Heavy Vehicle Drag Reduction Devices: Computational Evaluation & Design

Kambiz Salari, et al

DOE Heavy Vehicle Systems Review

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- ***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

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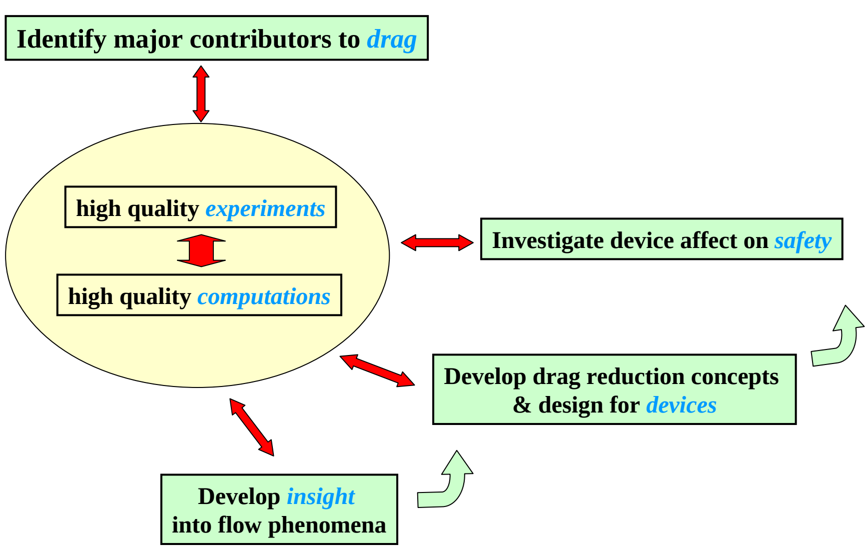
Technical approach



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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

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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

NRC Canada

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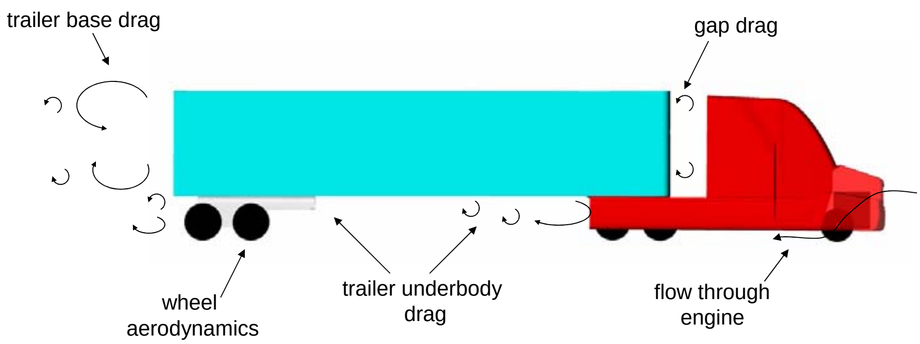
Critical flow regions for drag



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

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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?**

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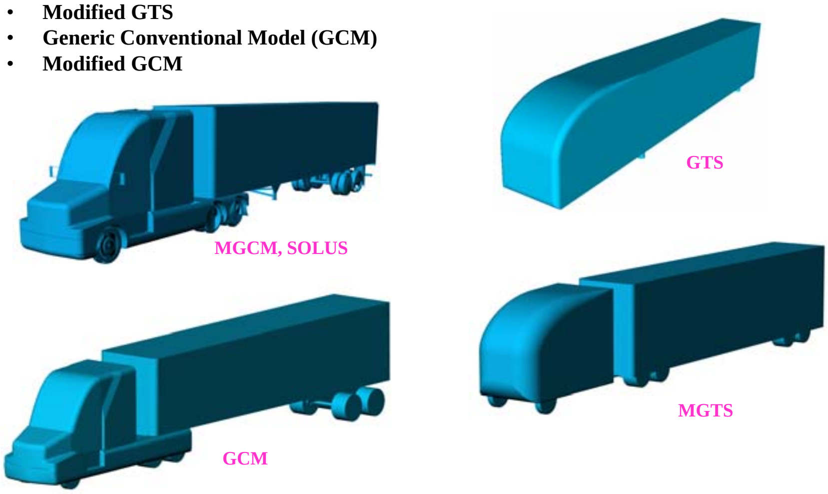
Heavy vehicle models with increasing realism

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



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Experimental Investigation

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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

