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March 2001 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

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March 2001
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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

Introduction

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory on March 28 and 29, 2001. The purpose of the meeting was to present and discuss technical details on the experimental and computational work in progress and future project plans. Due to the large participation from industry and other research organizations, a large portion of the meeting (all of the first day and part of the second day) was devoted to the presentation and discussion of industry's perspective and work being done by other organizations on the demonstration of commercial software and the demonstration of a drag reduction device. This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.

Industrial representatives from International Truck and Engine Corporation, PACCAR, and Freightliner participated in discussions and presented an industrial perspective. Representatives from Argonne National Laboratory presented an overview of computational results for heavy vehicles given to them by Adapco Corporation and a representative from Dynacs Corporation presented his plans for demonstration of a variety of commercial and NASA software packages. A representative of Georgia Technology Research Institute (GTRI) presented their experimental results and future plans for a drag reduction device developed by GTRI. The meeting introductory remarks included an overview of the Laboratory provided by a representative of LLNL's Energy Directorate.

Representatives from the Department of Energy (DOE) Office of Transportation Technology Office of Heavy Vehicle Technology (OHVT), Lawrence Livermore National

Laboratory (LLNL), Sandia National Laboratories (SNL), NASA Ames, University of Southern California's (USC), and California Institute of Technology (Caltech) gave presentations on the DOE Truck Aerodynamics Project and participated in discussions. The second day of the meeting included a review of experimental results and plans by the 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 turbulence model development and benchmark simulation for rounded cube shapes representative of a tractor and trailer being investigated by the Caltech. NASA Ames also presented information on the new geometry called the Generic Conventional Model (GCM) currently being evaluated in the 7x10 wind tunnel at NASA. Much of the second day discussion involved wind tunnel testing plans, analysis of existing experimental data, simulation results, and needed modeling improvements. One focus topic was the issue of careful verification and validation processes for software evaluation.

Summary of Major Issues

There were 3 major issues raised at the meeting.

1. A major topic of discussion was the process proposed for evaluation of NASA and commercial software. The Dynacs representative has proposed the evaluation of three separate NASA codes and three separate commercial codes for application to the Generic Conventional Model (GCM) by comparison of one or limited grid cases to experimental data. The question was raised whether the software could be evaluated without standard practices of verification and validation (e.g., demonstration of grid and time convergence)?

2. Another active topic of discussion was the DOE full-scale demonstration experiments proposed for the GTRI blowing device. A planning meeting at GTRI was suggested where industry participation will be encouraged.

3. The DOE Team has NEAR-term deliverables for FY01 that will be of value to industry in providing guidance in the use of RANS models. The fact that plans are to complete this effort by October 1st of this year was not made clear, and the Team was criticized for being 'too academic' and having deliverables that were 'too long term'. The Team did emphasize that they wish to present this information to industry and obtain feedback through an exchange of information during site visits and formal documentation. The majority was supportive of this communication approach.

Introduction, Overview of the Project, and Future Activities

After Ray Smith of LLNL gave an introduction to the Laboratory, Rose McCallen of LLNL presented the project overview. Some comments from the industry participants included

- Suggestion that an 'intermediary' for collaboration would be helpful,
- Separate meeting to update the multi-year program plan was recommended,
- Request that industry input be considered for wind tunnel model geometries, and
- Comment that industry wants near-term results.
-

Sid Diamond of DOE OHVT provided an update of the OHVT projects and budgets and some inspiring thoughts. He encouraged a consortium with industry with a 'modest' cost share from industry. His vision includes the involvement of not only the tractor manufacturers but also the added participation from trailer manufacturers, because of the well-recognized importance of integrating the tractor and trailer for reduction of aerodynamic drag.

The viewgraphs for the project introduction and LLNL overview are attached at the end of this report.

Industrial Perspective

Sunil Jain of International Truck and Engine Corporation emphasized that reducing drag is their objective and that the 21st Century Truck Initiative goal to reduce the drag by 25% over 20 years should be feasible with a strong team involving a tractor and trailer group. The wake and gap flow are the critical areas that need improvements for drag reduction. Sunil also provided an overview of the past and current aerodynamic effort at his company. International uses various commercial codes dependent on whether they are modeling internal, external components, or whole body flow. The predicted and measured drag are not always in agreement, but the commercial codes do provide a good match with wind tunnel pressures and good qualitative results. It is important, and often sufficient, to predict the correct *changes* in drag or *correct trends*. Typical problems involve 1-2 million zones, but can be up to 6-7 million zones. For underhood flows, changes in temperature need to be predicted to within 5%. Simple source and sink models for the fan are not adequate and more detailed models are required. The importance of understanding the flow phenomena, determining optimum vehicle shape to minimize drag, and to be able to correlate the computed and experimental drag coefficient was discussed. It was suggested that the DOE Truck Aero Team provide industry with the CFD tools they are using so that they can investigate their use. It was also suggested that the Team establish collaborative relationships with the commercial software industry providing advanced modeling guidance that will enhance those tools now being used by the tractor

manufacturers. Participation at the November 2001 SAE Truck and Bus Meeting in Chicago was encouraged. Further details are provided on Sunil's viewgraphs.

Dan Schlesinger of Freightliner provided an overview of market situations, overall development activities to reduce fuel consumptions, important issues in the design process to consider, aerodynamic testing, and CFD analysis. It was recognized that improvements in aerodynamic drag have the biggest payoff but the customer is not ready for an integrated tractor-trailer, the cubic capacity of the trailer can't be sacrificed so that a generous leading-edge radii is not acceptable, and bottails have overall length restrictions. It would be advantageous to have aerodynamics influence the design process upfront, but this is difficult if modifications or additions add cost, assembly time, complexity, or negatively impacts styling. It is also difficult to impact the design if the aerodynamic analysis takes too long. Wind tunnel testing can provide adequate changes in drag, but often not the absolute drag. CFD analysis is accomplished using commercial tools for internal flows, small-scale component analysis, and full body flow.

Everett Chu from PACCAR Technical Center provided an overview of his company's vehicle-aerodynamics development program including a description of their Heavy-Vehicle Manufacturing Divisions, methods used for product performance assurance, the use of CFD tools, wind tunnel experiments, and vehicle/track confirmation tools. PACCAR's Technical Center can provide support to it's other subsidiaries including Kenworth (US), Peterbilt (US), DAF (Netherlands), Foden (UK), and Leyland Trucks (UK). The Technical Center located in Mount Vernon, Washington has a 1.6-mile test track. Their product performance assurance follows a 4-stage development process including benchmarking and target setting, advanced concept, prototype validation, and product confirmation. CFD tools, wind tunnel experiments, and vehicle/track testing are part of this process. Different commercial CFD codes are used for application to underhood or external flows. Wind tunnel scaling issues (e.g., variation in results for different scale models) and several concerns involving the GCM design were mentioned (e.g., wheels too hidden, areas closed and open, cantilever of front end). Everett also provided input on the DOE program including 'helpful tools and techniques' and 'helpful analyses for specific vehicle areas and components' which are attached in the viewgraph section of this report.

Demonstration of Commercial Tools

Ross Sheckler of Dynacs Corporation presented his plans for the evaluation of 3 commercial and 3 NASA software packages. The focus of the discussion was on the proposed method of evaluation, as mentioned above, which is a 'best effort' approach. It was suggested that Ross document the criteria and evaluation process for review by the DOE Aero (SWAT) Team, and that both work towards some agreement in the approach. The results would then be submitted to DOE and industry for their review. Another topic was the use of vortex generators on the GCM during the wind tunnel experiments.

PACCAR representative, Everett Chu, mentioned that the vortex generators have been tested and that it is likely we will not see the results we are looking for. There was also discussion that our testing of the devices may be advertised as an endorsement for their use. Further details are provided in the attached viewgraphs.

Tanju Sofu of ANL presented some calculations performed by the software company Adapco using their code STARCD. Typical calculations involve roughly 10 million zones for simulation of automobile aerodynamics and 20-30 million zones for tractor-trailer simulations. Tabulated results are provided in the attached viewgraphs.

Aerodynamic Devices

Bob Englar of GTRI presented the results of wind tunnel experiments using a modified GTS with wheels, a gap between the tractor and trailer, with and without squared or rounded trailer leading and trailing edges, and tractor-trailer height mismatch. It was found that including the wheels on the GTS increased the drag. Rounding the leading edge of the trailer reduced the tractor-trailer height-mismatch imposed drag. Rounding the trailer rear corners is also helpful. Bob also presented the results of using a blowing device. Details can be found in the attached draft SAE paper to be presented at the 2001 SAE Government/Industry Meeting. Discussions on these results focused on plans for an upcoming demonstration full-scale field test. Questions raised were about the power source, what kind of instrumentation would be included on the field tests, what would be the cost of the tests, what are the ramifications of blowing: for example, would blowing have substantial drive-by noise, would icing be a problem, and what were the system maintenance issues. A meeting is scheduled in May in Atlanta to finalize the plans for the field tests and to further address some of these questions.

DOE Truck Aerodynamic ('SWAT') Team's Presentations

NASA's Current Tests on GCM in 7-ft x 10-ft Wind Tunnel Experiments and Plans for 12-ft Wind Tunnel Experiments

Jim Ross of NASA Ames presented the final report on the GTS 7-ft x10-ft experiments, some preliminary results on the 7-ft x10-ft experiments on the GCM which were started on March 19th, and the planning and preparation underway for the 12-ft pressure wind tunnel experiments with the GCM. Some of the parameters to be investigated with the GCM are Continuum Dynamics, Inc boattail plates, tractor trailing edge side extenders at two different lengths, vortex generators and under-slung cargo. Instrumentation will include 256 pressure taps, particle image velocimetry (PIV) in the tractor-trailer gap and at the trailer base, oil film interferometry (OIF) for measuring skin friction, unsteady pressure transducers at rear of side extenders, inside the gap surface and the back of the trailer, and independent measurement of tractor and trailer drag. The preliminary results with the GCM indicate a 'break' in the drag curve at 10°-yaw, which was not seen with

the GTS model. One hypothesis is that this characteristic is present because of the tractor-trailer gap flow. Jim also gave a reminder that the fairings on the bottom posts are not connected to the balance, so that one should not integrate over the fairing in calculating drag coefficients. Details of the NASA test plans are provided in the attached viewgraphs.

USC's Wind Tunnel Tests and a Look at an Aero Device

Fred Browand, Mustapha Hammache, and Albion Knight of USC gave an overview of their preparation work on the United Engineering Foundation Conference, a detailed presentation of their gap flow analysis, and a report on their progress in the development of a base drag reduction device. Fred has put together an advisory committee of outstanding internationally known researchers and industrial representatives from around the world for the United Engineering Foundation Conference on Aerodynamics of Trucks, Busses and Railcars planned for Fall of 2002. Mustapha presented his detailed analysis of the force coefficients as a function of gap and yaw angle. His preliminary conclusions are that at large yaw angles, there is a 'critical' gap where the tractor drag coefficient more than doubles with minimal effect on the trailer drag coefficient, unless the leading edge vertical sides of 'the trailer are rounded, and then trailer drag is also influenced by a 'critical' gap. Mustapha has also developed a novel approach for characterizing the gap flow by dividing the gap into two equal regions and comparing their 'gap outflow' velocities on a 'state space' plot using the PIV data. This method allows for evaluation of the gap flow in the various 'states' by use of conditional sampling based upon the location in the state space. With this type of guidance, industry can make intelligent technical (and economic) decisions on the use of aerodynamic devices for tractor-trailer modifications in the gap region. It was also mentioned that this information would be valuable to the manufacturers and installers of trailer refrigeration systems, who are concerned about air circulation in the gap where the refrigeration system is mounted on the trailer. Details of this described analysis can be found in the attached viewgraph presentation. Albion Knight gave a progress report on his plans for the development and testing of an oscillation device to control the trailer wake flow. The device is intended to alter the turbulent structure of the wake, resulting in a drag reduction. Details of the data acquisition and controls setup for testing the device and a preliminary experimental plan are provided in the attached viewgraphs.

RANS and DES Computations at SNL

Kambiz Salari of SNL gave an overview of the DOE Accelerated Strategic Computing Initiative (ASCI) and how it provides computer resources that can be utilized for this truck aerodynamics project. Kambiz also presented related issues of code verification and validation (V&V). Progress and status was reported on the Reynolds-averaged Navier Stokes (RANS) computational effort with the GTS geometry with some general findings of the predictive capability of RANS for simulation of a tractor-trailer configuration.

Information on the development and implementation of a detached-eddy simulation (DES) for application to the GTS model was also presented. (DES is a new turbulence modeling approach where RANS is used in wall regions and LES is used away from walls for reduced grid resolution requirements near walls.) Short-term deliverables for this fiscal year FY01 include careful evaluation of the application of RANS for modeling tractor-trailer drag and the transfer of this information to industry as guidance in their simulation process. SNL is investigating 4 different RANS models. The RANS calculations compare well with experiment except for the calculated pressure at the edges of the trailer base. It was recognized that accurate computation of the pressure gradient at the trailing edges of the trailer are essential for correctly determining the vehicle drag. The possible need for edge effect corrections by averaging the pressures for the perpendicular element segments at the edge was mentioned. Unfortunately, SNL has uncovered a 'bug' in their 'block patching' of computational grids. Even though it is believed that the above conclusions will not change, SNL has eliminated this problem and is currently rerunning the simulations to be sure there are no changes in their results. All scheduled tasks should still be completed on time, at the end of FY01. Details of the computations and analysis are provided in the attached viewgraphs.

Simulations using Vortex Methods: A Gridless Technique

Tony Leonard and Mike Rubel of Caltech gave an update on their progress in the effort to simulate a tractor-trailer configuration using a 'grid-free' (except for 2D grid on body surface) Vortex Method with improved, fast, parallelized, adaptive techniques. Current activities at Caltech include: incorporating bodies with arbitrary complexity, obtaining higher Reynolds numbers computations, and developing and analyzing subgrid models for large-eddy simulation. Using some demonstration calculations, Tony showed the need for 'vortex resolution' to capture the flow in the near wall region at turning edges around the tractor. Mike Rubel of Caltech provided an overview of his development work on a numeric time integration by 'dead reckoning'. This tool is needed to accelerate the vortex method for application to heavy vehicles. Details and results of computations with the vortex method code and on the turbulence modeling approach are in the attached viewgraphs.

LES/DES Incompressible Flow Computations/Analysis at LLNL

Rose McCallen, Tim Dunn, Roxana Greenman, and Jerry Owens of LLNL reported on the progress and status of their simulation effort. Rose described the near-term deliverables planned for this fiscal year, which include some general conclusions about the effectiveness of LES. Specifically, plans are to generate LES results of the GTS at zero yaw for direct comparison to the experimental data and the RANS simulations performed by SNL. This complimentary work should be of interest to industry, because it will supply them with some near term guidance on the adequacy of various turbulence models for application to predicting the base drag on a tractor-trailer. The approach and

development challenges were presented by Tim, recent validation results were presented by Roxana, and Jerry demonstrated a new graphics capability that provides movie generation with transparent contours. The code solution speed has in some cases increased by an order of magnitude with more effective use of a Finite Element Interface (FEI) and the introduction of stabilization and solver acceleration schemes. The V&V results for a flat plate, channel flow, and a sphere show good comparison with experiment. A simulation of the 7x10 NASA wind tunnel indicates promising projections of scaling and timing for LES simulations with the vehicle and tunnel. It was also demonstrated how with LES, stretched grids and adjustable parameters can be manipulated to produce widely different results. Thus, it is possible to 'tweek' parameters to match data, which is not a recommended approach. The LLNL team is struggling with a recent manpower shortage, but every attempt is being made so that scheduled tasks will be completed on time. See attached viewgraphs for details on the models.

