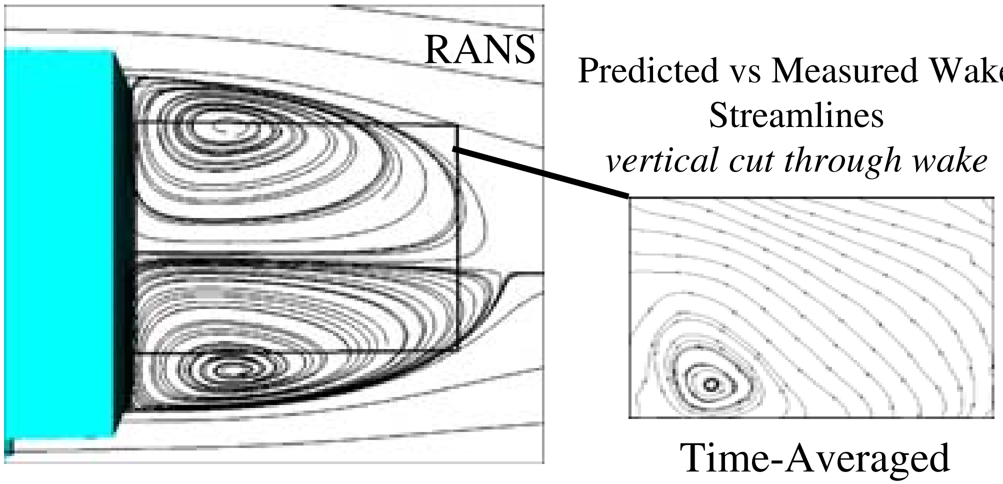


CFD Validation Experiments

- Data have been used by many researchers to validate codes
  - **Consortium members**
  - **CFD vendors**
  - **US and international**
- Requires significant interaction between disciplines to establish common understanding of data and how to best make comparisons
- Great progress in modeling accuracy - more to come

Predicted vs Measured Skin Friction Coefficient
GTS Geometry



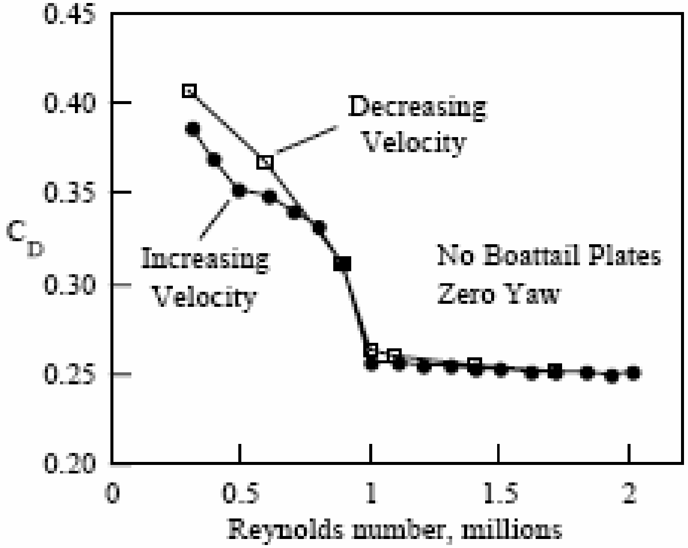


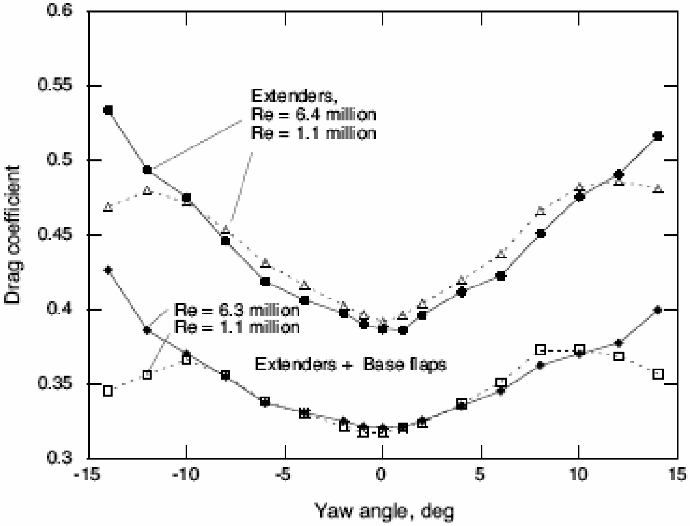
Predicted vs Measured Wake Streamlines
vertical cut through wake

