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September 2002 Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

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U.S. Department of Energy

Lawrence Livermore National Laboratory

November 22, 2002

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September 2002
Working Group Meeting on
Heavy Vehicle Aerodynamic Drag:
Presentations and Summary of Comments and Conclusions

Jointly written by
Lawrence Livermore National Laboratory
Sandia National Laboratories
University of Southern California
California Institute of Technology
NASA Ames Research Center
Georgia Tech Research Institute
Argonne National Laboratory

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at NASA Ames Research Center on September 23, 2002. The purpose of the meeting was to present and discuss technical details on the experimental and computational work in progress and future project plans. Representatives from the Department of Energy (DOE)/Office of Energy Efficiency and Renewable Energy/Office of FreedomCAR & Vehicle Technologies, Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), NASA Ames Research Center (NASA), University of Southern California (USC), California Institute of Technology (Caltech), Georgia Tech Research Institute (GTRI), Argonne National Laboratory (ANL), Freightliner, and Portland State University participated in the meeting. This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.

Introduction, Overview of the Project, and Summary

The meeting began with an introduction by the Project Lead Rose McCallen of LLNL, where she emphasized that the world energy consumption is predicted to relatively soon exceed the available resources (i.e., fossil, hydro, non-breeder fission). This short fall is predicted to begin around the year 2050. Minimizing vehicle aerodynamic drag will significantly reduce our Nation's dependence on foreign oil resources and help with our world-wide fuel shortage. Rose also mentioned that educating the populace and researchers as to our world energy issues is important and that our upcoming United Engineering Foundation (UEF) Conference on *The Aerodynamics of Heavy Vehicles: Trucks, Busses, and Trains* was one way our DOE Consortium was doing this. Mentioned were the efforts of Fred Browand from USC in organizing and attracting internationally recognized speakers to the Conference. Rose followed with an overview of the DOE project goals, deliverables, and FY03 activities. The viewgraphs are attached at the end of this report.

Sid Diamond of DOE discussed the reorganization of the Office of Energy Efficiency and Renewable Energy and that the once Office of Heavy Vehicle Technology is now part of the Office of FreedomCAR & Vehicle Technologies. Sid reviewed the FY03 budget and provided information on some plans for FY04. The soon to be posted DOE request for proposals from industry for projects related to parasitic energy losses was discussed. A minimum of 50% cost share by industry will be required and the proposal must be submitted by industry. Collaborative efforts in aerodynamic drag with members of the DOE consortium are encouraged. Sid also mentioned interest in aerodynamic drag contribution due to wheel wells and underbody flow. Sid also mentioned his continued interest in the application of our computational and experimental expertise to the area of locomotive and railcar aerodynamics for the reduction of drag effects and thus, the reduction of fuel consumption by trains.

In summary, the technical presentations at the meeting included a review of experimental results and plans by GTRI, USC, and NASA Ames, the computational results from LLNL and SNL for the integrated tractor-trailer benchmark geometry called the Ground Transportation System (GTS) model, and by LLNL for the tractor-trailer gap and trailer wake flow, and turbulence model development and benchmark simulations being investigated by Caltech. USC is also investigating an acoustic drag reduction device that has been named ‘Mozart’, GTRI continues their investigation of a blowing device, and LLNL presented their ideas for 2 new base drag reduction devices. ANL presented their plans for a DOE supported Cooperative Research and Development Agreement (CRADA) with Paccar Truck Company utilizing commercial software tools to simulate the flow and drag for an actual tractor and showed the results of some preliminary griding attempts. The attendees also had the opportunity to tour the 12-ft pressure wind tunnel the machine shop were the Generic Conventional Model (GCM, a.k.a. SLRT) was being readied for the scheduled November experiments. Much of the discussion involved wind tunnel testing plans, analysis of existing experimental data, investigations of drag reduction devices, simulation results, and needed modeling improvements. Further details are provided in the attached viewgraphs.

Project Goals, Deliverables, and Future Activities

Based on discussions at the Meeting, the project goals remain unchanged:

- Perform heavy vehicle computations to provide guidance to industry
- Using experimental data, validate computations
- Provide industry with design guidance and insight into flow phenomena from experimental and computations

- Investigate aero devices (e.g., boattail plates, side extenders, blowing and 'Mozart' device)

The following additional activities were identified:

1) Investigate expansion of the NASA FY03 test plan to include experiments in the 12-ft pressure wind tunnel that focus on the investigation of the blowing device and possibly, other add-on devices for reducing base drag.
2) The inclusion of inexpensive 'discovery experiments' lead by LLNL in a small-scale NASA wind tunnel which demonstrates the joint use of computational design guidance and wind tunnel optimization.
3) Investigation of aerodynamic drag contribution due to wheel wells and underbody flow.
4) Consider application of the Consortium's expertise and tools to the area of railcar and locomotive aerodynamic drag.
5) Determine what, if any, restrictions for trailer base add-on devices are specified in DOT regulations. This information is important in our evaluation of potential design options.
6) Respond to DOE/OHVT request for proposals (RFP) in collaboration with Freightliner.
7) Investigate issues related to heavy vehicle splash and spray. (USC has a small moving-ground-plane wind tunnel coming online and LLNL is interested in spray modeling.)
8) Plan for next working group meeting at UEF conference.
9) Send success stories (1 to 2 paragraphs) to Sid and Jules for publication in DOE weekly reports.
10) Provide Sid and Jules with names of heavy vehicle stability experts.

Technical Discussion Highlights

See attached viewgraphs for details.

Full-Scale Experimental Demonstration of Pneumatic Heavy Vehicles

Bob Englar of GTRI reported on the SAE Type-II fuel economy tests performed at the Transportation Research Center's 7.5 mile test track in Ohio with the GTRI blowing device mounted on a Great Dane trailer, pulled by a Volvo tractor. Results indicated a smaller improvement in fuel economy than expected. Bob discussed possible problem areas, such as, increased drag from under trailer compartment that housed the compressor for the blowing device, yawed large side winds, side extenders at a high angle that thickened the boundary layer on the sides of the trailer, and possible asymmetric blowing. What was most curious about the results was that the fuel economy was reduced with increased blowing, which was not the case in the GTRI wind tunnel experiments. Bob proposed testing in the GTRI tunnel to investigate further the identified problems in the track tests, and also proposed were experiments in the NASA 12-ft pressure wind tunnel for more definitive data on a realistic geometry at full scale Reynolds numbers with Mach number control.

Using RANS with Overset Grid Technology in Conjunction with Component LES Investigations

Kambiz Salari and Jason Ortega of LLNL demonstrated the benefits of using overset grid technology with a steady Spalart-Almaras (S-A) turbulence model to evaluate the aerodynamics of the full vehicle in conjunction with large-eddy simulation (LES) to capture the instantaneous flow field in evaluations of tractor-trailer gap and trailer wake flow. Overset grids provide the flexibility of defining a simple regular grid for the freestream flow in the wind tunnel while allowing the user to separately specify and overlay a fine grid around the vehicle geometry. Thus, the addition of even more detailed components, like side mirrors, is trivial. This technology is currently being utilized by the industry in evaluating production aircraft.

Simulations with an S-A RANS model with overset grids are being used to define positions where the computational models can be truncated to reduce the problem size and thus, the computational effort without significant loss of accuracy in capturing the flow physics. These truncated models are then utilized in evaluations of gap and wake flow using advanced but significantly more computationally demanding tools that capture the detailed instantaneous flow with LES. The LLNL Team demonstrated how these results, even though preliminary, are leading them to identify possible new add-on devices and the modification of existing devices to improve their effectiveness at reducing aerodynamic trailer base drag. The results for the tractor-trailer gap studies have identified flow structures that were also found to exist in the experimental data.

Improved Near Wall Treatment for Vortex Method Approach

Caltech is investigating the use of a vortex method approach for heavy vehicle simulation. The advantage of vortex methods is that only a triangulated grid on the vehicle surface is necessary and the very time consuming griding of the flow field is eliminated. Mike Rubel presented Caltech's work on improving near wall treatment for their vortex method approach. A particularly efficient algorithm to perform the closest point transform (CPT) method was developed that scales linearly and has reduced memory requirements compared to other options. The Caltech team demonstrated their improvements with simulations of the GTS geometry for a low Reynolds number case.

Planned Experiments of GCM (a.k.a. SLRT) Geometry in the NASA's 12-ft Pressure Wind Tunnel

Dale Satran and J.T. Heineck of NASA Ames provided information on the test setup and planned experiments in the NASA 12-ft pressure wind tunnel. Reynolds numbers will range from 550,000 to 6,500,000 based on trailer width for a constant Mach number of 0.15. Yaw angles will be varied from +15 to -15 degrees so that wind averaged results can be computed. These experiments will not only provide detailed information on the flow phenomena at the full range of Reynolds number for heavy vehicles traveling at both city and highway speeds, but it will also indicate the effects of Reynolds number and experiments on reduce scale models. This information is of primary importance to industry whose wind tunnel experiments are done almost exclusively on scaled-down models at reduced speeds.

Truck Aero Team Meeting Attendees

LLNL, Livermore, CA

September 23, 2002

Attendee	Organization	e-mail address and phone
Kim Abbott	DOE	**kim.abbott@oak.doe.gov**
Sid Diamond	DOE	sid.diamond@ee.doe.gov, 202-586-8032
Bob Englar	GTRI	bob.englar@grti.gatech.edu, 770-528-3222
Basil Hassan	SNL	**bhassan@sandia.gov**, 505-844-4682
J. T. Heineck	NASA ARC	jheineck@mail.arc.nasa.gov, 650-604-0368
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Mike Rubel	Caltech	mrubel@caltech.edu, 626-395-8310
Kambiz Salari	LLNL	salari1@llnl.gov, 925-424-4635
Dale Satran	NASA ARC	dsatran@mail.arc.nasa.gov, 650-604-5879
Tanju Sofu	ANL	tsofu@anl.gov

AGENDA

Heavy Vehicle Aerodynamic Drag: Working Group Meeting
NASA Ames Research Center
Moffett Field, CA

September 23, 2002

Purpose of Meeting
1. Presentation & discussion of DOE/EERE reorganization and budget
2. Tour of 12' pressure wind tunnel
3. Presentation & discussion of technical details of work in progress & future plans

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7:30 — 8:00	Badging and travel to conference room	
Introduction		
8:00 — 8:10	Welcome, introduction, & project overview	Rose McCallen
8:10 — 8:55	DOE/EERE reorganization & budget	Sid Diamond, Jules Routbort
Work Plans and Progress: Computational Effort		
8:55 — 9:00	Overview of computational effort	Rose McCallen
9:00 — 9:30	Gap and base flow analysis (LLNL)	Kambiz Salari, Jason Ortega
9:30 — 10:00	RANS computations, analysis (SNL)	Chris Roy
10:00 — 10:15	Break	
10:15 — 10:45	Caltech vortex method development & computations (Caltech)	Mike F
10:45 — 11:15	Results with a commercial tool (ANL)	Tanju Sofu
Work Plans and Progress: Experimental Effort and Devices		
11:15 — 12:15	Wind tunnel tour (NASA)	Dale Satran, J.T. Heineck
12:15 — 1:25	Lunch in NASA Cafeteria	
1:25 — 1:30	Overview of experimental effort	Rose McCallen
1:30 — 2:00	Data reduction, analysis, documentation, & test plans (NASA)	Dale Satran
2:00 — 2:30	Test results, plans, & aero 'Mozart' device (USC)	Tsun-Ya Hsu
2:30 — 3:00	Test results & plans for blowing device (GTRI)	Bob Englar
3:00 — 4:30	Discussion and Wrap-up	

‘Working Group Meeting’
Consortium for Aerodynamic Drag of Heavy Vehicles
Department of Energy, Office of FreedomCAR & Vehicle Technologies
September 23, 2002

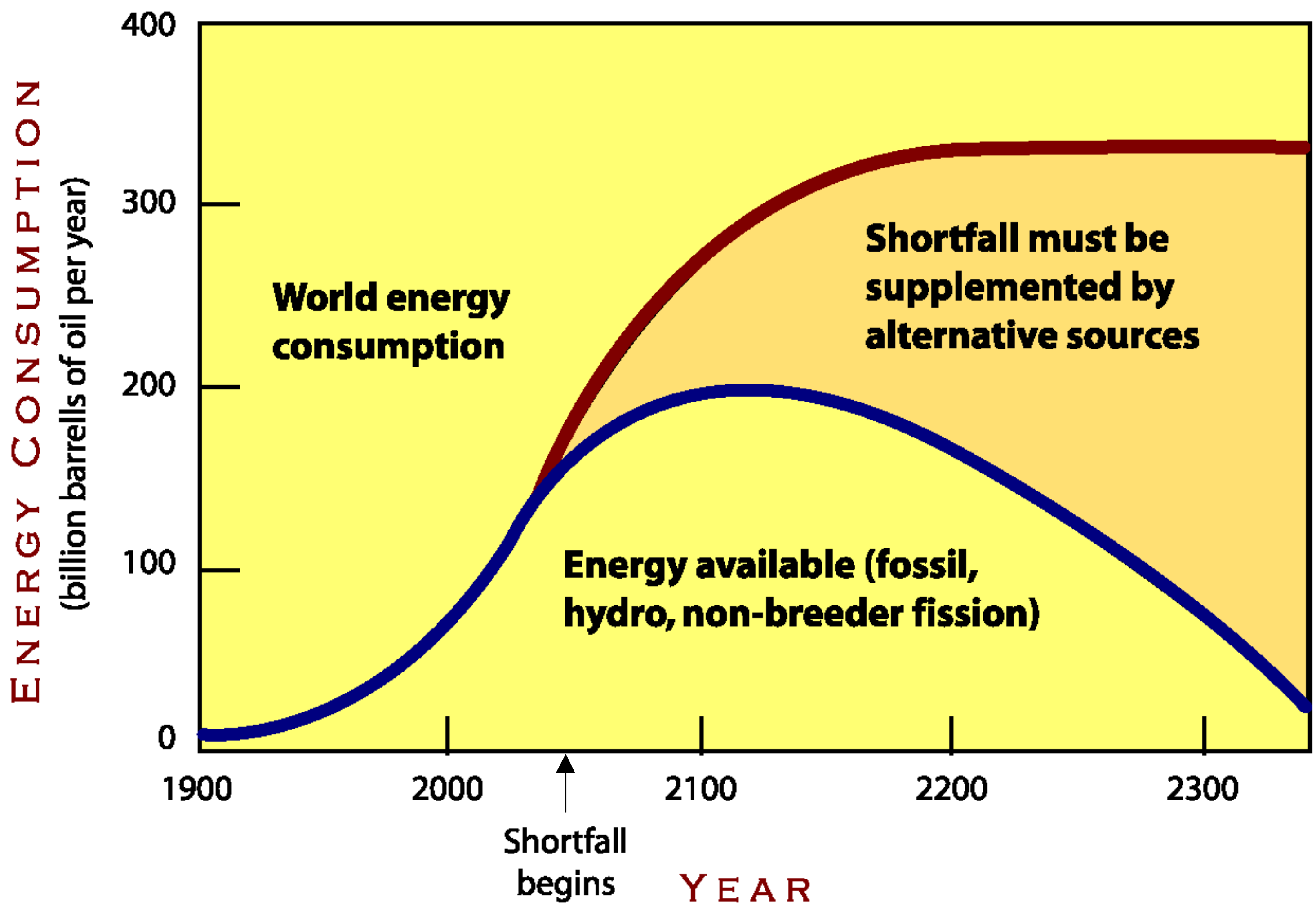
Rose McCallen, Kambiz Salari, Tim Dunn, Jason Ortega	*University of California* Lawrence Livermore National Laboratory
Chris Roy, David Kuntz, Basil Hassan	Sandia National Laboratories
James Ross, Dale Satran, J.T. Heineck, Bruce Storms, David Driver, James Bell, Steve Walker, Gregory Zilliac	National Aeronautics & Space Administration
Mustapha Hammache, Fred Browand, Tsun-Ya Hsu, Diego Arcas	USC University of Southern California
Anthony Leonard, Mike Rubel, Philippe Chatelain	Caltech *California Institute of Technology*
Robert Englar	Georgia Tech Research Institute
David Weber, David Pointer, Tanju Sofu	ARGONNE NATIONAL LABORATORY

*Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

Attendees

Sid Diamond	DOE/OEERE
Jules Routbort	DOE/ANL
Matt Markstaller	Freightliner
Gerry Recktenwald	Portland State University,Portland, OR
Kim Abbott	DOE Oakland Office

National Energy Consumption Projection



THE AERODYNAMICS OF HEAVY VEHICLES: TRUCKS, BUSES AND TRAINS

December 2-6, 2002

Asilomar Conference Center, Monterey-Pacific Grove, California

SCIENTIFIC COMMITTEE MEMBERSHIP

Peter Bearman, Imperial College, London, ENGLAND
Hudong Chen, Exa Corporation, Lexington, MA, USA
Everett Chu, PACCAR, Mount Vernon, WA, USA
Kevin Cooper, National Research Council of Canada, Ottawa, CANADA
John Foss, Michigan State University, East Lansing, MI, USA
Sunil Jain, International Truck and Engine Corporation, Fort Wayne, IN, USA
Y. Kohama, Tohoku University, Sendai, JAPAN
Anthony Leonard, Caltech, Pasadena, CA, USA
Edzard Mercker, DNW, Emmeloord, NETHERLANDS
Luis Novoa, Freightliner, Portland, OR, USA
Gene Olson, International Truck and Engine Corporation, retired, USA
Wolfgang Rodi, University of Karlsruhe, Karlsruhe, GERMANY
Anatol Roshko, Caltech, Pasadena, CA, USA
Gino Sovran, General Motors Research, retired, Troy, MI, USA
Philippe Spalart, Boeing Commercial Airplanes, Seattle, WA, USA

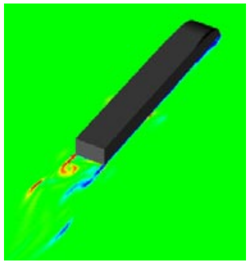
INVITED SPEAKERS…

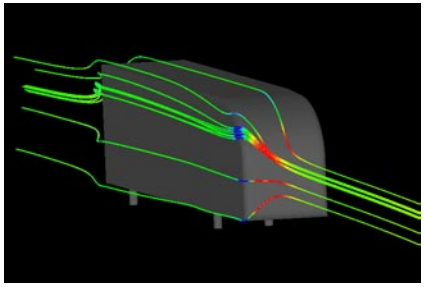
Aerodynamics and Other Efficiencies in Transporting Goods
PaulMacCready, AeroVironment Inc, USA

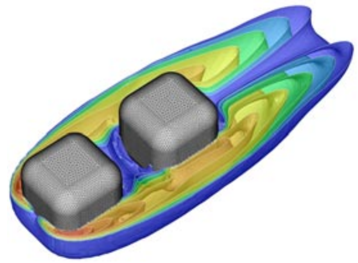
Commercial Vehicle Aerodynamic Drag Reduction-Historical Perspective as a Guide
Kevin Cooper, National Research Council of Canada

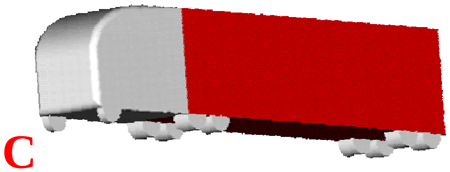
The Status of Detached Eddy Simulation for Bluff Bodies
Philippe Spalart, Boeing Commercial Airplanes, USA
Kyle Squires, Arizona State University, USA

GOOD SCIENCE



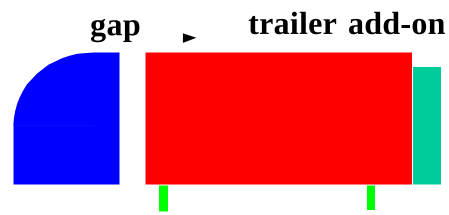






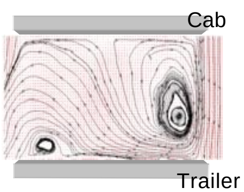
LLNL, SNL, ANL, Caltech
High quality numerical computations
Guidance on computational tools

NASA, USC
Data base of high quality
wind tunnel experiments

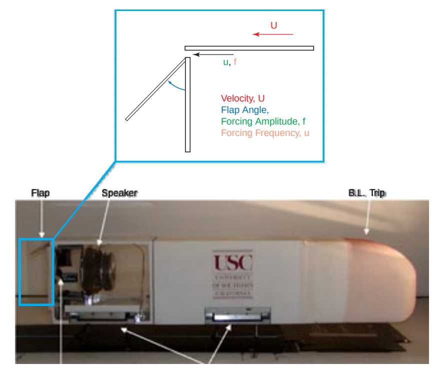


USC, NASA, LLNL, SNL
Comparisons and analyses
Insight into flow phenomena

USC, GTRI, LLNL
Concepts and designs of
aero devices



TEAM, Industry
Information exchange



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Overview of LLNL Flow Modeling and Development

Jason Ortega, Tim Dunn, Kambiz Salari, Rose McCallen

Lawrence Livermore National Laboratory

Heavy Vehicle Aerodynamic Drag Working Group Meeting
NASA Ames Research Center
September 23, 2002

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

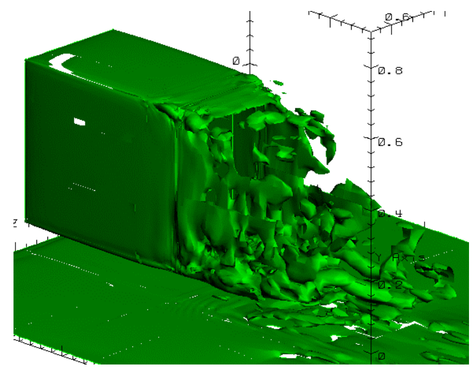
LLNL Budget for FY02

- **FY02 $400K + $40K UEF**
  - **Project management (Rose and Helen)** **40%**
  - **Technical Effort** **50%**
  - **Engineering Foundation Conference** **10%**
- **Leveraging**
  - **ASCI code development program** **> 1 FTE**
  - **LLNL Internal Tech Base Funding** **> 0.5 FTE**
  - **ASCI White massively parallel computer**

LLNL FY02 Tasks

- **Full vehicle simulation with OVERFLOW**
  - **Tunnel simulation to determine proper BC**
  - **GTS flow simulation in the NASA 7'x10' tunnel**
  - **Support truncated trailer wake simulation**

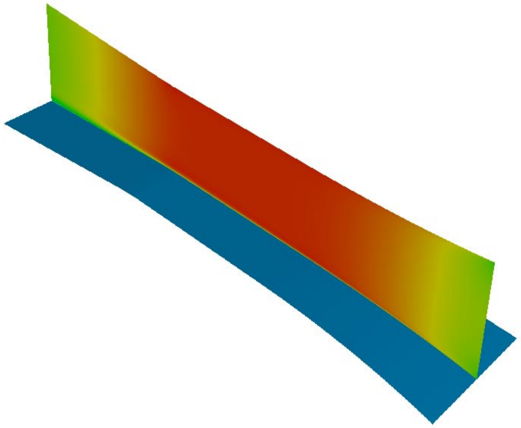
- **Gap flow simulation, USC**
  - **ALE3D, 2-D and 3-D, (LES, unsteady)**
  - **OVERFLOW, 3-D, (RANS, steady)**
  - **Sensitivity study**
    - **Ground plane BC (noslip vs. slip)**
    - **Far field boundary location (tunnel vs. open)**
  - **Experimental data from USC and NASA**

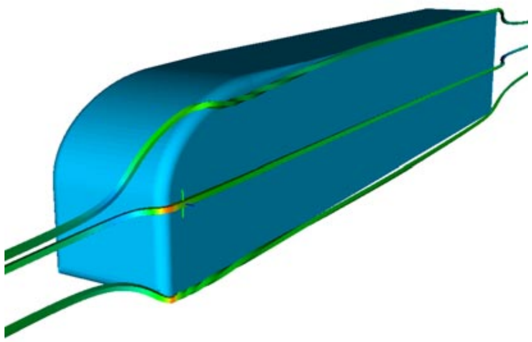


- **Trailer wake simulation, NASA**
  - **Analysis of flow structure with/without boattail**
  - **ALE3D, 2-D and 3-D, (LES, unsteady)**
  - **OVERFLOW, 3-D, (RANS, steady)**
  - **Boattail shape optimization**
  - **Experimental data from NASA**

GTS in NASA 7'x10' Tunnel, OVERFLOW

- **Tunnel simulation**
  - Boundary condition determination to establish proper flow condition in the tunnel test section
  - Using overset multiple grid topologies were tested
- **GTS in the tunnel**
  - Overset capability of OVERFLOW was used to significantly improve grid generation
  - Used boundary conditions obtained from the tunnel simulations
  - Turbulence models
    - Spalart-Allmaras
      - Grid size ~6 M
    - Wilcox k-ω
      - Grid size ~6 M





Gap Flow Simulations, USC

Modified GTS Geometry

- **ALE3D, LES**
  - **Smagorinsky, no van Driest damping, slip boundary condition on ground plane**
    - **two grids, ~1 and ~2 M elements**
- **OVERFLOW, RANS**
  - **tunnel walls with slip boundary condition**
    - **Spalart-Allmaras turbulence model**
      - **Two grids, ~5 and ~8 M elements**
    - **Wilcox *k*-ω turbulence model**
      - **Two grids, ~5 and ~8 M elements**
  - **No tunnel walls, open to free stream conditions, no-slip boundary condition on ground plane**
    - **Spalart-Allmaras turbulence model**
      - **Two grids, ~5 and ~8 M elements**
    - **Wilcox *k*-ω turbulence model**
      - **Two grids, ~5 and ~8 M elements**

Trailer-Wake Flow Simulation, NASA

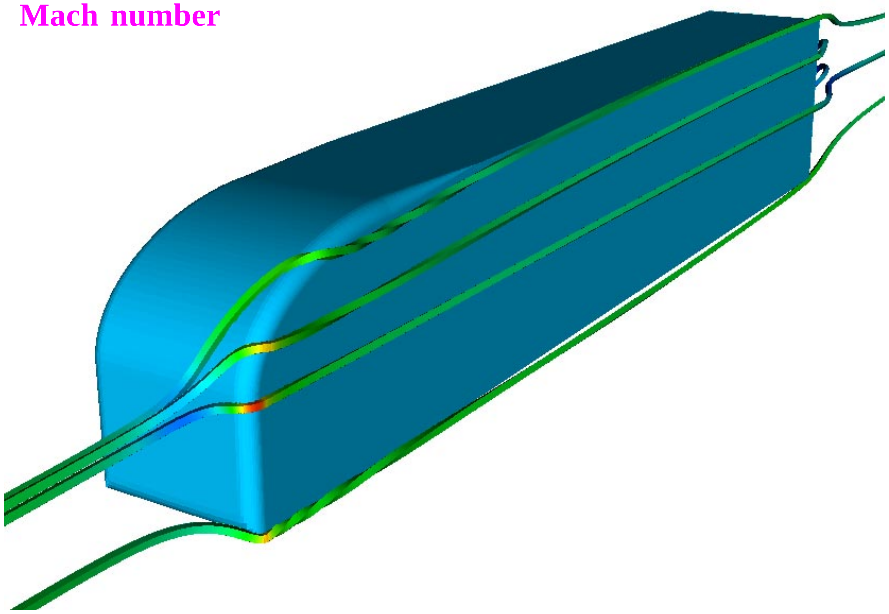
Truncated GTS Geometry with no wind tunnel modeling

- **ALE3D, LES, Unsteady**
  - **Smagorinsky, no van Driest damping, no-slip boundary condition on the ground plane**
    - **No boattail**
      - **Two grids, ~350,000 and ~800,000**
    - **With boattail**
      - **two grids, ~775,000 and ~1.5 M elements**
- **OVERFLOW, RANS, Steady**
  - **No-slip boundary condition on ground plane**
    - **Spalart-Allmaras turbulence model**
      - **Two grids, ~6 M and ~9 M elements**
    - **Wilcox k-ω turbulence model**
      - **Two grids, ~6 M and ~9 M elements**