NASA Ames 12' pressure wind tunnel

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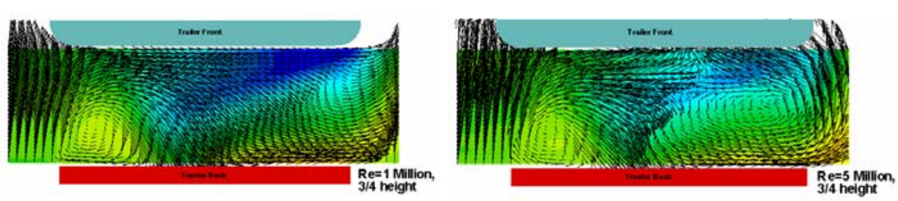
Knowledge gained through experimental testing

- 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



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Computational Modeling

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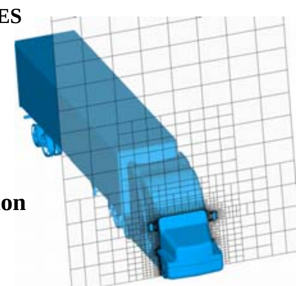
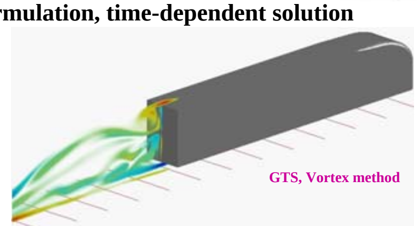
Several computational modeling approaches were used

- 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



Immersed boundary method



GTS, Vortex method

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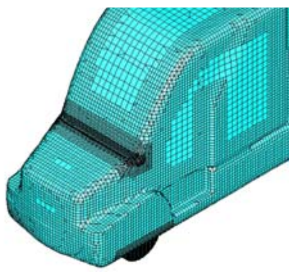
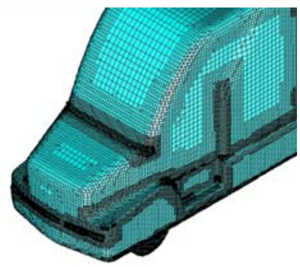
Guidelines developed for computational modeling

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, $\Delta C_d \approx 25\%$**



GCM coarse surface mesh



GCM fine surface mesh

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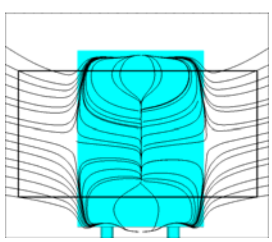
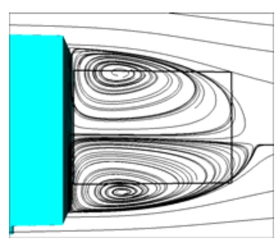
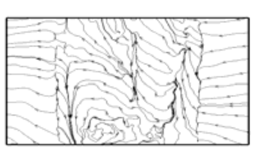
Difficulty with prediction of trailer wake at 0° yaw, GTS



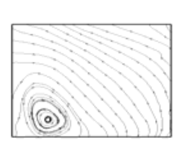
Particle traces, back



Particle traces, side



Particle traces, vertical plane parallel to the base of the trailer, x/w=8.45



Particle traces, streamwise (y/w=0)

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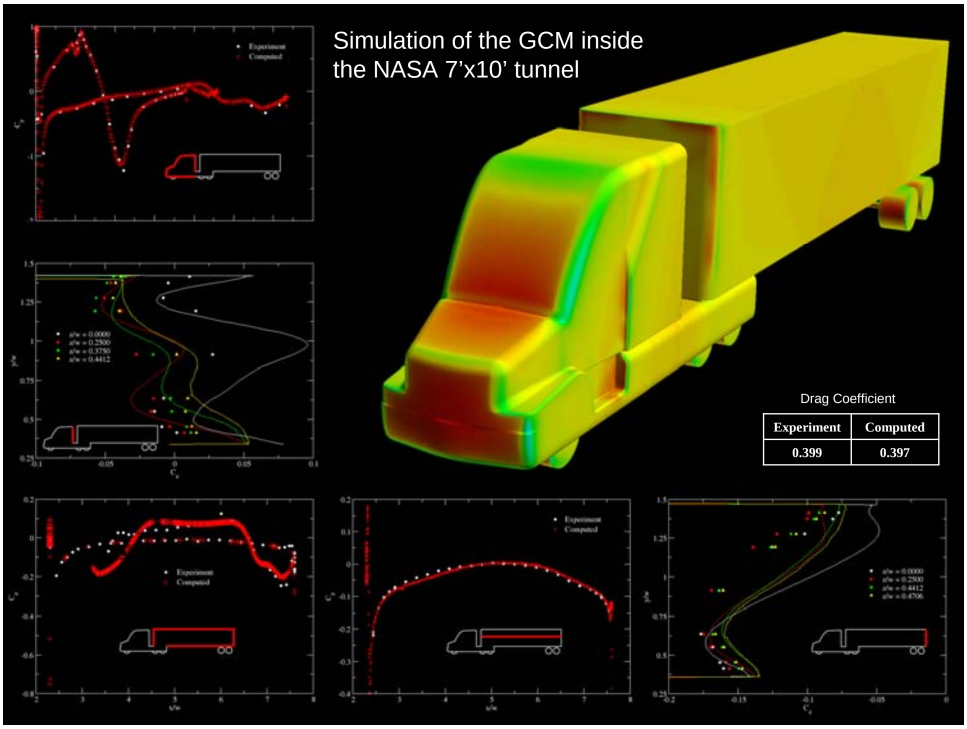
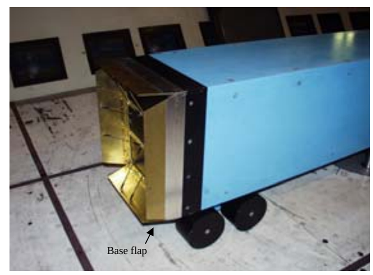