Time-Averaged Measurements

Reynolds-Number Effects - to provide confidence in sub-scale data

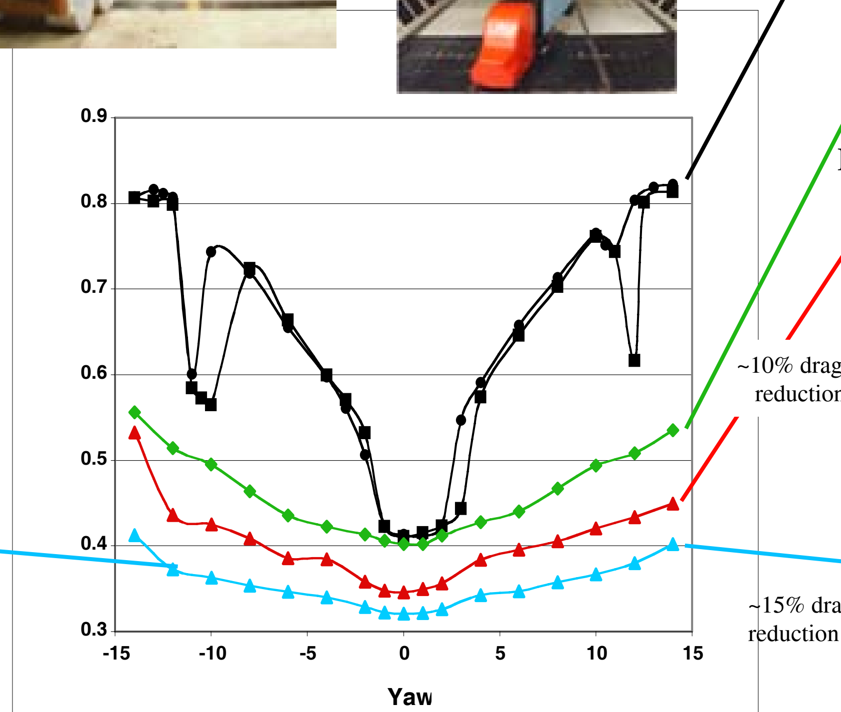
- Subscale testing can give accurate drag measurements
- For GTS geometry, zero-yaw drag showed hysteresis with velocity for Re < 750,000 - C_D nearly constant above Re = 10^6
- For GCM geometry, Re effects on C_D were isolated to yaw angles higher than ~10°
  - **Not significant for wind-averaged drag**
  - **Tests in Ames 12-Foot Pressure Wind Tunnel (up to 5 atm.)**
  - **Vary Re with density to eliminate Mach number effects**

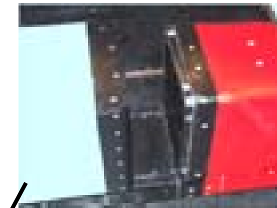




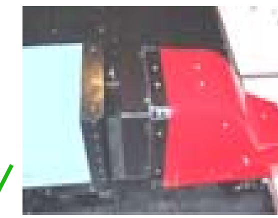
Experimental Activities

- Development of drag-reduction devices in wind-tunnel and road tests
- Improved understanding of flow physics