Action Items

The follow-on action items with the individuals responsible for the tasks are as follows:

Unified Engineering Foundation Conference
- Set date and location (R. McCallen)
- Include more international representatives on advisory committee and finalize (F. Browand)
- Send letters requesting support (R. McCallen)

Generate draft document of code evaluation criteria and distribute to SWAT Team for review and then present to DOE and industry for comment (R. Sheckler)

Review and comment on R. Sheckler's evaluation criteria (all)

Attend GTRI meeting in May (Rose, Mustapha)

Generate new SWAT Team budget estimate for FY02 before next meeting (R. McCallen)

Generate and distribute meeting report with viewgraphs (R. McCallen)

Establish location and schedule next working group meeting (R. McCallen)

Truck Aero Team Meeting

LLNL, Livermore, CA

March 28-29, 2001

Attendee	Organization	e-mail address and phone
Ron Bradley	ORNL	
Fred Browand	USC	browand@spock.usc.edu, 213-740-5359
Everett Chu	PACCAR	echu@paccar.com, 360-757-5270
Sid Diamond	DOE	sid.diamond@ee.doe.gov, 202-586-8032
Tim Dunn	LLNL	dunn13@llnl.gov, 925-422-5258
Bob Englar	GTRI	bob.englar@grti.gatech.edu, 770-528-3222
Roxana Greenman	LLNL	greenman2@llnl.gov, 925-424-2501
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Albion Knight	USC	aknight@usc.edu, 213-740-5320
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Dan Schlesinger	Freightliner	Dan Schlesinger@freightliner.com, 503-745-6975
Ross Sheckler	Dynacs	dynacsny@dynacs.com, 315-626-6800

Ray Smith	**LLNL**	**smith40@llnl.gov, 925-422-7802**
Tanju Sofu	**ANL**	**tsofu@anl.gov, 630-252-9673**
Frank Tokarz	**LLNL**	**tokarz1.llnl.gov, 925-423-3459**
Dave Weber	**ANL**	**dpweber@anl.gov, 630-252-8175**

AGENDA

Heavy Vehicle Aerodynamic Drag: Working Group Meeting
Lawrence Livermore National Laboratory
Livermore, CA

March 28 & 29, 2001
Building 123, Conf. Room A

Purpose of Meeting

3. Presentation & discussion of industry's perspective
4. Presentation & discussion of technical details of work in progress & future plans

Wednesday, March 28

Introduction

10:00 — 10:30	Welcome & introduction to LLNL	Frank Tokarz
10:30 — 11:00	Meeting introduction & project overview	Rose McCallen
11:00 — 11:45	DOE/OHVT update & budget	Sid Diamond
11:45 — 1:00	Working Lunch	

Industry Perspective

1:00 — 1:30	International perspective	Sunil Jain
1:30 —2:00	Freightliner perspective	Dan Schlesinger
2:00 — 2:30	Paccar perspective	Everett Chu
2:30 — 2:45	Break	
2:45 — 3:45	Discussion	

Demonstrations

3:45 — 4:15	Evaluation of commercial tools: plans & progress	Ross Sheckler
4:15 — 4:45	Results with a commercial tool	Dave Weber, Tanju Sofu
6:00	Dinner at Cattlemen's in Livermore	

Thursday, March 29

7:45 — 8:00	Continental Breakfast	

Summary and Discussion

8:00 — 8:30	Introduction, summary, issues from previous day	Rose McCallen

Aerodynamic Devices

8:30 — 9:30	GTRI project: description & status	Bob Englar

Work Plans and Progress: Experimental Effort

9:30 — 10:30	NASA data reduction, analysis, documentation, & test plans	Jim Ross
10:30 — 10:45	Break	
10:45 — 11:45	USC test results, plans, & aero devices	Fred Browand, Mustapha Hammache, Albion Knight
11:45 — 1:00	Working lunch	

Work Plans and Progress: Computational Effort

1:00 — 2:00	SNL RANS computations, analysis & DES development	Kambiz Salari, Walt Rutledge, Mary McWherter-Payne
2:00 — 3:00	Caltech vortex method development & computations	Tony Leonard, Mike Rubel
3:00 — 4:00	LLNL LES/DES incompressible computations/analysis & development	Tim Dunn, Roxana Greenman, Jerry Owens, Rose McCallen
4:00 — 5:00	Discussion & wrap up	

‘Working Group Meeting’
Consortium for Aerodynamic Drag of Heavy Vehicles

Department of Energy
Office of Heavy Vehicle Technology

March 28-29, 2001

Rose McCallen, Dan Flowers, Tim Dunn, Jerry Owens, Roxana Greenman, Greg Laskowski

University of California
Lawrence Livermore National Laboratory

Kambiz Salari, Walter Rutledge, Mary Payne

Sandia National Laboratories

James Ross, Bruce Storms, J.T. Heineck, David Driver, Dale Satran, James Bell, Steve Walker, Gregory Zilliac

National Aeronautics & Space Administration

Mustapha Hammache, Fred Browand

USC UNIVERSITY OF SOUTHERN CALIFORNIA

Anthony Leonard, Mark Brady, Philippe Chatelain

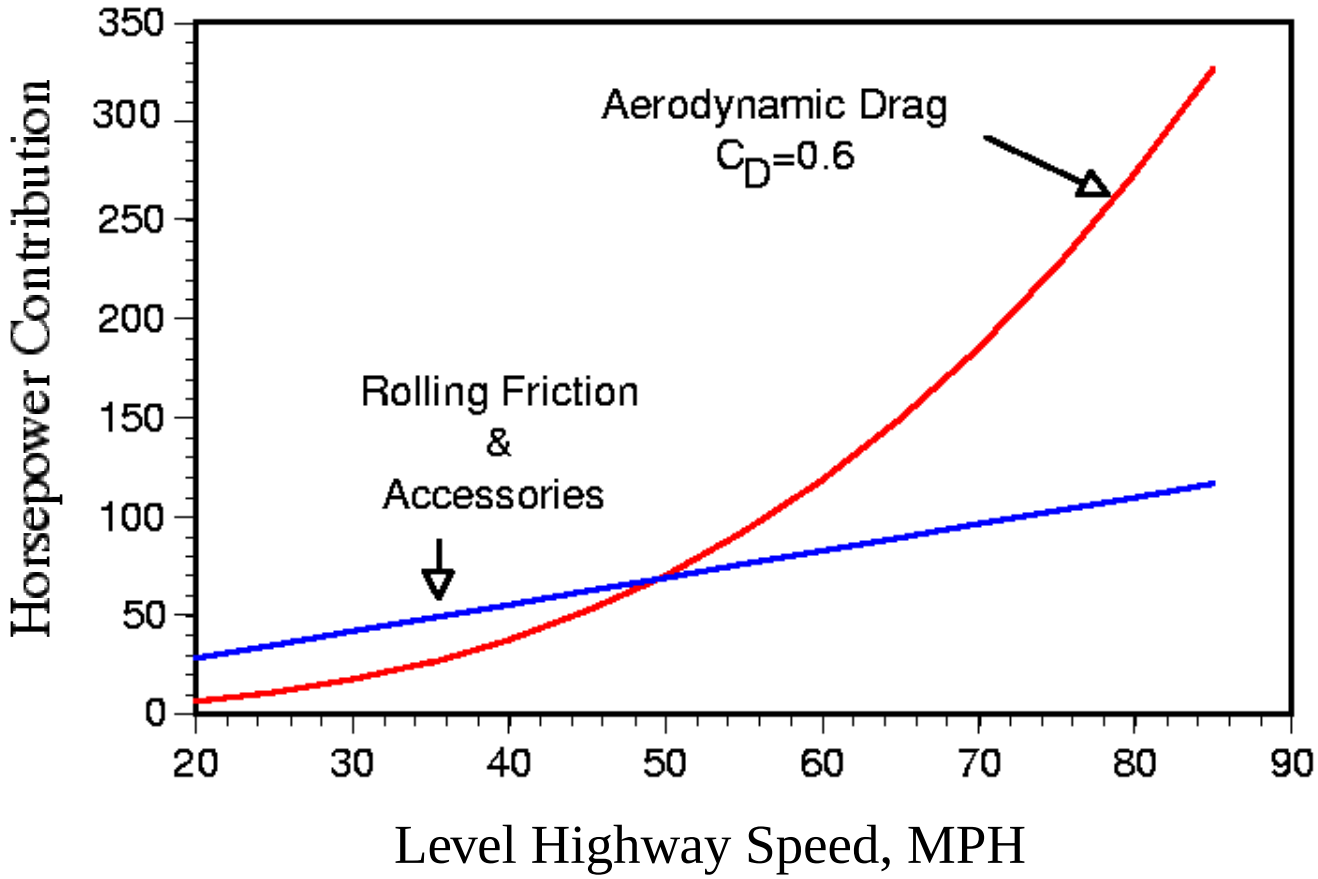
Caltech
California Institute of Technology

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

DOE wants to reduce fuel consumption by reducing aerodynamic drag.

At 70 mph, 65% of the engine's total energy output is in overcoming aerodynamic drag

Typical Class 8 tractor-trailer



The consortium was formed to provide advanced technology to industry.

Needed for significant impact on drag

- Integrated tractor-trailer
- Drag reduction devices
- Aerodynamic
  - Front-end shape components
  - trailer-base underbody
- Improved thermal management (underhood flow)

Technologies

- Coupling experiments and computations for design guidance
  - Advanced computational methods and tools
  - Experimental validation
  - State-of-the-art experimental techniques
- Design and testing

Approach: A marriage of computations and experiments.

Perform high quality numerical computations utilizing a variety of modeling schemes

Perform high quality wind tunnel measurements utilizing the most up-to-date data acquisition—including DPIV

Perform analyses of results and provide detailed comparisons between numerical results and experimental results (and between various numerical schemes)

Make information available to all interested parties

The current project focus is on a validated simulation capability and some design effort.

Computational

- Turbulence modeling
  - Reynolds-averaged Navier-Stokes (RANS) modeling
  - Large-eddy simulation (LES) modeling
  - Detached-eddy simulation (DES) modeling
- Numerical methods
  - Finite difference, finite element, and vortex methods
  - Compressible and incompressible

Experimental validation and phenomena investigation

- Ground transportation system (GTS) cab-over model
  - full geometry, gap distance, and add-ons
- Generic conventional model

Design and testing

- Acoustic device for base pressure/wake control

Name?

GCM?

“Vision”

Applied Research

Industry

Experimental Validation

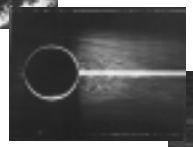
Simple Shapes

GTS

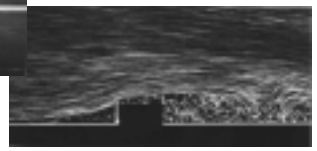
GTS +

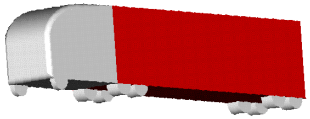
Full Detail Models

Full-Scale Truck Simulation



DPIV, PSP, OFI





RANS
LES
DES

Careful Validation

Future Efforts

This Project fills a void

The process will build confidence in CFD and identify areas in need of further development.

Start simple (numerically and experimentally)

Gain confidence in numerical solutions through established verification and validation processes

Anticipate future revolutionary advances in computer power (push next generation technology)

Demonstrate utility of CFD methods and advanced experimental techniques

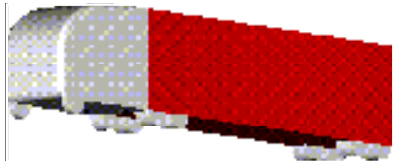
Team with Industry and share "lessons learned", methods, and tools.

We are looking for industry participation.

Accomplishments: The team of experts is established and significant progress has been made.

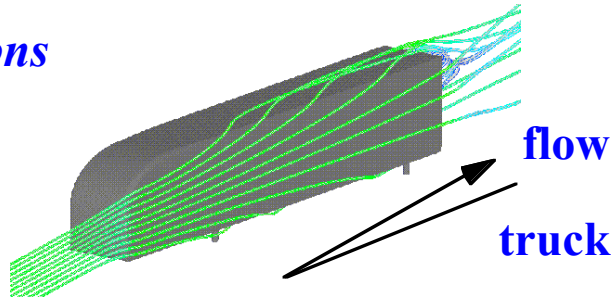
- Established multi-lab, multi-university team
- Multi-year program plan in place
- Experiments completed for baseline case (first time 3D, unsteady velocity field measured in a production wind tunnel)
- Understanding of gap flow phenomena
- Preliminary RANS and LES calculations
- Advanced model development in progress
- Continued data base development
- Preliminary design effort

Baseline Case



Experiments

Computations



FY01 project tasks in order of priority – submitted with budget

- - Analysis of existing experimental data with comparison to RANS, LES, and DES computations,
- - Presentation of results to industry through site visits and conference papers,
- - Investigation of various shapes/configurations in the NASA 7-ft x 10-ft wind tunnel, with preparation for FY02 tests in the 12-ft PWT,
- - Development of an acoustic device for reduction of trailer base drag,
- - Continued development of advanced subgrid models for high Re flows,
- - Continued experimental investigation of various shapes and configurations at lower Reynolds number in the USC wind tunnel,
- - Organization of a special Heavy Vehicle Aerodynamics Session at the March 2002 SAE Meeting, and
- - Organization of an Engineering Foundation Conference.

Break-out by Task

SNL@Albuquerque

- Numerical modeling utilizing Reynolds-Averaged Navier-Stokes and Discrete Eddy Simulation

LLNL@Livermore

- Numerical modeling utilizing Large Eddy Simulation

CALTECH@Pasadena

- Numerical modeling utilizing vortex particles as elements

NASA AMES@Moffett Field

- High Reynolds number wind tunnel testing including 3D DPIV flow field measurement

USC@Los Angeles

- Rapid prototyping and testing at moderate Reynolds number, DPIV flow field measurement

NGV LAUNCH

International Perspective

- Objective:
  - Continue Reducing Aerodynamic Drag of Class 8 Tractor-Trailer System
- Guidelines:
  - Each Truck Industry Has Its Own
  - 21st Century Truck Initiative
    - **Reduce Truck Fuel Consumption while Meeting Emission Requirements**
      - Reduce aerodynamic drag by 25% over 20 years

International Perspective

- Tools used at International
  - In-House
    - **Encouragement from Leadership Team**
    - **Wind Tunnel Tests**
    - **CFD**
    - **Extensive as well as Expensive Knowledge Base of Last 20 Years**
  - External
    - **CFD Software Vendors**
      - International not in Code Development & CFD Vendors not in Wind Tunnel Test
    - **Participation in Activities of Various External Agencies**
      - DOE
      - SAE

Wind Tunnel Test

- An Important Part of Aerodynamics Group for Last 15 Years
- Consistent Procedure
- Expensive and Time Consuming
- Usage
  - Pro-active
  - Re-active
  - Fundamental Study
    - Extensive Wind Tunnel Test Program AISDS - A generic truck
  - Complimenting CFD process establishment for the last 2 years
    - Extensive Wind Tunnel Test Program AISDS - A generic truck

AISDS Scope & Goals

- Goals
  - Better Understand of Truck Shape Interactions
  - Develop Correlation between Wind Tunnel Test & CFD Results
- Approach
  - Multi-Phase Parametric Investigations
  - Surface Pressure Measurements
  - Flow Field Definition