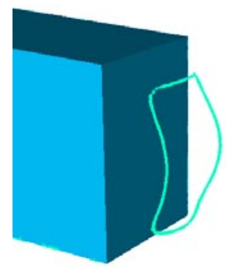
GTS in NASA 7'x10' tunnel, OVERFLOW

Spalart-Allmaras turbulence model

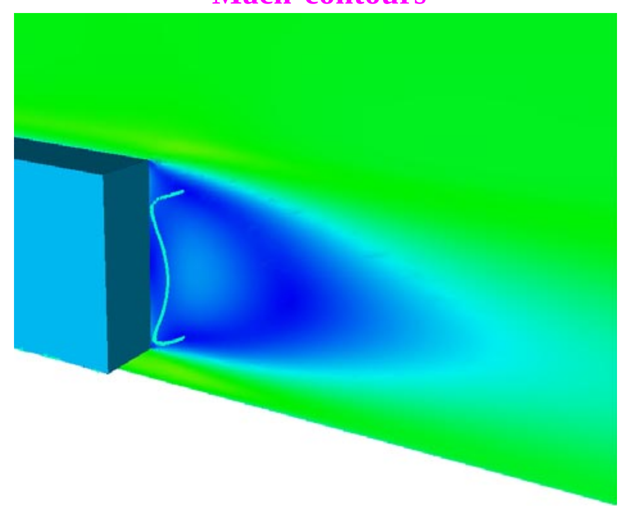
Particle traces colored by Mach number



Vortex core

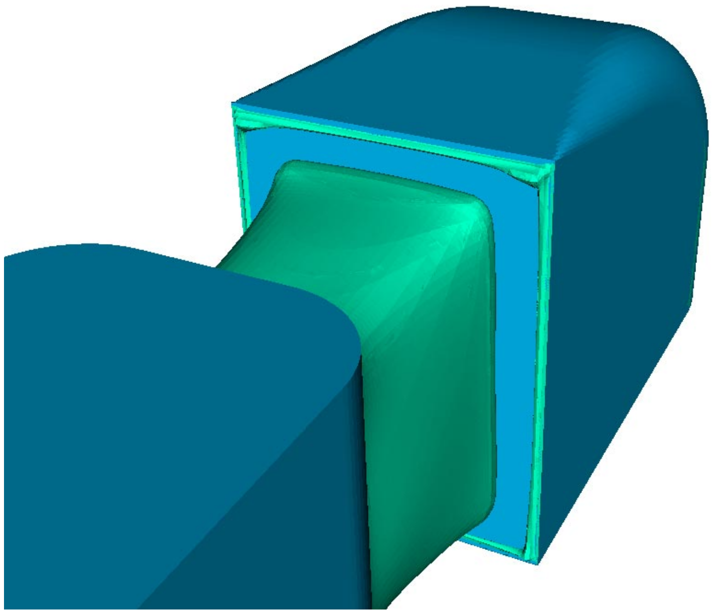


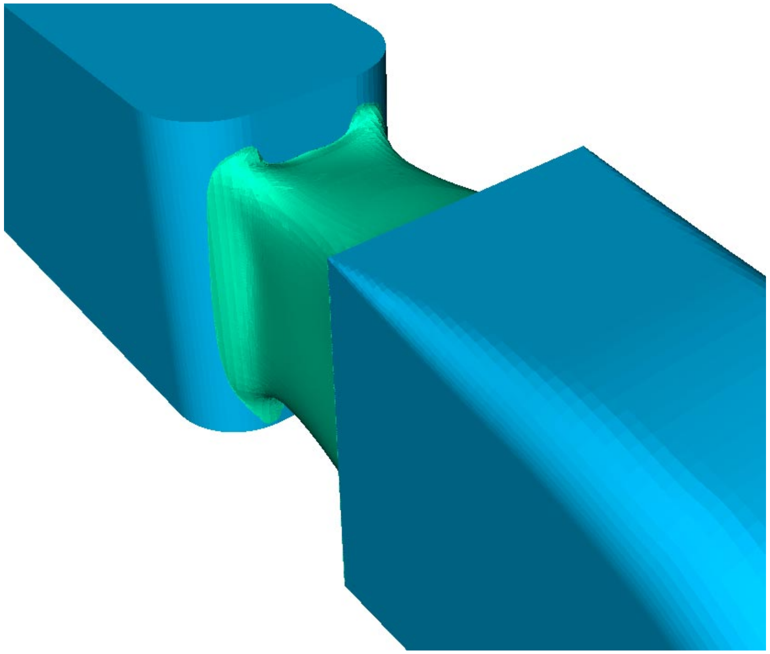
Mach contours



Gap Flow Simulation, OVERFLOW

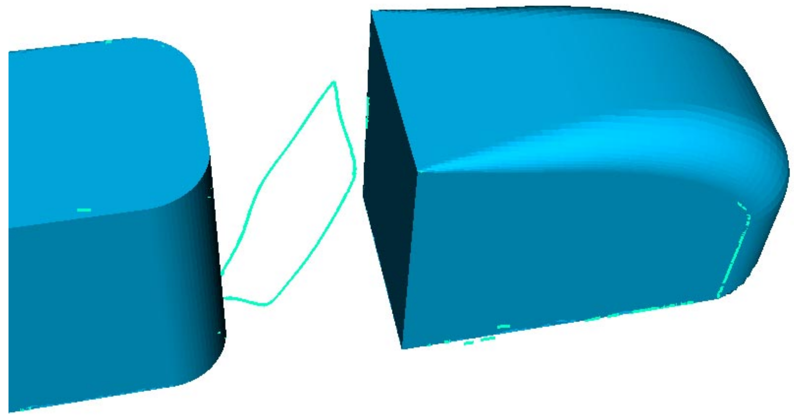
IsoSurface of U = -0.0001 m/s, SA turbulence model





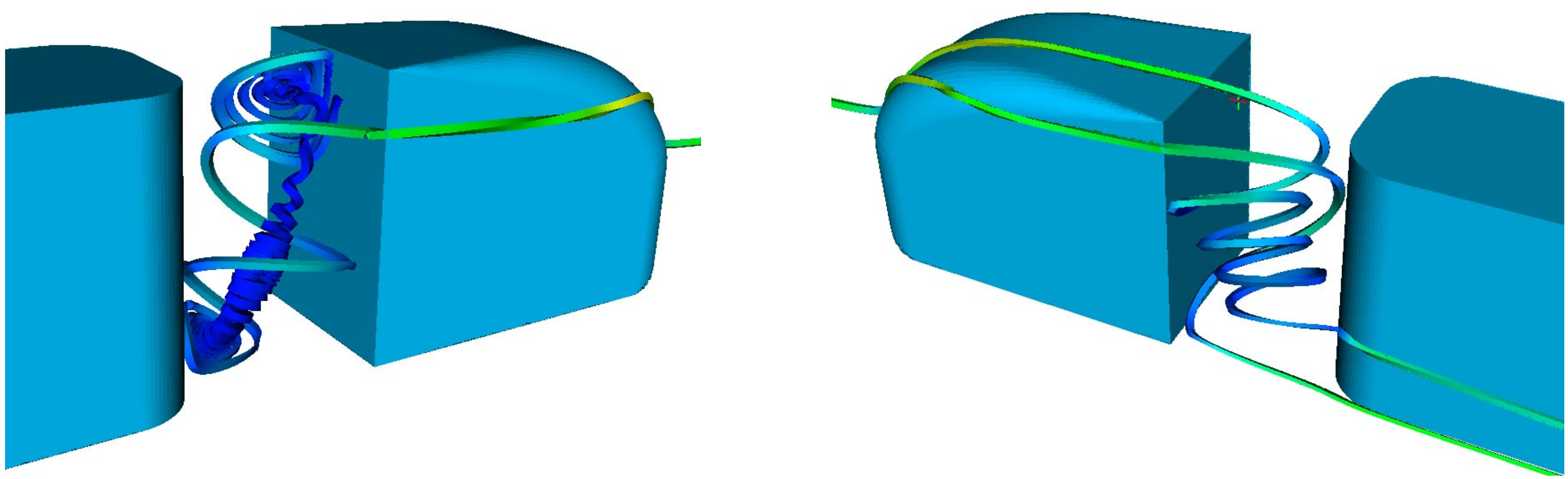
Gap Flow Simulation, OVERFLOW

SA turbulence model



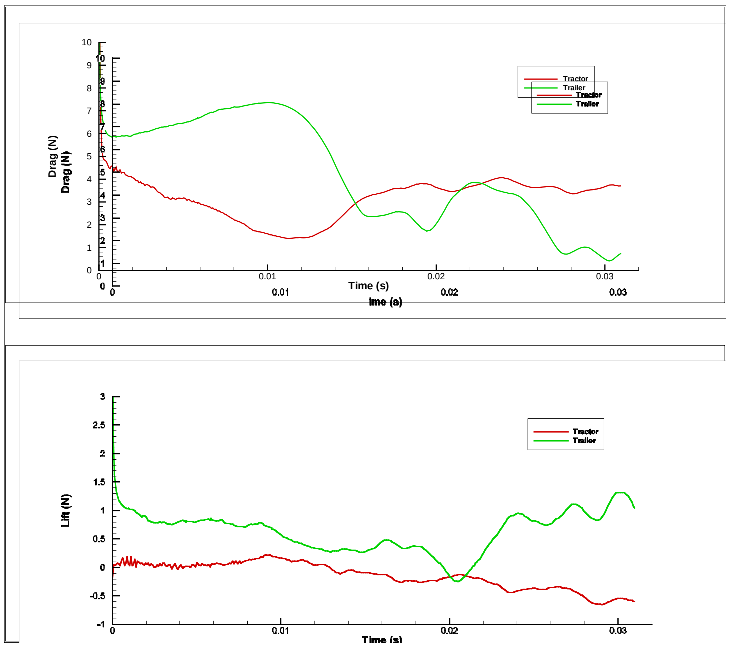
Vortex core

Particle traces colored by Mach number

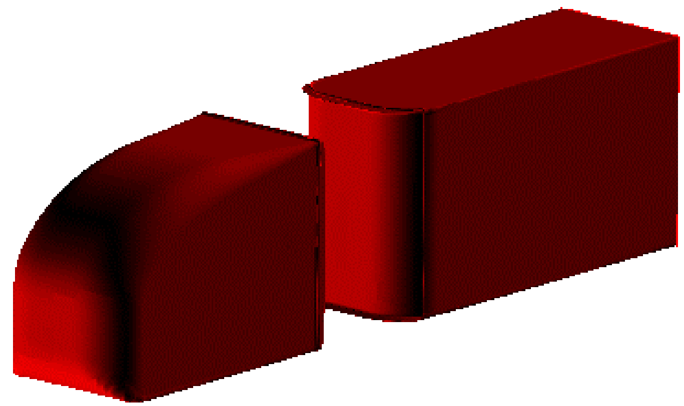


Gap Flow Simulation, ALE3D

Aerodynamic Forces



Smagorinsky



Summary

- OVERFLOW was utilized with its overset grid capability to model NASA 7'x10' tunnel for boundary condition determination for the full GTS simulation
- Full GTS flow simulation in the NASA 7'x10' tunnel was conducted with OVERFLOW using two different turbulence models. Grid construction was significantly aided with the overset grid capability of OVERFLOW in both grid quality and construction time
- Trailer wake flow simulation with/without boattail was conducted. RANS and LES were used to investigate the flow structure in the wake. The wake structure of the full GTS simulation was compared to the truncated trailer wake to identify what flow features were lost in the truncated case.
- Straight boattail plates may not be the optimal shape for maximum drag reduction. Curved boattail plates may provide additional drag reduction.
- Gap flow study was conducted using USC modified GTS model with a gap distances above the critical limit, G/L=50%. RANS and LES were used to investigated the flow field. Interesting flow structures in the gap were detected.

A Computational Study of a Truncated Trailer Geometry

Jason Ortega, Tim Dunn,
Rose McCallen, Kambiz Salari

Lawrence Livermore National Laboratory

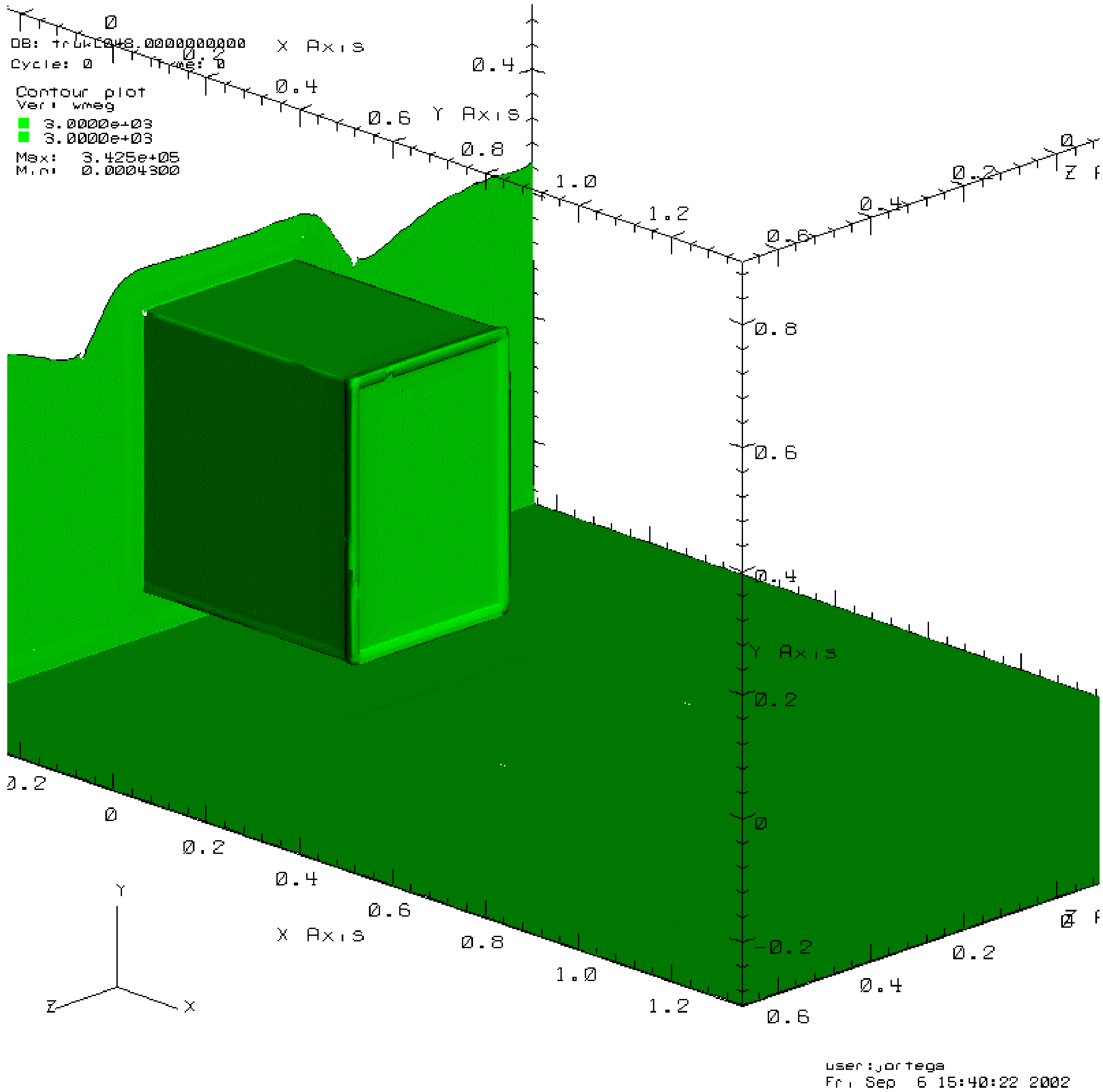
Computational Physics

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

ALE3D Simulations

Vorticity Magnitude for No Boattail

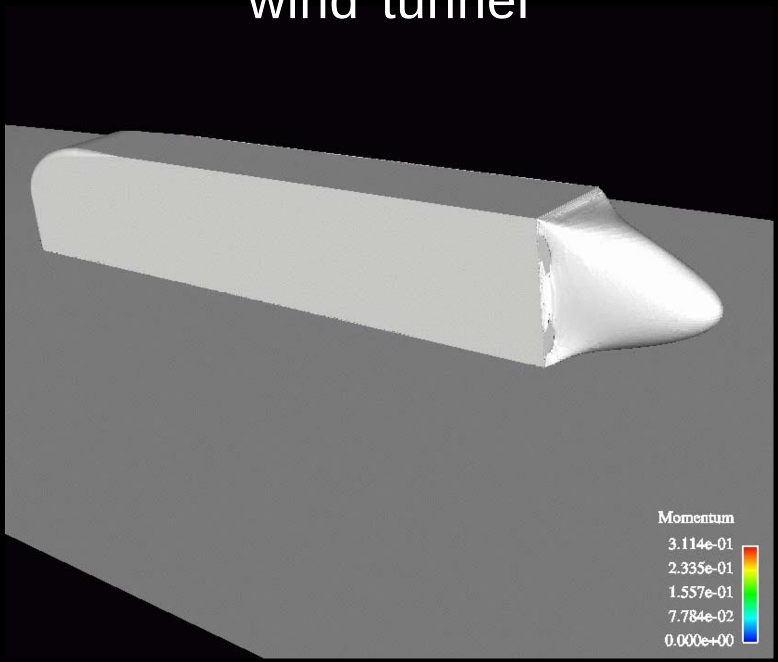
- Iso-vorticity surface at |w| = 3000 1/s
- 384,000 elements
- 0^o yaw
- $Re_w = 2.0¥10^6$
- Smagorinski LES model



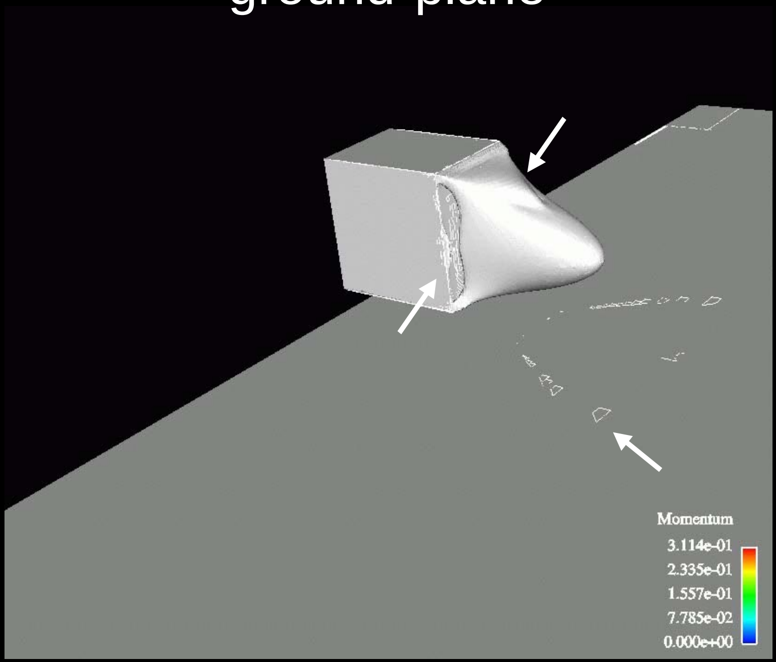
OVERFLOW Simulations

Effects of Truncation and Elimination of the Wind Tunnel Confinement

GTS in 7’¥10’ wind tunnel



Truncated GTS above a ground plane



- Isosurface of momentum magnitude
- Re_w = 2.0¥10^6
- Spallart-Almaras turbulence model

Computational Predictions for the GTS Truck Geometry

Chris Roy, Mary McWherter-Payne,
Dave Kuntz, Jeff Payne, and Basil Hassan
Aerosciences and Compressible Fluid Mechanics Department
Sandia National Laboratories

Heavy Vehicle Aerodynamic Drag: Working Group Meeting
NASA Ames Research Center

September 23rd, 2002

Sandia National Laboratories

Outline

- Introduction
  - SNL role
  - Personnel
- FY02 Tasks and Budget
  - Status
  - New 3D GTS grid
  - Preliminary results for new 2D GTS grid studies
- Leveraging

Introduction

- **Overall SNL Role: To provide technical insight to industry relative to:**
  - **the role of current and future (advanced) computational methods for truck/trailer aerodynamic design**
  - **Aerodynamic drag reduction for truck/trailer systems**
- **FY02:**
  - **The focus was on better y+ resolution for turbulence modeling (new 2D and 3D grids)**
  - **Examination of the Wilcox k-omega two-equation turbulence model**

Sandia Computational Approach

Steady RANS

- Spalart-Allmaras
- k-epsilon
- k-omega Wilcox

Unsteady RANS

- Spalart-Allmaras
- k-omega Wilcox

Hybrid RANS/LES

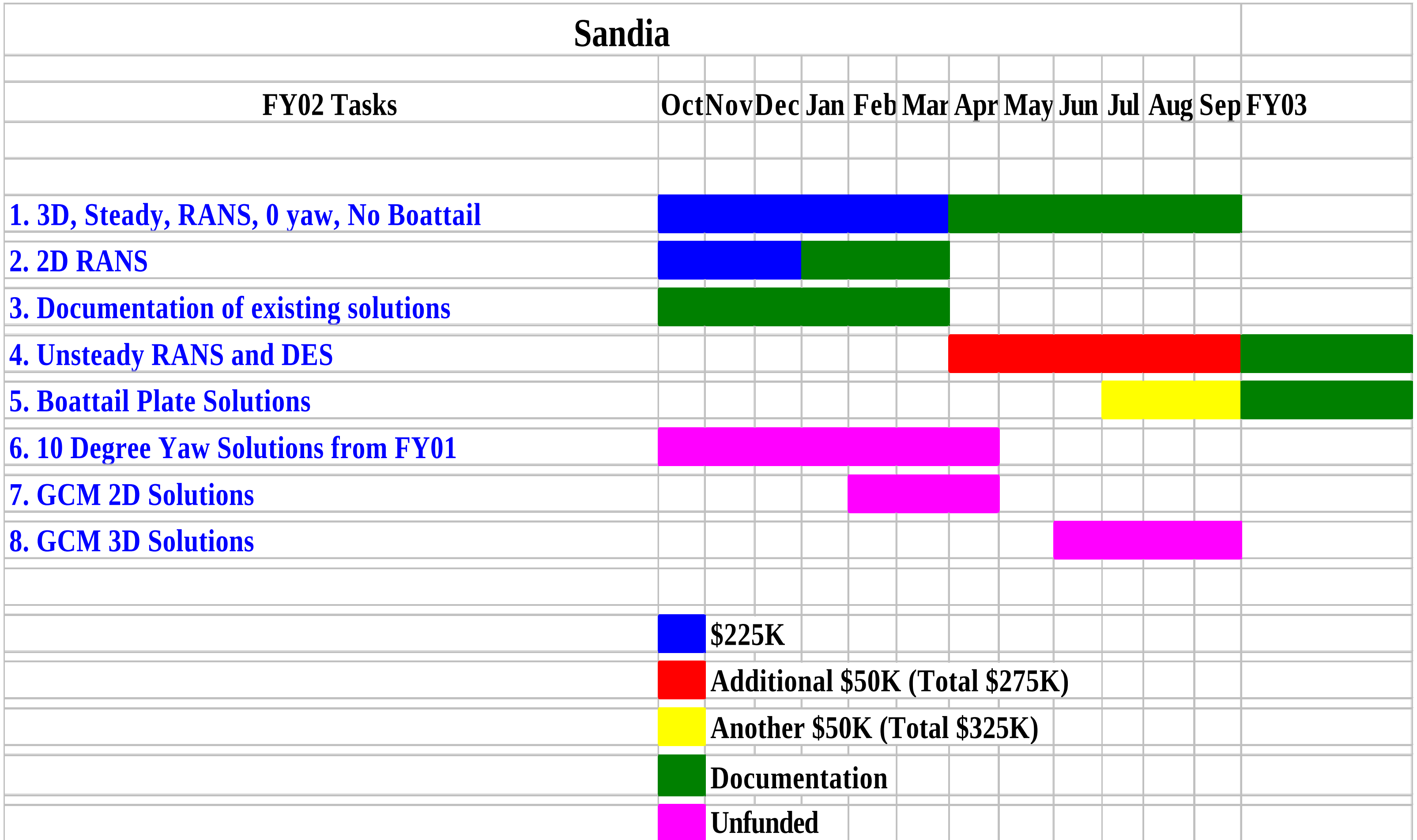
- Detached Eddy Simulation
- Hybrid RANS/LES

Sandia National Laboratories

Budget & Personnel

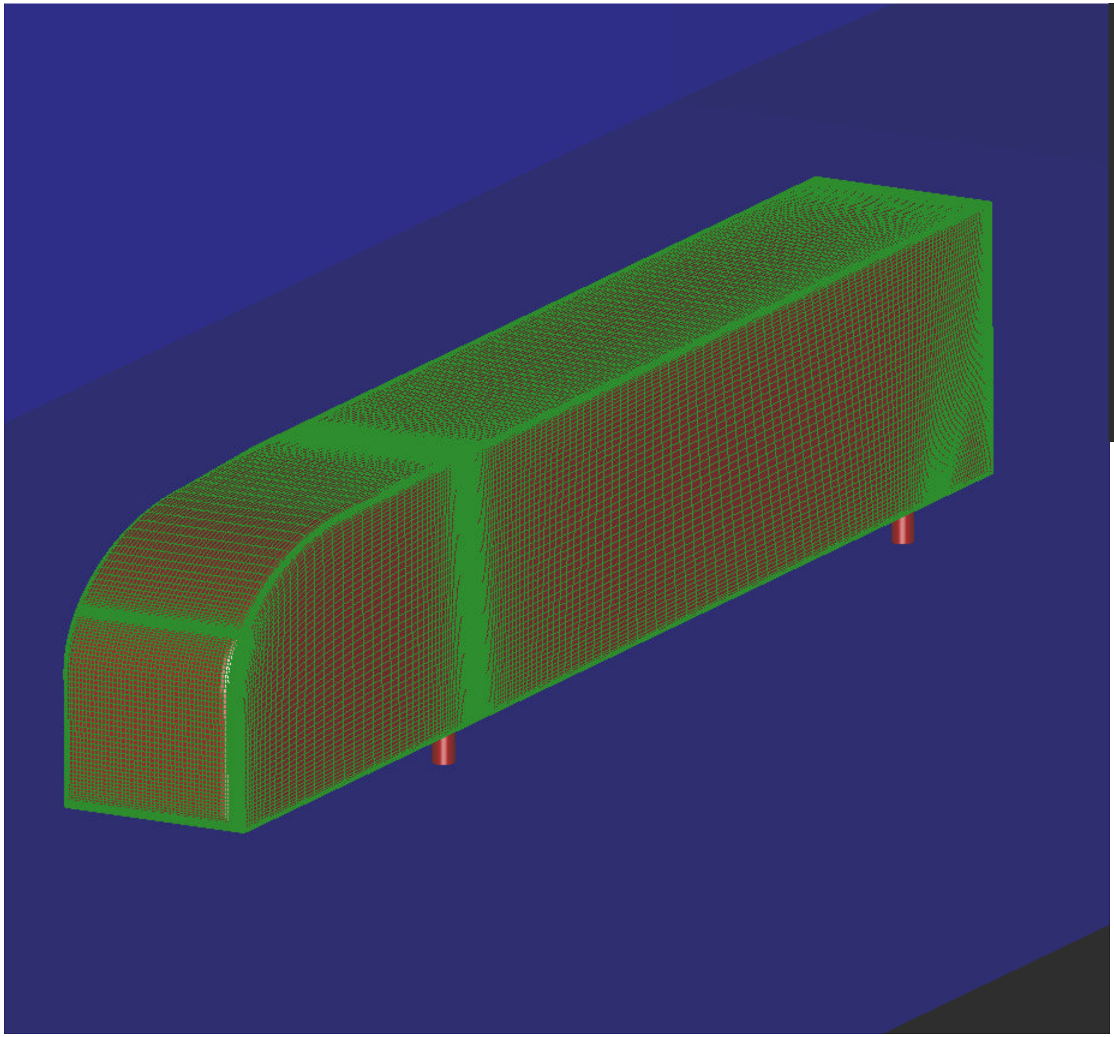
- The Budget: $225K ($50K less than anticipated)
- The Team:
  - Chris Roy
  - Mary McWherter-Payne
  - Dave Kuntz
  - Jeff Payne
  - Basil Hassan (Manager)

