Heavy Vehicle Drag Reduction Devices: Computational Evaluation & Design

Kambiz Salari, et al

DOE Heavy Vehicle Systems Review
April 18-20, 2006

Acknowledgment

• Rose McCallen, Kambiz Salari, Jason Ortega, Craig Eastwood, John Paschkewitz, Paul Castellucci

• Fred Browand

• Dave Whitfield, Ramesh Pankajakshan

• Anthony Leonard, Mike Rubel

• James Ross, Bruce Storms

• Robert Englar

• David Pointer

• Collaborator: Kevin Cooper, Jason Leuschen
Goal: Reduce heavy vehicle drag by 25%

Approach:
- Identify major contributors to drag
  - Experimental discovery and testing
  - Modeling and simulations
- Design drag reducing add-on devices
  - Utilize accumulated knowledge gained in both experiments and simulations
- Evaluate and test add-on devices using
  - Experiments
  - Modeling and simulation
  - Track test
  - Road test
- Evaluate add-on devices safety issues
- Get drag reducing add-on devices on the road
  - Assist with operational and design concerns

Technical approach

Identify major contributors to drag
- high quality experiments
- high quality computations
  - Investigate device affect on safety
  - Develop drag reduction concepts & design for devices
  - Develop insight into flow phenomena
Achievements

- Conducted experiments to gain insight into flow physics
- Successfully investigated many different computational approaches for their predictive capabilities
- Developed new turbulence modeling techniques
- Established set of guidelines for computational modeling
- Designed drag reducing add-on devices
- Investigated safety impacts of add-on devices
- Designed flow conditioning techniques to achieve drag reduction
- Track, experimental, and computational testing of drag reduction concepts
- Generated 8 record of invention
- Received 3 patents
- Meet and exceeded the 25% drag reduction goal
  - ~12% improvement in fuel efficiency

Approaches to achieve drag reduction

- Geometry modification
  - Make tractor and trailer more streamlined
  - Aerodynamically integrate tractor and trailer
  - Add-on devices
    - Trailer base
    - Trailer underbody
    - Gap
- Aerodynamic flow conditioning
  - Trailer base
  - Gap
- Flow through engine
- Climate influence
Critical flow regions for drag

At highway speeds ~ 65% of the engine's power production is used to overcome aerodynamic drag

Steps to ascertain critical flow features around heavy vehicles

- Scaled heavy vehicle models
  - Models with increasing realism are needed
- Experimental investigation
  - For small scale testing be cautious of Re number sensitivity/effect
- Computational modeling
  - There are many nontrivial issues to be concerned about, such as, how predictive are these models?
Heavy vehicle models with increasing realism

- Ground Transportation System (GTS)
- Modified GTS
- Generic Conventional Model (GCM)
- Modified GCM

Experimental Investigation
Extensive experimental testing was performed

**NASA Ames Research Center**
- 3'x4' wind tunnel, GTS, MGTS
  - 300,000 Reynolds number
  - Testing trailer base and underbody drag reducing concepts
- 7'x10' wind tunnel, GTS, MGTS, GCM
  - 2 million Reynolds number
  - Testing drag reducing concepts and flow physics
- 12' pressure wind tunnel, GCM
  - Full-scale Reynolds number is achieved!
  - Several drag reducing aero-devices were tested

**University of Southern California (USC)**
- 3'x4' wind tunnel, MGTS
  - 300,000 Reynolds number
  - Testing gap and trailer base drag reducing devices and flow physics

Knowledge gained through experimental testing

- Improved understanding of flow physics
- Generated comprehensive data set for computational validation
  - Wind averaged aerodynamic forces
  - Surface pressure, steady and time dependent
  - Flow visualization, Particle Image Velocimetry
- Demonstrated Reynolds number effects
  - Reynolds number effects were relatively small above ~1.5 million.
  - Care should be taken in interpreting smaller-scale data
Computational Modeling

Several computational modeling approaches were used

- Navier-Stokes formulation, steady and time-dependent solutions
  - Discretization schemes, FD, FV, and FEM method
  - Turbulence modeling, RANS, LES, and hybrid RANS/LES
  - Structured, unstructured, and overset meshes
  - Boundary representation
    - Boundary fitted
    - Cartesian mesh with trim cells to fit boundaries
    - Cartesian mesh with immersed boundary technique

- Vorticity equation formulation, time-dependent solution
  - Meshless, requires only a surface mesh
  - Turbulence modeling, LES, DNS, and hybrid models

- Lattice Boltzmann formulation, time-dependent solution

GTS, Vortex method

Immersed boundary method
Guidelines developed for computational modeling

Predictions of aerodynamic forces and the flow structure are significantly influenced by

- Geometry characteristics, coarse vs fine surface mesh, $\Delta C_d \approx 15\%$
- Turbulence modeling selection, RANS, LES, $\Delta C_d \approx 5\%$
- Grid resolution, mesh refinement, $\Delta C_d \approx 10\%$
- Large yaw angles, massive flow separation, $\Delta C_d \approx 25\%$

Difficult with prediction of trailer wake at 0° yaw, GTS

Particle traces, back

Particle traces, side

Particle traces, vertical plane parallel to the base of the trailer, $x/w=0.45$

Particle traces, streamwise ($y/w=0$)
Drag Reducing Devices
Investigated many types of drag reduction concepts/devices

- Trailer base
  - Base flaps
  - Boat-tails
    - Plates
    - Ogives
  - Flow conditioning
- Trailer underbody
  - Skirts
    - Side
    - Wedges
- Tractor-trailer gap
  - Cab extenders
  - Splitter plate
  - Flow conditioning

Tested several trailer base devices

- Angled base flaps
  - $\alpha_{top} = 5^\circ, 10^\circ, 15^\circ, 20^\circ$
  - $\alpha_{side} = 5^\circ, 10^\circ, 15^\circ, 20^\circ$

- Curved base flaps
  - $R/w = 0.32, 0.49, 0.91, 1.78$
Tested several trailer skirts

- Long wedge skirt
- Short wedge skirt
- Short wedge skirt w/ center skirt
- Straight side skirts

Tested gap add-on device

The gap add-on device will stabilize the gap flow, for the gap distance above the critical limit, and in turn reduce the total aerodynamic drag of the vehicle.

