Heavy Vehicle Drag Reduction: Experimental Evaluation and Design

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Collaborators

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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

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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
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\text{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

High drag

Measurement Area

V

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
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
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 $\sim 10^\circ$
    - 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
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

Baseline

-16% wind-average drag

-25% wind-average drag

Collaborator: FREIGHTCAR AMERICA

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