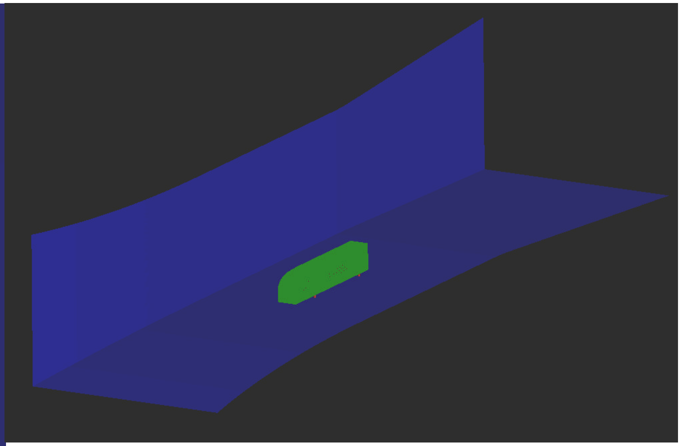
Sandia FY02 Tasks and Budget



Sandia National Laboratories

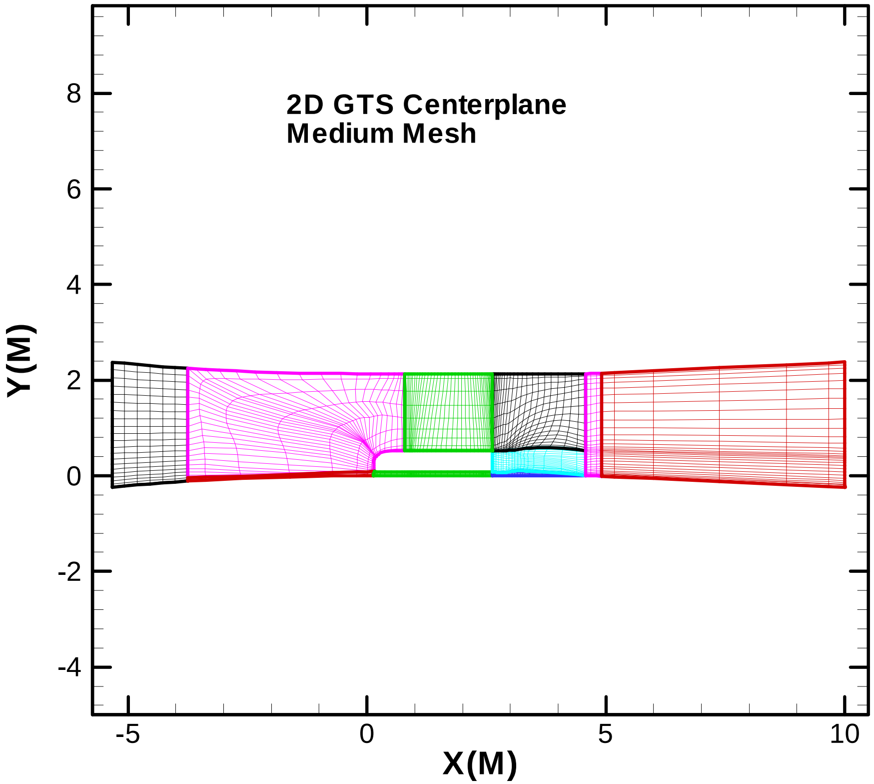
Task 1: New 3D Grid for GTS

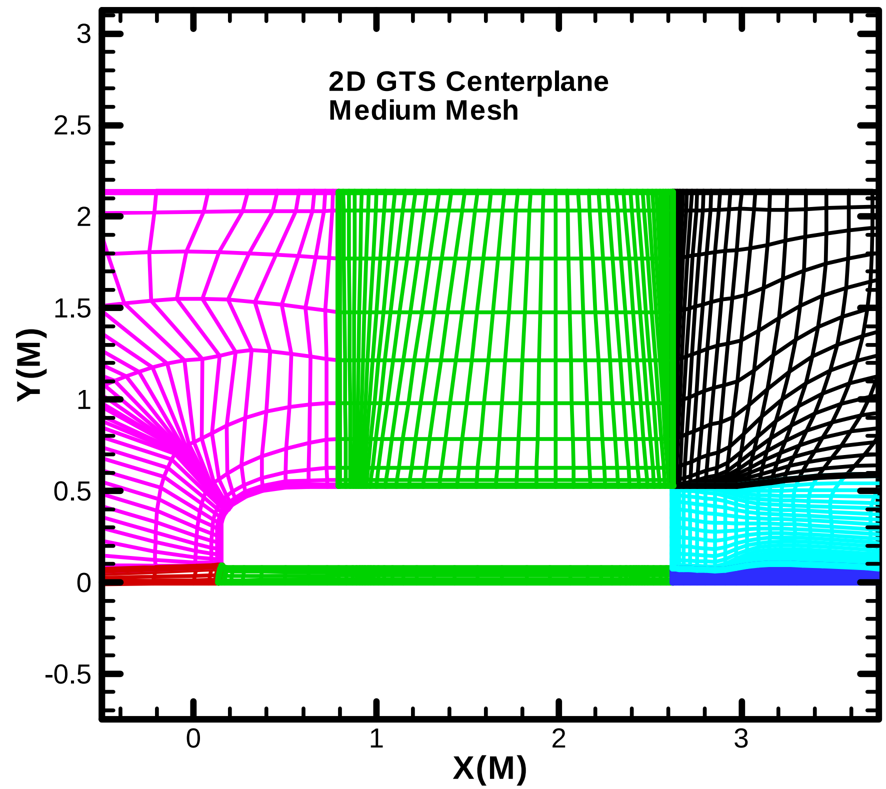




- New 3D meshes complete
  - Medium (2.5 million cells)
  - Fine (20 million cells)
- Will run:
  - k-omega/Wilcox
  - k-epsilon (time permitting)

New 2D RANS Simulations

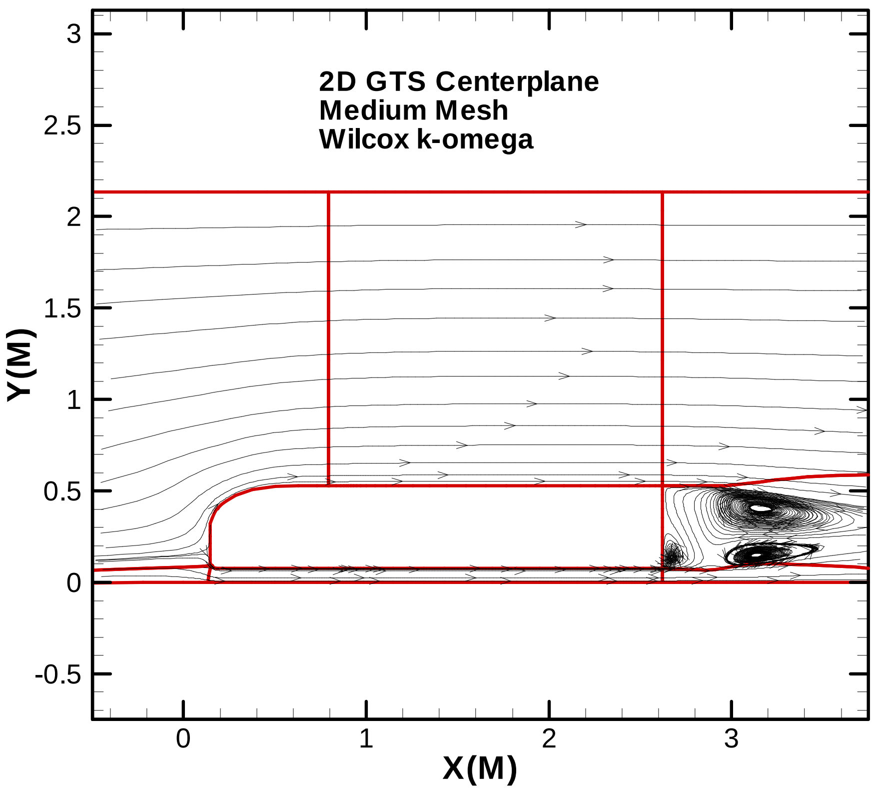


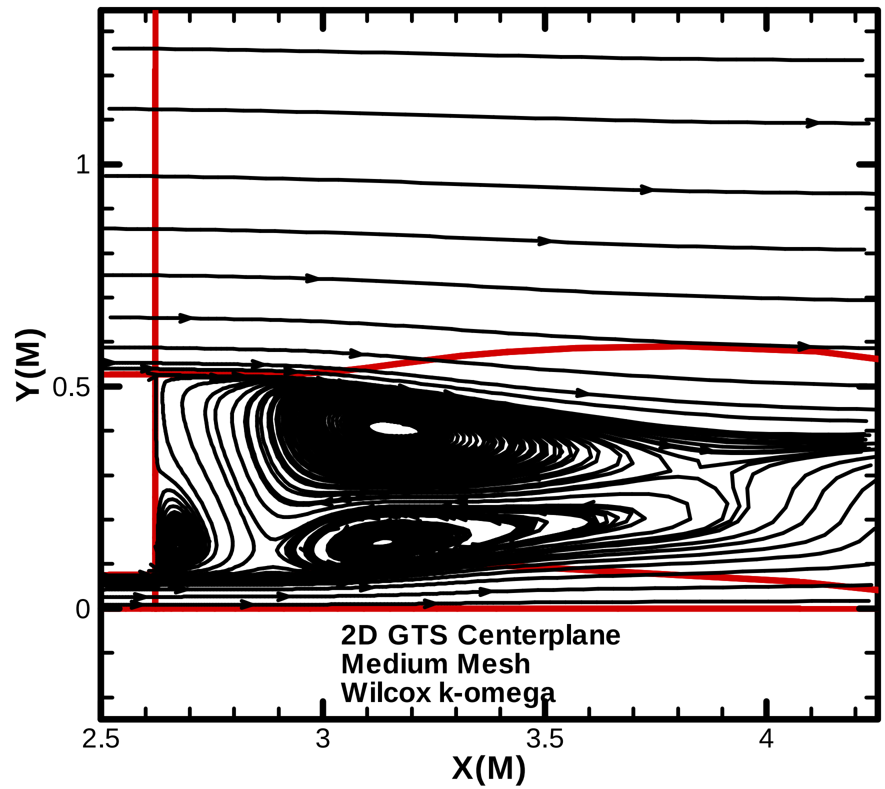


2D Centerplane Grid – Medium Mesh

Sandia National Laboratories

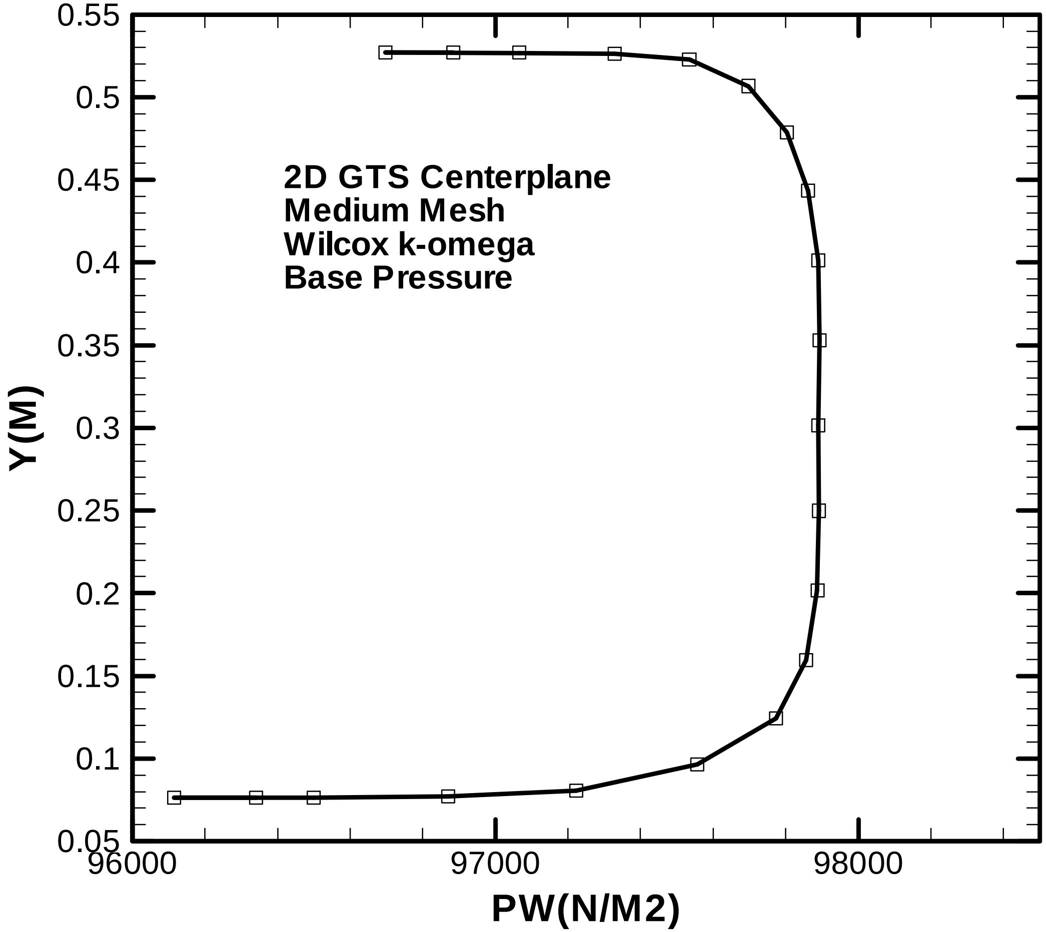
New 2D RANS Simulations





2D Centerplane Grid – Medium Mesh

New 2D RANS Simulations



2D Centerplane Grid – Medium Mesh

Sandia Leveraging

- Engineering Sciences Research Foundation
  - Unsteady RANS and hybrid RANS/LES turbulence modeling
- ASCI Material and Physical Models
  - RANS turbulence modeling
- ASCI Code Development
  - Verification and Validation methodologies/procedures
- ASCI Red Teraflop Computer
  - 9000 processor parallel machine

Conclusions and Path Forward

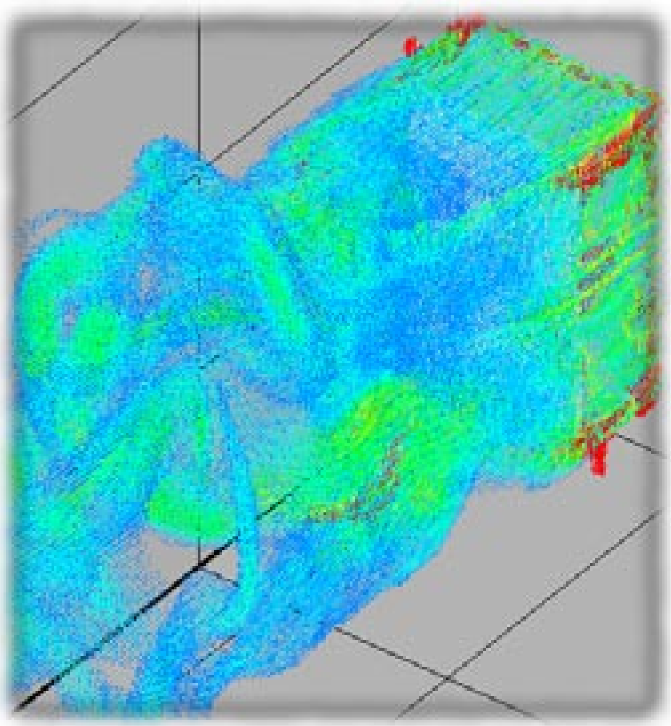
- RANS models can accurately capture surface pressure and skin friction on attached flow regions
- Need unsteady RANS or hybrid RANS/LES to accurately predict base flow
- Continue 3D GTS RANS solutions :
  - Focus on Wilcox k-omega model
  - 2D studies to augment numerical error estimation
- Documentation
  - Kambiz Salari/Mary McWherter-Payne: existing S-A RANS solutions (UEF conference)
  - 2D/3D GTS studies on new FY02 Grids (UEF conference)

FY03 Planned Work

- Complete full tunnel GTS RANS simulations
- Documentation of RANS work at UEF conference
- Perform steady-state RANS studies on truncated geometry
  – Unsteady RANS simulations on truncated geometry
  – Hybrid RANS/LES simulations on truncated geometry (time permitting)
- Initial GCM gridding – transition to new CFD tool Premo

Sandia National Laboratories

- Prof. Anthony Leonard
- Dr. Demosthenes Kivotides
- Philippe Chatelain
- <u>Michael Rubel</u>



Vortex Methods: Essentials

Mike Rubel
Caltech

- Numerical technique to solve the Navier-Stokes equations
- Suitable for Direct Simulation and Large-Eddy Simulation
- Uses vorticity (curl of velocity) as the solution variable
- Computational elements move with fluid velocity
- Viscous, 3-D, incompressible, with boundaries

Mike Rubel
Caltech

Vortex Methods: Advantages

- Computational elements only where voriticity is finite
- No mesh in the flow field
- Only 2-D grid on the vehicle surface
- Boundary conditions in the far field automatically satisfied

Caltech: FY 2002 Tasks

Mike Rubel
Caltech

1. Vortex code extensions
   A. Vortex Filament Method
   B. Near-wall treatment
   C. Truck Geometries
2. Subgrid Modeling
   A. DES-like subgrid model
   B. Advanced subgrid model
   C. Near-wall vortex elements
3. Simulation with Dead-Reckoning Timestopping
   A. Method ODE s
   B. Vortex Tree Code

Talk Topics Outline

Mike Rubel
Caltech

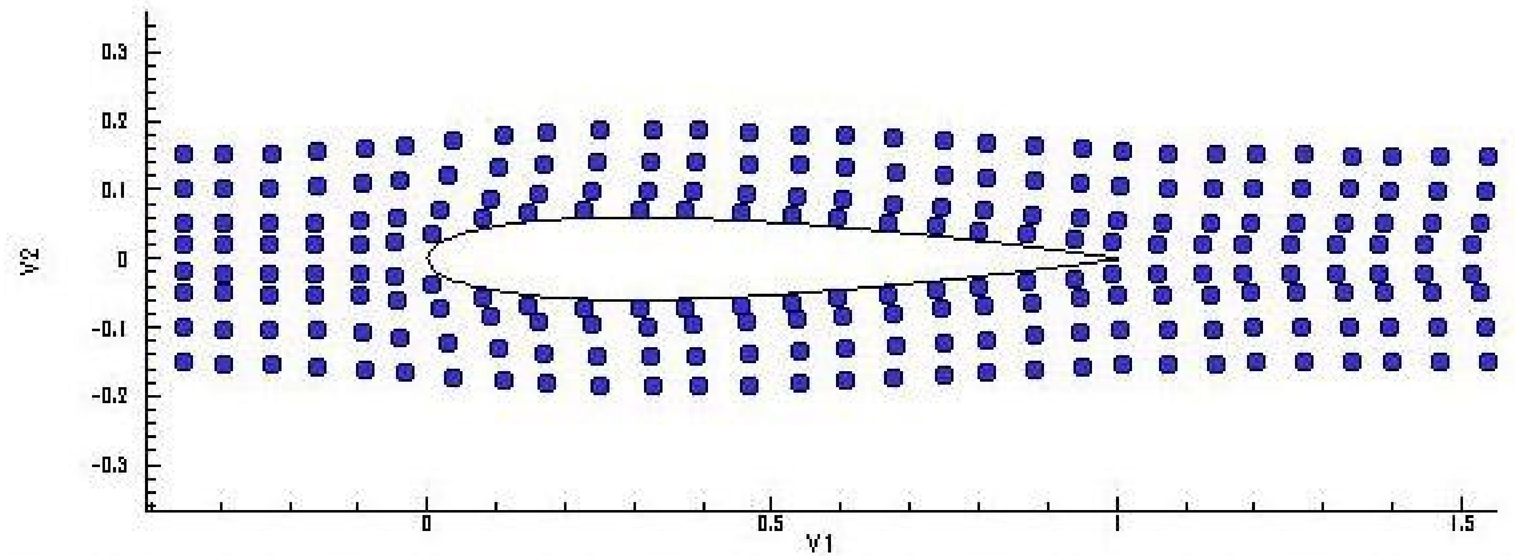
1. Boundary conditions for vortex methods
2. The Closest Point Transform
3. Collaborative Results
4. Plans for Future Work

Vortex Method Boundaries: The Inviscid Part

Mike Rubel
Caltech

1. Measure the cross-flow, [math], along the surface

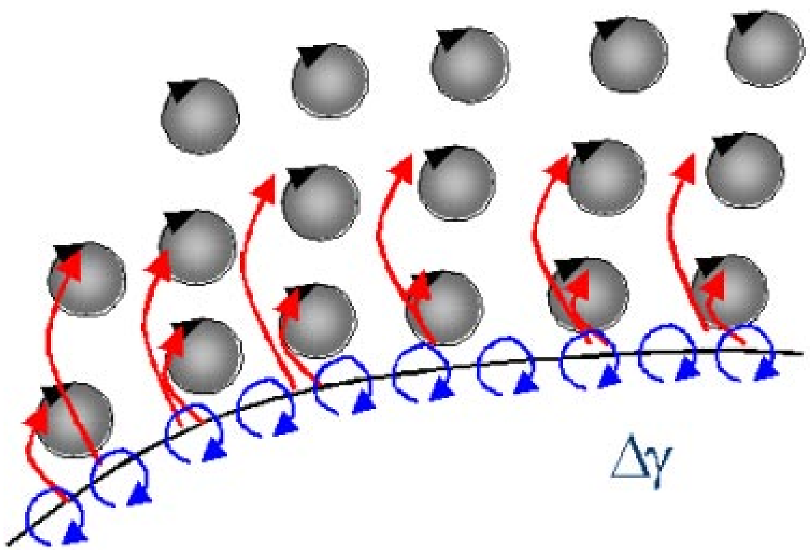
2. Compute a vortex sheet [math] to cancel it out



Vortex Method Boundaries: The Viscous Part

Mike Rubel
Caltech

In accordance with Lighthill s model, the vortex sheet created during a timestep can be diffused onto the neighboring particles.



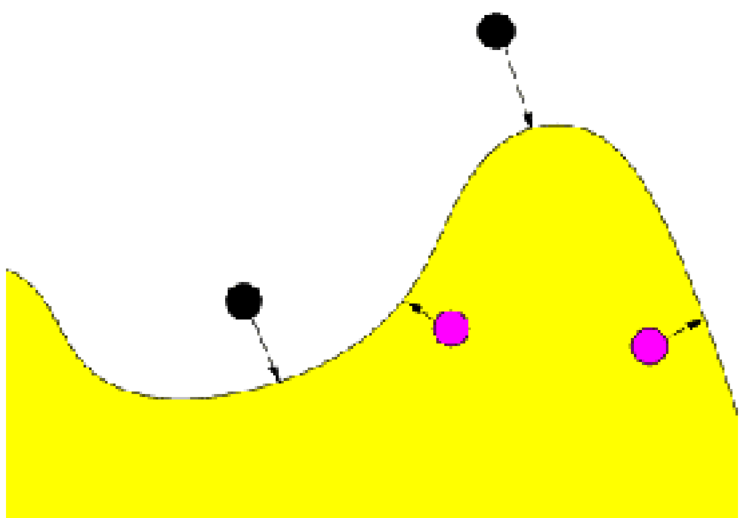
Aside: numerically, this is a noisy process. One of our other tasks is to improve it.

What Info Do We Need From Geometry?

Mike Rubel
Caltech

At each timestep, need to know the following:

- How far is each particle center from its closest point on the surface?
- What is the surface {normal | curvature | character} there?
- Is the particle inside or outside the body?
- Which particles are within a given distance of some surface?



The Closest-Point Transform

Mike Rubel
Caltech

Information needed is that given by the *closest point transform*. Several approaches exist in literature.

- Brute force (far too slow)
- Finite-difference methods (several issues)
- Triangle inequality method (still too slow, insufficient information)
- LUB tree methods (initially a possibility)
- Mauch s algorithm (characteristic planes, scan conversion, linear scalings; good but cannot apply directly)

Tried an improved LUB tree method and a modified Mauch s algorithm.

First strategy: LUB tree-based method

Mike Rubel
Caltech

Concept

Divide the body into facets; divide space hierarchially into cells. For any test point in a given cell, only a subset of the facets could possibly contain the closest point.

Algorithm

Beginning with the root cell, apply the following recursively:

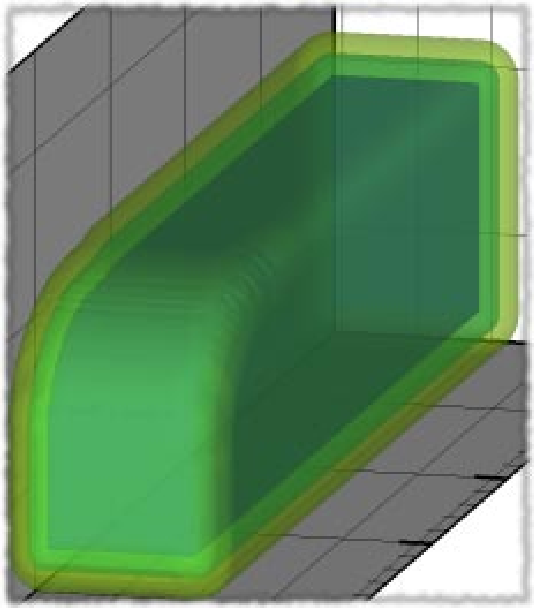
Compute lower and upper bounds on the minimum distance from any point inside that cell to each facet on the body. Take the least of the upper bound distances (LUB); keep only those facets whose lower bound distance is less than LUB. If more than some number of facets remain, split the cell.

In general, each facet will appear in several cells.

LUB Tree-Based Method: Results

Mike Rubel
Caltech

Several issues came to light:



- Algorithm works, and is fast
- Memory use does not scale acceptably
- Near centers of curvature, many facets per cell
- Possible switch to approximate solution

Second Strategy: Modified Mauch s CPT

Mike Rubel
Caltech

Concept

The set of all points closest to a given body facet, edge, or vertex is a convex region bounded by characteristic planes of the Eikonal equation [math] when u(0) is the body surface. Mauch uses scan conversion to find these test points inside each region. Our test points are not on a regular grid so that is not an option.

Algorithm

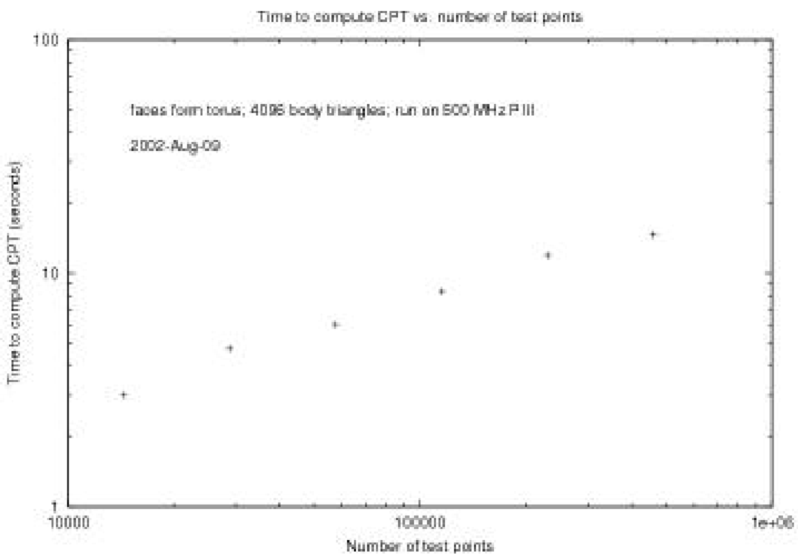
Build an oct tree of test points, then find the cells inside each region in turn by clipping the tree against the relevant characteristic planes.

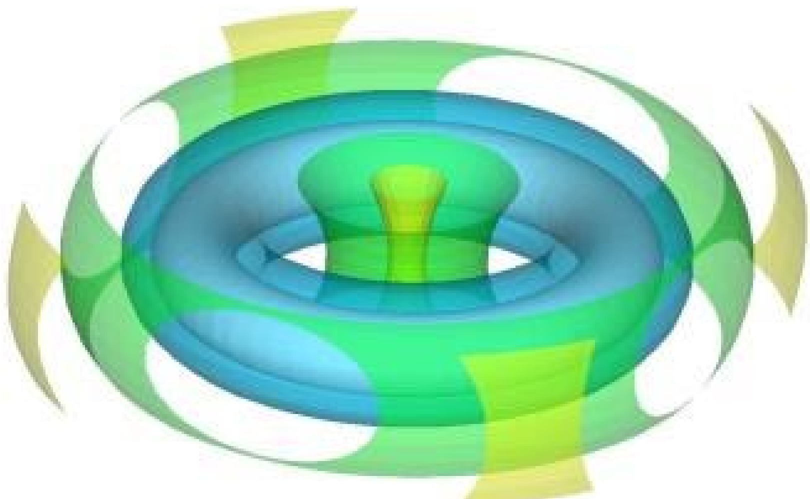
CPT Tree-Based Method: Results

Mike Rubel
Caltech

Implementation notes:

- Algorithm works, and is fast (scales linearly; 10^6 test points or body complexity no problem, even on laptop)
- Memory use small, linear





Torus isosurfaces by CPT

CPT Tree-Based Method: Issues

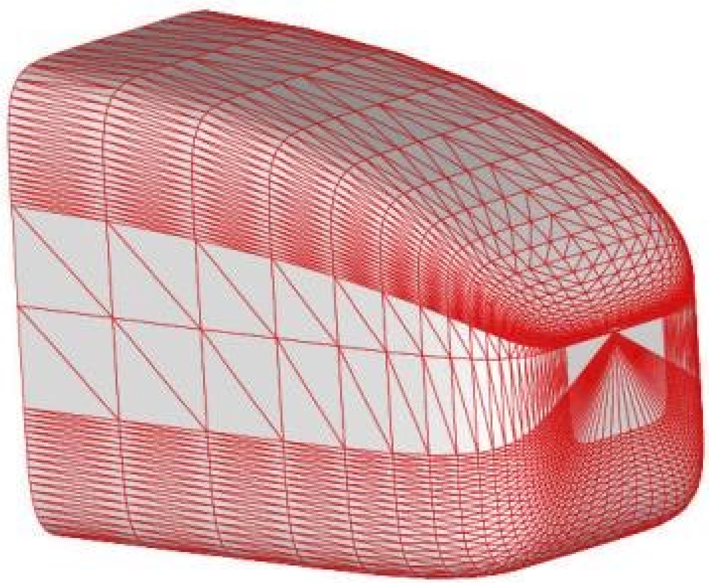
Mike Rubel
Caltech

- Algorithm wants all test points in tree, up front. Realized (at end) that vortex code wants CPT as implicit function of test points; need results from some test points to decide which other points to test.
- Modifying code to store possible closest objects in cell, similar to LUB approach but more time- and memory-efficient.
- Fix should be done/written soon.