Drag Reducing Devices

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



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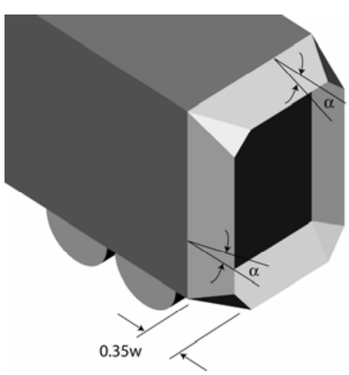
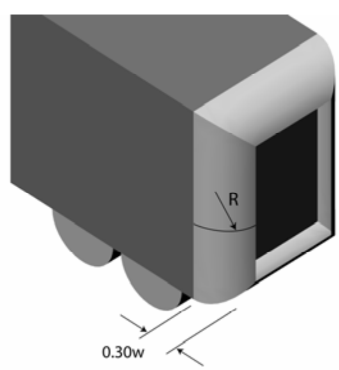
Tested several trailer base devices





Angled base flaps

- α_{top} = 5°, 10°, 15°, 20°
- α_{side} = 5°, 10°, 15°, 20°

Curved base flaps

- R/w = 0.32, 0.49, 0.91, 1.78

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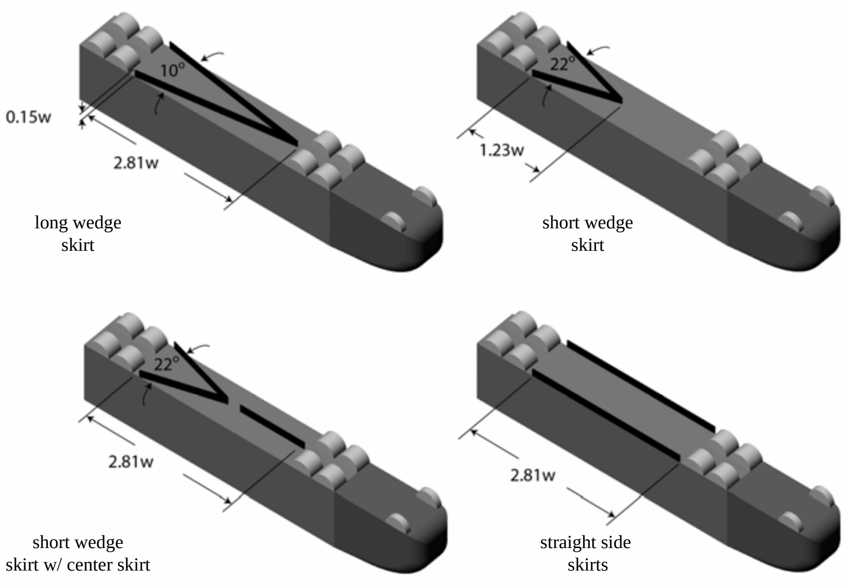
Tested several trailer skirts



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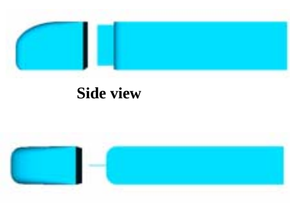
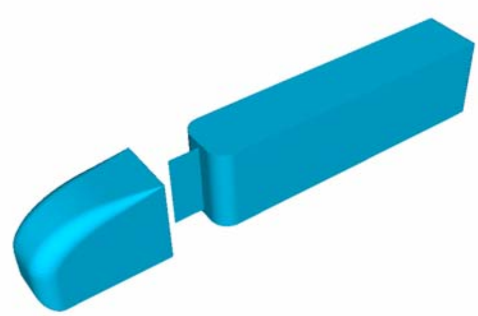
Tested gap add-on device

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

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Performance of drag reducing add-on devices

Device	NASA	USC	GTRI	LLNL
Cab Extenders	**37%**	———	———	———
Gap Splitter Plate		**~ 1-12%**	———	———
Boattail 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.