AISDS Model

- Generic mathematically-based shapes

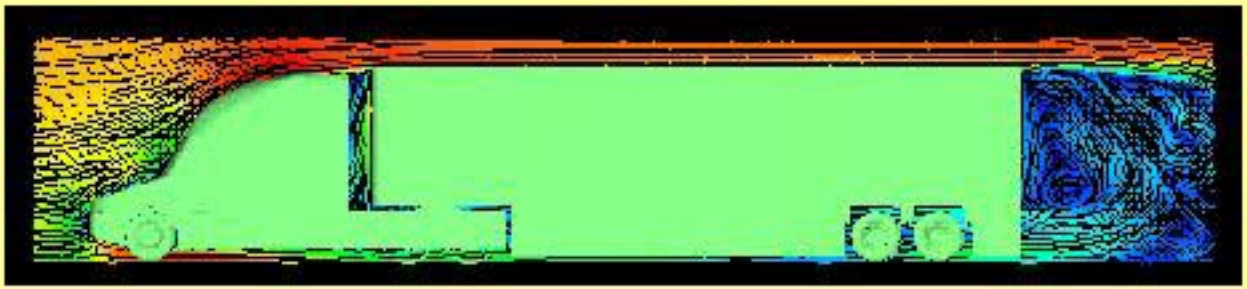
AISDS

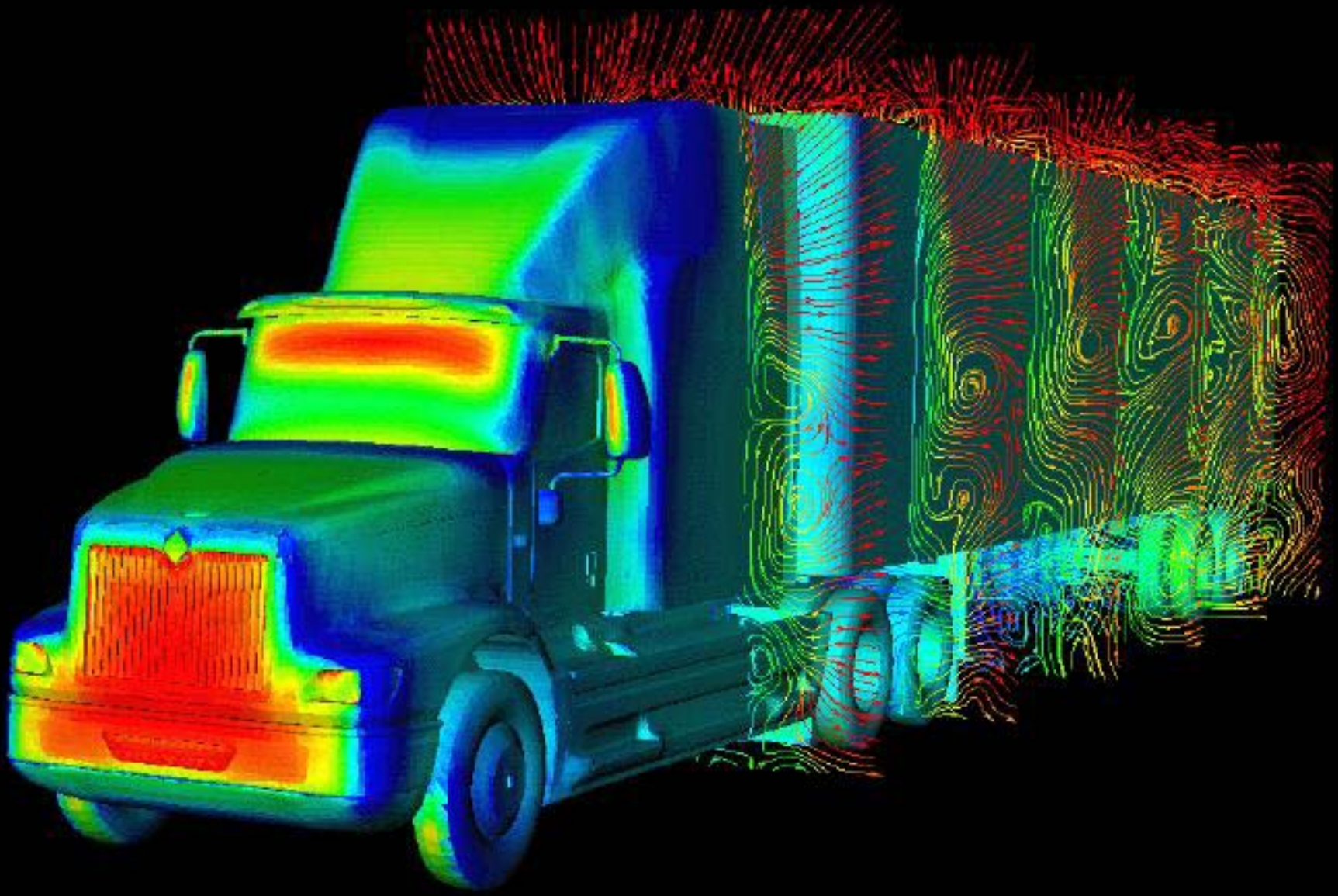
Computational Fluid Dynamics

- In-House Group Established 2 Years Back
- Usage
  - Pro-active
  - Re-active
  - External Flows
    - PowerFlow
  - Internal Flows
    - Fluent
  - Total Vehicle
    - Fluent
  - Correlation with Wind Tunnel Results Being Established

CFD Correlation

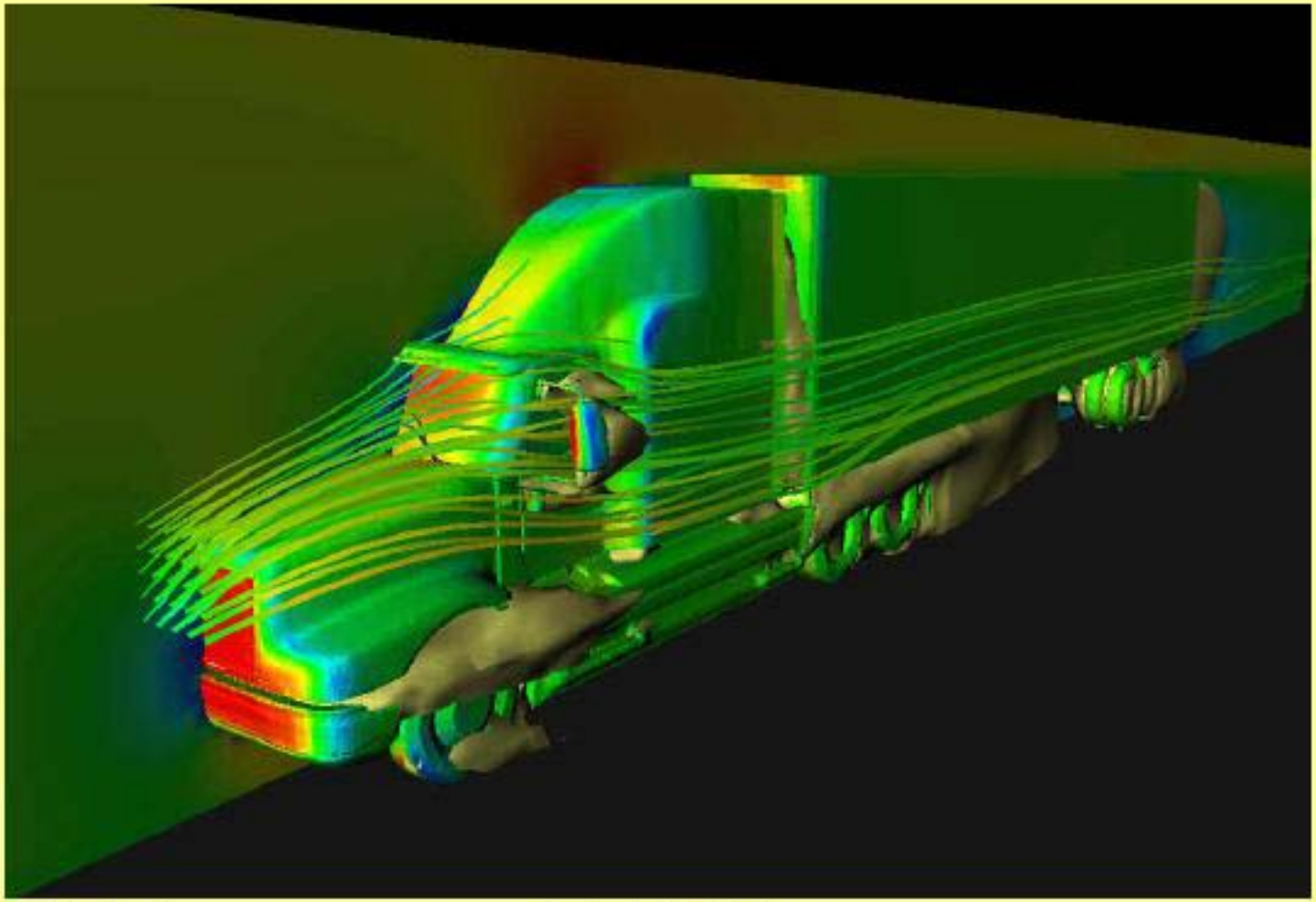
- Numerous Simulations Completed
  - Drag results don't match yet Consistently
  - Good qualitative results
  - Good match with pressures from wind tunnel
- Working with software vendor to resolve accuracy issues
  - Comparison using GTS Model





Exa
CORPORATION

CFD Pro-Active/Re-Active



External Agencies

- DOE
  - Looking for Near Term Benefits
    - Access to the Code
    - Results on GTS Incl. Cd Comparison
    - Suggestions for Improving Truck Aerodynamics
    - Involvement of Software Vendors
- SAE
  - Organizing Upcoming Truck & Bus Meeting
  - Numerous Papers
- RFPs

Roadmap & Conclusion

- Near Term
  - **Establish Cost Effective as well as Sufficiently Accurate CFD Methodology for Truck Configuration Evaluation**
    - Continue CFD correlation studies using PowerFlow 3.2
  - **Integration of CFD in our Future Product Design Process**
- Continue Exploring Technologies for Drag Reduction as well as to Improve our Methodology as well as to Drag reduction
  - **DOE Efforts**
  - **Software Vendors**
  - **Joint Efforts with Various Other Agencies**
- We Believe These Efforts along with Continuous Encouragement from Leadership Team will not only Keep our Products BIC, but also will Help us Move towards the 21st Century Truck Initiative Projection on Aerodynamic Drag.

PACCAR'S VEHICLE-AERODYNAMICS DEVELOPMENT PROGRAM

28 March 2001

PACCAR and Heavy-vehicle Manufacturing Divisions

- Business profile
- Truck divisions

Product Performance Assurance

- Development stages: benchmarking and target setting, advanced concept, prototype validation, production confirmation
- Evaluation/assurance tools: CFD, wind tunnel, vehicle/track

CFD Modeling Tools

- Star-CD
- EXA
- Others

Wind Tunnel Experiment Tools

- Sub-scale test
- Full-scale test

Vehicle/Track Confirmation Tools

- Pressure test
- Force test
- Energy (fuel) test

PACCAR'S INPUTS TO DOE'S HEAVY VEHICLE AERODYNAMIC DRAG PROGRAM

28 March 2001

Helpful Tools and Techniques

1. Evaluation of selected CFD codes (NASA, DOE, and commercial) suitable for analyses of heavy vehicles. Advice in their capabilities and limitations (including accuracy and computing speeds vs. costs) for specific applications.
2. Similarly, advice in available technologies and techniques for wind-tunnel experiments and road evaluations that would facilitate the development of more-aerodynamic vehicle models.
3. Development of new reference-vehicle model, replacing the existing GTS model, that would be more similar in geometry to the vehicles on the road today.
4. Analysis and correlation of the above reference model for CFD, wind-tunnel, and full-scale vehicle experiments to demonstrate drag-reduction practices and suggest design guidelines.

Helpful Analyses for Specific Vehicle Areas and Components

5. Effect of trailer gap and gap-reduction devices/treatments, and the integration between tractor and trailer for drag reduction.
6. Underbody airflow as influenced by ground proximity.
7. Wheel-well effect and splash/spray (also fouling) performance.
8. Under-hood (engine compartment) airflow and interaction with external aerodynamics for optimized energy conservation.
9. Base-pressure distribution around the vehicle for not only drag evaluation but also in-cab flow optimization (HVAC and exhausters) and wind-noise reduction.
10. Wind/yaw-angle effect on aerodynamic performance of vehicles and components.

Task Overview

- Evaluation of current Technology
- Support of Testing Activities
- Liason with industry
- Other near term aero activities
  - Removal of mirrors

Evalutaion of Current Technology

- Selected Public Codes
  - USM3D - unstructured, multi-block, preconditioned
  - Overflow -overset multi-block, preconditioned
  - INS3D -overset multi-block, incompressible
- Selected Commercial Codes
  - Fluent
  - Star CD
  - EXA Powerflow

Evalutaion of Current Technology

- $ Agreements have been reached with holders of each code
- $ EXA, Adapco and Fluent will donate computing power
- $ Overflow and INS3D will run on Athlon PC (~500M RAM)
- $ Need PC cluster or supercomputer for USM3D
- $ <u>Waiting for 'as built' geometry</u>

Support of Testing Activities

- $ Geometric modeling
- $ Assisted in pressure tap location
- $ Assisting in planning and execution of vortex generator tests

Liason with Industry

- Conversations with Frieghtliner, Mack and PACCAR reveal two strong themes.
  - <u>Efforts to provide validation data should be continued and expanded.</u>
    - High Reynolds number tests
    - Calibrated road tests
    - Underhood data
  - <u>Convert analysis focus to design focus</u>
    - Accelerated convergence
    - Solution perturbations
    - Parametric geometry methods
    - Optimization methods or design space navigation

Other near term aero activities

- Removal of mirrors
  - Fuel savings of 1% to 3%
  - Significant increase in safety
- Multi-agency meeting to discuss roles.
- DOT has started visibilty studies

Heavy Vehicle Aerodynamic Drag Working Group Meeting

Results with a Commercial Tool

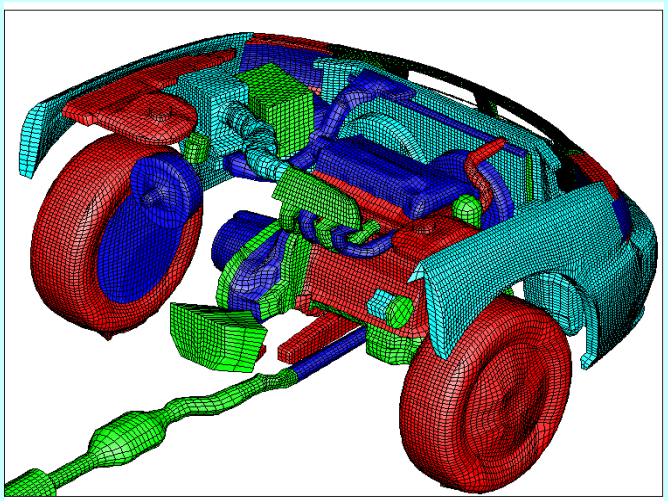
David P. Weber
Tanju Sofu

March 28, 2001

Argonne National Laboratory

Underhood Thermal Management

- Cooperative Research and Development Agreement with adapco, GM, Ford, DaimlerChrysler and ORNL
  - Fan, Radiator and Heat Transport System Models
  - Improved Numerics in CHAD
  - Radiation Heat Transfer Model
  - Verification & Validation

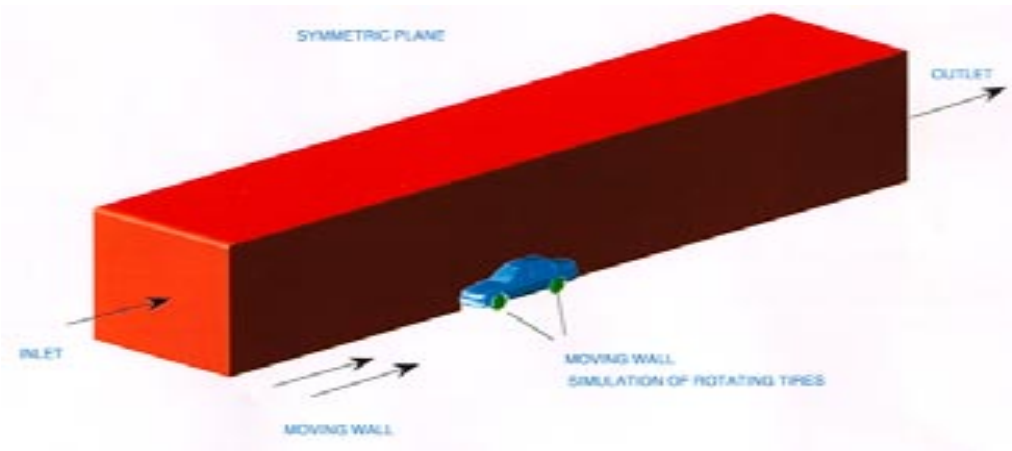


- Hybrid Vehicle Thermal Management with adapco
  - Exploratory Use of STAR-CD for Hybrid Vehicles
  - Comprehensive Model of Underhood Environment
  - Validation through utilization of ANL Hybrid Vehicle Experimental Test Facility

- Virtual Reality for Examination of Results
  - Application of High Performance Application of High Performance Computing to Automotive Design and Manufacturing

MODEL DESCRIPTION

- The model consists of flow domain that approximates a wind-tunnel like environment for a stationary car (ground moving)