No Gap Treatment



Baseline Side and Roof Extenders

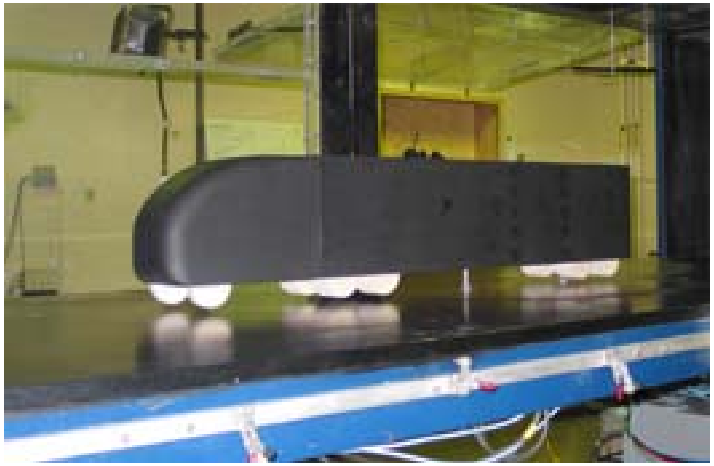
Lowboy Trailer

Trailer Base Flaps

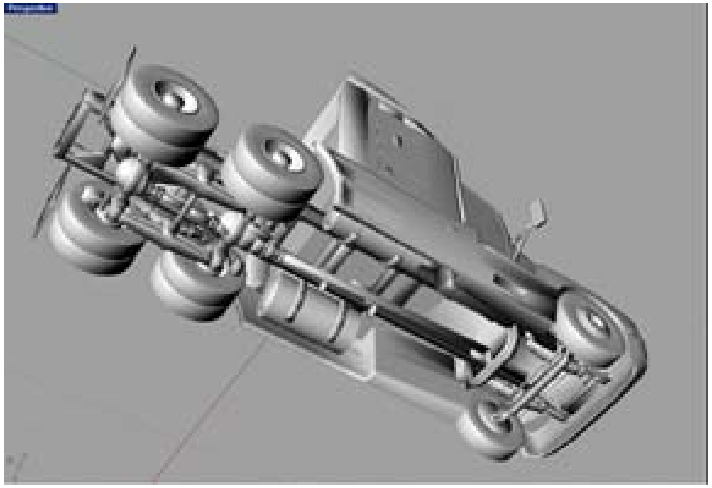
Discovery Experiments

- Ongoing effort used to screen new ideas quickly & cheaply
- Small wind tunnel with limited instrumentation
- Stereo-lithography models to include important geometric details
- Future
  - Cooling and underbody flow research
  - ‘Flow conditioning’

3- by 4-Foot Wind Tunnel and simple model



T-600 model for underbody flow study

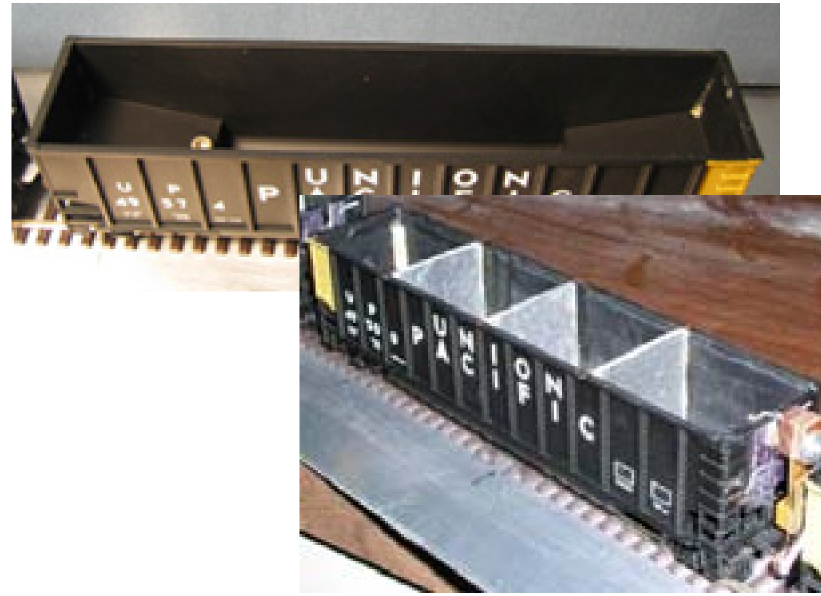


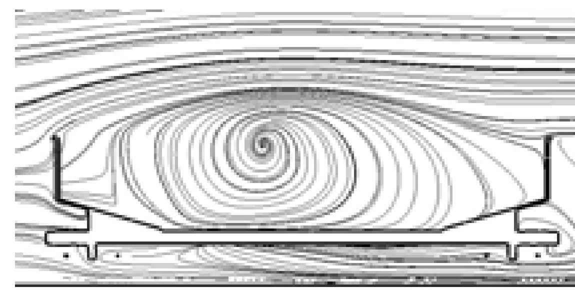
Cooling and Underbody Flows

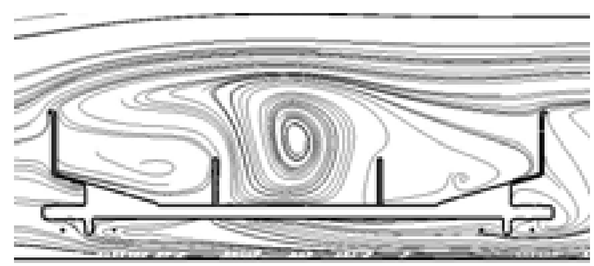
- Look at applying general aviation cooling approach to trucks
  - Reduce losses in flow path
  - Direct air where needed for both radiators and auxiliary equipment
  - Improved driver visibility
- Examine tractor underbody flow and ways to reduce drag and better manage the air
  - Improved brake cooling
  - Better management of air flow using natural pressure distribution