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Flow Conditioning Concepts

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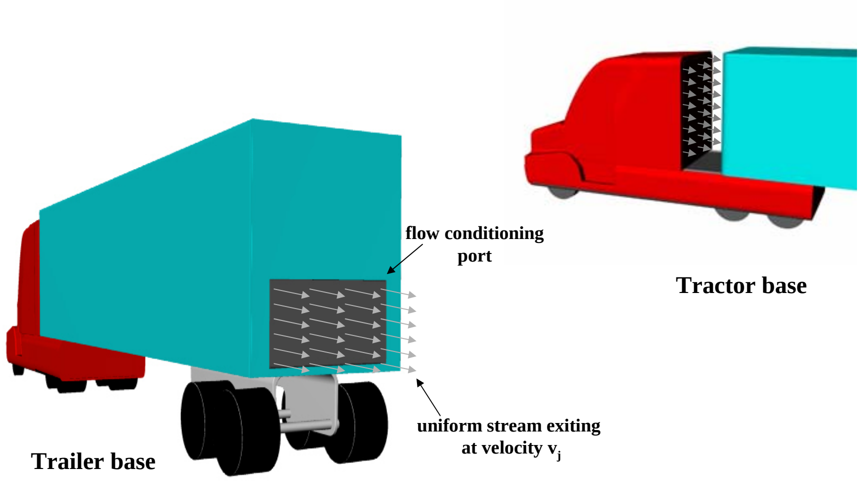
Devised flow conditioning concepts for the gap and the trailer base



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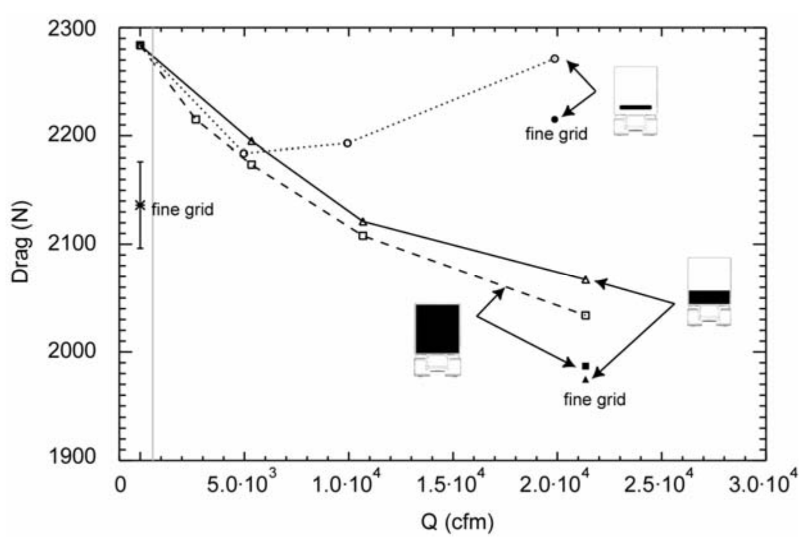
Larger areas of trailer base flow conditioning provide better drag reduction



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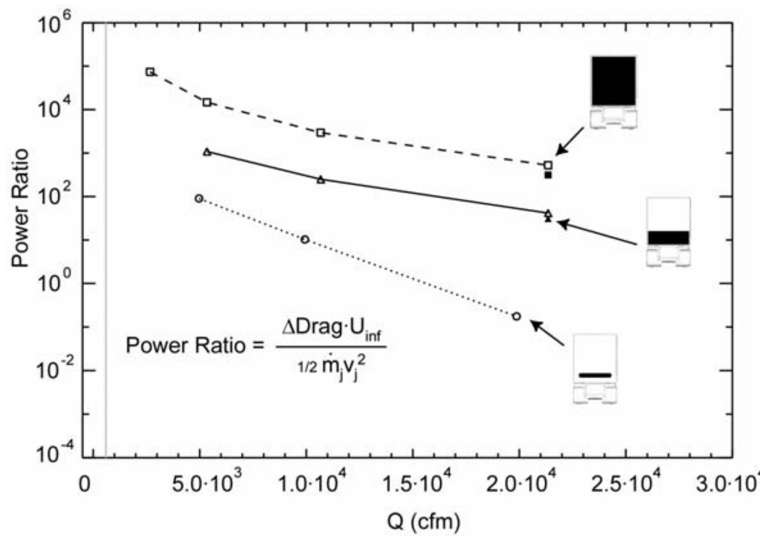
Efficiency of trailer base flow conditioning increases with larger areas