Recent Collaboration

Mike Rubel
Caltech

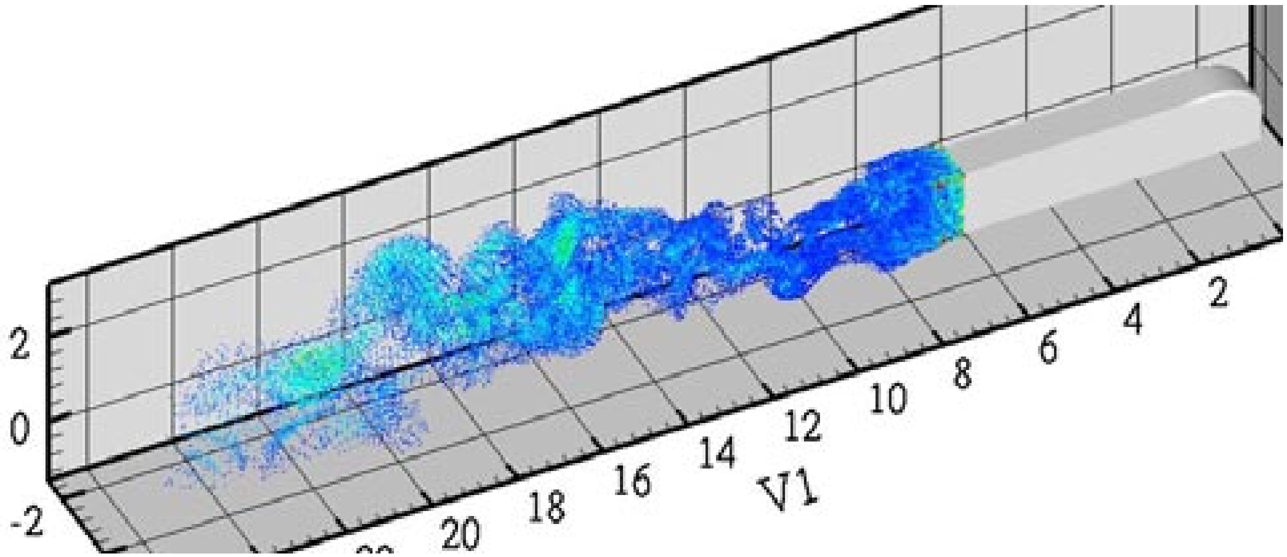
- Additional truck geometry from USC
- Go ric came to visit! Plugged in our geometry routines. More on this shortly.



GTS Geometry Wake Flow

Mike Rubel
Caltech

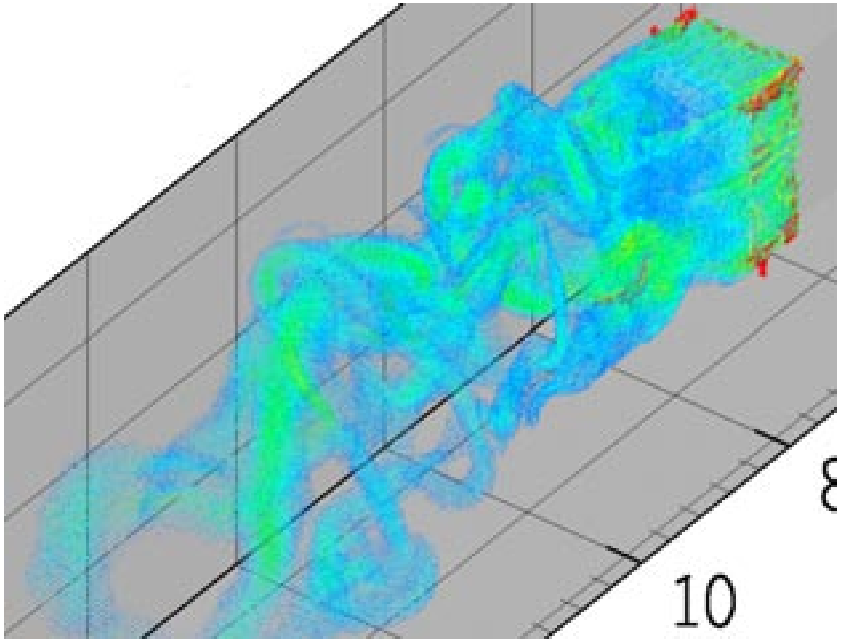
- Re=1000 based on truck width
- Inviscid panels up to about 90% length, then viscous diffusing panels



GTS Geometry Wake Flow: Detail

Mike Rubel
Caltech

- Same computation, earlier time
- Wake looks physical
- Can see corner vortices coalescing



Mike Rubel
Caltech

Future Work

- Joint UEF paper with Winckelmans group
- Try GSM geometry (if available)
- Numerical experiments: gap flow
- Back to timestepper work: APS talk
- Write-up on new geometry tools
- Continued work on boundary elements, LES

The End

Mike Rubel
Caltech

Assessments of Commercial Tools

Dave Pointer, Tanju Sofu, and Dave Weber

Reactor Analysis and Engineering

Argonne National Laboratory

Heavy Vehicle Aerodynamic Drag Working Group Meeting
NASA Ames Research Center
September 23, 2002

Current Heavy Vehicle Projects

- **Caterpillar CRADA**
  - Validation and benchmarking of computational predictions of external heat rejection
    - *Currently evaluating external heat rejection using Star-CD*
      - Using boundary conditions specified from experimental data provided by caterpillar
      - Blind validation comparing bulk exit temperature
    - *Future evaluations*
      - Couple Star-CD and internal coolant loop code FlowMaster
      - Predict engine component temperatures based on ambient conditions
      - Blind validation using experimental surface temperature data provided by Caterpillar

Current Heavy Vehicle Projects

PACCAR CRADA

- Cooperative agreement with PACCAR Technical Center has been signed (September 2002)
- Detailed geometry data will be provided to ANL in early October 2002
- First Phase (funded FY02)
  - *Initial evaluations will be completed using two commercial codes*
    - Star-CD
      - Using standard k-epsilon models and logaritmic "law of the wall" approximations
    - PowerFLOW
      - Lattice Boltzmann approach with single turbulence model option for sub-grid turbulence modeling.
- Blind validation using wind tunnel data provided by PACCAR Technical Center

Current Heavy Vehicle Projects

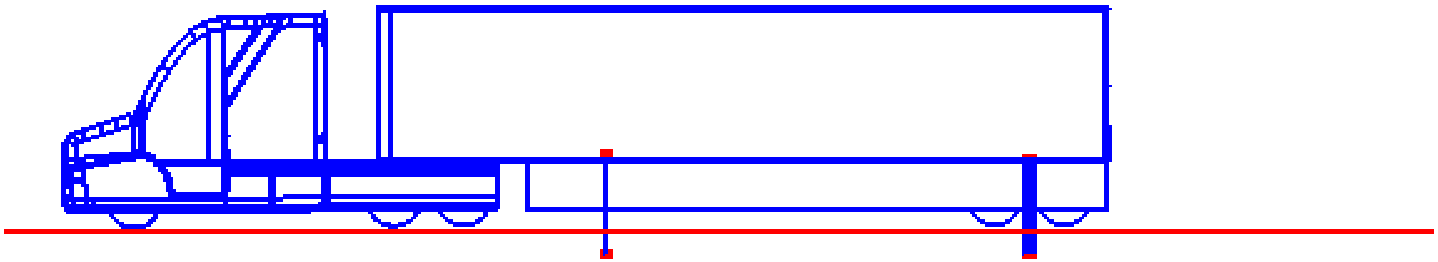
- **PACCAR CRADA (Cont.)**
  - Second Phase (proposed for FY03)
    - *Evaluation of Improvements obtained through employment of more advanced turbulence modeling strategies in Star-CD*
      - V2F
      - Two-Layer RANS models
        - Low Re k-epsilon model near wall
        - High Re k-epsilon model in bulk flow
      - Other combinations with near wall low-Re k-epsilon models ?
      - Segmented solutions using multiple model types ?

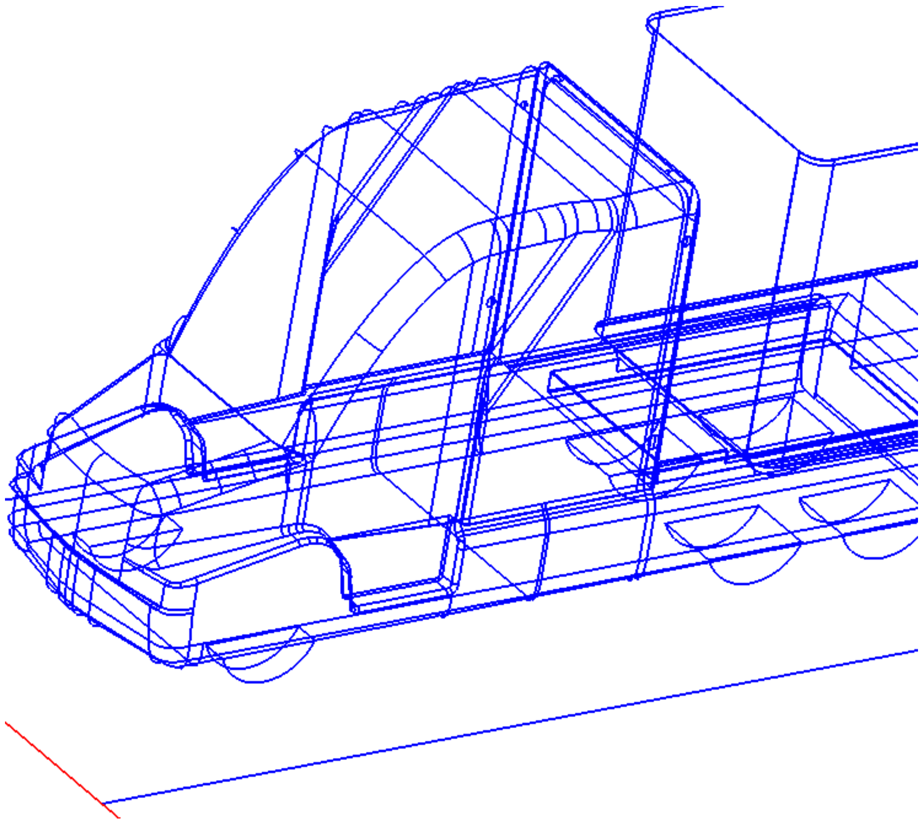
Proposed Heavy Vehicle Projects

Pioneering Science and Technology

- **Simulation of GCM experiments**
  - Evaluation of commercial software capabilities for prediction of drag coefficients measured in GCM experiments (7' x 10')
    - *Star-CD*
      - Standard high-Re k-epsilon models and logarithmic "law of the wall"
    - *PowerFLOW*
      - Standard turbulent Lattice Boltzmann features
  - Provides several opportunities
    - *Initial evaluation of requirements for heavy vehicle external aerodrag simulations before investing in CPU-intensive studies using real PACCAR geometries*
    - *Incorporate experience of working group into ANL evaluations using a commercial code*
    - *Simulation data can be shared with software vendors*
      - Enhanced training
      - Assistance with debugging / problem setup

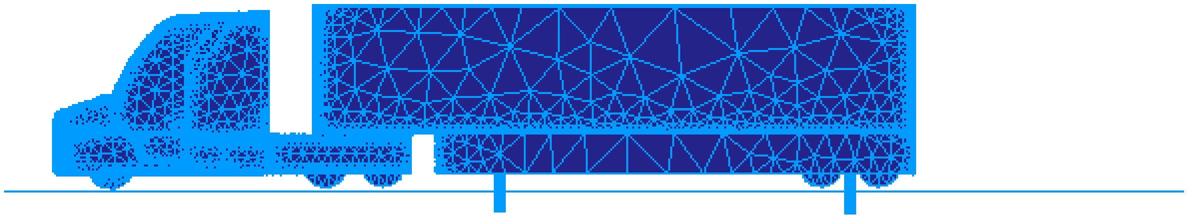
IGES Files provided by NASA

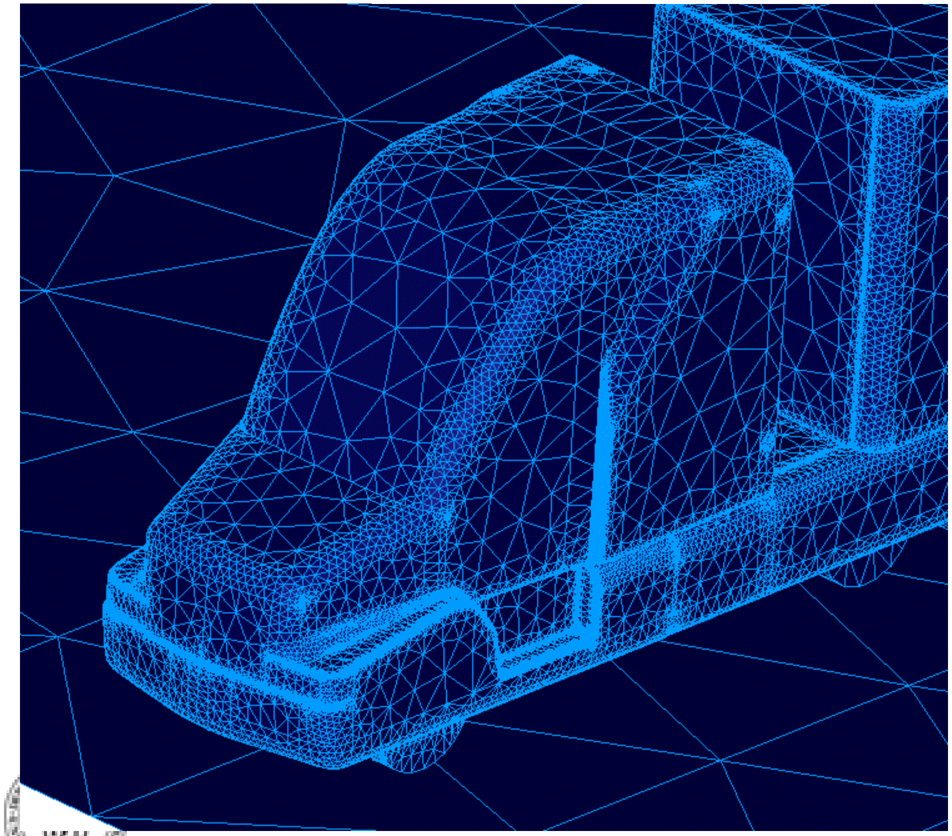


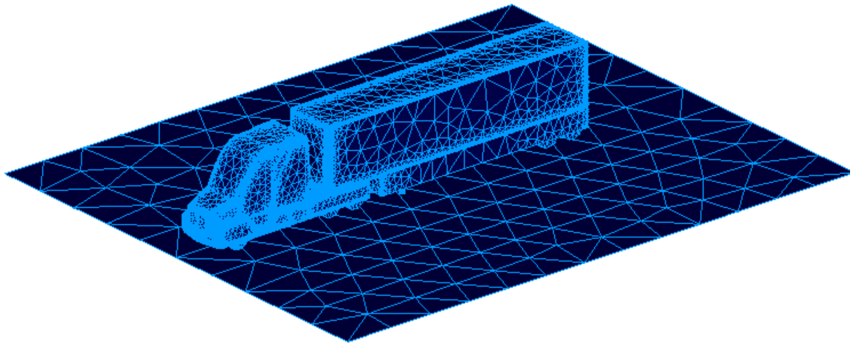


Triangulated surface mesh

Pioneering Science and Technology

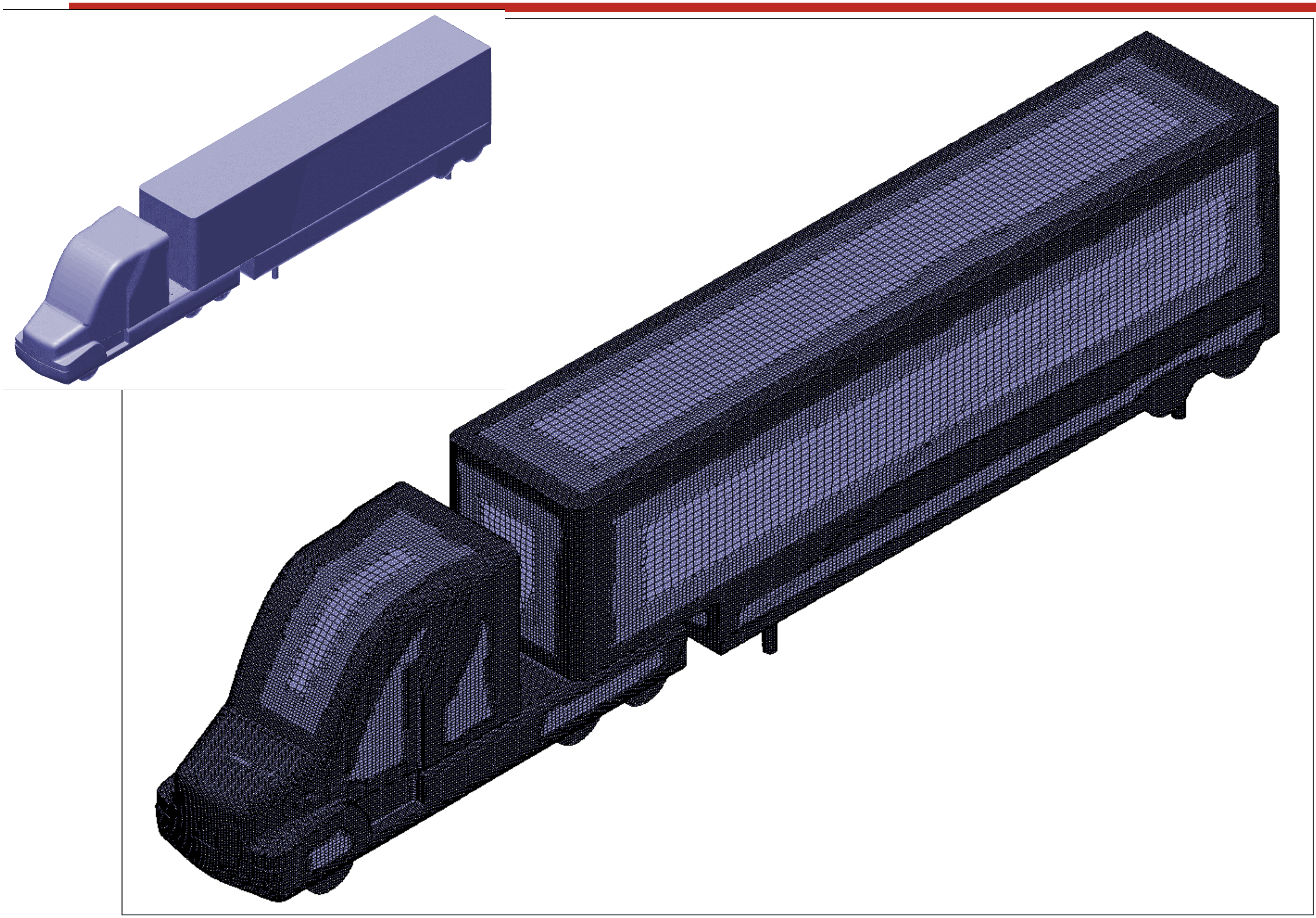






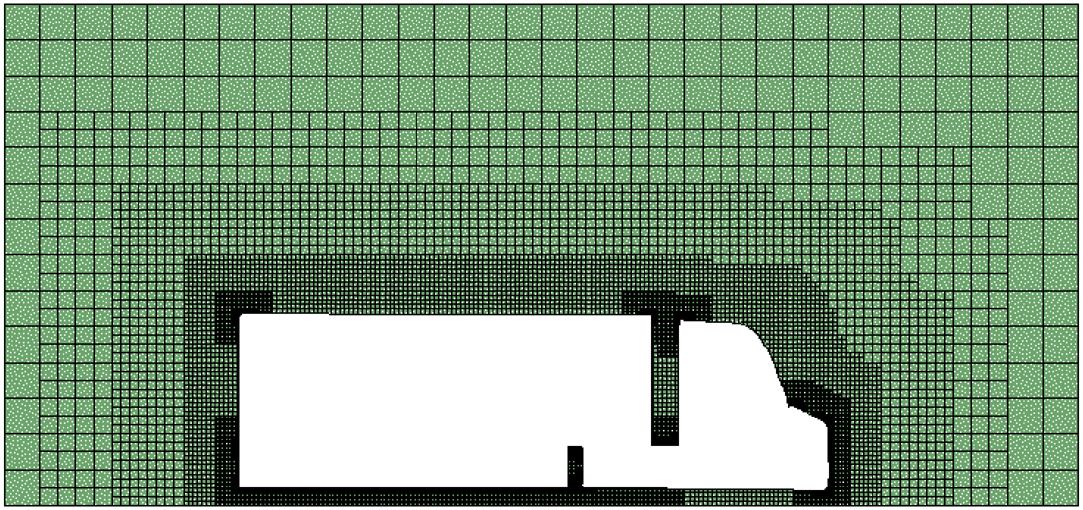
Star-CD hexahedral surface mesh

Pioneering Science and Technology



Initial Star-CD Fluid Mesh

- **Initial mesh output from automatic meshing utility**
  - Cut hexahedral mesh (portion shown from default wind tunnel size – ~18' x ~20')
  - Compressed by factor of 1.5 in main flow direction
  - Final pre-processing step will
    - *Expand mesh to full size*
    - *Extrude brick cell surface mesh from inner surface of opening in cut mesh*
    - *Provide any refinements to wake/near wall regions as specified*



Generic Conventional Model (GCM) Truck Test in 12-Ft.

Dale Satran
dsatran@mail.arc.nasa.gov
650-604-5879

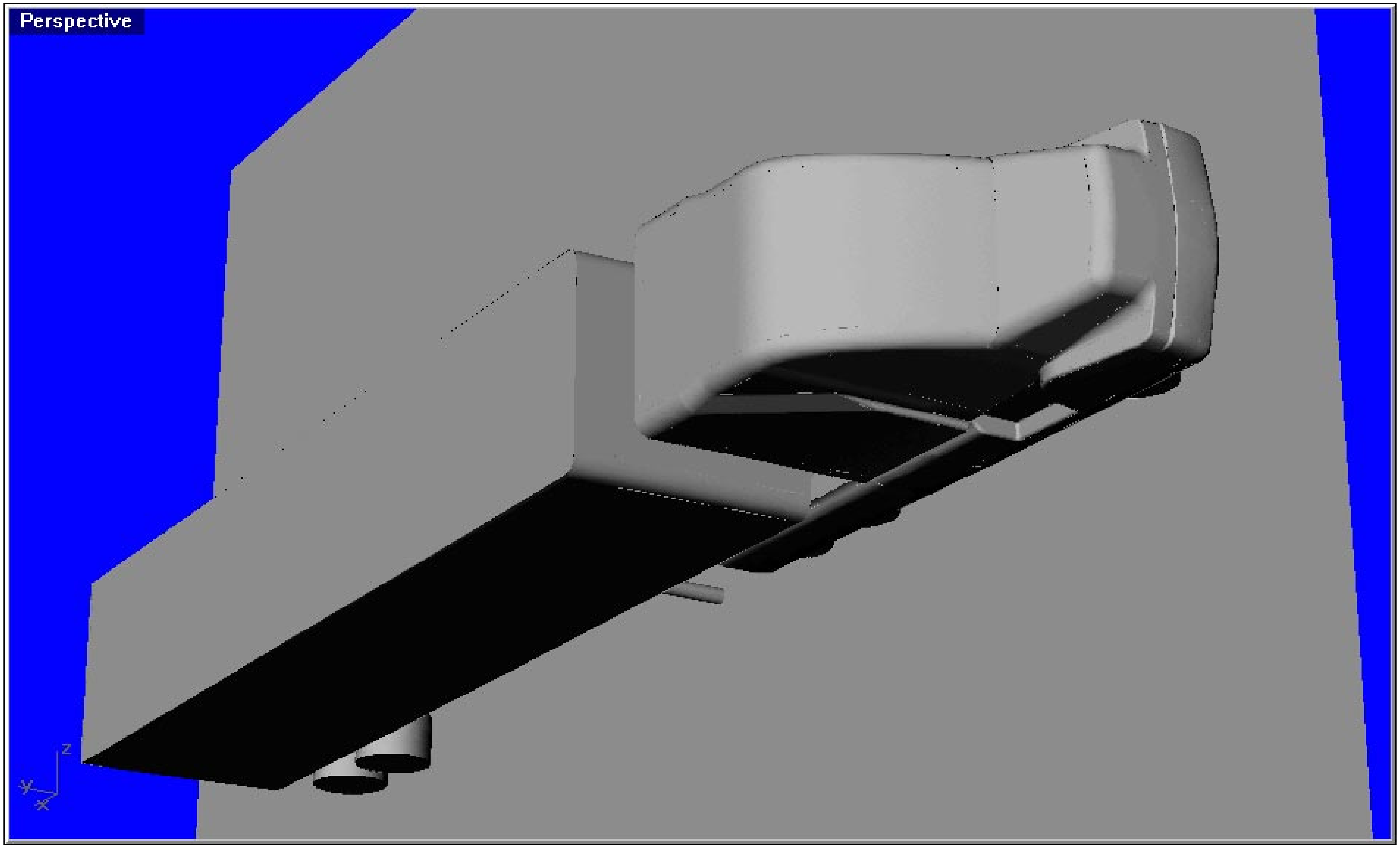
Deliverables

- **Digitized model geometry**
- **CFD validation data**
- **Reynolds Number effects**
- **Drag reduction**
- **PIV data**
- **Final reports**

Actions

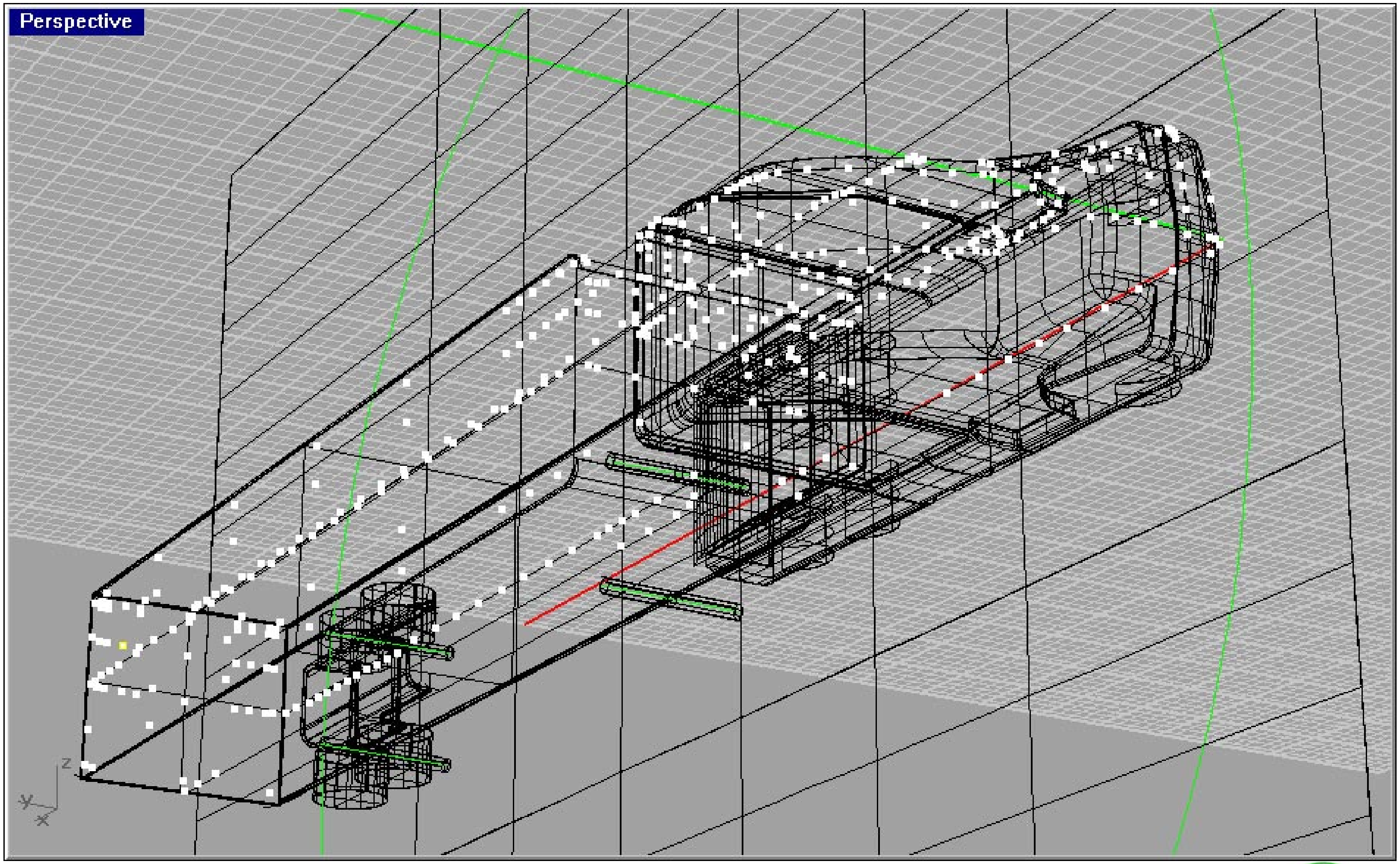
- Digitize model - complete
- Analyze 7 x 10 results - on going/recompute in progress
- Modify model based on 7 x 10 results - on going
- Modify model for mounting in 12-Ft. - on going
- Restore instrumentation - late Oct.
- Conduct test - early Nov.
- Analyze results - Jan.
- Prepare final report - Mar.