Coal Car Aerodynamic Drag Reduction

- Original charter of team included rail issues
  - Total = 1 billion tons, 66% carried by rail
  - Average coal haul = 696 miles
- Aero Drag Reduction Potential
  - ***Fuel consumption: empty ≈ full***
  - Aero drag ~ 15% of round-trip fuel consumption
  - 25% reduction –> 5% fuel savings (75 million gal/year)
- Found that dividing cargo volume with simple dividers provided ~25% drag reduction
- Record of Invention on concept - patent in process

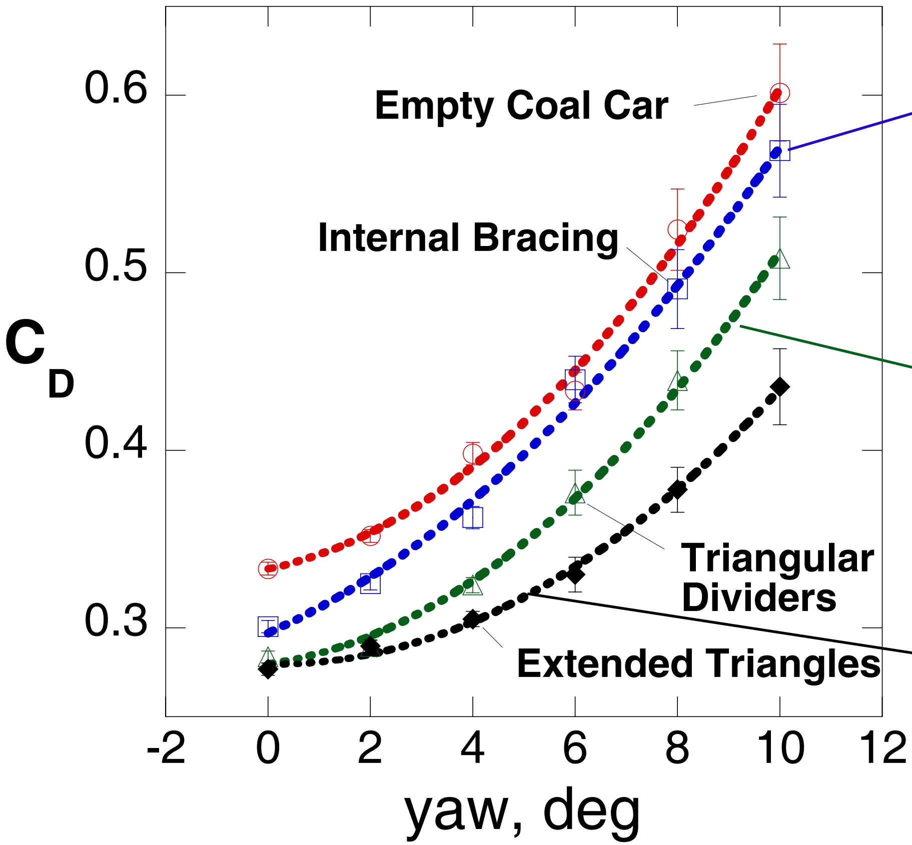


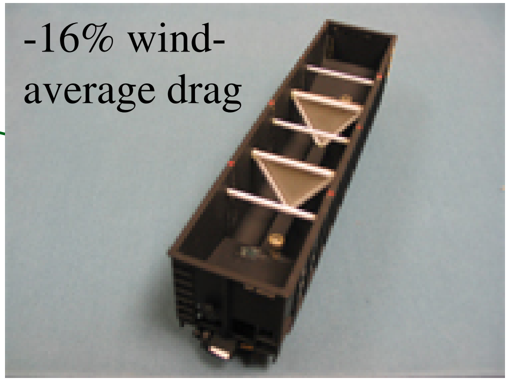


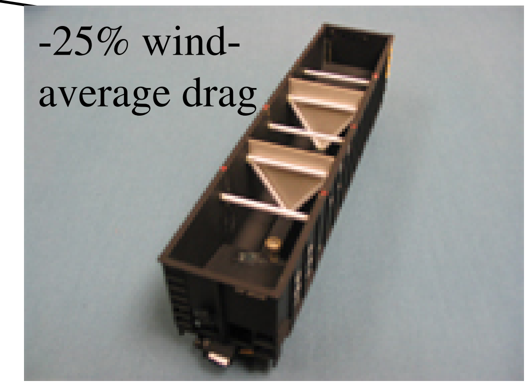


Idea: Splitter(s) in pickup trucks

Effect of Bracing & Dividers on Coal-Car Aerodynamic Drag







Collaborator: FREIGHTCAR AMERICA
Paper presented at the 2005 Joint Rail Conference and 2005 Railroad Environmental Conference