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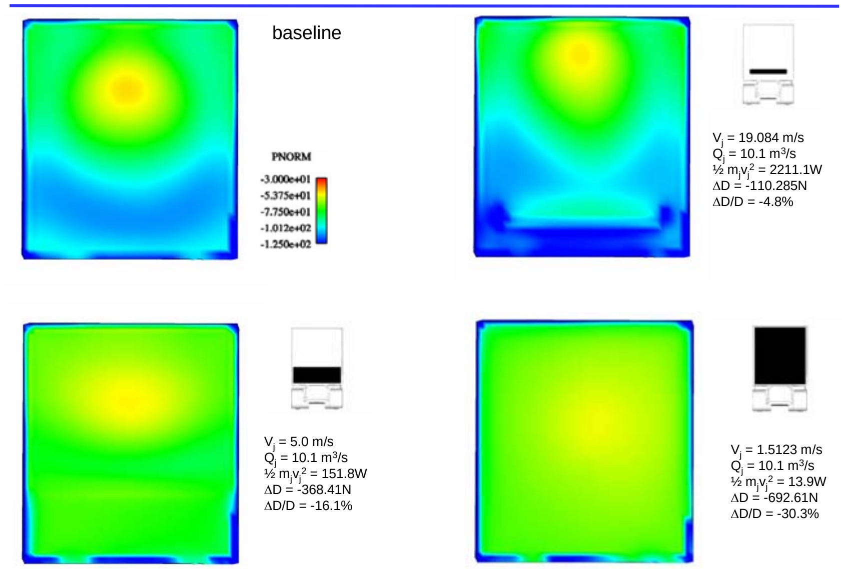
Flow conditioning impacts base pressure



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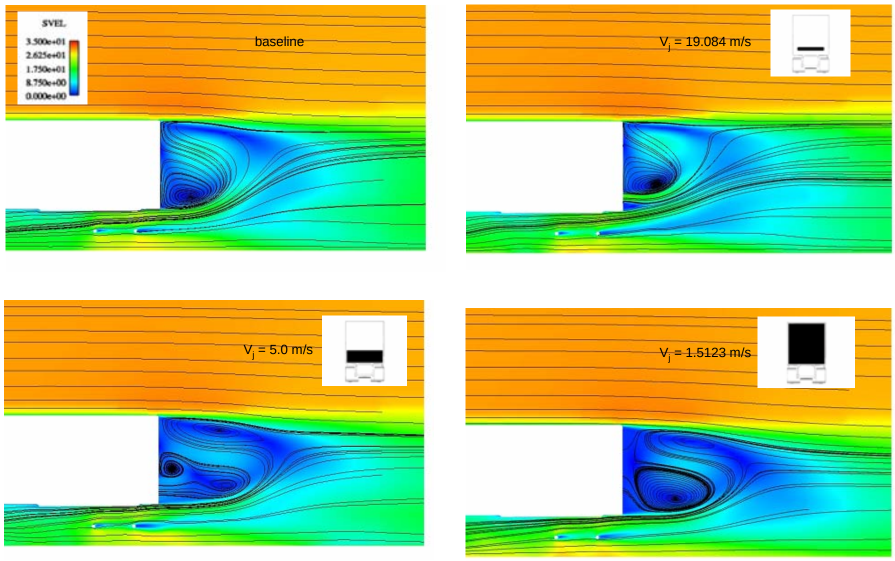
Flow conditioning affects the trailer wake flow structure

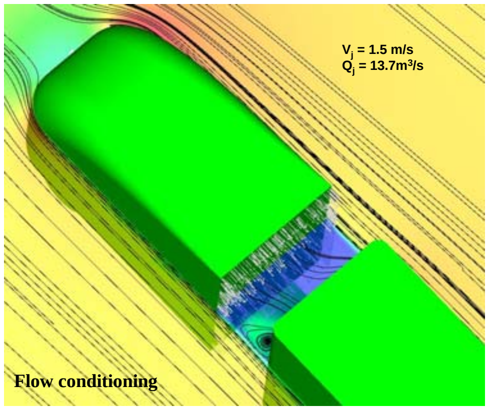


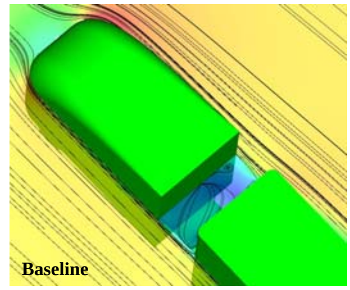
Flow conditioning over the entire trailer base moves the wake flow structure downstream