USC Modified GTS with a Gap Add-on Device
Performance of drag reducing add-on devices

<table>
<thead>
<tr>
<th>Device</th>
<th>NASA</th>
<th>USC</th>
<th>GTRI</th>
<th>LLNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab Extenders</td>
<td>37%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Splitter Plate</td>
<td>~1-12%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Boutil tail Plates| 13.7%|      |      | 8.8%
| Base Flaps        | 19.4% (20°) | ~8.3% (13°) |      | 16.4% (10°) |
| Straight Side Skirts| 6.5%  |      |      | 1.4% |
| Long Wedge Skirt  |      |      |      | 2.1% |
| Low Boy           | 11.8%|      |      |      |
| PHV               |      |      | ~8%  |      |

Combination of base flap, lowboy gives about 30% drag reduction. Additional drag reduction is possible through the use of flow conditioning.

Flow Conditioning Concepts
Devised flow conditioning concepts for the gap and the trailer base

Trailer base

flow conditioning port

uniform stream exiting at velocity $v_j$

Tractor base

Larger areas of trailer base flow conditioning provide better drag reduction

Fine grid

Drag (N)

Q (cfm)

1900 2000 2100 2200 2300

0 5.0\times10^3 1.0\times10^4 1.5\times10^4 2.0\times10^4 2.5\times10^4 3.0\times10^4
Efficiency of trailer base flow conditioning increases with larger areas

Flow conditioning impacts base pressure
Flow conditioning affects the trailer wake flow structure

Flow conditioning over the entire trailer base moves the wake flow structure downstream
Flow conditioning in the gap reduces drag

<table>
<thead>
<tr>
<th>7° yaw</th>
<th>$C_D$</th>
<th>Δ$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>0.496</td>
<td></td>
</tr>
<tr>
<td>Cab extenders</td>
<td>0.457</td>
<td>- 8.0%</td>
</tr>
<tr>
<td>Flow conditioning</td>
<td>0.400</td>
<td>- 19.5%</td>
</tr>
</tbody>
</table>

Impact of Flow Through Engine on Drag (collaboration with NRC Canada)
Flow through engine increases drag

Engine compartment increases drag

GCM w/o eng. comp.: $C_d = 0.429$
GCM w/ eng. comp.: $C_d = 0.444$
Drag Reducing Add-on Devices

Add-on devices impact on flow structure

Baseline

Long Wedge Skirt

Base Flaps

upwash beneath trailer

upwash

downwash in wake
Base flap evaluation with rotating wheels

Drag reducing devices affect safety

- White lines -- vortex cores (low pressure regions)
- Trailer wake with base flap is dominated by downwash
- Drops can accumulate into passing motorist region
Gap flow physics captured by simulation

0° yaw, Non-Dimensional Gap Distance of 0.72

USC Experiment, 50% Height

\[ \text{Re} = \frac{U \sqrt{A}}{\nu} = 300,000 \]

Add-on device stabilizes gap flow structure

Horizontal plane, 25% height

Horizontal plane, 75% height

Velocity vector plot, horizontal plane, 50% height
Future Research

- Assist industry with design and operational concerns to put add-on devices on the road (USXpress, WalMart, Norcan/Wabash)
- Optimize add-on devices for drag reduction or vehicle stability (active or passive)
- Investigate the full potential of flow conditioning concepts for drag reduction, collaboration with NRC
- Further improve computational capabilities for testing add-on devices and flow conditioning concepts
  - Steady vs time-dependent solutions
- Reduce time investment on a drag reduction concept from inception, design, and implementation phases with use of computational simulation (virtual testing)

World-class computational resources

Massively parallel systems
- MCR, 11.2 TFs, 2,304 processors
- Thunder, 23 TFs, 4,096 processors
- BG/L, 71 TFs, 131,000/4 processors
Effect of climate variation on drag

Seasonal variation in fuel efficiency

\[ Drag = C_D \times S \times \left( \frac{1}{2} \right) \rho U^2 \]

- \( \rho \) = air density
- \( U \) = wind speed
- \( S \) = cross-sectional area
- \( C_D \) = drag coefficient

Wind and temperature variation attributed \( \sim 50\% \) of the observed fuel efficiency. *Change in air density has the largest effect.*
Flow transition from laminar to turbulent

Difficultty with prediction of trailer wake at 10° yaw, GTS

Particle traces, BSL solution

Particle traces, horizontal plane at trailer mid-height

Particle traces, vertical plane parallel to the base of the trailer, 1.2w from the base
Add-on devices impact on flow structure, ... 

“suspended” vortex hoops

counter-rotating vortex pair

horseshoe vortices

trailing vortices

Baseline Base Flaps Long Wedge Skirt

Base flap evaluation with rotating wheels

URANS simulation of GCM model

Iso-Q surfaces: Large, positive values of Q identify regions of the flow dominated by rotational motion

\[ Q = \frac{1}{2}(\Omega \otimes \Omega - S \otimes S) \]

(Perry & Chong, 1994, Blackburn et al., 1996; Dubief & Delclaye, 2000)