Digitized Geometry



Ames Research Center
Experimental Physics Branch

Digitized Geometry



Ames Research Center
Experimental Physics Branch

Test Matrix

- Basic model
- Basic model plus side extenders
- Basic model plus boat tail
- Basic model plus Mozart
- Basic model plus side extenders and boat tail
- Lowboy model
- Lowboy model plus side extenders
- Gap variation with/without side extenders
- Basic model no gap
- GTS configuration
- Wheel effects
- Trailer alone

Test Conditions

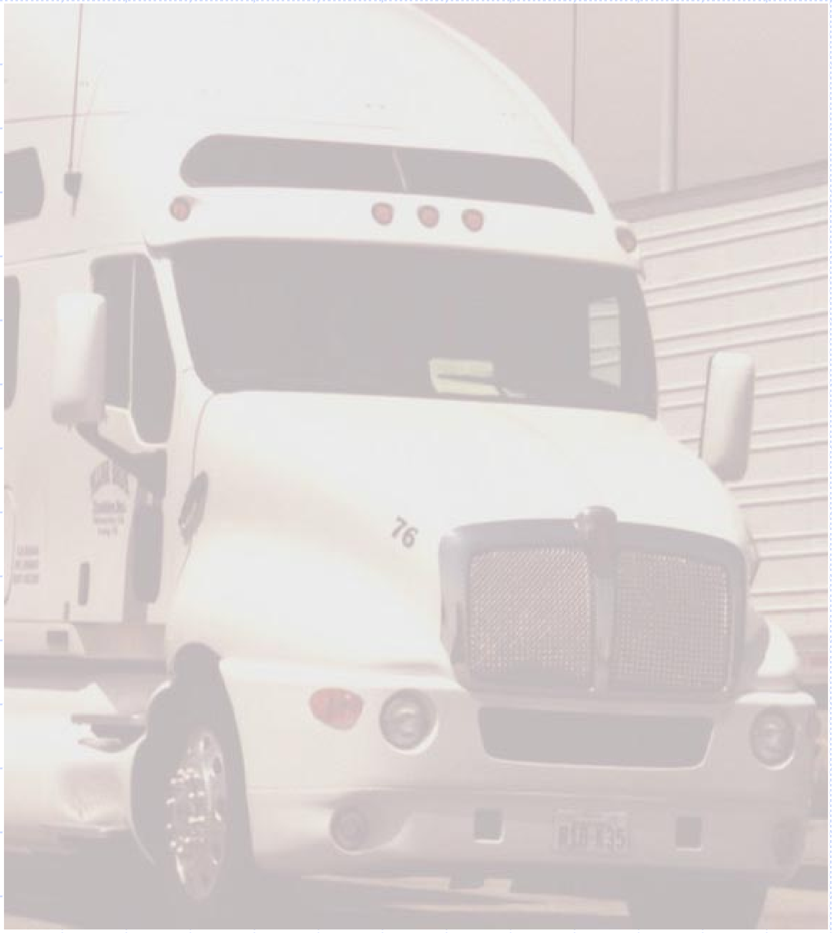
- **Primary Mach Number: .15**
- **7x10 comparison: .1 to .27 at 1 atmosphere**
- **Reynolds Numbers at M= .15 from 550,000 to 6,500,000 based on trailer width**
- **Yaw angles from 15° to -15°**

USC Presentation for DOE Office of Transportation Technology Office of Heavy Vehicle Technology

M. Hammache, staff
T.Y. Hsu, staff
D. Arcas, PhD student
R. Blackwelder, staff
F. Browand, staff
P. Lissaman, staff

USC UNIVERSITY OF SOUTHERN CALIFORNIA

Ground Vehicle Aerodynamics Laboratory



Base Geometry Modifications and Acoustic Forcing to Reduce Drag

Tsun-Ya Hsu, Mustapha Hammache

State-of-the-Art in Forcing (II)

Nishri & Wygnanski,
"Effects of Periodic Excitation on Turbulent Flow Separation from a Flap"

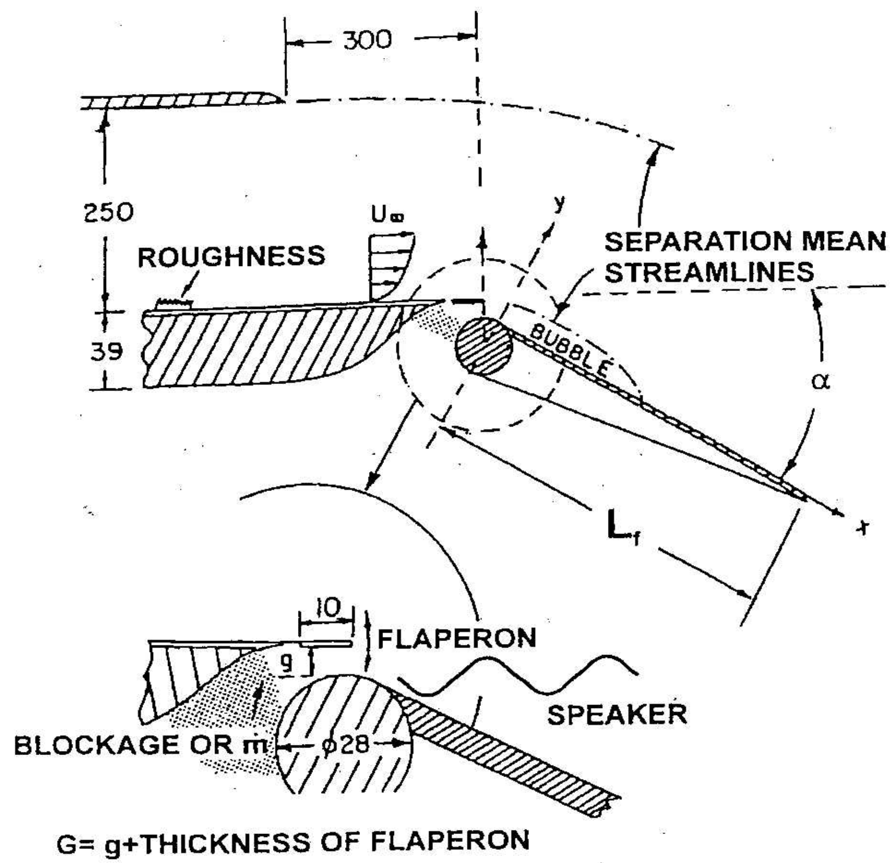


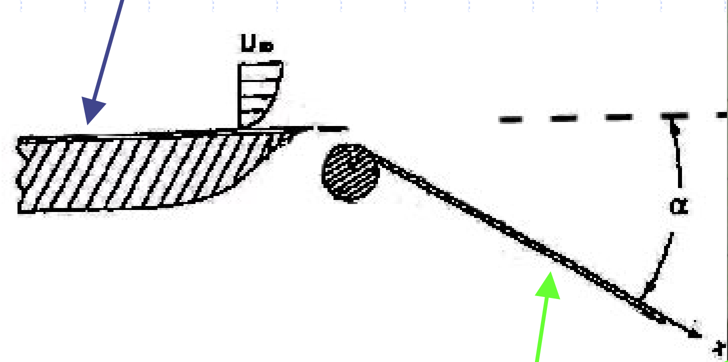
Fig. 1 Sketch of the flap and the region around the flap shoulder.

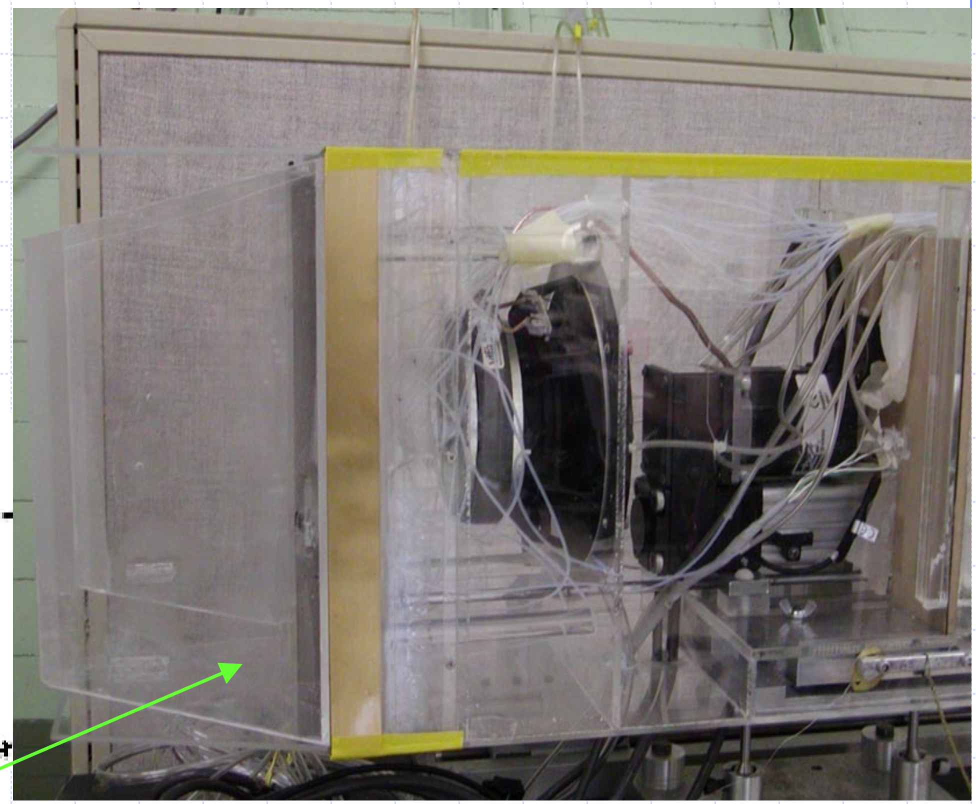
Contents

Base Geometry Modifications and Acoustic Forcing to Reduce Drag

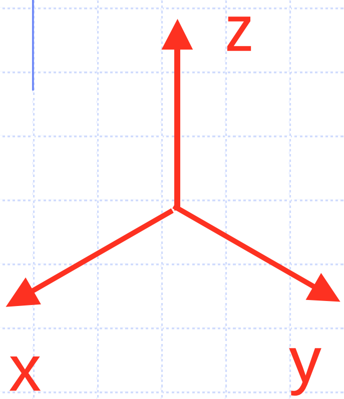
Tsun-Ya Hsu, Mustapha Hammache

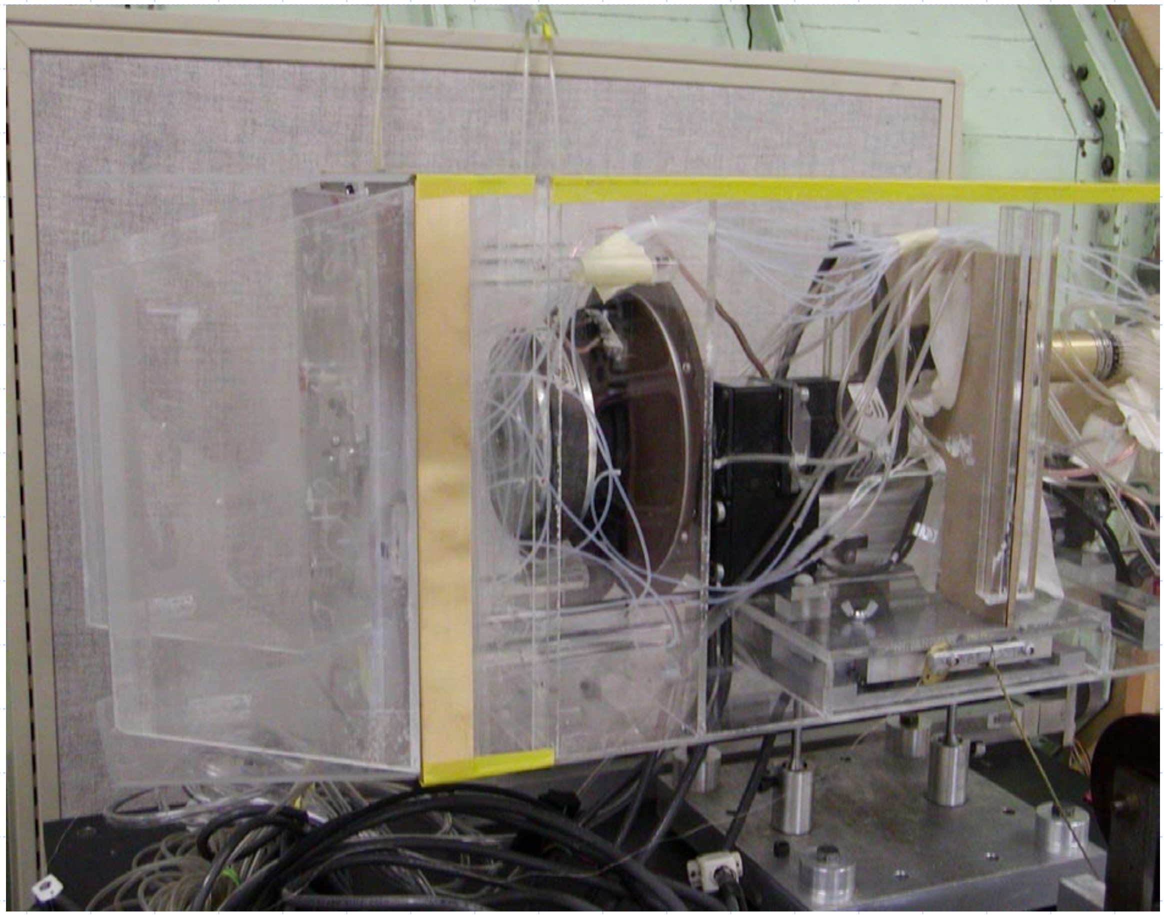
Forcing Design at USC





Experimental Apparatus





Experimental Details

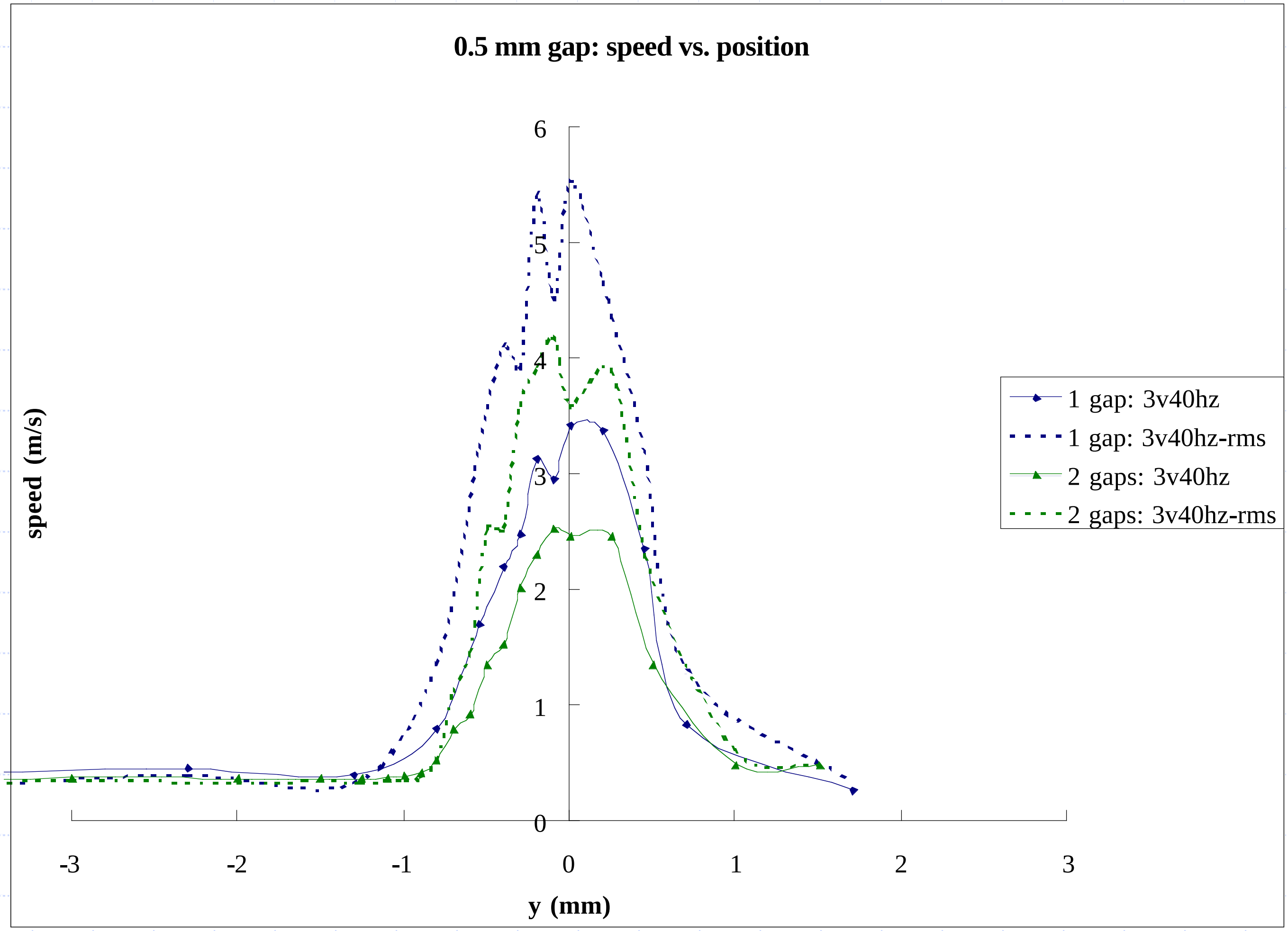
- Free Stream Velocity, U = 16 m/s
- $A = 0.0535\ m^2$
- $Re_{sqrt(A)} = 3 \times 10^5$
- Flap lengths: 5.08 cm
- Sine & square wave with frequency, f = 0 to 300 Hz
- Two-side forcing at $F^+ = 0.5$ to 0.65
- Gap width for the slot, g = 0.5-2 mm

Experimental Results

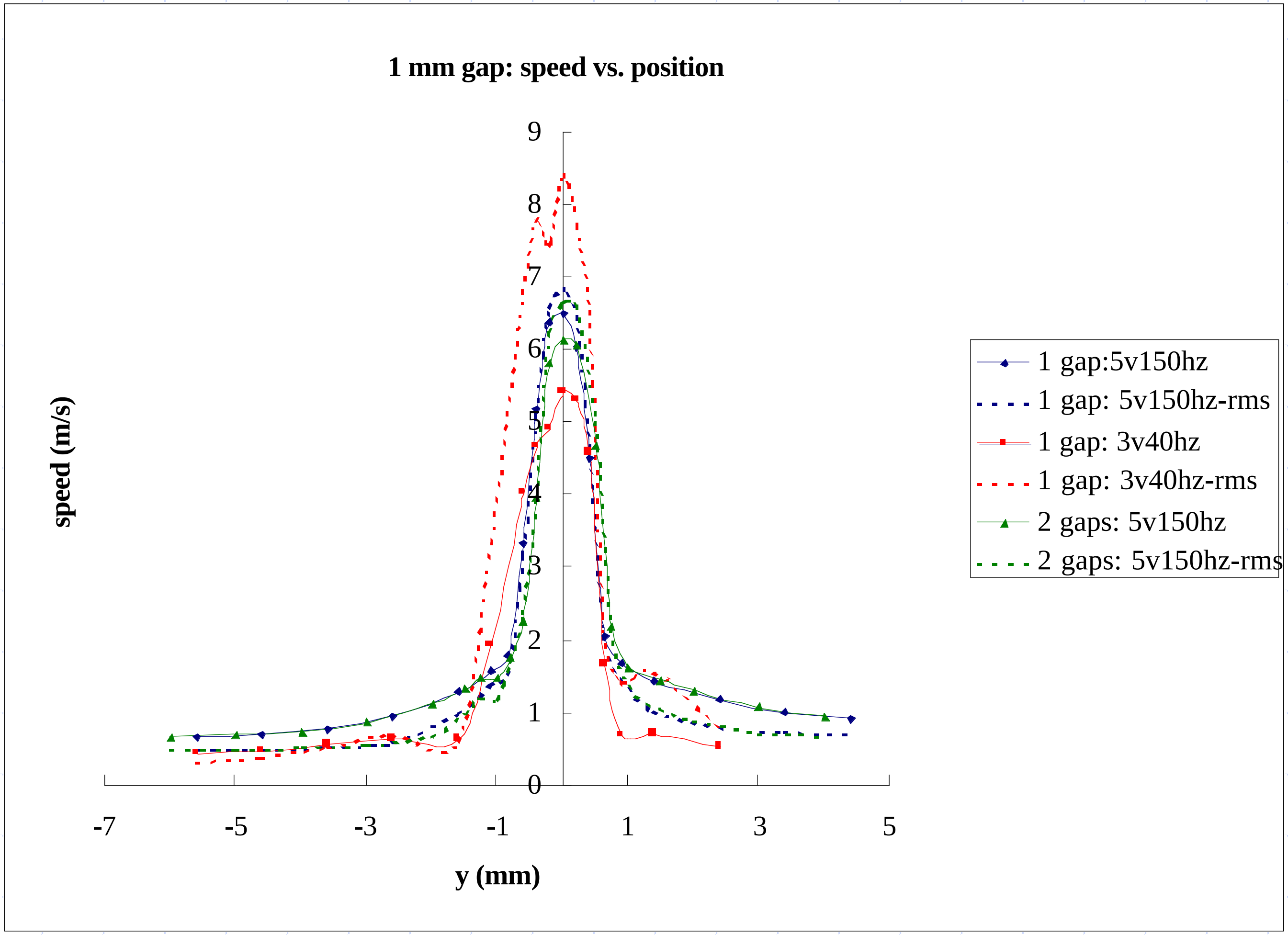
- Hot film measurements for the oscillatory jet
- Drag measurements
- Base pressure measurements
- Hot film measurements at the wake of the flaps
  - 1.5 L_f and 3 L_f

Hot film measurements for the oscillatory jet

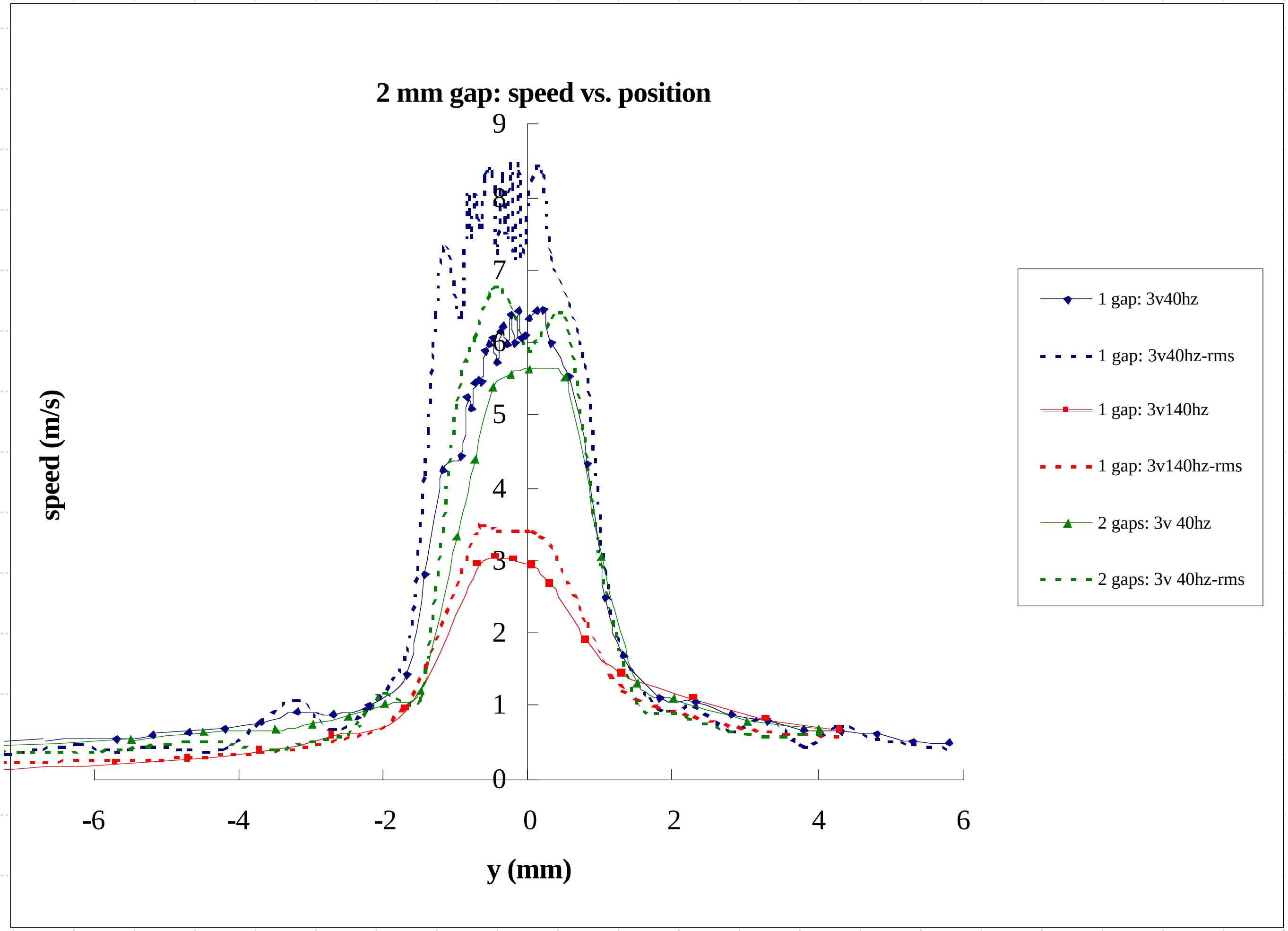
Velocity profile for the 0.5 mm wide gap w/ sine forcing function input