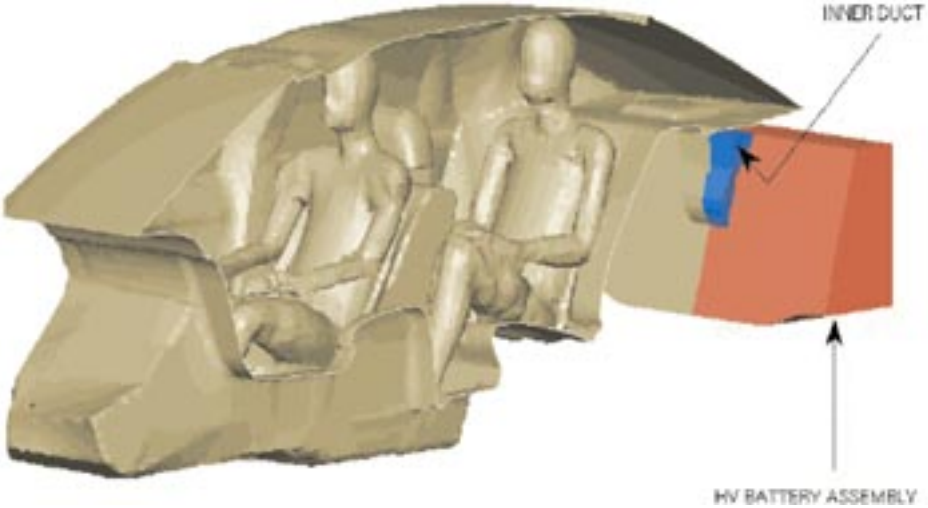


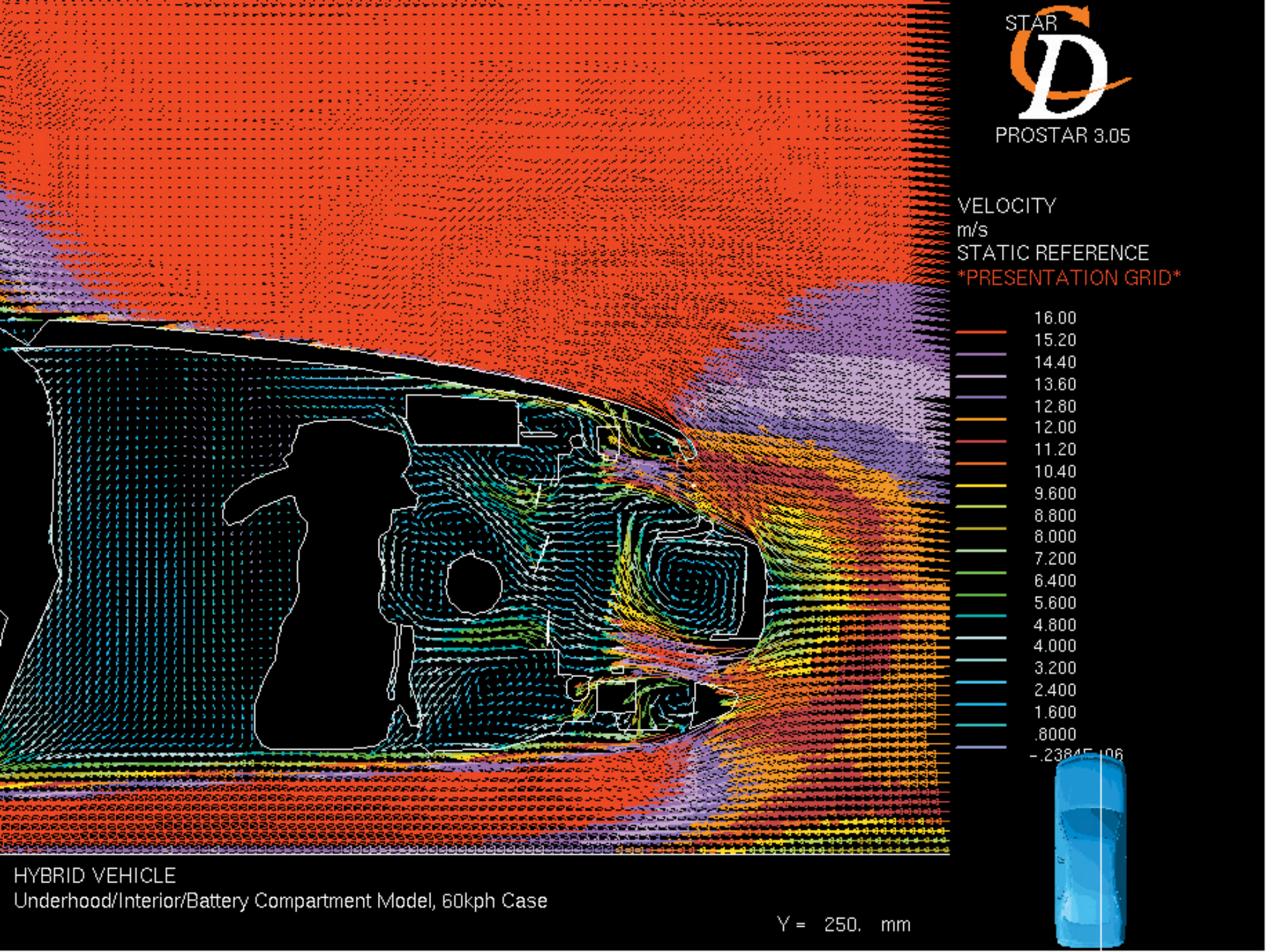
Boundary Conditions for Vehicle Speed of 60 km/h

Air Inlet Velocity	16.67 m/s
Air Inlet Temperature	20 ^{o}C
Ambient Pressure	1.0 atm
Wheel Speed	500 rpm
Coolant Flow Rate	1.0 kg/s
Coolant Inlet Temp.	85 ^{o}C
Fan Speed	1350 rpm

MODEL DESCRIPTION (cont.)

- Entire vehicle (including the passenger compartment) is represented to model various interrelated airflow phenomena and thermal activity
- Combining 3-D flow and heat transfer into one large model allows assessment of inherent interdependency of components




STAR
PROSTAR 3.05
VELOCITY
m/s
STATIC REFERENCE
PRESENTATION GRID
16.00
15.20
14.40
13.60
12.80
12.00
11.20
10.40
9.600
8.800
8.000
7.200
6.400
5.600
4.800
4.000
3.200
2.400
1.600
.8000
HYBRID VEHICLE
Underhood/Interior/Battery Compartment Model, 60kph Case
Y = 250. mm

adapco

Drag Comparisons

New Model Turn Around Time: 2-7

Vehicle	Description	Case	Drag	Difference
A-Class	Medium Detail	Baseline- 1999 v3050	0.300	1.4%
		Baseline-Edges	0.307	1.0%
		Baseline-No Edges	0.306	0.6%
		Experiment	0.304	
		Mod 2	0.278	3.0 %
		Experiment	0.270	
Large Sedan	Low Detail	EZAero	0.281	4.1%
		Experiment	0.270	
Benchmark 1	Low Detail Small Vehicle	EZAero	0.212	0.5%
		Experiment	0.213	
Benchmark 2	Low Detail Slanted Rear	EZAero	0.280	1.4%
		Experiment	0.276	
Truck	Medium Detail 6 million cells	EZAero	0.815	0.6%
		Experiment	0.820	

Heavy Vehicle Simulations with STAR-CD

Heavy Vehicle Aerodynamic Drag Working Group Meeting
Lawrence Livermore National Laboratory

Tanju Sofu
March 28-29, 2001

Argonne National Laboratory

Summary and Outline

- Results with a commercial tool for two industrial applications
  - Commercial Truck Analysis
    - Aerodynamic simulation of reference design
    - Drag coefficient comparisons for three proposed design changes
  - Integrated Systems Simulation (aerodynamic and underhood cooling analysis)
- Both simulations are performed by adapco, Inc. using STAR-CD
  - “On the road” simulation
    - symmetry boundaries
    - stationary vehicle
    - rolling wheels, ground moving
  - Combined 3-D flow and heat transfer in a large model for assessment of inherent interdependency of components
  - Blind Pre-Test Analyses

Commercial Truck - Reference Design

- Detailed geometric modeling starting from CAD surfaces (full suspension and undercarriage included)
- Unstructured mesh with refinements (10 million cells)
  - Near walls
  - Under the truck
  - In the cabin-trailer gap
  - Behind the truck
- Analysis for reference design demonstrates a steady flow field (not oscillating). κ-ε model is used.

Commercial Truck - Reference Design

Aerodynamic simulation (frontal area 9.44 m^2)

- Drag coefficients:

	STAR-CD	Wind Tunnel
0º Yaw	0.815	0.82
10º Yaw	1.613	1.51

- Reported values for C_d are raw measurements prior to any correction factors due to the walls of wind tunnel
- Calculated values are for “on the road” simulation (closer to a corrected value)
- Blind Pre-Test Calculations

Commercial Truck - Case Comparisons

Calculated Drag Coefficients

	0° Yaw	10° Yaw
Reference Case	0.815	1.613
Case 1: New gap fairing	0.807 (1% reduction)	1.576 (2% reduction)
Case 2: Full aerodynamic kit	0.751 (8% reduction)	1.472 (9% reduction)
Case 3: Idealized truck design	0.583 (29% reduction)	0.994 (38% reduction)

Integrated Systems Simulation

- A two-axle compact truck
- Aerodynamic and underhood analysis
- Unstructured mesh with refinements near walls, under the truck, under the hood, and behind the truck (20 million cells)
- “On the road” simulation at 85 km/h
- Geometric details included (full suspension and undercarriage)
- Calculated drag coefficient = 0.583
- Model for underhood flow and thermal analysis
  - Radiator as a dual-stream, single phase heat exchanger
  - Condenser as a dual-stream, two-phase heat exchanger
  - Fan rotation modeled with implicit multiple reference frames
  - Effect of bottom cover on underhood cooling estimated

Turbulence Modeling Options

- κ-ε models
  - Standard model (high Re form in conjunction with 'law of the wall' representation of flow, heat and mass transfer within boundary layers)
  - Damping function based low-Re model (κ and ε equations solved everywhere, including the boundary layers)
  - Renormalization group (RNG) variant and Chen's version (employs both the production and dissipation time scales in closing the ε equation)
  - Alternative non-linear (quadratic and cubic) κ-ε models for High- and Low-Re flow
- Two-layer models. Near wall flow is simulated via either
  - κ equation and an algebraic prescription for ε (single equation model)
  - Mixing length model (turbulent viscosity from Prandtl's mixing length hypothesis)

Turbulence Modeling Options (cont.)

- Large Eddy Simulation
  - large-scale turbulent motion is explicitly solved while small scale eddies are approximated by a model (sub-grid scale Reynolds stresses are also included)
- V2F (Stanford) model through a license from Cascade Tech. Inc.
  - Full low Re model (valid throughout the flow domain including the viscous-affected near-wall region)
  - Accurate prediction of flow-separation, skin friction, and heat transfer

Conclusions

- Aerodynamic analyses with STAR-CD for two commercial trucks
  - Rapid model development with semi-automated mesh generator
  - Full geometric details for a first-principles based analysis
  - Good agreement for drag coefficient estimations
  - Case comparisons for design improvements
- Integrated aerodynamic and underhood cooling analysis for the entire vehicle
  - A systems simulation capability for studying load conditions
  - Assessment for interdependence of underhood components
  - Tool for identifying critical components and their long-term reliability

Draft of SAE Paper 2001-01-2072
to be Presented at the SAE Government/Industry Meeting,
DOE OHVT-Systems Session, Dr. Sid Diamond, Chairman
Washington, DC
May 16, 2001
Draft date: April 2, 2001

Advanced Aerodynamic Devices to Improve the Performance, Economics, Handling and Safety of Heavy Vehicles

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ABSTRACT

Research is being conducted at the Georgia Tech Research Institute (GTRI) to develop advanced aerodynamic devices to improve the performance, economics, stability, handling and safety of operation of Heavy Vehicles. The objective of this program is the application to tractor/trailer configurations of pneumatic (blown) aircraft technology previously developed and flight-tested by GTRI personnel. Earlier GTRI experimental results using blowing on a streamlined car wind-tunnel model had shown drag coefficient reductions of up to 35%, plus lift increases or reductions (downloads) of 100-150%, depending on the blowing location and the force direction desired. Also demonstrated was the ability to control aerodynamic moments about all three axes without any moving control surfaces.

Recent wind-tunnel investigations of a generic Pneumatic Heavy Vehicle model with blowing slots on both the leading and trailing edges of the trailer have been conducted under contract to the DOE Office of Heavy Vehicle Technologies. These results have shown overall aerodynamic drag reductions on the Pneumatic Heavy Vehicle of over 50% using only 1 psig blowing pressure in the plenums, and over 80% drag reductions if additional blowing air were available. Blowing-reduced drag coefficients of less than half that of a Corvette coupe were measured experimentally. Furthermore, an increase in drag force for braking was made possible by blowing different slots. Lift coefficient increase was generated by blowing only the top slot, while downforce was produced by blowing only the bottom. Also, side force and yawing moment were generated on either side of the vehicle and directional stability was restored by blowing the appropriate side slot.

These experimental results and the predicted full-scale payoffs are presented in this paper. Also provided is an introduction to this new aerodynamic/automotive technology, plus discussion of additional applications to conventional commercial autos, buses, and Sport Utility Vehicles, as well as to Formula 1 and other race cars.

INTRODUCTION

Users of heavy trucks such as tractor/trailer combination vehicles face a number of less than optimum operating conditions. Despite significant reductions in drag coefficients in the latest generation of tractors, these Heavy Vehicles (HVs) remain "draggy" compared to much more streamlined automobiles. This is due in part to practical limitations on: physically providing a long smooth aft surface such as a boat tail to prevent flow separation and turbulence at the rear of the trailer; completely sealing the gap between the tractor and the trailer; and smoothing the underbody of the vehicle. In addition, front radiators have not been optimized from a drag-reduction standpoint. Typical drag coefficient values for a variety of HVs can range from 0.65 to 0.9 (from Reference 1). Figure 1 shows the significant fuel savings that can result if the drag coefficient can be reduced. It has been estimated by engineering personnel of the American Trucking Associations (ATA) that, if applied to today's US Heavy Vehicle fleet operating on level roads, these drag reductions approaching 35% could result in roughly 1.2 billion gallons of fuel saved per year. Extrapolated, a 50% drag reduction could save over 1.7 billion gallons of diesel each year. A further result of aerodynamically "dirty" vehicles is the production of splash and spray, a nuisance to motorists and truck drivers alike, as well as turbulence in the vicinity of large vehicles, which is disturbing to passenger car drivers. These shortcomings are explained further in the ATA Statement of Need for Improved Heavy Truck Aerodynamics, Reference 2.

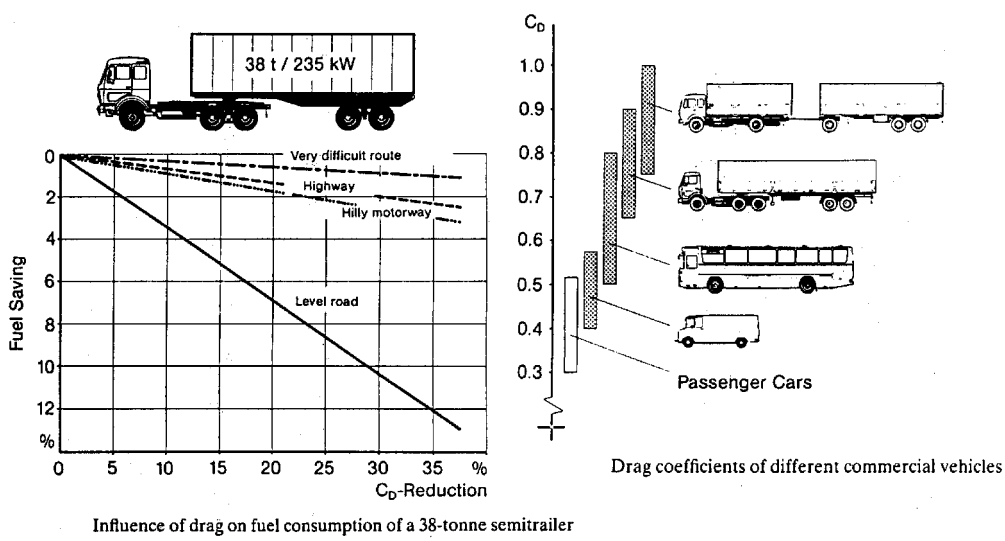


Figure 1 – Effect of Drag Coefficient Reduction on Fuel Consumption (from Ref. 1)

Considerable recent interest has arisen in techniques to reduce Heavy Vehicle drag to improve highway operating efficiency, primarily because the drag force rises with the square of the vehicle speed while the required horsepower to overcome that drag increases with the cube of the truck's velocity. With fuel prices rising dramatically recently, drag reduction is thus a vital concern to the trucking industry. However, there is significant reason to believe that appreciable additional gains can also be had by careful control of aerodynamic forces and moments other than drag, which for the most part have been ignored in current truck design and operation. For instance, the creation of lift on the vehicle (effective weight reduction) can unload the tires and reduce rolling resistance, while creation of negative lift or downforce can increase "weight" on the wheels and traction, thus increasing braking as well as handling in wet/icy weather. This aerodynamic download can also eliminate hydroplaning. While it has been shown that drag increases greatly due to side wind or yaw angle (Refs. 1 and 3), this also implies increased side force and yawing moment on the trailer, thus reducing its directional

stability and safety. Safety, stability and handling can be enhanced by blowing control of side loads and moments on these Heavy Vehicles if caused by side winds, gusts or other vehicles passing. This pneumatic concept may also help to eliminate the jack-knifing problem if resulting from extreme wind side loads on the trailer. Lastly, there are instances where additional drag increase is desirable, such as steep downhill operations in mountains, or sudden need for emergency braking from high speed.