Summary
Drag Reduction Technology

- Identified and tested numerous drag-reducing techniques
  - Trailer base
  - Tractor/trailer gap
  - Underbody/skirts
  - Active and passive
- Gap/base 'flow conditioning' under study by LLNL
- Full-scale testing
  - Base flaps - over 6% fuel used reduction seen in on-road evaluations
  - Coanda blowing - ~4% fuel used reduction but significant system complexity and air-pumping costs

Summary
Flow Physics & CFD Validation

- High-quality validation data
  - Pressure distributions
  - Skin friction
  - Off-body velocity field
- Better understanding of
  - Re sensitivity - guidance for more reliable testing
  - Gap flows and effects on overall drag
  - Wake structure and effects of boat tail/base flaps

Future Work

- Vehicle aerodynamic design integration
  - External component design
  - Cooling flow-path integration
  - Underbody treatment
- Subscale evaluation of new concepts
  - ‘Flow conditioning’
  - Underbody flow devices
- Continued interaction with industry

Program Review – DOE Consortium for Heavy Vehicle Aerodynamic Drag Reduction

Relevance to DOE Objectives

- Class 8 trucks account for 11-12% of total US petroleum consumption
- 65% of energy expenditure is in overcoming aerodynamic drag at highway speeds
- 12% increase in fuel economy is possible and could save up to 130 midsize tanker ships per year

Approach

- Good Science: Computations in conjunction with experiments for insight into flow phenomena
- **Near-Term Deliverables: Design concepts and demonstration (wind tunnel, track, road testing)**
- Information Exchange: collaboration with industry, dissemination of information (website, conferences, workshops)

Accomplishments

- DOE Consortium: MYPP with industry, leveraged ASCI funds, complimentary, LDRD/Tech Base, University, NASA funds
  - We understand flow mechanisms/restrictions, how to design, and model/test/evaluate
- Supporting DOE objective while addressing industries' most pressing issues
  - Computational modeling: choice of turbulence models/wall functions, grid/geometry refinement, commercial tools, validated methodology and tools for industry guidance and use
  - **Experiments: advanced diagnostics at relevant highway speeds in pressure wind tunnel, realistic geometry with and without devices, validation database, experimental scaling - Determined if and when okay to test scaled models at reduced speeds, and road/track tests**
  - Design: boattails, baseflaps, blowing, splitter plate, wedges/skirts – 8 Records of Invention and 3 Patents
- Increased fuel economy : >4% base treatment, >6% skirts/wedges, ~2% gap device, savings 4,200 millions of gal/yr
- **Other transportation issues that benefit, e.g., reduce drag of empty coal cars by 20%, savings 1-2 millions of gal/yr**
- Addressing consequences with aerodynamics and use of devices - Underhood, brakes, visibility, etc

Technology Transfer/Collaborations

- Multi-Lab (LLNL, ANL, SNL, NASA, GTRI), multi-university (USC, Caltech, UTC, Auburn) effort with NRC-Canada
- Industry
  - Vehicle Aero - PACCAR CRADA, design of Freightliner wind tunnel
  - Devices – track tests/WT experiments/computations with NORCAN/WABASH, Volvo/Great Dane, Solus, Aerovolution
  - Underhood - CAT CRADA complete, new Cummins CRADA, NRC-Canada full-scale wind tunnel testing
  - Safety - Michelin splash/spray funding, sought DOT support
  - Fleets – US Xpress, Dana, DFS, Payne

Future Directions – Integrated vehicle design

- Getting devices on road
  - Develop less obtrusive/optimized device concepts and transfer technology to industry
  - Demonstration wind tunnel, track, road tests - leverage work with Dana/ORNL, NRC-Canada, TMA
- Underhood - improved aerodynamics with enhanced thermal control
- Economic/duty cycle evaluation with PSAT
  - Provide mechanistic data, review road/track test plans, provide needed assistance in calibration/evaluation to Dana/ORNL