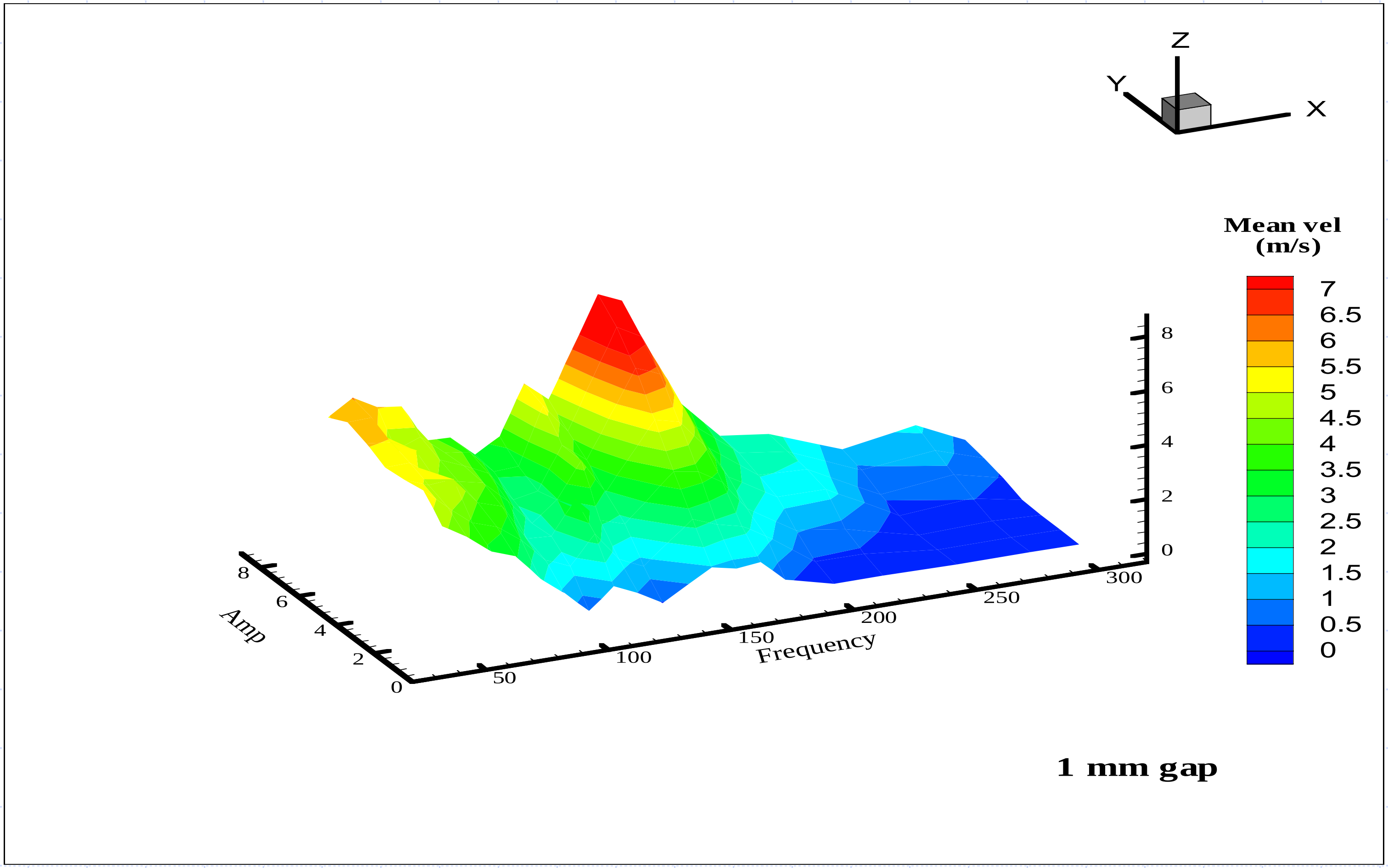
Velocity profile for the 1 mm wide gap w/ sine forcing function input



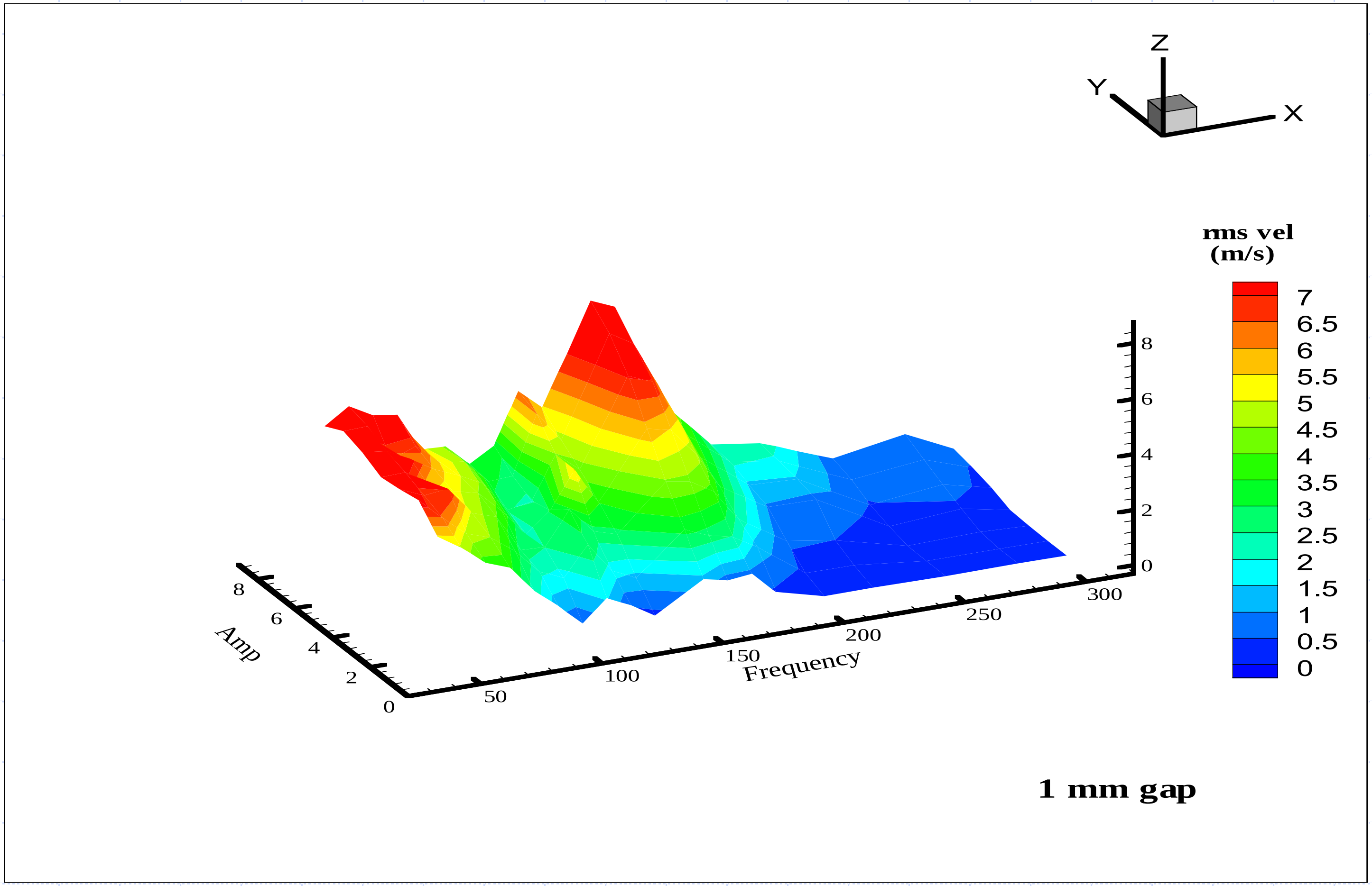
Velocity profile for the 2 mm wide gap w/ sine forcing function input



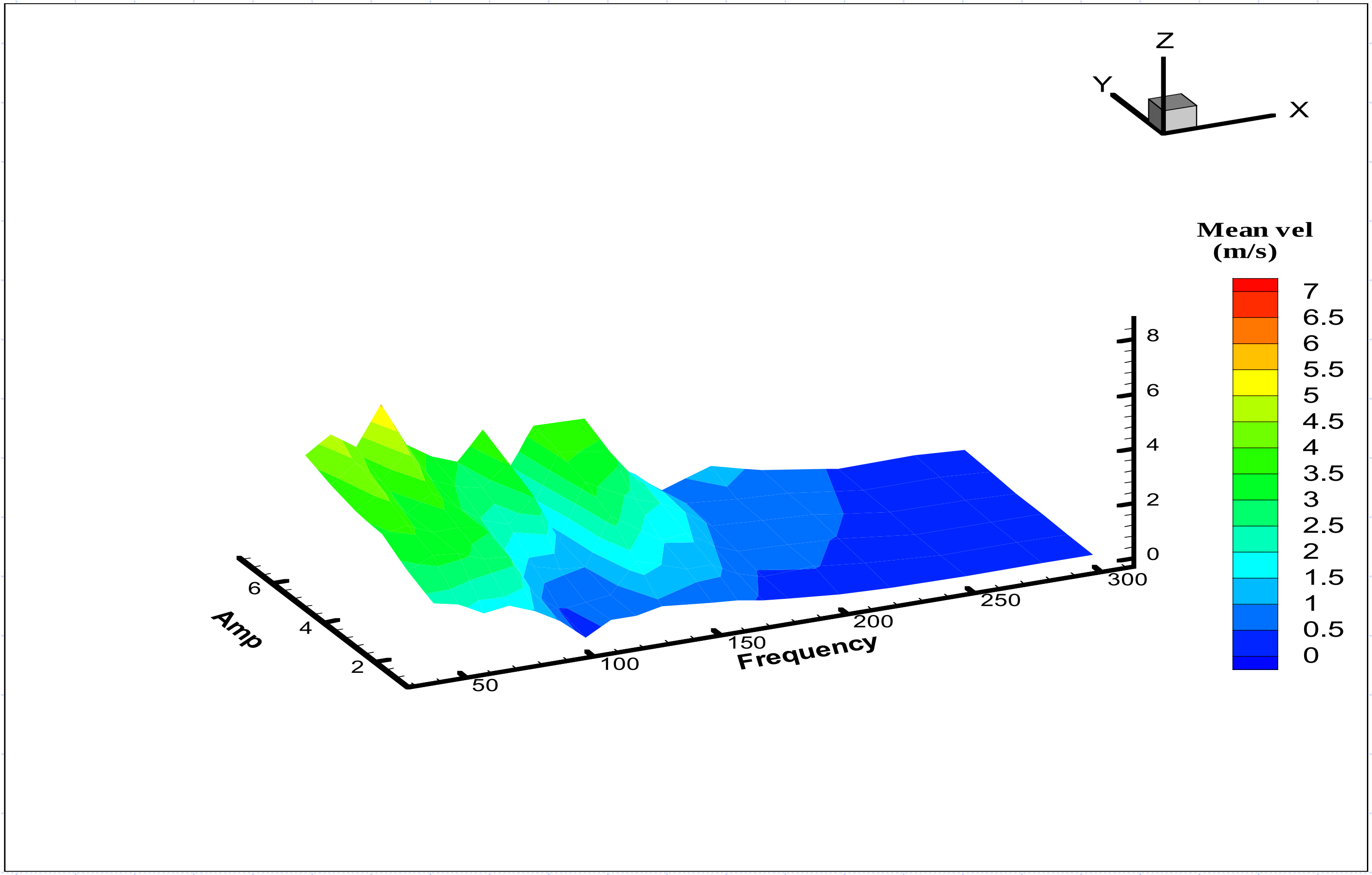
Strength of the oscillatory jet for 1 mm gap w/ sine forcing function input (a)



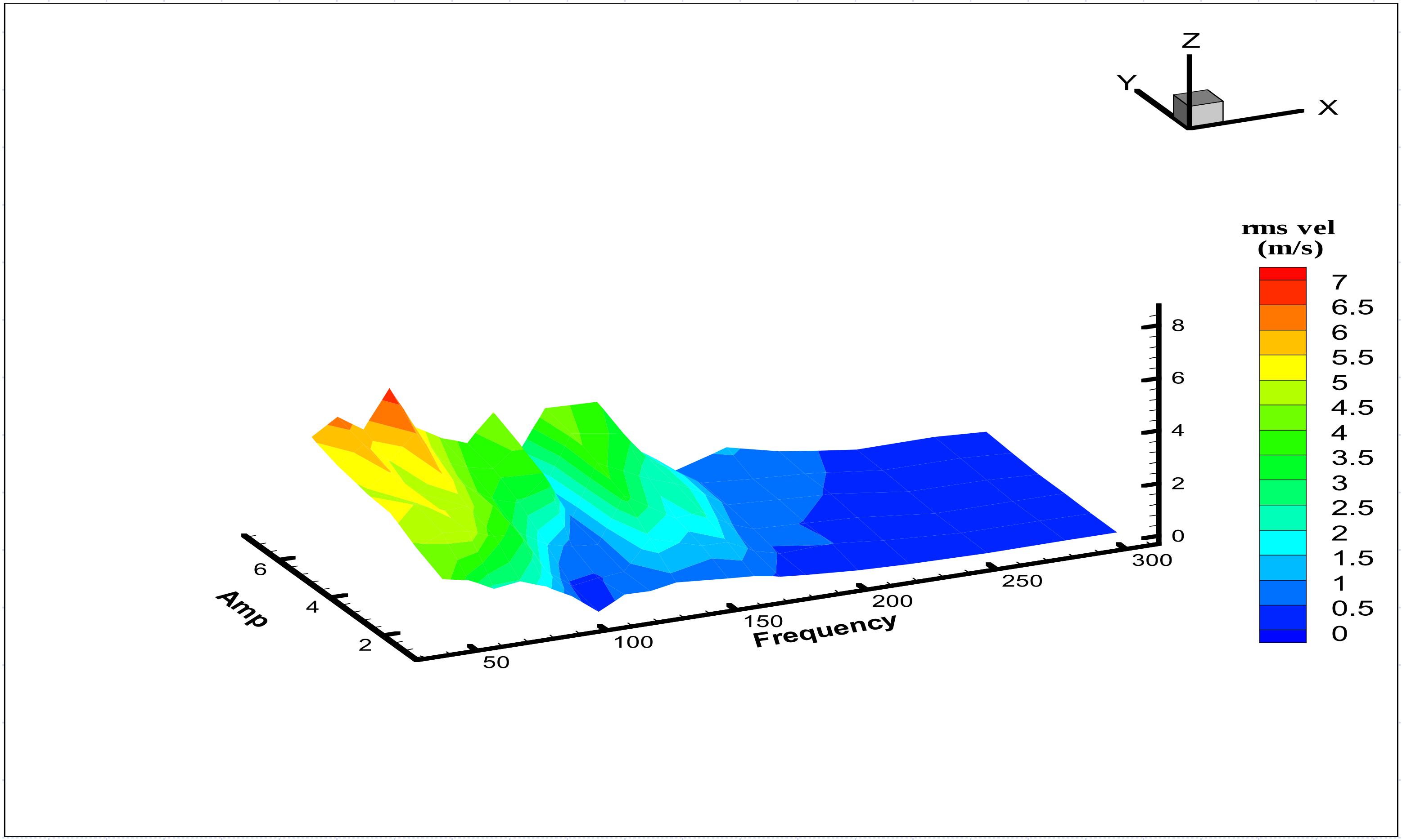
Strength of the oscillatory jet for 1 mm gap w/ sine forcing function input (b)



Strength of the oscillatory jet for 1 mm gap w/ square forcing function input (a)

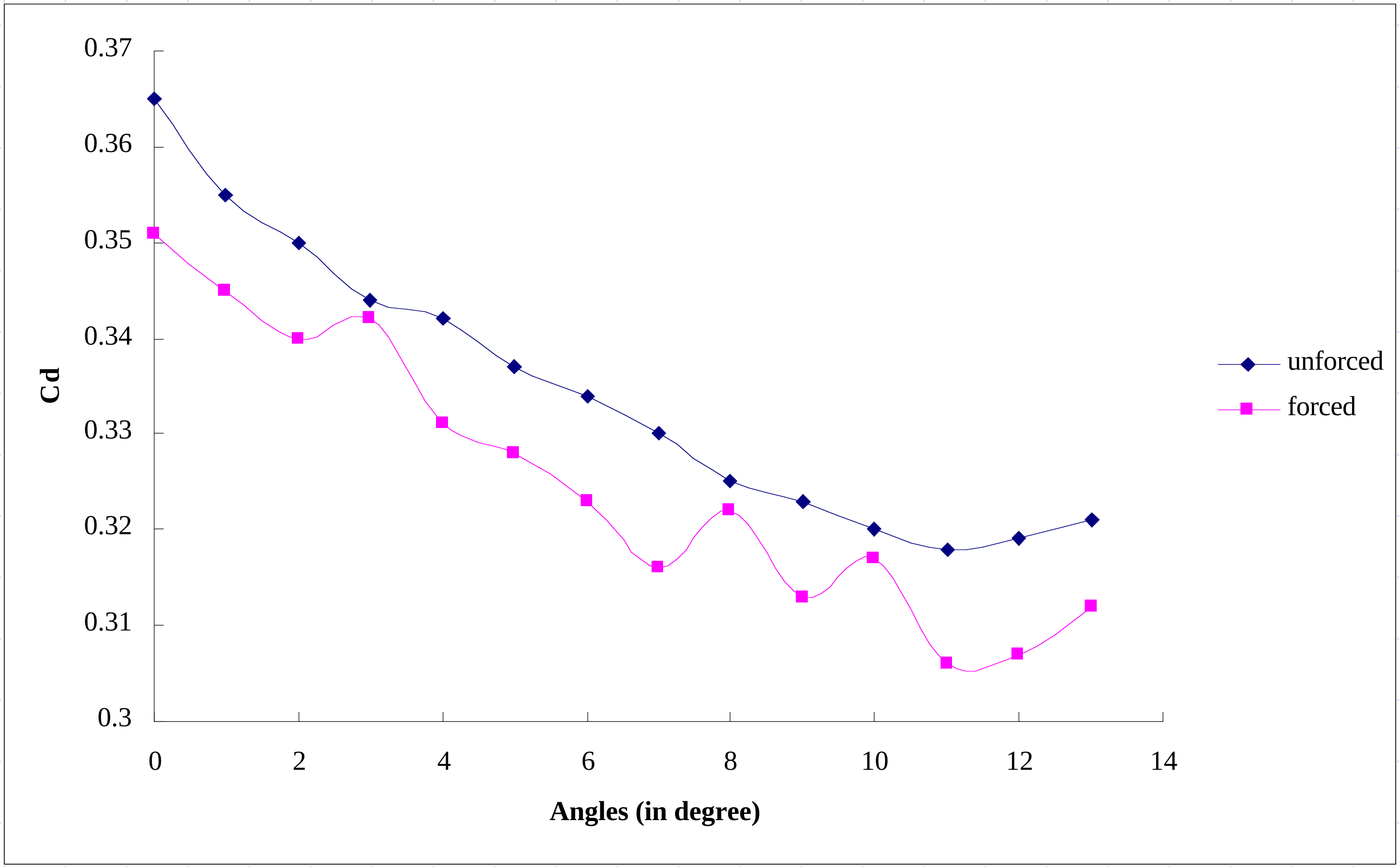


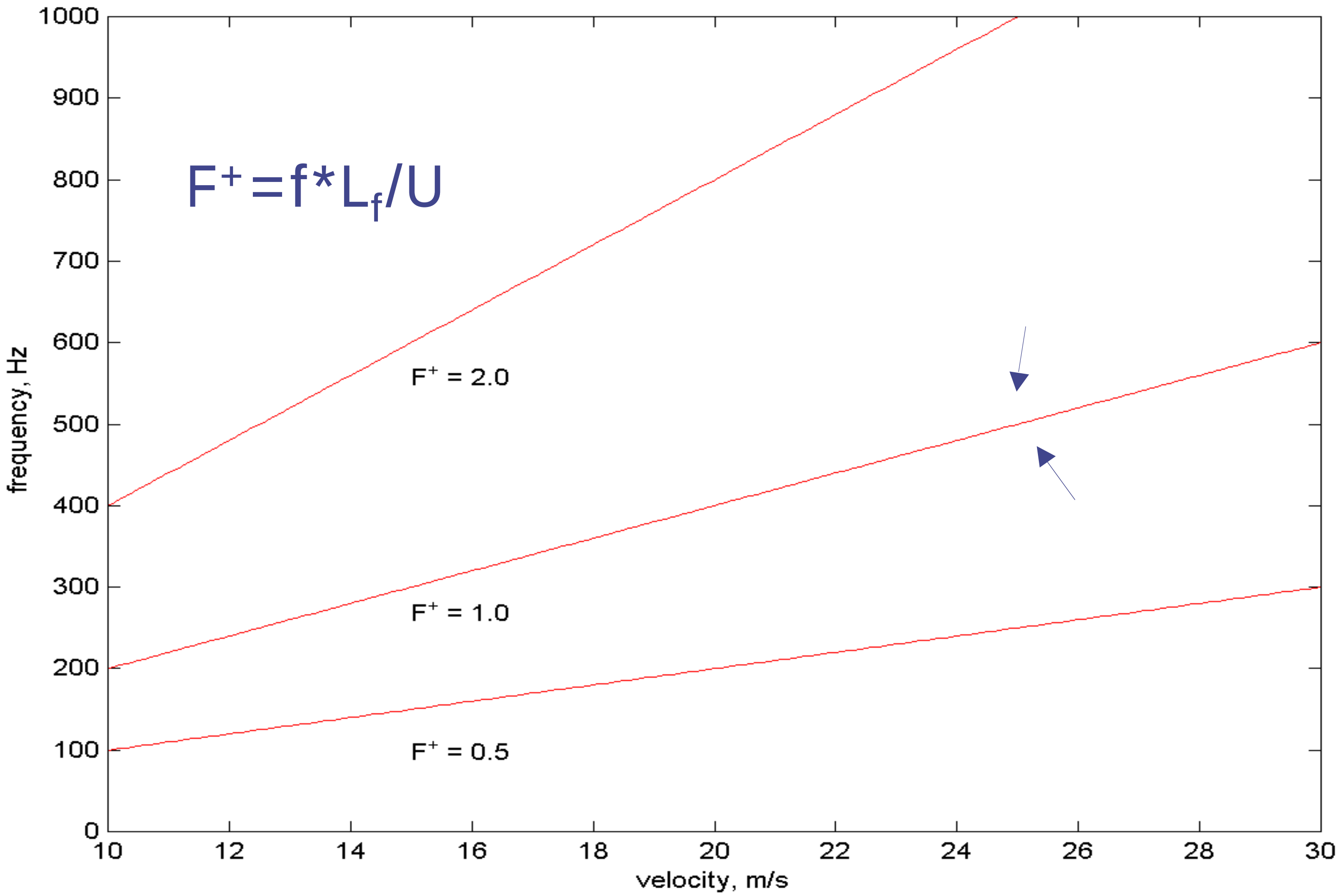
Strength of the oscillatory jet for 1 mm gap w/ square forcing function input (b)



Drag measurements

C_d vs. flap angles

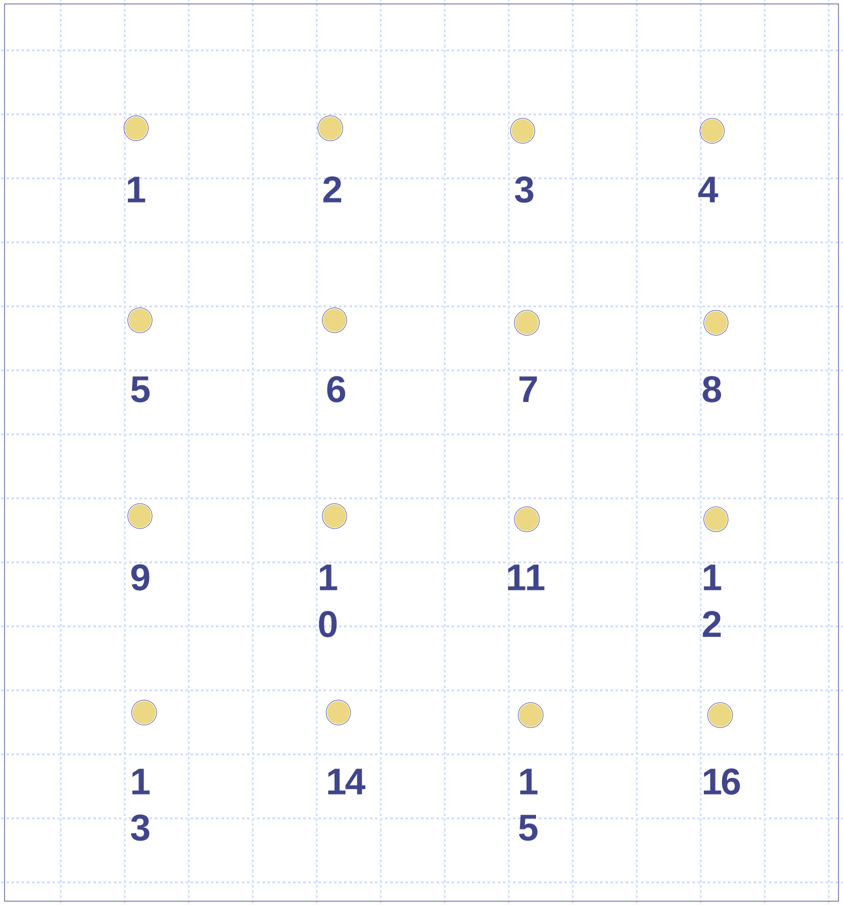




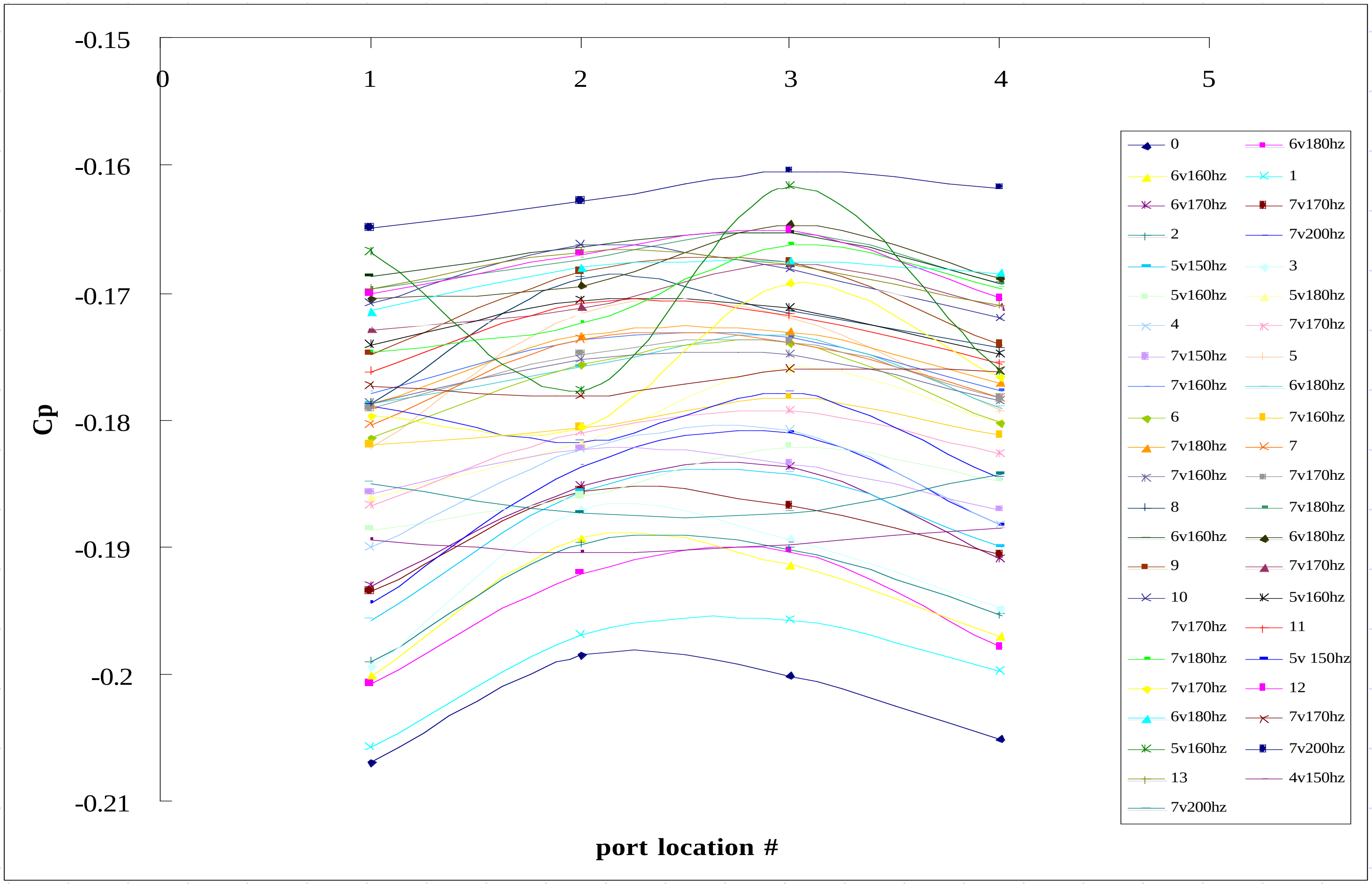
$F^+ = f*L_f/U$
$F^+ = 2.0$
$F^+ = 1.0$
$F^+ = 0.5$
frequency, Hz
velocity, m/s
0
100
200
300
400
500
600
700
800
900
1000
10
12
14
16
18
20
22
24
26
28
30