Based on the above considerations, it should be quite desirable to develop aerodynamic devices that could achieve two or more of these potential gains while requiring little mechanical restriction or impact on vehicle operation. Recent aerodynamic research (Reference 3) at GTRI's Aerospace, Transportation and Advanced Systems Lab has identified significant reductions and/or augmentations of vehicle forces and moments which can be achieved on automotive vehicles by the use of tangential injection of pressurized air into the vehicle's aft boundary layer, strongly modifying the aerodynamic flowfield around that vehicle. Since momentum injection can affect the vehicle's lift, drag, and side force as well as aerodynamic moments, the impact of blowing on the performance, safety, economics and stability appears to offer significant improvements in Heavy Vehicle operation. These potential gains have led to a current research program being conducted at GTRI for the DOE Office of Heavy Vehicle Technologies (Reference 4). A basic description of this program and the novel aerodynamic technology to be employed is provided in Reference 5. Since that paper was presented in June, 2000, two series of wind-tunnel evaluations have been conducted at GTRI to confirm aerodynamic improvements yielded first by novel unblown geometry changes, and second by the addition of blowing to various portions of a Heavy Vehicle model. The objectives of these tests were to verify the blown pneumatic concept's capabilities to: reduce aerodynamic drag for efficiency or increase drag for braking; increase lift (and thus reduce tire rolling resistance) or reduce lift (and thus increase traction and braking); and provide increased lateral/directional stability and safety, all without use of external moving aerodynamic components. The present paper describes the basis of pneumatic aerodynamics and its application to Heavy Vehicles, and then provides details of the two wind-tunnel programs, their results, and possible future applications.

PNEUMATIC AERODYNAMICS

GTRI researchers have been involved for a number of years in the development of pneumatic (pressurized air blowing) concepts to yield efficient yet mechanically simple means to control and augment or reduce the aerodynamic forces and moments acting on aircraft. This was detailed in References 5, 6, 7, and 8, but will be summarized briefly here to familiarize the reader with the technology. Figure 2 shows the basic pneumatic concept, which has become known as Circulation Control (CC) aerodynamics. Here, an airfoil's conventional mechanical trailing edge device has been replaced with a fixed curved surface and a tangential slot ejecting a jet sheet over that surface. That jet remains attached to the curved surface by a balance between sub-ambient static pressure on the surface and centrifugal force (the so-called Coanda Effect, Reference 8). This greatly entrains the external flowfield to follow the jet, and thus enhances the circulation around the airfoil and the aerodynamic forces produced by it. The governing parameter is not angle of attack, but rather the blowing momentum coefficient:

$$C_\mu = m\, V_j / (q\, S)$$

where m is the jet mass flow, V_j the isentropic jet velocity, S is a reference wing area (or frontal area for a vehicle configuration) and q is the freestream dynamic pressure, $0.5\, \rho\, V^2$, with ρ being the free-stream density, not the jet's density. At lower blowing coefficient (C_μ) values, augmentation of the aerodynamic lift by a factor of $\Delta C_l / C_\mu = 80$ has been recorded, representing an 8000% return on the invested momentum (which in a physical sense is also equal to the jet thrust). Familiarity with

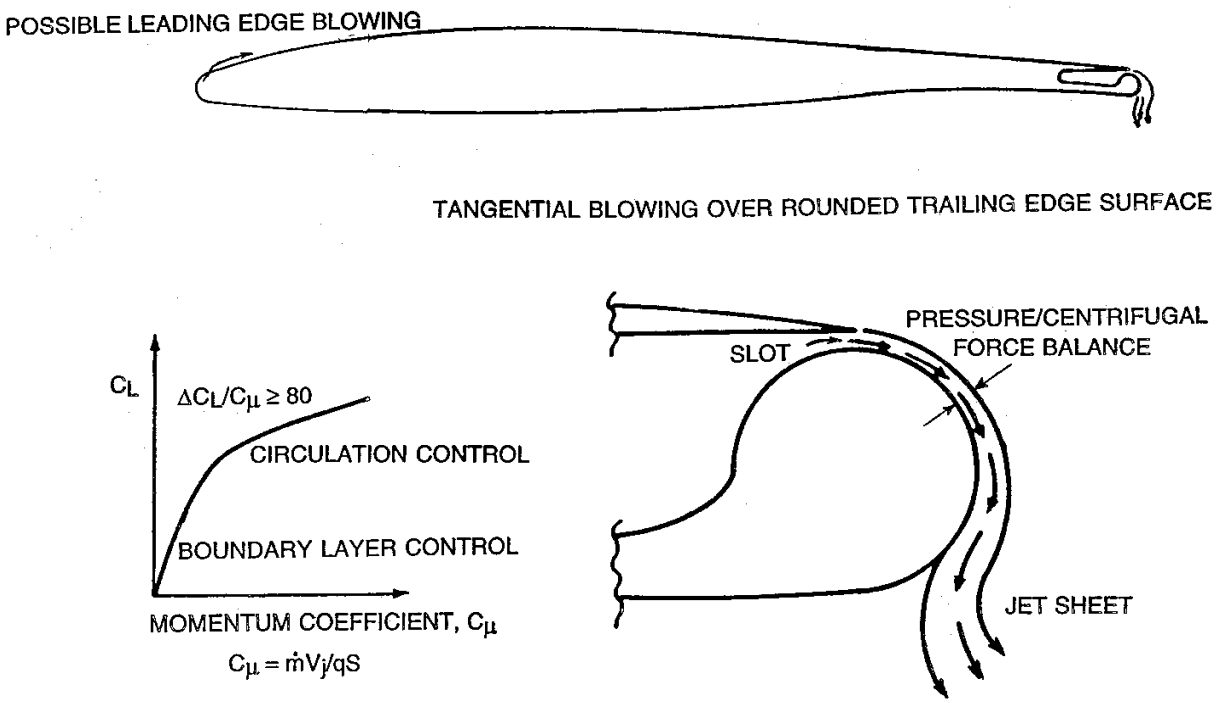


Figure 2 – Basis of Circulation Control Aerodynamics on a Simple 2-D Airfoil

blown aerodynamic systems will remind the reader that this is quite extraordinary: thrust-deflecting Vertical Take-Off and Landing (VTOL) aircraft are fortunate if they recover anything near 100% of the engine thrust expended for vertical lift. It is because of this high return, and conversely, because of very low required blowing input and associated power required to achieve a desired lift, that Circulation Control airfoils appear very promising for a number of applications. The A-6/CC Wing Short Take Off & Landing (STOL) flight demonstrator aircraft, Figure 3 and Reference 6, showed the STOL performance listed, but also suggested capabilities very useful to ground vehicles: during short takeoff, it demonstrated very high lift and reduced drag, while in the approach/landing mode, high lift with high drag was shown.

These advantages led to the application of this pneumatic concept to improve the aerodynamics of an already streamlined car (Reference 3). The resulting large jet turning angle and the curved rear of the vehicle are shown in Figure 4. Significant but distinctly different trends were observed depending upon which portion of the tangential slot was blown. Blowing the full slot produced the large jet turning in Figure 4, and drag increases of greater than 70%, showing potential for pneumatic aerodynamic braking. Blowing only the outside corner of the slot weakened the corner vortex rollup, lessened aft suction, and reduced drag by as much as 35% (refer back to Figure 1 for representative fuel savings). Blowing the aft slot also yielded a lift increase of 170%. One can envision a similar slot applied to the lower surface that could yield negative lift or positive down force instead. This concept has been patented by GTRI and verified by a similar installation on a model of a European Formula 1 race car (Reference 5).

Flight Test Results: 140% Increase in Usable Lift Coefficient, C_L
30-35% Reduction in Takeoff & Approach Flight Speeds
60-65% Reduction in Takeoff & Landing Ground Rolls
75% Increase in Liftable Takeoff Payload
Confirmation of Full-Scale Blown CCW Operation

Figure 3 – A-6/CCW STOL Flight Tests Confirming Pneumatic Devices for Aerodynamic Force Augmentation or Reduction

Figure 4 - Experimental Confirmation of Pneumatic Technology on a Streamlined Car; Aft View showing Blown Jet Turning

DOE PNEUMATIC HEAVY VEHICLE PROGRAM

Based on the above results, a research program was funded at GTRI by the Department of Energy's Office of Heavy Vehicle Technologies (Reference 4). The goal was to apply this pneumatic technology to tractor-trailer configurations to develop an experimental proof-of-concept evaluation that would hopefully lead to an on-the-road demonstration on an operating blown Pneumatic Heavy

Vehicle (PHV). Portions of that effort, including a preliminary feasibility study, pneumatic Computational Fluid Dynamics (CFD) analyses, and design of baseline and pneumatic wind-tunnel configurations, have been completed and were reported in Reference 5. Figure 5 shows a possible schematic of a generic Pneumatic Heavy Vehicle with tangential blowing slots on each of the trailer's aft edges as well as blowing on the rounded upper leading edge of the trailer.

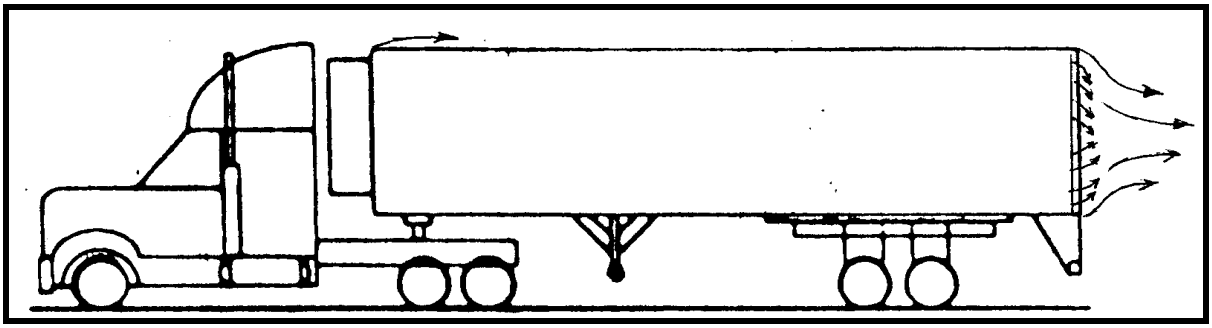


Figure 5 – Schematic of Application of GTRI Pneumatic Aerodynamic Technology to Heavy Vehicle Trailer, Showing 4 Aft Blowing Slots and Upper Leading-Edge Blowing Slot

Phase I Wind-Tunnel Evaluations of Baseline Unblown HV

To serve as a reference data base and to investigate initial non-blown aerodynamic improvements, a Phase I baseline wind-tunnel test was conducted. For this, a baseline model was needed to act as a standard prior to the planned blowing tests, and as a basis upon which to install the pneumatic model configuration. A team of current researchers working for DOE on the HV aerodynamic drag problem had determined that an existing generic Heavy Vehicle configuration, the Ground Transportation Systems (GTS) vehicle (Reference 9), was quite appropriate. It is sketched in Figure 6, and is actually representative of a faired cab-over-engine vehicle based on the Penske racing team's car carrier, before the blowing modifications shown. As such, it is relatively generic and independent of the numerous and varying cab roof fairings employed on a number of current Heavy Vehicles.

Full Scale Vehicle: W=8.5', H=13.5' , $L_{TRAILER}$=48', L_{RIG}=65'; at V=70 mph, $Re_{Tlr}=29.3\times10^6$

Model:

Blockage	W,in.	H,in.	Scale	$L_{Trailer}$, in.	L_{Rig},in.	$Re_{Trailer}$ (V=70mph)	$Re_{Trailer}$ (q=50psf)
0.051	6.63	10.53	.0650	37.44	50.70	1.90×10^6	3.90×10^6

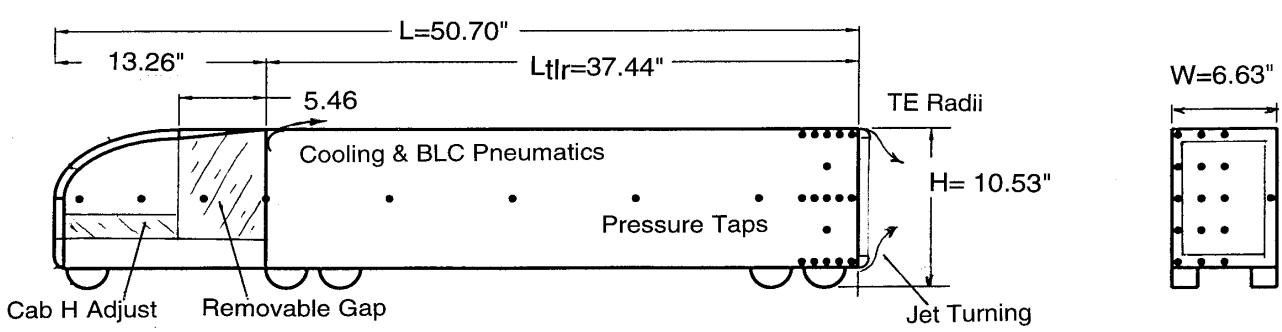
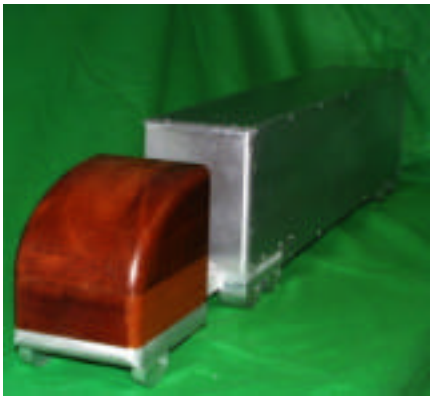


Figure 6- GTRI 0.065-scale Baseline GTS & PHV Wind-Tunnel Model and Variables

Full-Height Tractor and Yawed Trailer
with Rounded Leading Edge and Square Trailing Edge



Shorter-Height Tractor, Unyawed Trailer

Front Wheels removed

Figure 7 – Photos of Various Configurations of GTRI's Baseline GTS Model, Full Open Gap

Before being fabricated as a valid wind-tunnel model, issues such as model size, wind tunnel blockage and test Reynolds number were important. The test model was scaled to be compatible with the GTRI tunnel test section area of 1290 in^2. Based on Reference 10 criteria, a physical blockage of 5 to 6 percent of tunnel area was desired, as well as reasonably high Reynolds number. Figure 6 shows that a 0.065-scale model produces a blockage of 5.1% and Reynolds number based on trailer length of 1.90×10^6 at V=70 mph, or 3.90×10^6 at maximum tunnel speed. These factors were incorporated into the Figure 6 design, and fabricated into the model of Figure 7 by prototype shop Novatek Inc. of Smyrna, GA. Here, a number of parameters are variable, including cab/trailer gap, cab height, a removable gap fairing, trailer leading-edge and trailing-edge radii, wheels on/off, vehicle height above the road (floor) and yaw angle between the tractor and trailer. The model was mounted on a single strut, which was hollow and was later used as the blowing air supply duct into the model. This strut was mounted on a six-component floor balance below the tunnel floor, which could be yawed and raised vertically to vary ground clearance height. The test setup will be very similar to that described in Reference 3 for the blown streamlined car test program. Particle imaging laser velocimeter data was used to quantify the flowfield characteristics aft of the vehicle.