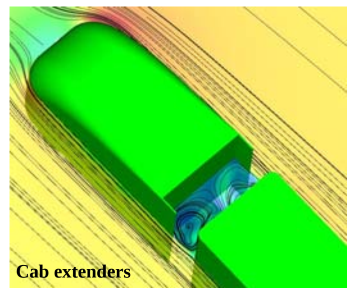
Baseline

Flow Conditioning
Over Entire Base

Flow conditioning in the gap reduces drag







7° yaw	C_D	ΔC_D
baseline	0.496	
Cab extenders	0.457	- 8.0 %
Flow conditioning	0.400	- 19.5 %

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Impact of Flow Through Engine on Drag (collaboration with NRC Canada)

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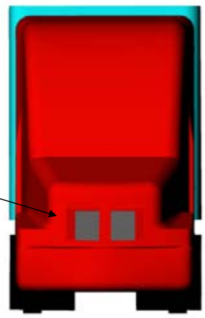
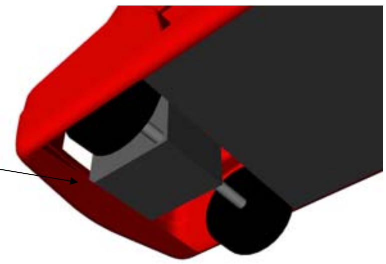
Flow through engine increases drag





<u>Engine compartment increases drag</u>

GCM w/o eng. comp.: C_d = 0.429
GCM w/ eng. comp.: C_d = 0.444

Drag Reducing Add-on Devices

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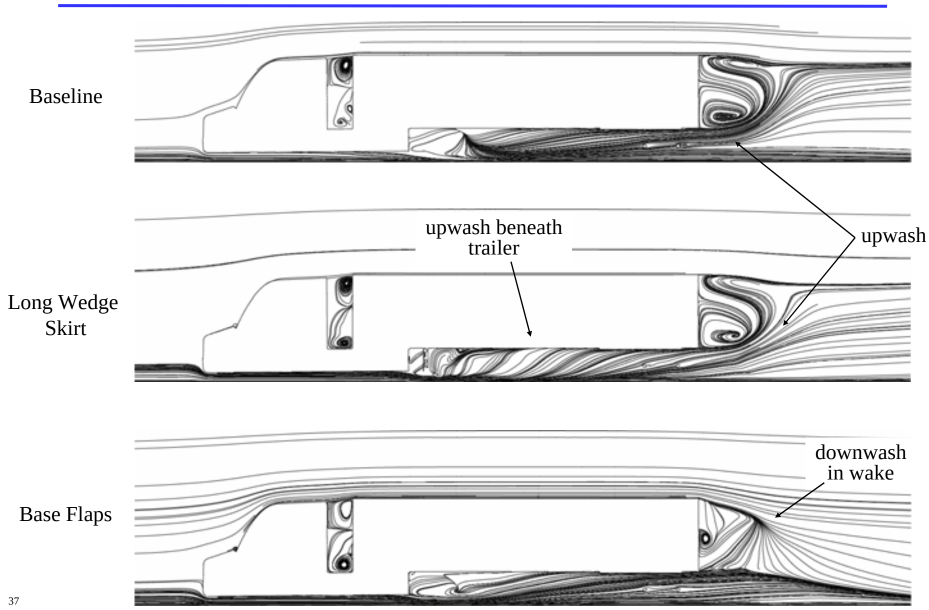
Add-on devices impact on flow structure



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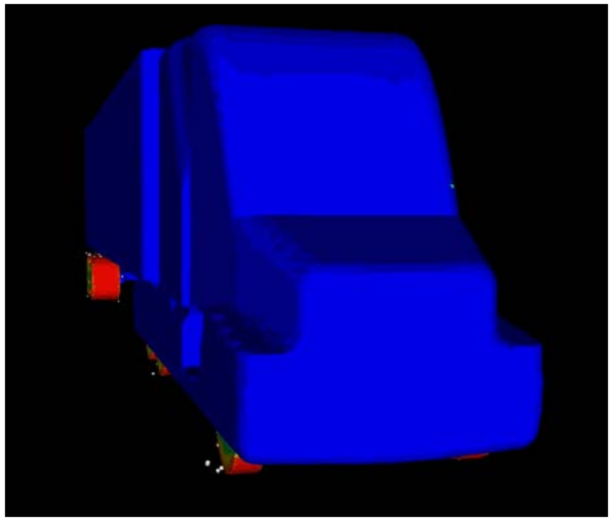
Base flap evaluation with rotating wheels