Base pressure measurements

Pressure port locations at the model base

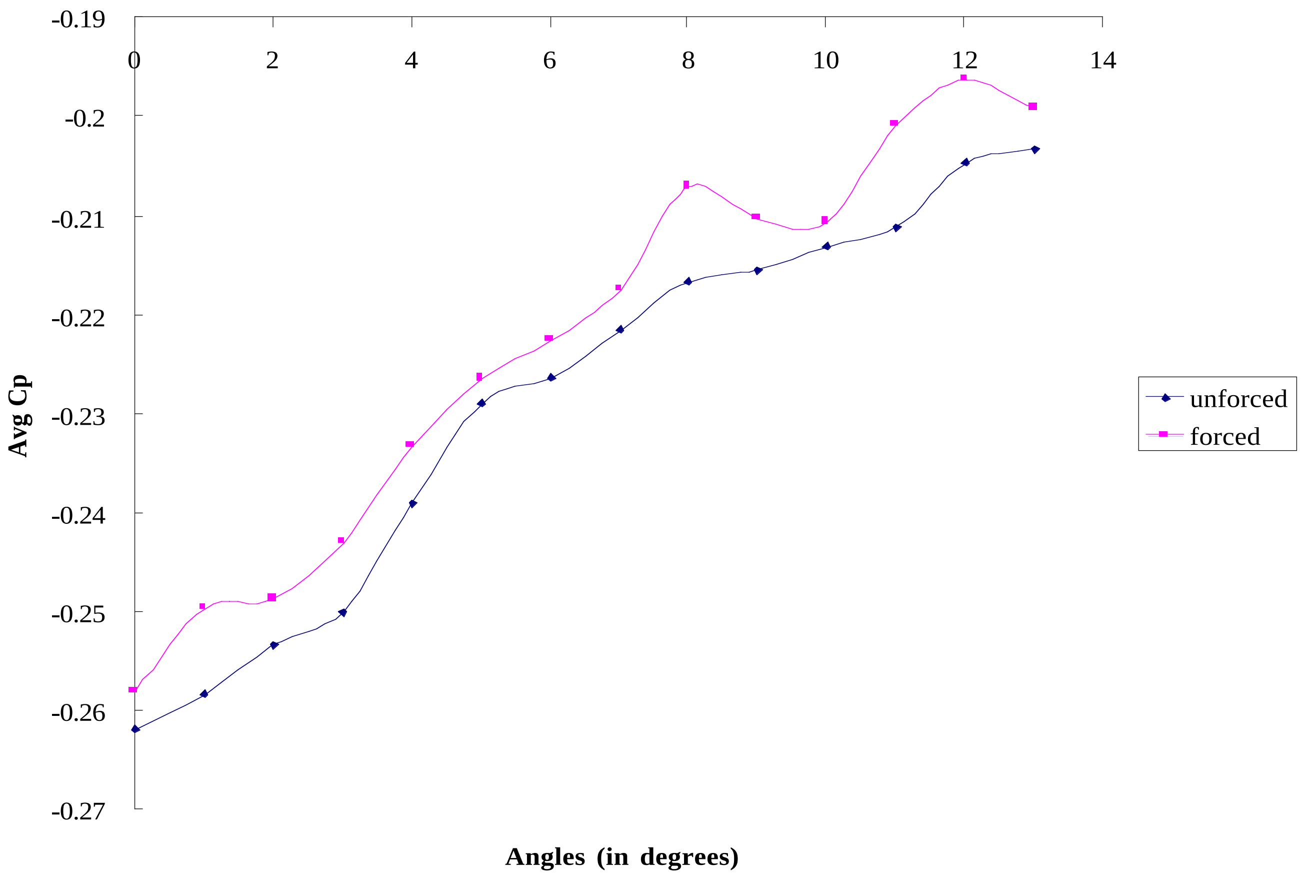


Cp at the model base for port #1-4

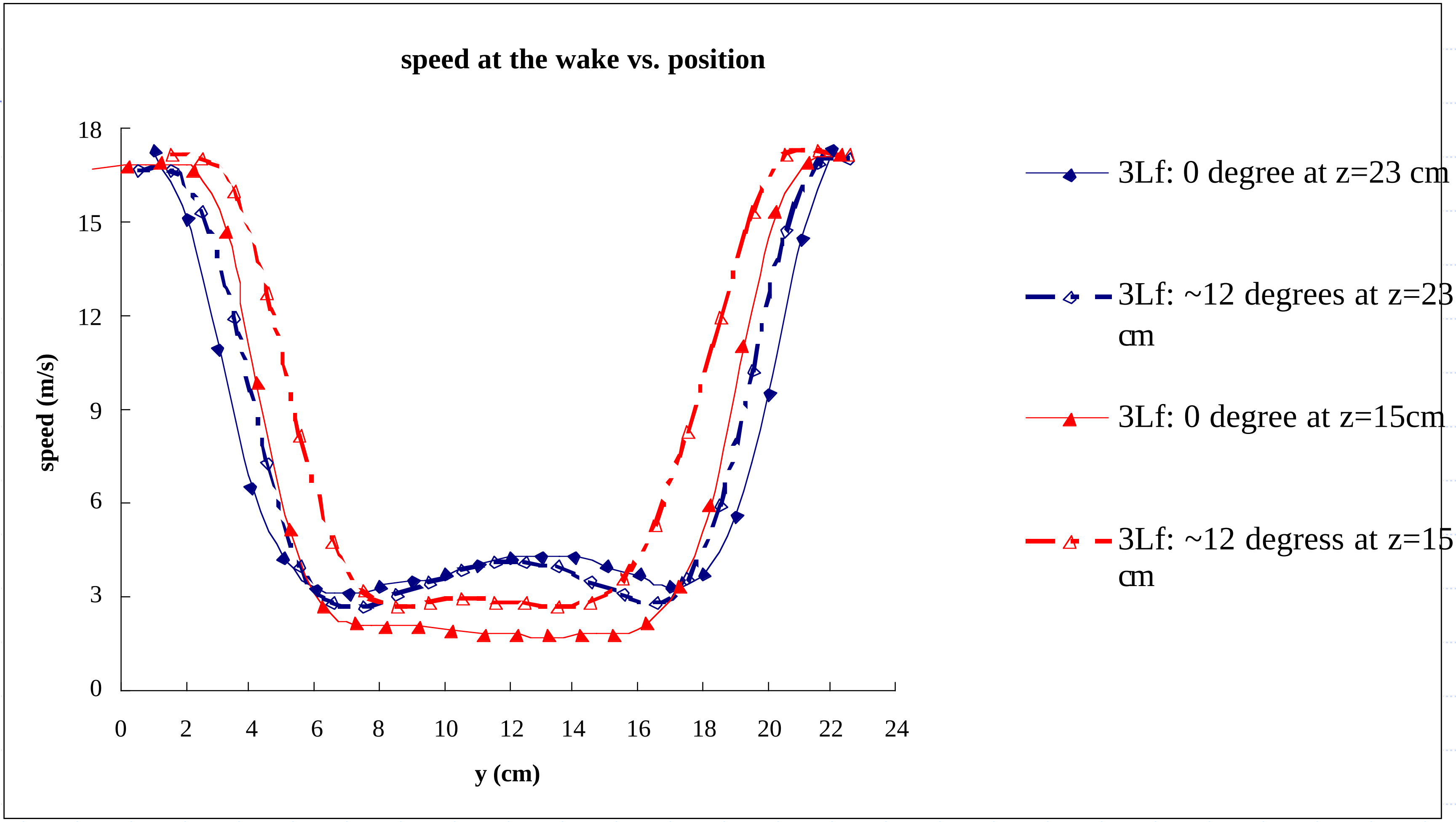


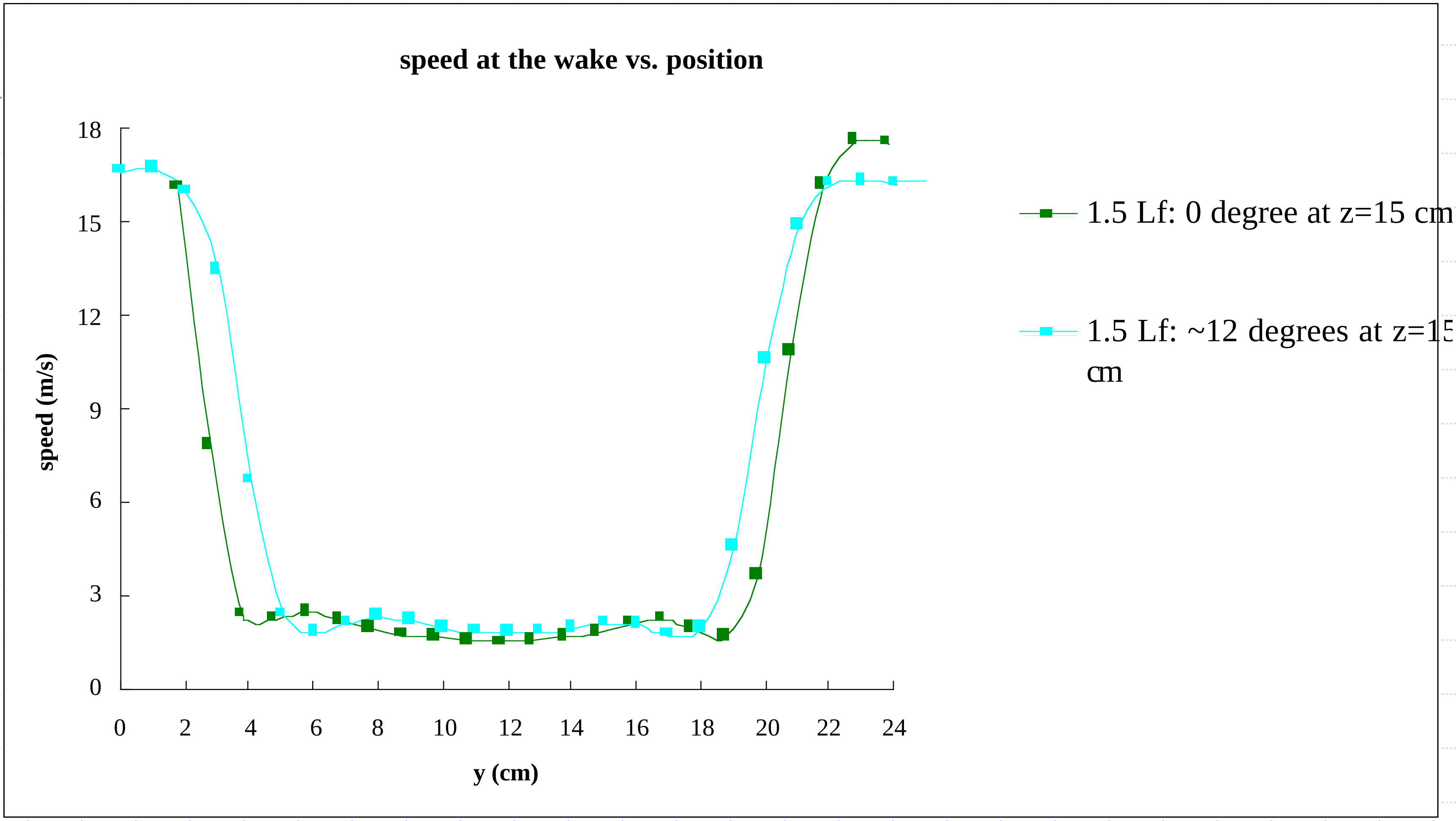
GROUND VEHICLE AERODYNAMICS LABORATORY

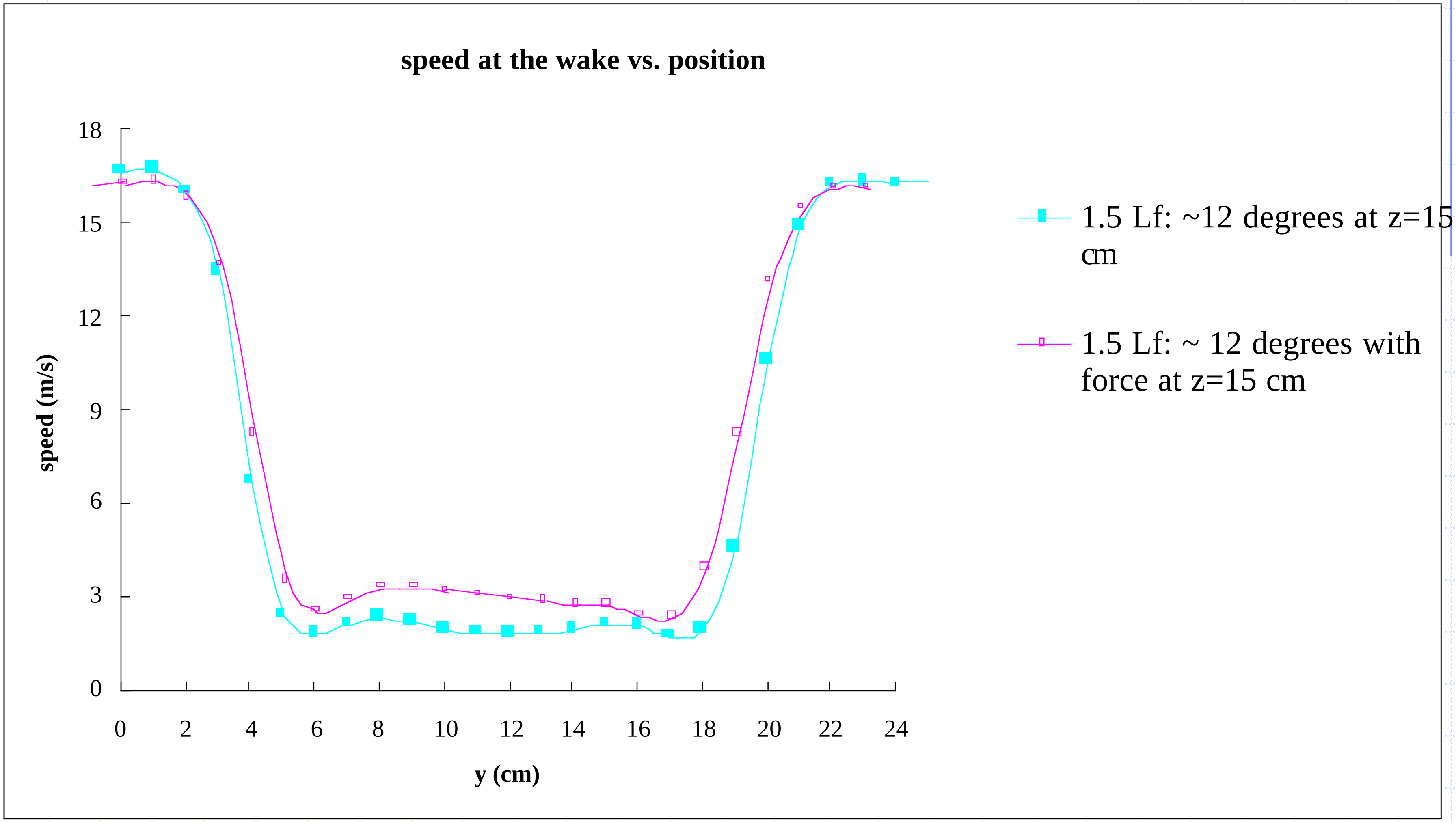
Average Cp at the model base vs. flap angles



- Hot film measurements at the wake of the flaps
  - 1.5 L_f and 3 L_f


speed at the wake vs. position
speed (m/s)
0
3
6
9
12
15
18
y (cm)
0
2
4
6
8
10
12
14
16
18
20
22
24
3Lf: 0 degree at z=23 cm
3Lf: ~12 degrees at z=23 cm
3Lf: 0 degree at z=15cm
3Lf: ~12 degress at z=15 cm


speed at the wake vs. position
speed (m/s)
0
3
6
9
12
15
18
0
2
4
6
8
10
12
14
16
18
20
22
24
y (cm)
1.5 Lf: 0 degree at z=15 cm
1.5 Lf: ~12 degrees at z=15 cm


speed at the wake vs. position
speed (m/s)
y (cm)
1.5 Lf: ~12 degrees at z=15 cm
1.5 Lf: ~ 12 degrees with force at z=15 cm
0
3
6
9
12
15
18
0
2
4
6
8
10
12
14
16
18
20
22
24

Summary

- The velocity profile of the jet generated by the speaker was measured.
  - The most effective frequency and amplitude ranged from 5-7 V and 150-200 Hz.

- Without forcing:
  - The wake of the model was reduced when the flaps move from 0 to 12 degrees.
  - At optimal flap angles (12degrees), the average Cp at the base increases 21%.
  - At optimal flap angles, 18% of drag reduction was found.

- With forcing:
  - The wake of the model was reduced further in comparison with the non-forcing case.
  - At optimal flap angles, the average Cp at the base increase 25.1%.
  - At optimal flap angles, 21% of drag reduction was found.

Near-Term Tasks

- Try a new speaker which could provide higher frequency range with the amplitude desired for this study.
- Identify the optimal forcing function for the model.
- Understand the physics of the flow at the optimal angles.

Georgia Tech Research Institute

Novatek, Inc

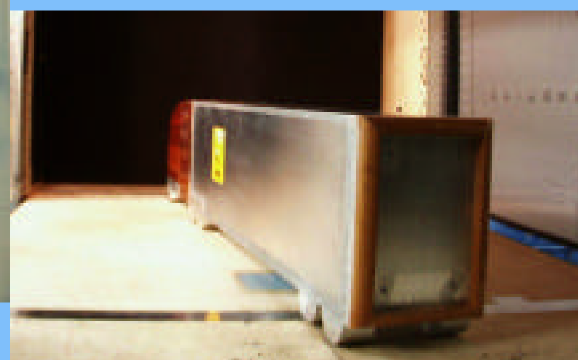
PROTOTYPE DESIGN AND FABRICATION

VOLVO

New Roads.™

Full-Scale Test and Evaluation of the Fuel Economy Increase of DOE/GTRI Pneumatic Heavy Vehicle
~DOE Heavy Vehicle Aerodynamic Drag Workshop, 9/23/2002~
by Robert J. Englar, Georgia Tech Research Institute

Application of Advanced Pneumatic Aircraft Technology….



...Through Analytical & Experimental Development ...

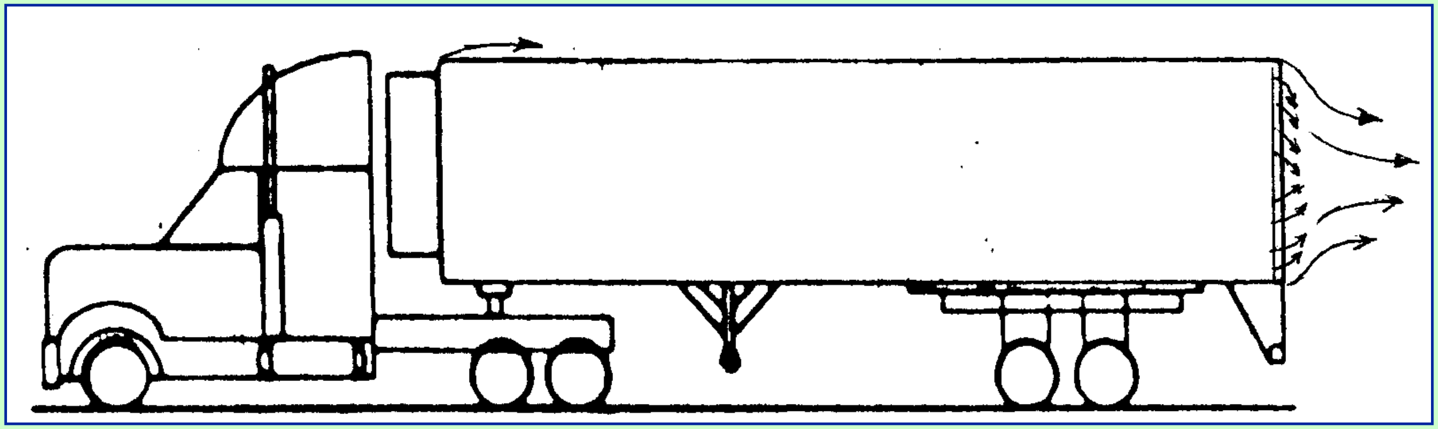
..To Test Track Proof-of-Concept Full-Scale Tests

Outline of Presentation

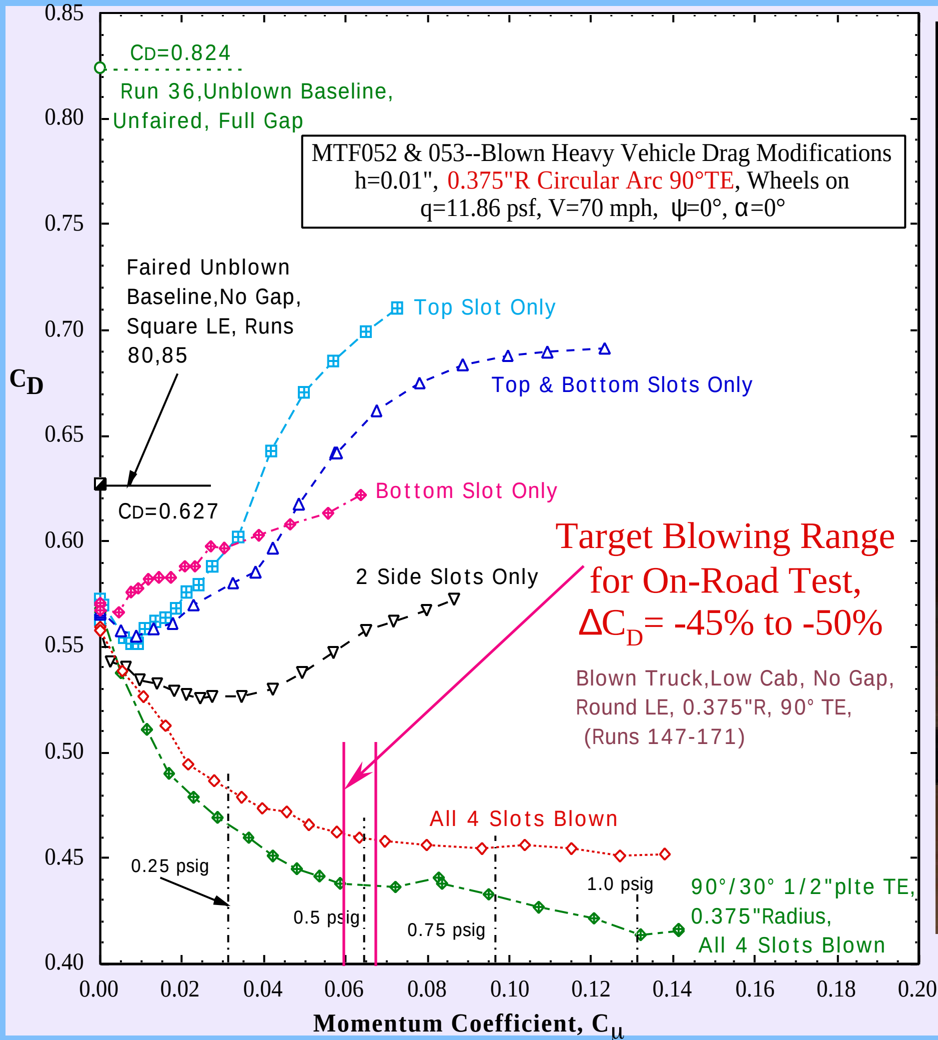
- Introduction: Pneumatic Heavy Vehicle (PHV) Technology
- Pneumatic Heavy Vehicles….Multi-Purpose Aerodynamic Devices:
  - Force & Moment Reductions or Augmentations
  - Drag Reduction, Fuel Efficiency & Wear Reduction
  - Improved Safety of Operation
  - Increased Stability (Directional & Lateral)
  - Reduced Splash, Spray Turbulence & Hydroplaning
  - No-Moving-Part Integrated Systems
  - Pneumatic Cooling Systems
- Full-Scale PHV Test Vehicle Design
- Initial Tuning Tests 1 and 2 at Volvo Trucks in N.C.
- Type II Fuel Economy Tests at TRC in Ohio
- Preliminary Results & Discussion
- Conclusions: So, where do we go from here ?…

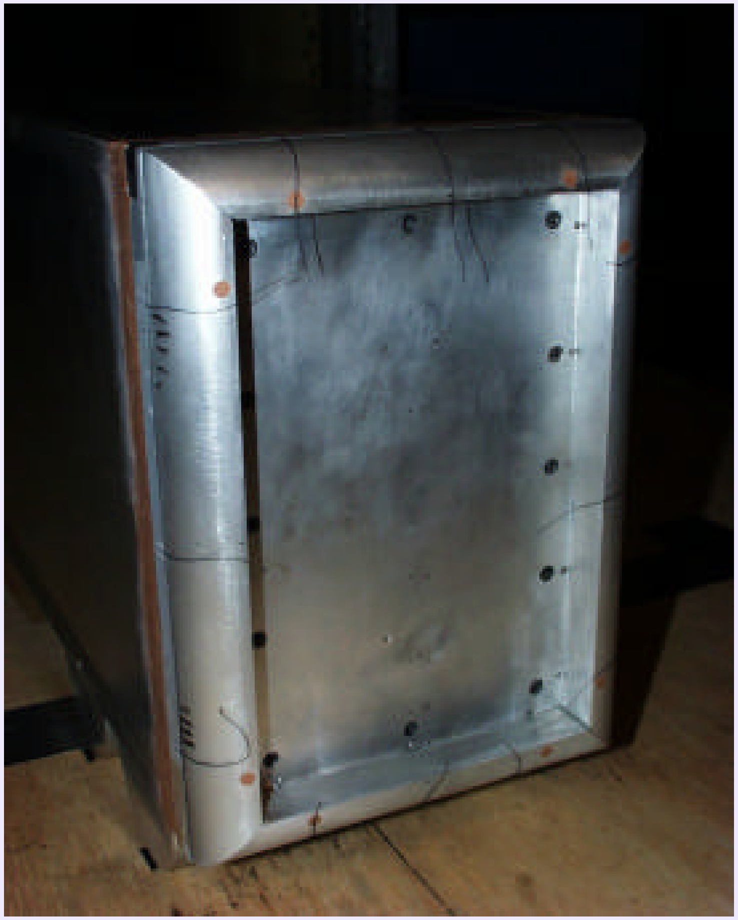
  Or, how do we CONTINUE this development on a real vehicle ??

Pneumatic Heavy Vehicle Configuration with Potential for 5 (or more) Blowing Slots for Performance, Economy & Safety



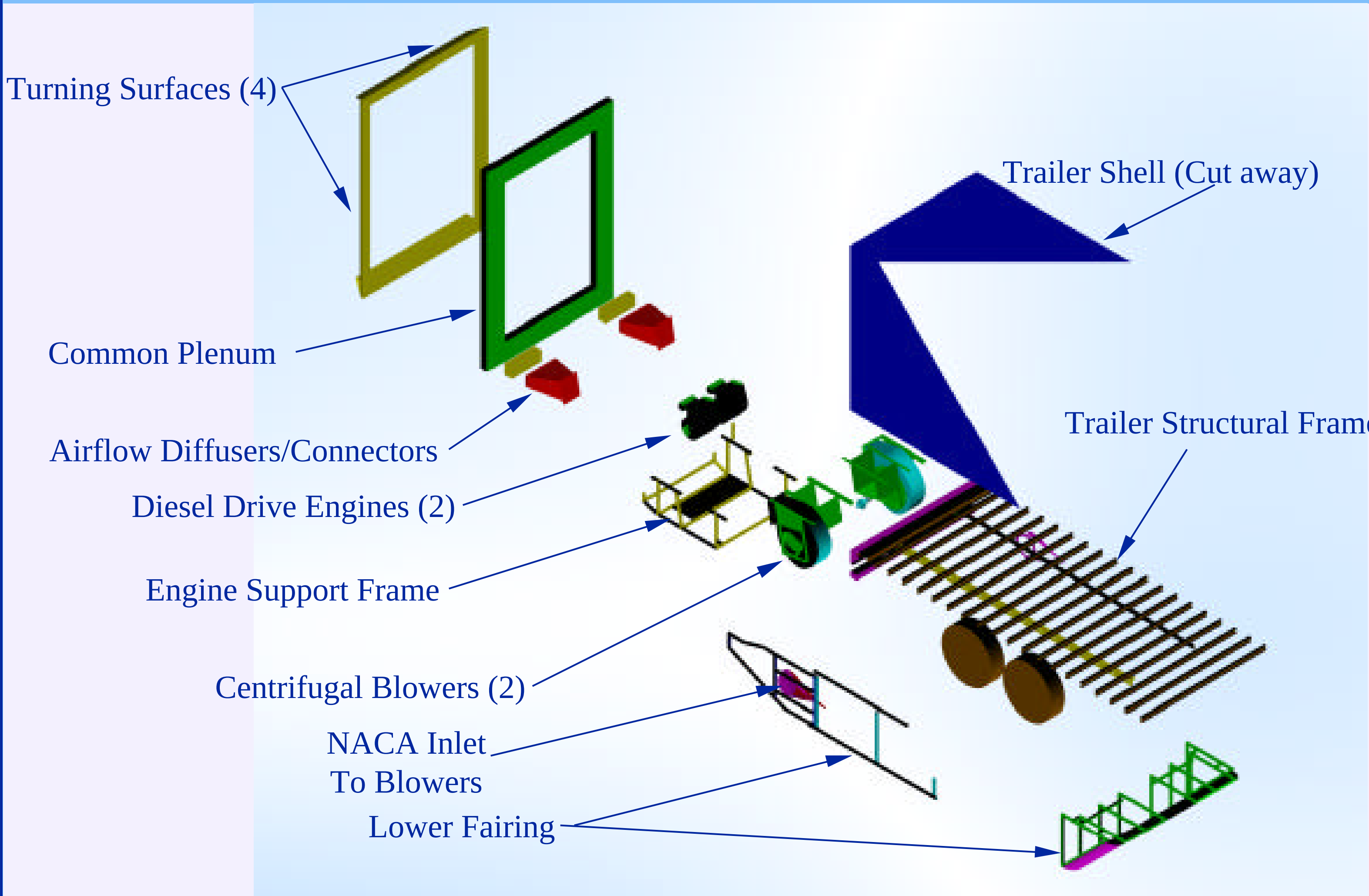
Background: Aero Development & Tunnel Tests at GTRI Showed 50%(or more) Drag Reduction due to Aft Blowing of Various Slots





4 Blown Slots on Trailer Rear Doors
Of Wind-Tunnel Model

PHV Trailer Modifications for Blowing Systems



Designed & Modified by Prototype Shop Novatek, Inc.