The Phase I unblown investigations were intended to determine the effects of various cab/trailer geometries prior to initiation of the blowing tests. Figures 8 and 9 are plots of drag coefficient (based

on a model truck projected frontal area of A=0.4542 ft^2, including the wheel projections) versus freestream dynamic pressure, $q = 1/2\ \rho\ V^2$. Reynolds number (now based on vehicle total length) and several wind speeds in mph are also shown. The uppermost curve of Figure 8 shows a cab height lower than the trailer height, and a rather large gap (0.824 x width) between the cab and trailer. The flow visualization tuft seen in the gap shows significant separation and vorticity there, and the flow unsteadiness is also seen in the data-point scatter for that run. Raising the cab height to a value level with the trailer reduces the drag coefficient by 7% at 70 mph because it shields the sharp square leading edge of the trailer. Then, filling the gap entirely ("Hi Cab, No Gap") reduces C_D by another 20.1%, or 25.7% from the initial configuration. Whereas this solid configuration is not actually possible because of the need for some clearance/movement between the cab and trailer, it does represent an ideal, which might nearly be achieved by flexible connections. Figure 8 also notes the significant drag reduction if the wheels are removed. This also is not a feasible configuration, but identifies the large increment which must be added back to model test data or CFD predictions for non-wheeled vehicles. Notice in all of these runs that as the regions of separated flow are reduced, so also are the C_D values and the C_D variations with Reynolds number, i.e., the C_D versus q curves become flatter, and the percentage drag reductions become greater. For reference, the full-scale HV at 70 mph would experience a Reynolds number of 40.0×10^6 at sea-level standard-day conditions.

Figure 9 shows additional drag reductions due to further geometry improvement. Run 19 is the "No Gap" configuration from Figure 8, and the curve immediately above it shows a drag increase if the no-gap cab is lowered slightly to expose the square leading (LE) edge of the trailer. This is an actual condition seen on many current faired HVs, where the fairing frequently does not extend high enough to totally shield the trailer's square top LE corner. However, for the same height difference, if the square top LE of the trailer is merely rounded (here a 3/8"radius is sufficient), C_D is reduced by 8.3%. Then, if a 90° arc with 3/4" radius is added to each of the aft edges of the trailer (this represents the unblown pneumatic trailing edge (TE), see Figure 21 of Reference 5), an additional 7.3% drag reduction occurs due to aft flow reattachment and reduced separation. Thus, adding unblown LE and TE round corners reduces drag by 15% over the square LE/TE configuration. Significant improvement has been achieved by the pneumatic LE and TE geometries before blowing has even been applied. It should be noted that in both of these figures, and in all the following data, the HV model was situated so that the wheels were 0.06" above the tunnel floor, and the tunnel boundary layer was eliminated by tangential floor blowing (see Reference 3).

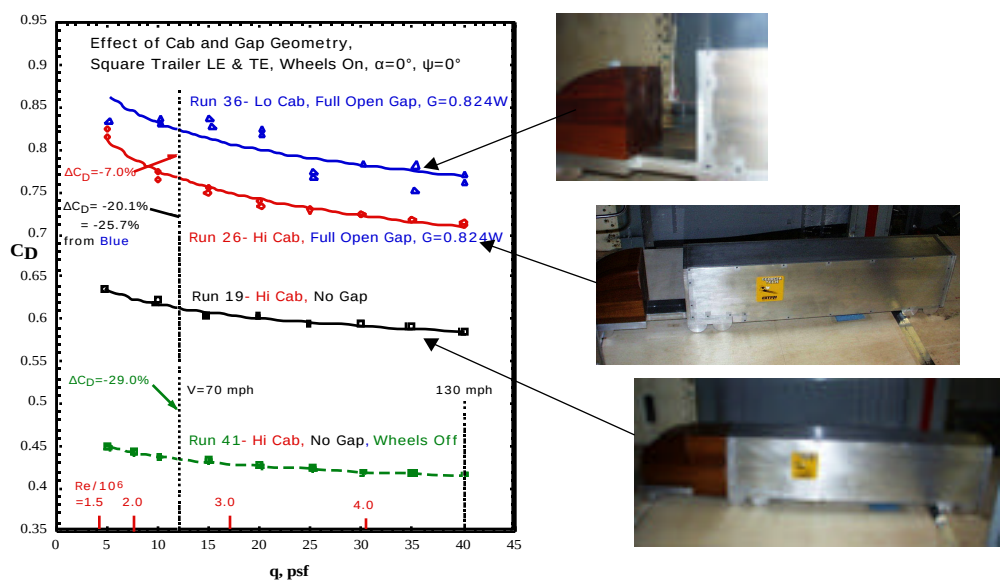


Figure 8 – Phase I Test Results for Unblown Configurations, Showing Effects of Cab Height, Cab/Trailer Gap, Reynolds Number and Wheels

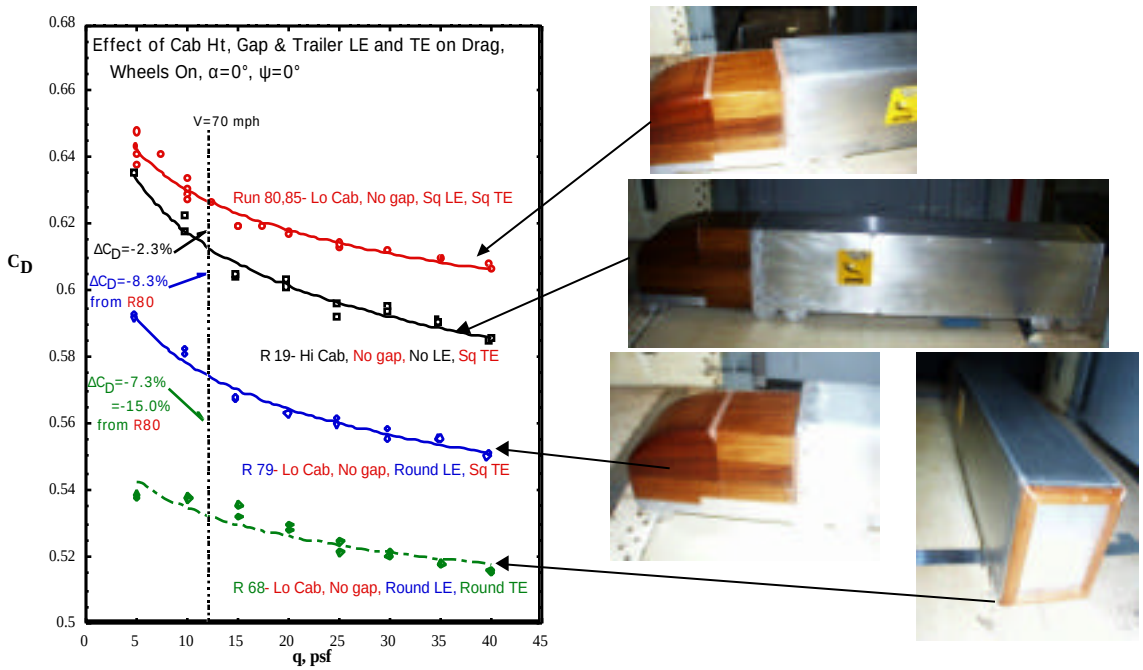


Figure 9 – Phase I Test Results for Unblown Configurations with No Gap, Showing Effects of Cab Height and Trailer Leading- and Trailing -Edge Geometries

Phase I also investigated the effects of side winds (or yaw angle) on the forces, moments and stability of the unblown HV. Figure 10 shows drag variation with side-wind angles up to ±15°. Not only do the open-gap configurations have higher zero-yaw drag values, but they also show dramatic drag increases by a factor of 2 or more with side winds as low as only 5-7° due to higher separation and greater yawed-flow over-pressures on the trailer front face. The "no-gap" models show much lower zero-yaw drag as well as lesser drag increases with yaw because these detrimental gap effects don't occur. Figure 11 shows resulting side force and yawing moment for these same configurations. Whereas there is little difference in side force (C_Y) for those configurations, the models with a gap show much less yawing moment (C_N) versus yaw angle and thus much less loss in directional stability ($C_{N\psi} = dC_N/d\psi$) than the non-gapped models. Thus the lower-drag "No-Gap" HVs may encounter a problem with directional stability as shown here.

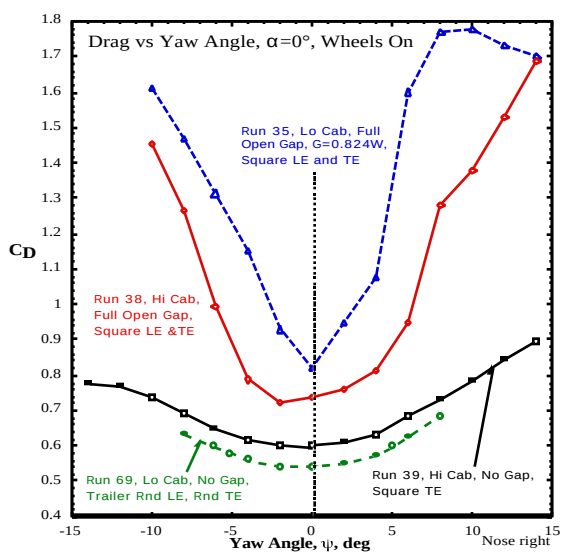
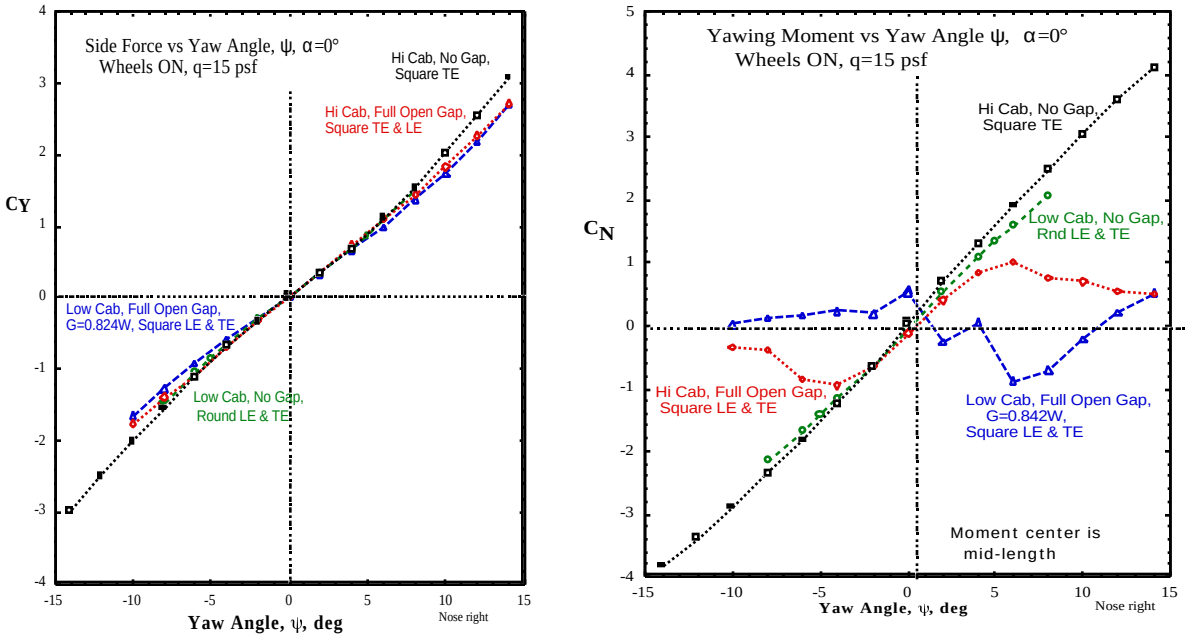


Figure 10 – Effects of Side Winds on Drag for Various Unblown HV Model Configurations



Side Force Yawing Moment about Mid-Length

Figure 11 – Effects of Side Winds on Stability: Side force and Yawing Moment Variation (Postitive $dC_N/d\psi$ is unstable)

Phase II Wind-Tunnel Evaluations of Blown Heavy Vehicle Configurations

Based on the lower-drag configurations of Phase I, Phase II was intended to thoroughly evaluate the additional aerodynamic improvements resulting from various blowing arrangements. Phase II consisted of 99 wind tunnel runs evaluating a range of pneumatic configurations and parameters, including:

- Blown trailer trailing-edge (TE) radius, jet turning angle, jet slot height, blown slot combinations and TE geometry modifications
- Blown trailer leading-edge (LE) radius and blown slot combinations
- Blowing pressure, jet velocity, mass flow, and momentum coefficient, C_μ
- Tunnel dynamic pressures from 5 to 40 psf, wind speeds from 67.3 to 190.3 ft/s (45.9 to 129.8 mph) and Reynolds number (based on tractor/trailer total length) from 1.61×10^6 to 4.61×10^6
- Trailer wheel configuration
- Gap between cab and trailer, plus gap side plates
- Yaw (side wind) angle

Details of these investigations are presented in the following sections and emphasize near-term aerodynamic improvements generated by these pneumatic devices. Unless otherwise noted, the

blowing variations were run at tunnel (vehicle) wind speeds of approximately 70-71 mph (q=11.86 psf) and blowing slot heights set at h= 0.01" if not closed.

Drag Reductions (Fuel Economy) or Increases (Braking & Stability)

The slot heights at each aft edge of the trailer could be tested either blown or unblown in any combination of the 4, or later, with the leading edge slots on the trailer front face also blown. For best drag reduction, simultaneous blowing of all 4 of the aft trailer slots proved more effective than blowing individual slots. Flow visualization tufts in Figure 12 show jet turning of 90° on all four sides, even the bottom slot blowing upwards. This is the 0.75" radius TE configuration. Figure 13 shows even greater turning for the smaller radius (0.375"R) TE surfaces. This smaller radius on the 0.065-scale model represents a full-sized turning radius of only 5.77". Figure 14 shows the results of this jet turning on reducing or increasing aerodynamic drag by blowing various combinations of these aft slots. In order to represent meaningful values of the jet velocity/free stream velocity ratio, these data were run at blockage-corrected tunnel speeds of approximately 70-71 mph, dynamic pressure of 11.86 psf and Re=2.51×10^6 based on tractor/trailer length. The combination of all 4 slots at the same slot height blowing together yielded the greatest drag reduction. Compared to the typical unblown baseline configuration from Phase I (full gap between cab and trailer, square trailer LE and TE, and cab fairing slightly lower than the trailer front) which produced a C_D =0.824 at this Reynolds number, the blown configuration reduced drag coefficient to 0.459 at C_μ = 0.065. This is a 44% C_D reduction, and the internal plenum blowing pressure required was only 0.5 psig. A second blown configuration (labeled 90°/30° TE) used less jet turning on the upper and lower surfaces to generate even greater drag reduction: at 0.5 psig, C_D was reduced by 47%, and at 1.0 psig (C_μ=0.13), C_D was reduced by 50%.