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Drag reducing devices affect safety

Spray transport

Baseline GCM

Trailer base flaps

- White lines -- vortex cores (low pressure regions)
- Trailer wake with base flap is dominated by downwash
- drops can accumulate into passing motorist region

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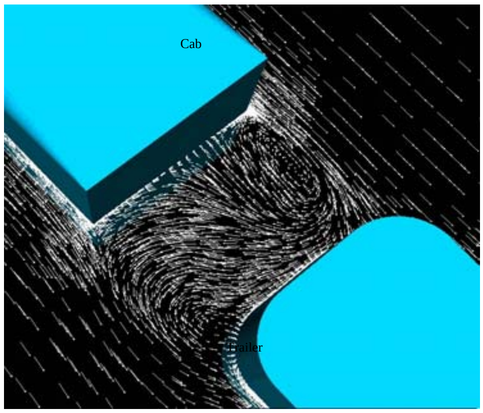
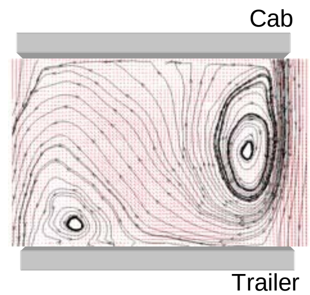
Gap flow physics captured by simulation

0° yaw, Non-Dimensional Gap Distance of 0.72



OVERFLOW Computation, 50% Height

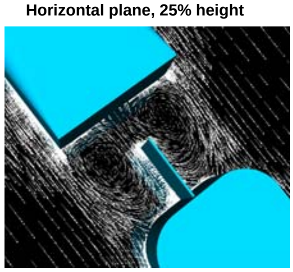


USC Experiment, 50% Height

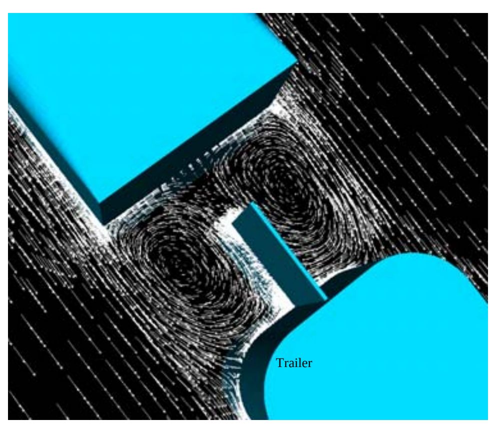
$$\mathrm{Re} = \frac{U\sqrt{A}}{\nu} = 300{,}000$$

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)

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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

MCR

Thunder

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Backup Slides

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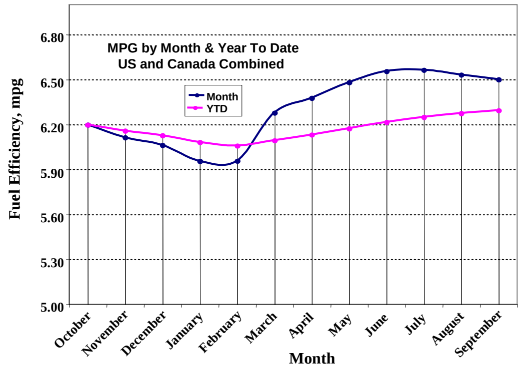
Effect of climate variation on drag

Seasonal variation in fuel efficiency



$$Drag = C_D \times S \times (1/2)\rho U^2$$

ρ = air density
U = wind speed
S = cross-sectional area
C_D = drag coefficient

Wind and temperature variation attributed ~50% of the observed fuel efficiency. ***Change in air density has the largest effect.***

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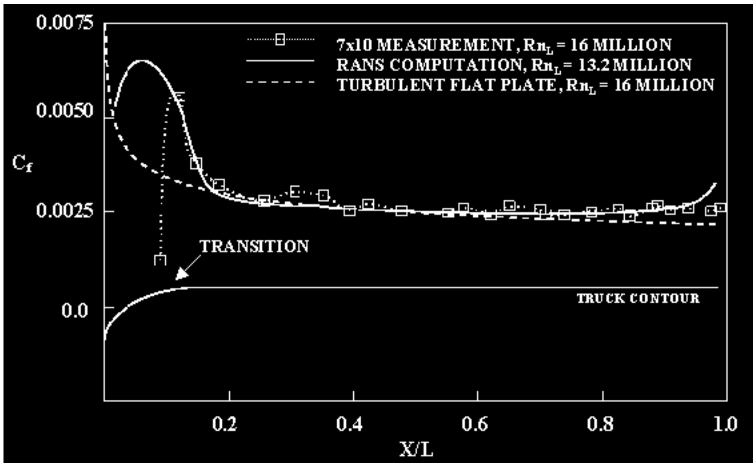
Flow transition from laminar to turbulent