First Tuning Test Conducted at Volvo Trucks of North America, February 28-March 1, 2002

Objectives: • Blowing Optimization for Upcoming Fuel-Economy Test at TRC
• Instrumentation, Blowing, Data Reduction, & Control Systems Checkout

Conducted by : GTRI, Novatek,Inc., and Volvo

Static Jet Turning Displayed During Blower Run-up Testing

Setting Slot Heights and Confirming
Jet Turning at Low Blowing Rate

Right Rear Corner, looking up--
Tufts Show Jet Turning to Left:
90° on Side and 30° on Top

On-the-Road Operation:Jet Turning Entraining the Flowfield and Reducing Vehicle Drag

Rear View with Jets Blowing

Close-up of Tufts
Showing Jet Turning

Tuning Test Preliminary Results (V=65 mph), Comparison to GTRI Wind Tunnel Results, and Conclusions

Configuration	WindTunnel C_D	% C_D Change	% Equiv. GPM Reduction	Road Test Run No.	% GPM Reduction	% Equiv. C_D Change	% MPG Increase
Baseline, No Gap, Sq. LE & TE	0.627	0	0.0	13 (Gap)	0.00	0.00	0
Unblown PHV, Cmu=0	0.57	-9.1	-4.6	9	-10.21	-20.42	11.37
PHV,4 Slots Cmu=0.05	0.44	-29.8	-14.9	5	-13.27	-26.54	15.30

CONCLUSIONS:

- Limited Tuning Runs confirmed up to **15.3% increase in MPG,** or about **26.5% reduction in C_D**, due to blown PHV configuration, **but** this first Tuning Test **was not optimized** (Speed, Temps, Blowing rate, etc.)
- Conducted 2nd Tuning Test (TT2) in May 2002 with suggested test procedure and vehicle improvements prior to SAE fuel economy test at TRC

Pneumatic Heavy Vehicle Test Trailer (left) Compared to Baseline Control Trailer from Great Dane

Test PHV Features:
- 4 jet turning surfaces with plenums and blowing slots
- NACA inlet to entrain free-stream total pressure into blowers
- Diesel-driven external blowers feeding diffusers to plenums to slots
- GTRI data telemetry of blowing parameters

SAE Type-II Test Conducted at Transportation Research Center

- 1 PHV **Test** Truck & 1 **Control** HV, running simultaneously on 7.5-mile track
- Each Configuration Tested : 3 Acceptable (+-2%) Runs (1 Run= 6 laps ~45 miles) at each of 3 speeds: 55, 65, 75 mph = 9 Runs minimum
- Both HVs Loaded to Typical Operating Weight (~60,000 lbs.)
- 6 Test Configurations for PHV Comparisons:

  2. Blowing Surfaces & Fairings **On** , **0 RPM,** **Cμ = 0**
  1. Blowing Surfaces & Fairings **On** , **1/3 RPM,** **Cμ = Low (0.01-0.02)**
  3. Blowing Surfaces & Fairings **On** , **2/3 RPM,** **Cμ = Mid (0.02-0.04)**
  4. Blowing Surfaces & Fairings **On** , **Max. RPM,** **Cμ = Max (0.042-0.075)**
  5. Blowing Surfaces **Off,** Lower Fairing **On**
  6. Blowing Surfaces **Off,** Lower Fairing **Off,** = **Baseline Reference Trailer**

- Fuel weighed and re-filled after each run = lbs.burned/mile, corrected by Control HV

For Configs. 1-6: Minimum test runs needed: 6 x 9 = 54
Runs required to meet SAE Type II = 59; ~2655 miles; 14 test days

Test and Control Vehicles in Pits at TRC

Front View of **Test** and **Control** Vehicles

Rear View of **Test** and **Control** Vehicles, Showing Blown Tufts Turning

PHV Test Vehicle on Track at 75 mph with Blowing

PHV Testing on the TRC Track

View from Cab on Straightaway
(2 miles long)

View from Cab on
1.75-mile Banked Turn

Initial Fuel Economy Results - Unofficial

Measured Fuel Economy Results:

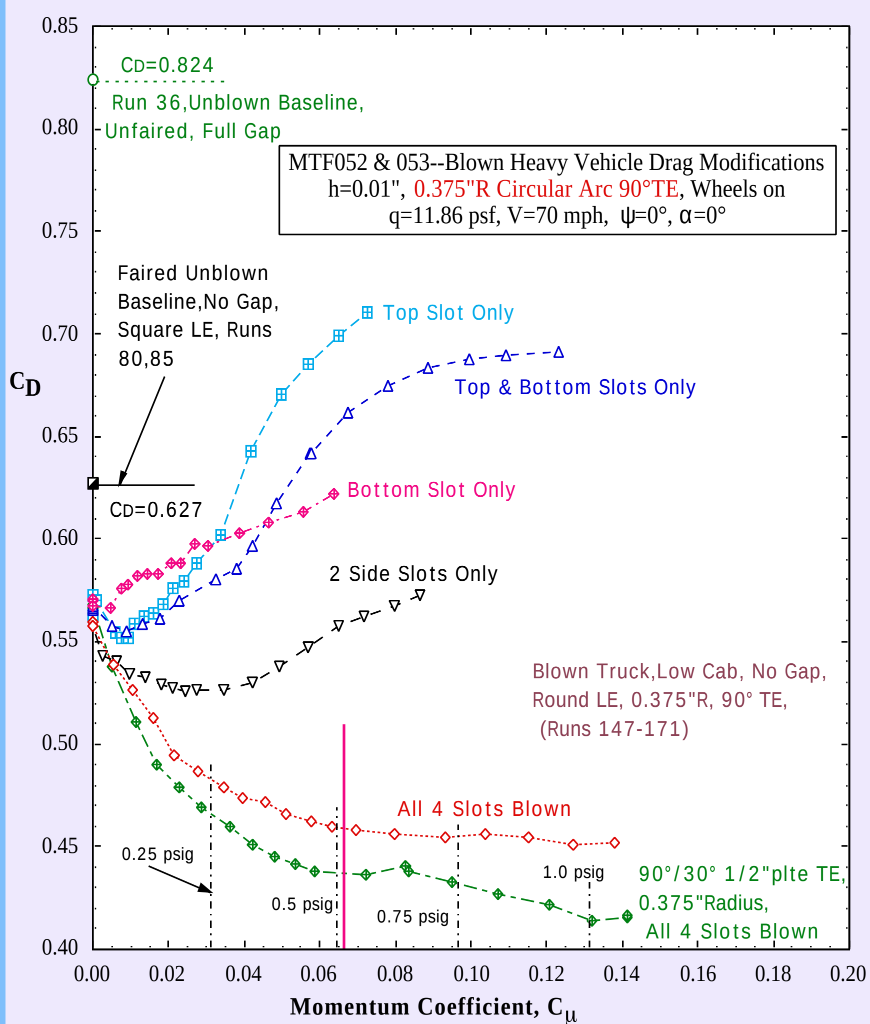
- % Fuel Economy Improvement (%FEI) Positive for all Cμ, but less than Anticipated from Wind-Tunnel Results
- At Cμ = 0, ~4/5 of anticipated %FEI value;
  at low Cμ , ~ 1/2 of anticipated %FEI; at increased Cμ, <1/2 of anticipated %FEI
- Static Jet Turning Performance of 90° on track was verified visually
- Lower %FEI Increase at Higher Speeds
- No Drag Reduction Measurable from Fuel Economy Testing (no load cells)

Postulated Reasons:

- Lower Surface Aerodynamic Fairings & Asymmetric Jet Turning
- Effective Cab Extender Fairings and Reduced Flowfield at Trailer Blown Corners
- Excessive Side Winds and Gusts
- Increased Blowing Slot Height to Accommodate Blower Output → Reduced V_{jet}
- PHV Test Vehicle Significantly Different from Tunnel Model
  - Floor-to-Ground Clearance
  - Cab Gap & Fairing

How these can affect test results…....

Possible Cause of C_D Increase with Cμ: Asymmetric Blowing due to Lower Surface Fairing and Aft-Facing Step



4 Blown Slots on
Wind-Tunnel Model:
Smooth Undersides

4 Blown Slots on
PHV Test Vehicle:
Lower Fairing,
Aft Facing Step,
Blown Asymmetry &
C_D Increase

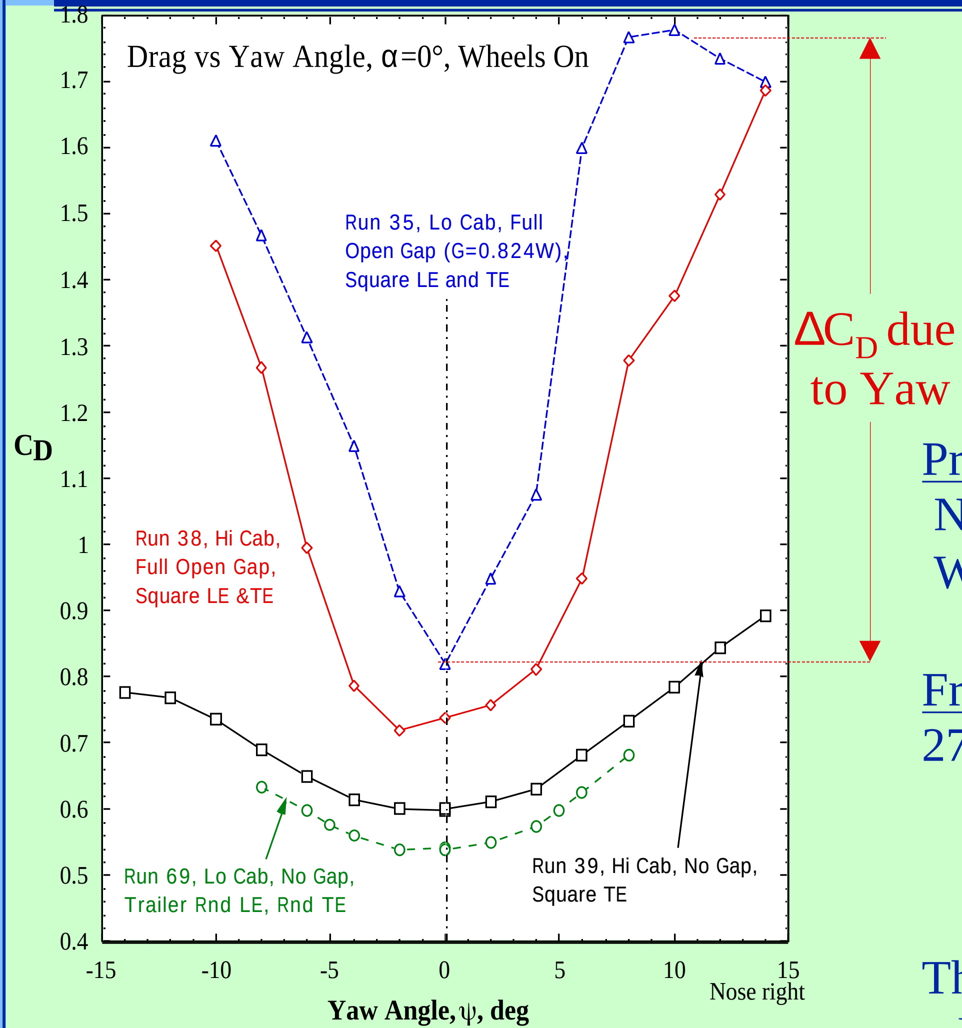
Problem of Effective Cab Extenders

- V measured by Probe=60% -80% of Speedometer thus q on side~36%-64% of Freestream q
- Less BL & Separation to Entrain (THIS is what the blowing does to reduce C_D)
- Less q to turn and pressurize base for C_D reduction
- Cover Trailer Leading Edge Fairing

(q= dynamic pressure, psf)

Probe location on Opposite Side

Effects of Excessive Side Winds and Gusts on the Road



1/16-Scale GTRI Model, Cμ=0

Previous GTRI Tunnel Results:

No Gap: ψ=10°, ΔC_D=32%-53%

With Gap: ψ=10°, ΔC_D=85%-120%

From TRC Tower:

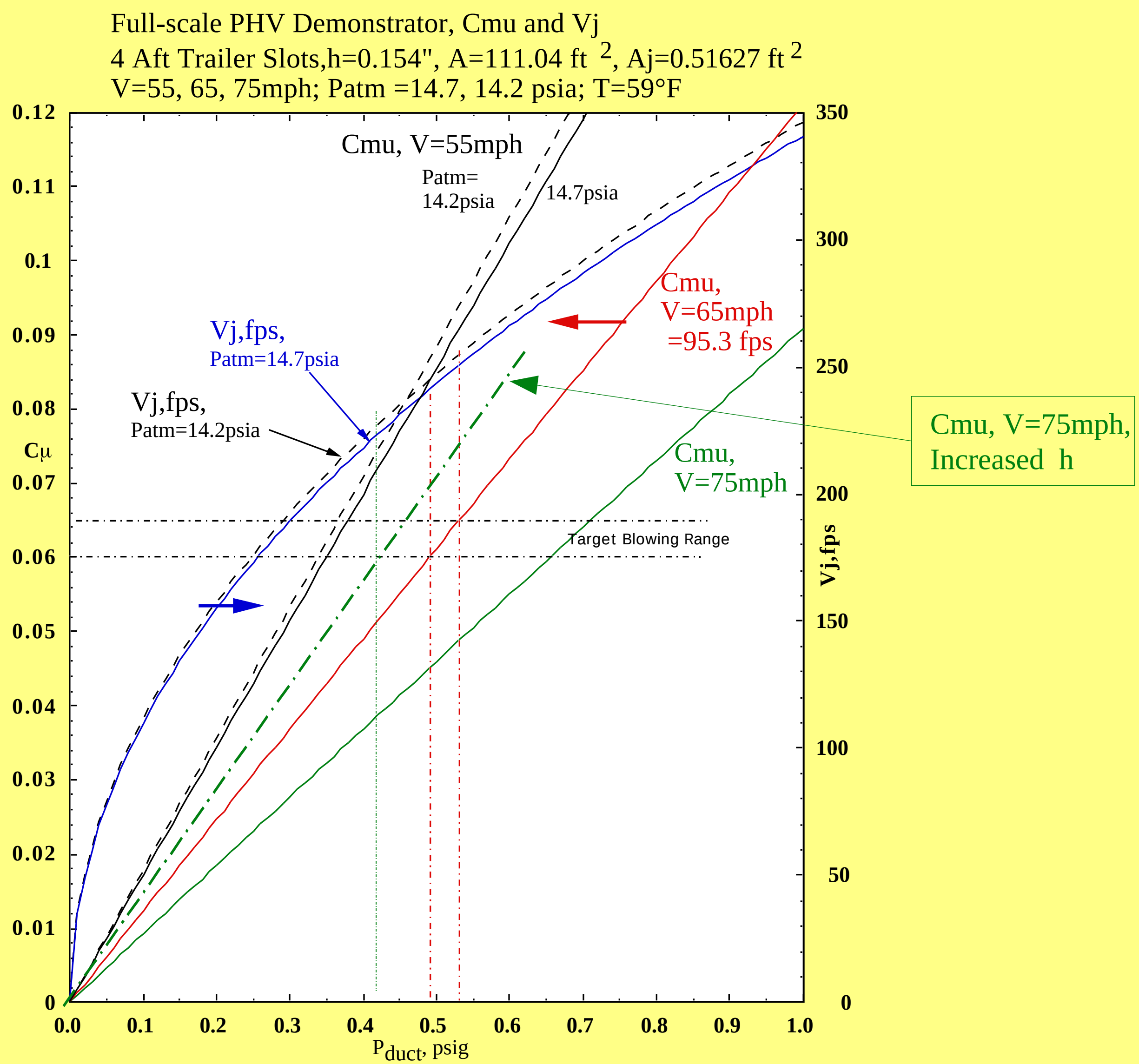
27 mph Wind Gusts at High Cμ Runs

ψ=26° at V=55 mph

ψ=20° at V=75 mph

Thus, C_D could have **Doubled** or more during blowing cases with Side wind causing Reduced Fuel Economy

Blowing Design Parameters; Effect of Slot Height Increase



Differences Between PHV Model and PHV Road Test Vehicle

Difference	Effect on Test Vehicle
• Cab Extender Fairing	Less C_D Reduction due to $C\mu$
• Trailer/Cab Gap	Increased C_D due to Increased Vorticity
• LE Radius behind Fairing	Less C_D Reduction
• Trlr Floor-to Ground Clearance	Higher C_D, Less Blowing Effectiveness

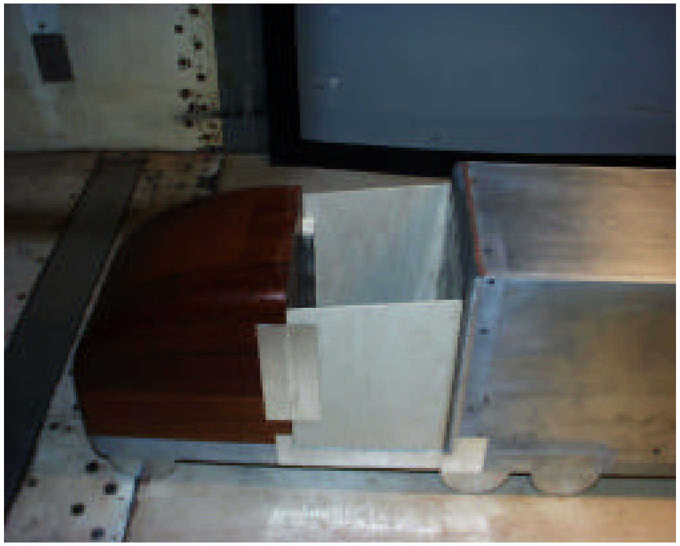
...In addition to Previous Items (Lower Fairing,, Cab Extender Flowfield, Side Winds, etc

Confirmation of Test Performance Hypotheses

<u>Conduct Follow-on Small-Scale Tests of GTRI 1/16 Pneumatic Model:</u>

- Simulate Lower Surface Aerodynamic Fairings (ON & OFF)
- Simulate Cab Gap of Test Vehicle and Add Cab Extender Fairings
- Conduct Yaw (Side wind) Tests with Asymmetric Blowing (Lower Fairings)
- Vary Blowing Slot Heights with Asymmetric Blowing
- ALL of these modifications should approach the Test Vehicle Configuration and degrade PHV blowing/ drag-reduction performance

GTRI can do the above with FY02 DOE funds if we adjust the scheduled Yaw Tests slightly



PHV Configuration/Performance Improvements

GTRI 1/16-Scale Model Modifications to Approach PHV Full-Scale Config.

- New Modern Tractor (not Cab-over) = "SLRT"
- Raise Trailer Floor-to-Ground Clearance = Full Wheel Diameter
- Cab Extenders ON & OFF
- Cab Gap vs. No Gap vs. Partial Gap
- Improve TE Blowing Configuration
- Move Blowers & Engines Inside (i.e., No Lower Fairing)
- Pulsed Blowing to Reduce Slot Mass Flow Requirements

Modifications to NASA Ames 1/8-Scale SLRT Model To PHV Configuration

- Plenums, Slots and Turning Surfaces
- Flow controls and instrumentation
- Conduct High Reynolds Number Tests with Blowing Modifications

Perform these tasks under new FY03 DOE funding

Pneumatic Heavy Vehicle Follow-on

- Re-design Full-Scale PHV Test Configuration based on Above Results: Blowing System Inside, Tractor Fairings, TE Blowing Surfaces, Pulsed Blowing
- Conduct Full-Scale Tunnel Tests, or Large-Scale Tunnel Tests; All External Devices (springs, axles, fairings, gaps, slots, etc.) at Full-Scale Reynolds No. Also Evaluate True Side-Wind Effects and Control Systems, Safety, Braking, and Directional/Lateral Stability
- Modify Full-Scale PHV Road Test Vehicle-- Return to TRC for SAE Type-II Fuel Economy Test No. 2



CONCLUSIONS:Pneumatic Aerodynamic Concept Now Demonstrated as Drag Control Device

- Blowing Proved Positive on Full-Scale PHV Tests at TRC, but showed less Drag Reduction than anticipated from Tunnel Tests; Causes Identified

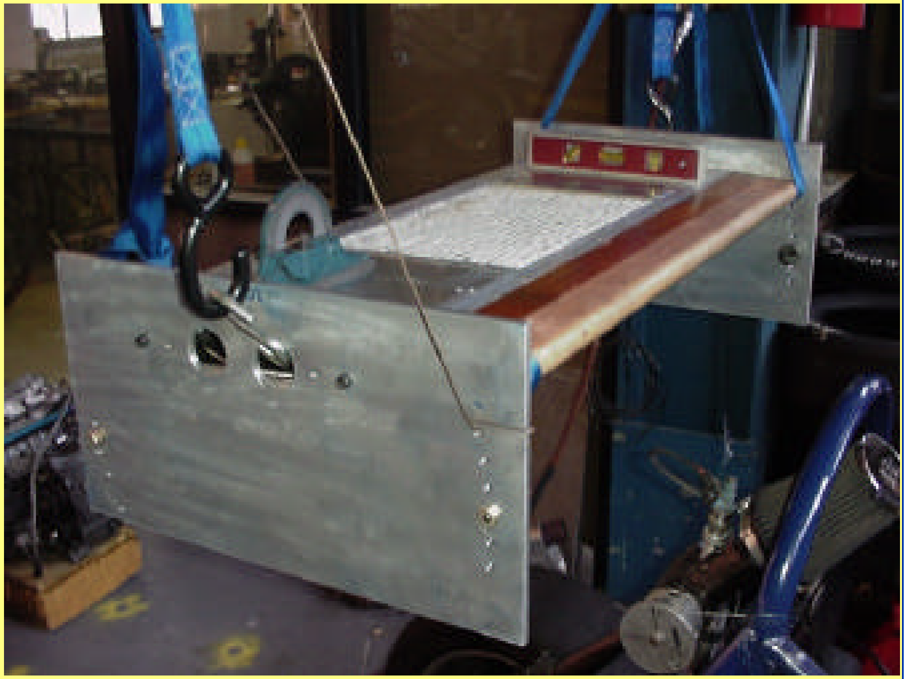
- Need to Confirm All Hypotheses w.r.t. Degrading Items, then Pose Positive Solutions

- 23% to 25% Fuel Efficiency Improvement is Possible Based on 46–50% CD Reduction if PHV Test Vehicle Approaches Tunnel Model Characteristics

- Effect of Asymmetric Blowing in Yielding Drag Increase Implied from our Tests → Aerodynamic Braking Possibility

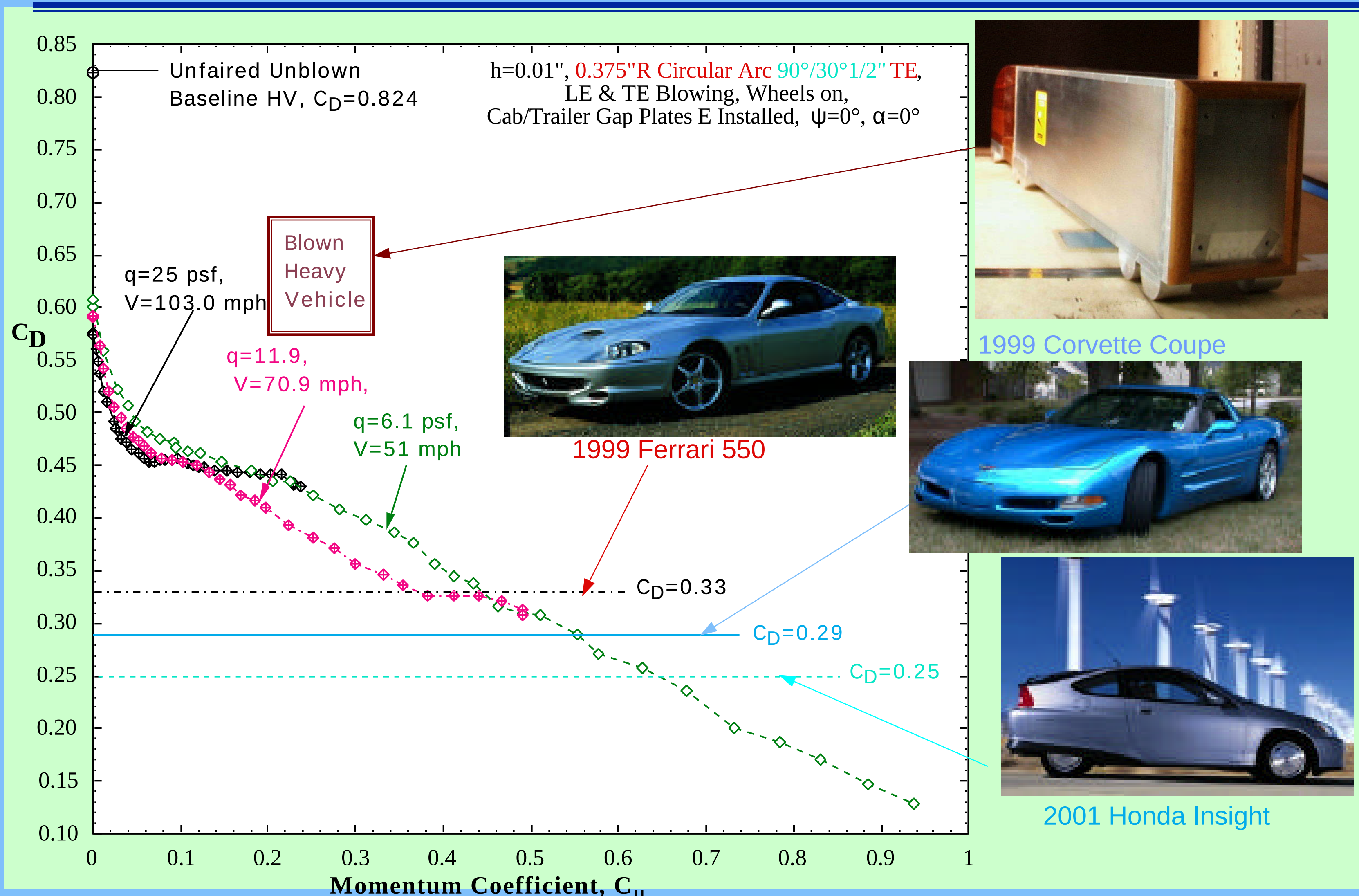
- Test Vehicle Improvements Underway!!

Pneumatic Aero Heat Exchanger Radiator/Wing Applied to Formula SAE Demonstrator Race Car (GTRI Proprietary)~ Results Applicable to Pneumatic HV & Pneumatic SUV



BACKUP Slides

GTRI Extended Tunnel Tests Showed State-of-the-Art Drag Reduction!!



Flow Visualization of Blowing Jets

Tuft Showing Flow Uniformity at Diffuser Center

Combined Jet Strength and
Wake Contraction (see Shirt)