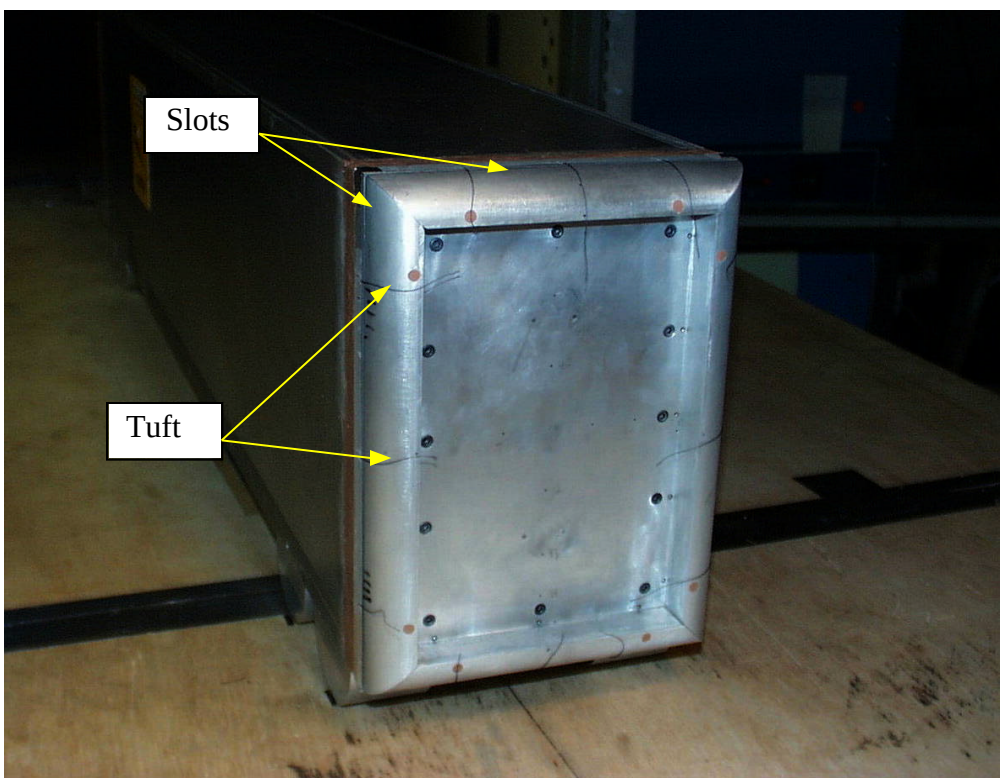


Figure 12–Jet Turning on all 4 Sides of Blown TE, 0.75"R

Figure 13 – Jet Turning on Smaller 0.375”R, 90°/30°Blown Trailer TE with 1/2“ plates

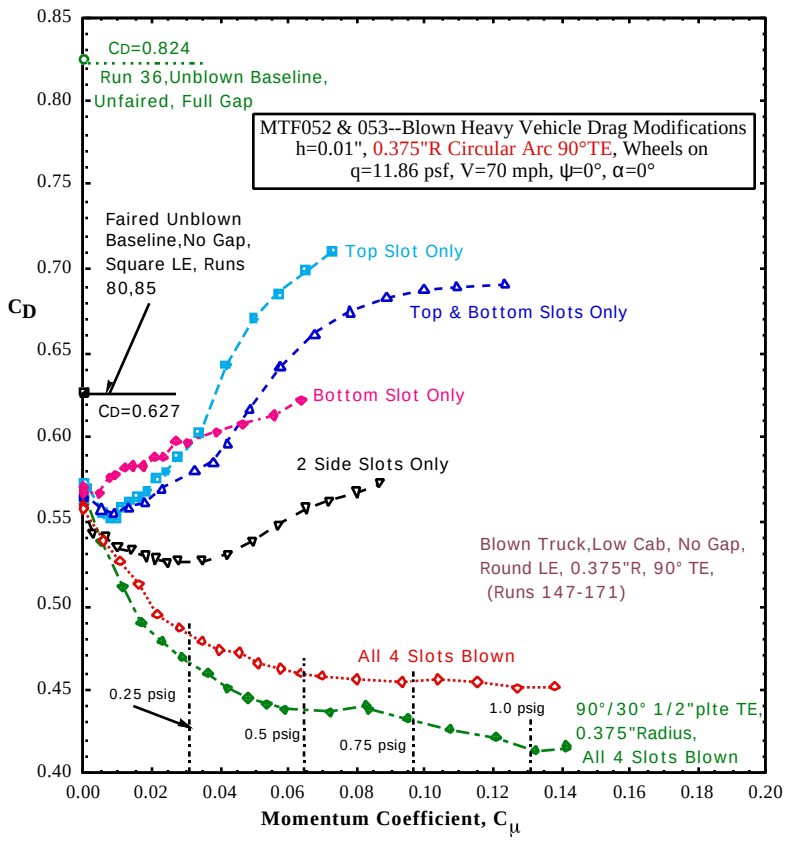


Figure 14 - Drag Reduction or Augmentation on Blown Trailer with 0.375"R Turning Surfaces

When only the top slot, the bottom slot, or both of these slots were blown in the absence of the side jets, drag initially reduced, but then significantly increased with the addition of blowing. This represents an excellent aerodynamic braking capability to supplement the hydraulic brakes. Blowing

efficiency is plotted in Figure 15, where ΔC_D is an increment from the blowing-off value (negative ΔC_D is reduced drag). Absolute values of $\Delta C_D/C_\mu$ greater than 1.0 represent greater than 100% return on the input blowing C_μ = (total mass flow x jet velocity) / (tunnel dynamic pressure x frontal area). It is seen that the 4-slotted configuration generates values as high as -5.50, representing 550% of the input blowing momentum recovered as drag reduction. The figure also shows the opposite trend as well, with up to 200% of the blowing momentum from top/bottom slots recovered as increased drag for braking. When $\Delta C_D/C_\mu$ is less than ±1.0, the blowing efficiency diminishes. However, should additional air be available from an onboard source such as an existing turbocharger or an electric blower, additional drag reduction is possible, as shown in Figure 16. The drag on the previous "worst unblown baseline configuration" with a large open cab/trailer gap is reduced 30% by the blown configuration. Drag coefficients of less than 0.30 are shown for faired blown HV configurations. This is in the arena of streamlined sports cars. (The drag coefficient of a 1999 Corvette coupe is C_D = 0.29.) Figure 17 shows drag reductions as high as 590 to 600% of the input blowing momentum for the Figure 16 configurations, with the greatest reductions occurring on the previous "worst" unblown configurations due to their large regions of separated flow. Figure 18, originally intended to show that the drag curves tend to converge onto one slope independent of Reynolds number, also shows a measured drag coefficient of 0.13 for a Pneumatic Heavy Vehicle. Even though not achieved in the most efficient blowing operation range, this is an 84% drag reduction compared to the unblown baseline configuration. Note that the tractor cab in Figure 18 has "gap plates" (or fairing extensions) instead of the full "No Gap" fairing, and is thus much closer to actual tractor/trailer configurations.

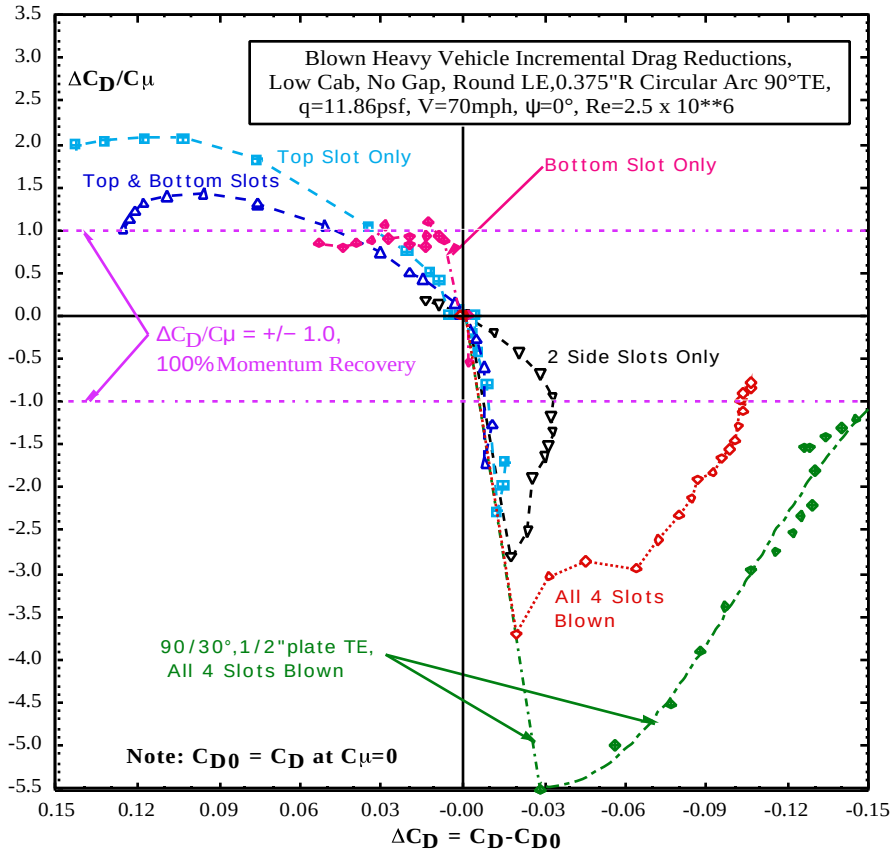


Figure 15 - Blowing Efficiency & Drag Increments due to Blowing Slot Configuration

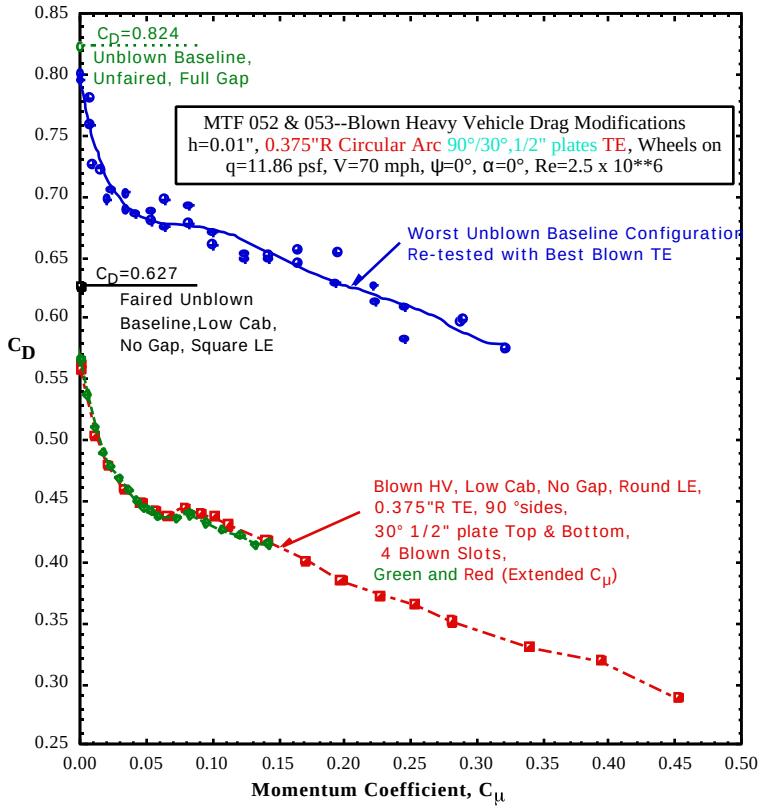


Figure 16 - Additional Drag Reductions and Comparative Configurations

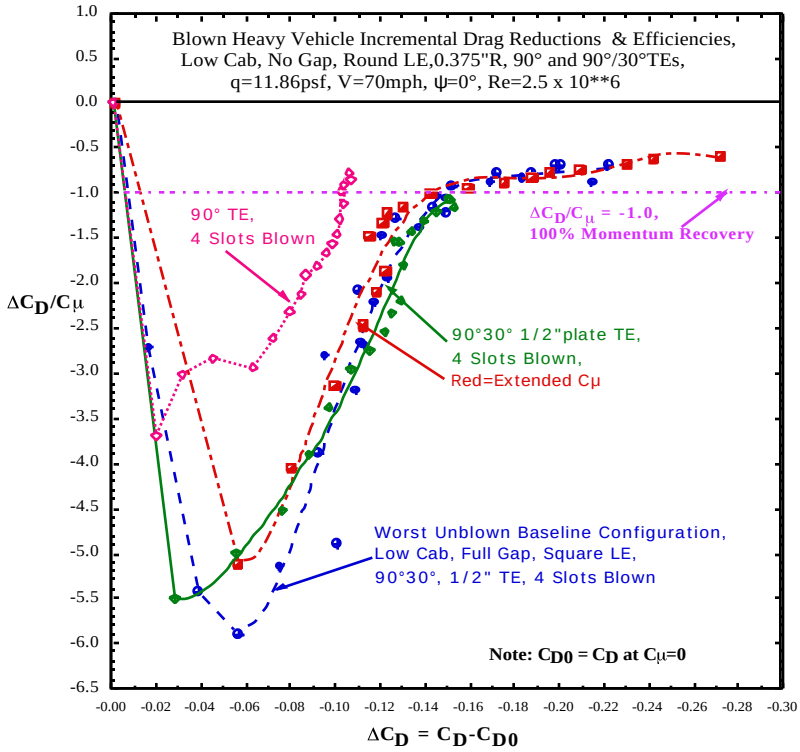


Figure 17 - Blowing Efficiencies and Drag Increments at Increased Blowing Levels

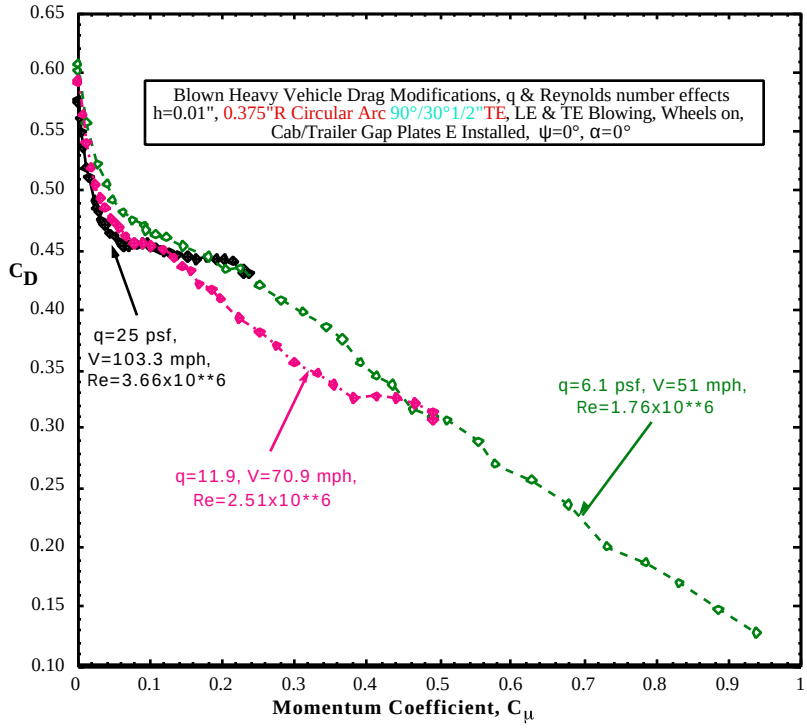


Figure 18 - Reynolds Number Effects and Increased Blowing Values, Plus Leading-Edge Blowing and Cab Gap Plates

It should again be mentioned when comparing these data to other experiments on similar GTS models being conducted by other researchers, that these GTRI data above and below include simulated wheels, which as Figure 8 shows, should add about $\Delta C_D = 0.18$ to these non-wheeled vehicles' C_D values, perhaps more, depending on how well the tunnel ground effects are treated experimentally. GTRI measured data are generated using test section tangential floor blowing to eliminate the floor boundary layer interference, as discussed in References 3 and 11.

Lift and Down Force Generation

Figure 19 shows lift and down force generated by various slot combinations for the blowing configurations of Figure 14. The baseline unblown configurations show slight positive lift due to underbody overpressures and cab upper surface curvature. Blowing the trailer upper slot alone can more than triple these values, which can be used to "lighten" the vehicle and thus reduce tire rolling resistance. Conversely, blowing the bottom slot can generate a down force increment 2.5 times the unblown lift, which can thus increase traction, increase braking, and reduce hydroplaning.

Stability and Control

Strong directional instability can be experienced by Heavy Vehicles at yaw angles (i.e., experiencing a side wind) because of large side forces on the flat-sided trailers (see Figure 11). Figure 20 shows the model yawed and the unblown aft pneumatic surfaces. This yaw sensitivity is confirmed by the unblown ($C_\mu = 0$) yawing moment shown in Figure 21, where yaw angle as small as -8° produces a large unblown yawing moment coefficient of C_N=-2.0 about the model mid-length.