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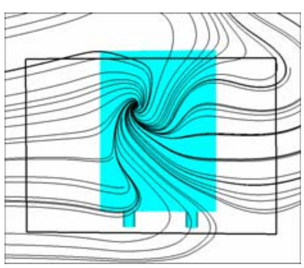
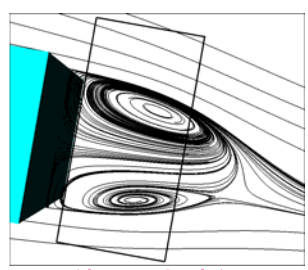
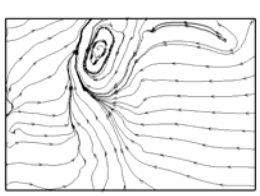
Difficulty with prediction of trailer wake at 10° yaw, GTS



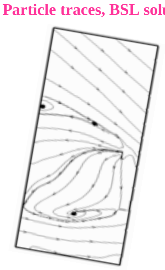
Particle traces, BSL solution



Particle traces, BSL solution



Particle traces, vertical plane parallel to the base of the trailer, 1.2w from the base



Particle traces, horizontal plane at trailer mid-height

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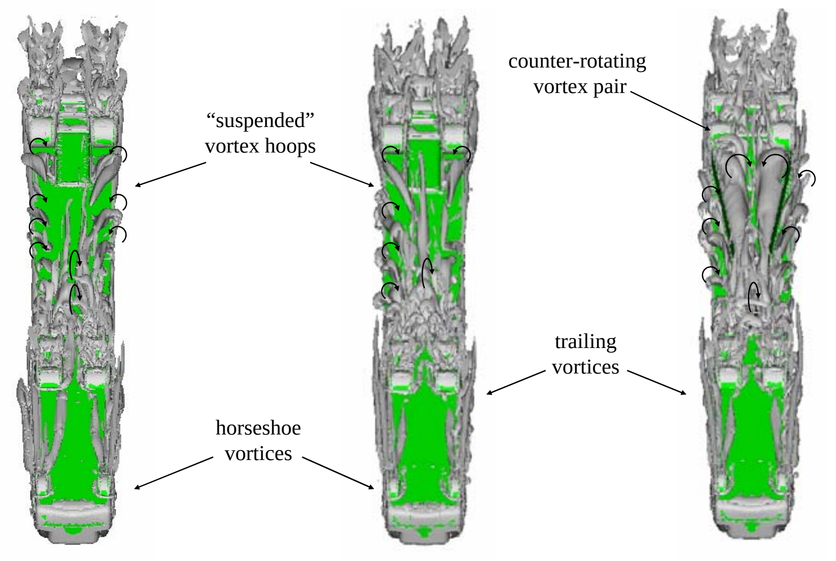
Add-on devices impact on flow structure, ...



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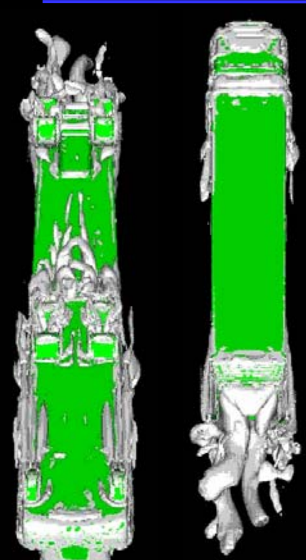
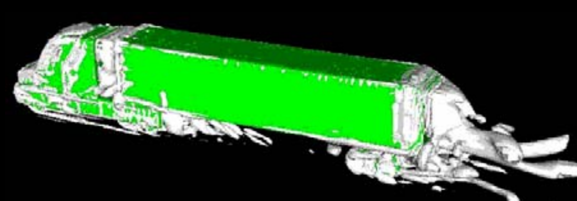
Baseline | Base Flaps | Long Wedge Skirt

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 = ½(Ω⊗Ω - S⊗S), (Perry & Chong, 1994; Blackburn *et al*., 1996; Dubief & Delcayre, 2000)