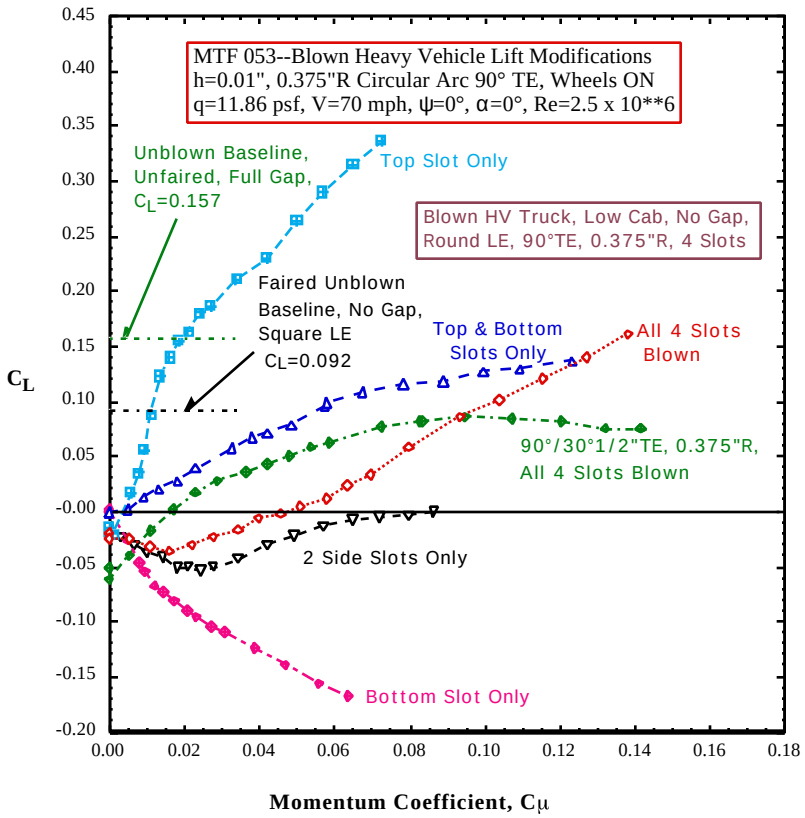


Figure 19 -Lift and Downforce Generation on Blown Trailer with 0.375"R Turning Surface

Figure 20 - Pneumatic Heavy Vehicle Model Installed Yawed (at Side-Wind Angle) in the GTRI Model Test Facility Subsonic Wind Tunnel

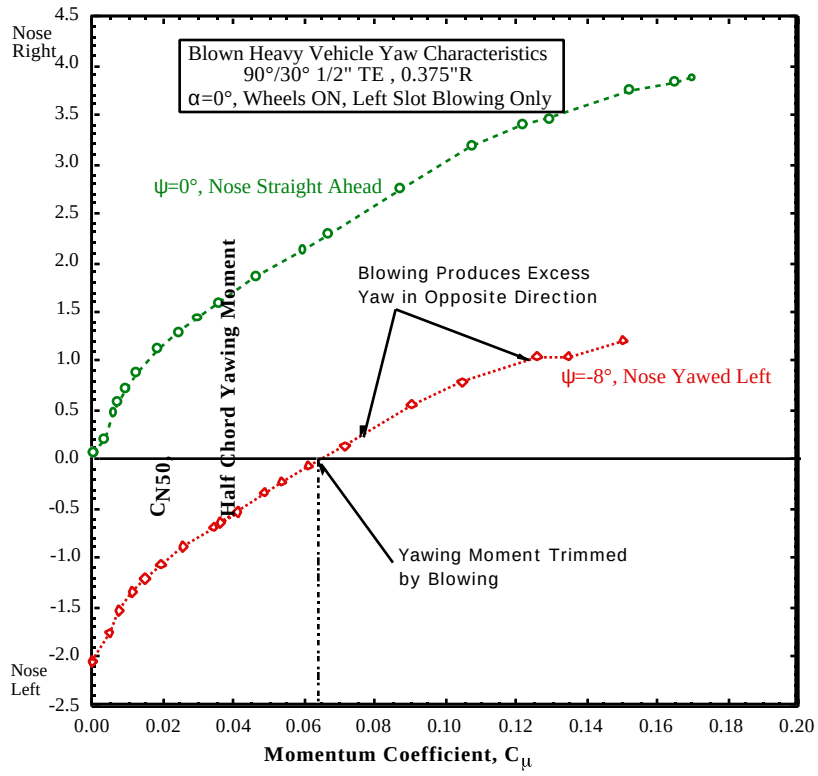


Figure 21 - Directional Control Capability Provided by Blown HV Configuration

Blowing only one side slot can easily correct this: with the nose straight ahead, blowing the left slot at C_μ = 0.06 yields the equivalent opposite yawing moment (C_N=+2.0). With the nose yawed left (for example, ψ = -8°), slightly higher blowing (C_μ = 0.065) returns this unstable yawing moment to C_N=0.0. Then, increasing the blowing a bit more causes the nose to yaw in the opposite direction, to the right. The opportunity for a no-moving-part quick-response aerodynamic control is apparent.

Feasibility Study: Blowing Effect on Performance and Blowing Power Required

To evaluate the effects on performance which can be produced by the above pneumatic changes in aerodynamic lift and drag, required power was calculated for a range of highway speeds. Figure 22 shows the results for a hypothetical 65,000 pound 18-wheel tractor-trailer rig with a frontal area of 107.5 sq. ft. traveling over flat highway at sea level. Three cases are considered: a conventional rig with C_D = 0.80 (from Figure 1, typical); a pneumatic rig showing a 35% drag reduction (i.e., the pneumatic streamlined car's drag reduction levels); and a pneumatic rig with a 50% drag reduction below the conventional rig (from Figure 14). This produces the three "Aerodynamic" horsepower-required curves, where drag force $D = C_D\ q\ A = C_D\ (0.5\ \rho\ V^2)\ A$, and $HP_{req'd} = DV/\ 550$. Thus the required *aerodynamic* horsepower reduces in the same proportion as the drag coefficient, i.e., 35 or 50% at any given speed. Also included here is horsepower required to overcome rolling resistance of the tires, which is directly proportional to effective weight on the wheels times the effective tire friction coefficient, taken here to be 0.015. For the conventional rig, the HP to overcome rolling resistance varies linearly with velocity. For the blown configurations, lift varies with blowing available and dynamic pressure, so the "effective weight" of the vehicle reduces as the lift increases proportional to V^2. The upper curves are the total horsepower required at the wheels (exclusive of gearing and

internal engine losses), so total engine horsepower required would be greater. For these cases, at a sample speed of 70 mph, the horsepower required for the conventional rig to overcome drag plus rolling resistance can be reduced 24% by the lesser pneumatic configuration and 32% by the more effective one. If fuel consumption is reduced proportionally, these numbers indicate considerable increase in cruise efficiency for these blown vehicles. Note also how blowing lessens the dominance of aerodynamic drag at higher speeds. For the conventional Heavy Vehicle, horsepower required to overcome drag is equal to horsepower to overcome rolling resistance at about 66 mph, but that speed moves to about 77 mph for the 35% C_D reduction curve, and to 86 mph for the 50% C_D reduction.

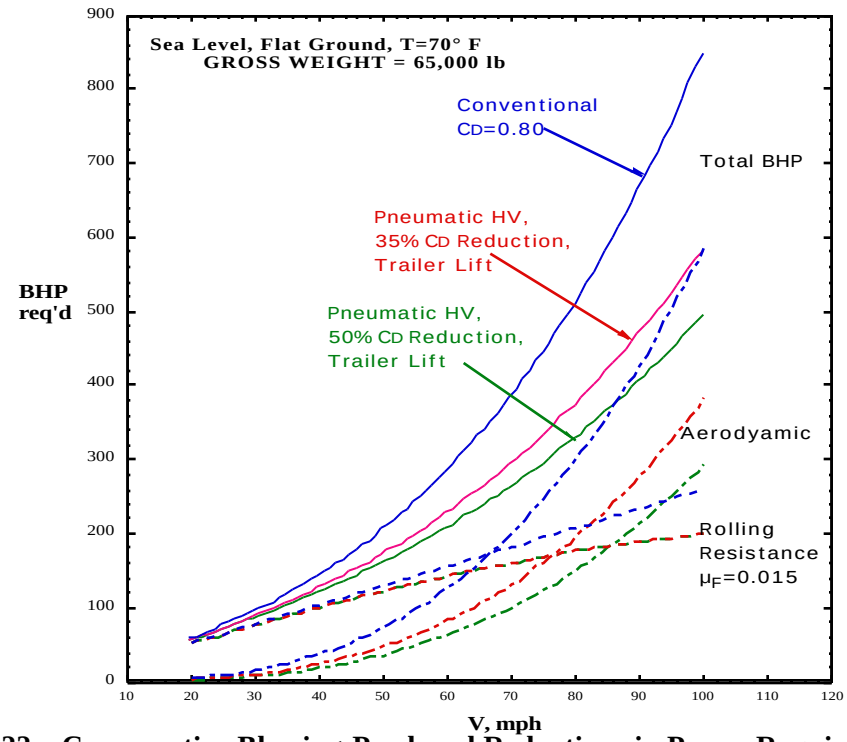


Figure 22 – Comparative Blowing-Produced Reductions in Power Required to Overcome Drag and Rolling Resistance

To the discussion above must be added a consideration of any power expended to compress the air for aerodynamic blowing. Figure 23 makes this comparison, where the blowing performance is derived from the lowest C_D vs C_μ curves of Figures 14 and 16 (these are the same configurations). In Figure 23, the C_D is converted to horsepower required at a typical speed of 70 mph using the equations above with q=11.86 psf. This yields Curve A, $HP_{aero\ required}$, which when subtracted from the HP value for the baseline unblown reference configuration yields Curve B, showing $HP_{aero\ saved}$. At this speed, the compressor HP required to compress the air from ambient to the C_μ required is given by Curve C, $HP_{pump} = \Delta P\ Q / 33000$, where ΔP is the pressure rise required in psf and Q is the volume flow rate through the slots in ft^3/min. Then the net HP_{saved} is Curve D, which is the difference $HP_{aero\ saved} - HP_{pump}$. A maximum HP_{saved} occurs between $C_\mu = 0.05 – 0.06$, and is 43% below the baseline HV, slightly less than the 50% HP_{saved} from C_D reduction alone without compressor power removed. HP_{saved} continues to be positive until about C_μ =0.355, at which point $HP_{aero\ saved} = HP_{pump}$. Note, however, that if the blowing power were obtained totally from the output of a turbocharger waste gate at cruise speed (i.e., no extra blowing power required), then $HP_{pump} = 0$ and HP_{saved} would converge to Curve B, which continues to increase until C_μ reaches the limits of the turbo output. In reality, the

saved horsepower curve would probably end up somewhere between Curves B and D depending on the turbocharger, but this still represents HP_{saved} of at least 43% of the baseline vehicle's aerodynamic horsepower required.

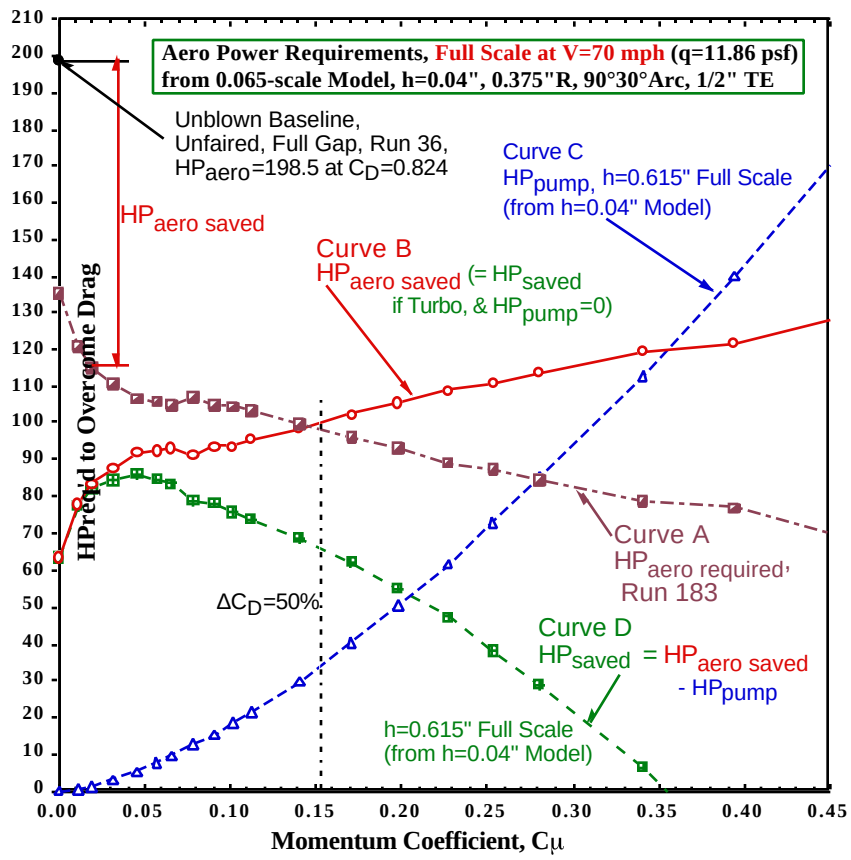


Figure 23 – Horsepower Required to Overcome Drag at 70mph, plus Required Compressor Power and Horsepower Saved

ADDITIONAL APPLICATIONS OF PNEUMATIC AUTOMOTIVE AERODYNAMICS

In addition to HV usage, the above results appear quite promising to other forms of automotive vehicles. Clearly, buses and Sports Utility Vehicles are also prone to large drag values and directional stability issues due to aft flow separation and large side panels exposed to side winds. These vehicles do offer the built-in advantage that rear corners as well as front corners are usually already at least partially rounded, and thus application of a blown system like that above would be easier than on square-edged HVs whose design doesn't want to yield internal volume in the trailer. Discussions between GTRI personnel and representatives of these industries are already underway. The possible payoffs are implied in Figure 24, which plots yearly fuel consumption in the US for various vehicle types (from References 12 and 13). Whereas automobile fuel usage is relatively level in recent and projected years, values for HVs and buses continue to rise with year, but light trucks and SUVs continue to rise at a much greater rate. Reduction in drag levels could help considerably here, especially relative to highway "cruise" fuel usage. GTRI personnel have also been contacted by motor home users, as these vehicles are likely to have squared and draggy front and rear corners causing high drag and fuel consumption. Another possible application is relative to improving aerodynamic performance of trains, not only high-speed bullet trains but also the very boxy freight trains. For these

boxy trains, the key to large economic improvements depends on the average operating speed of these connected vehicles. In a related application, GTRI is also currently developing a patented aerodynamic heat exchanger that is based on these pneumatic principles and can further reduce the drag associated with the vertical radiator and related cooling system, while also adding favorable aerodynamic characteristics to the vehicle.

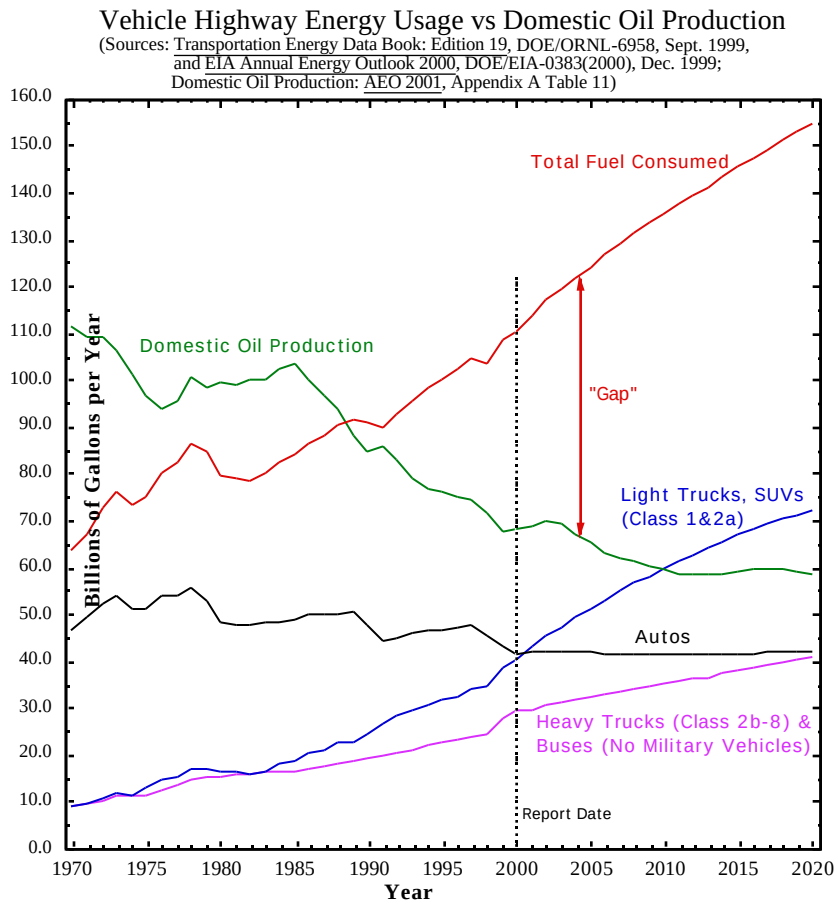


Figure 24 - Highway Energy Usage Comparisons by Vehicle Type

CONCLUSIONS

Blown and unblown wind-tunnel evaluations have been completed at GTRI in a research program conducted for the DOE Office of Heavy Vehicle Technologies to develop, evaluate, and apply pneumatic aerodynamic devices to improve the performance, economy, and safety of operation of Heavy Vehicles. The data presented above confirm the aerodynamic potential of Pneumatic Heavy Vehicle configurations. Summarizing the above:

- Drag coefficient can be pneumatically increased or decreased as desired to multiples of as high as 600% of the input blowing momentum coefficient, $C\mu$.

- Drag coefficient reductions of as much as 50% were produced with internal blowing pressures of only 1.0 psig; C_D values as low as 0.13 (an 84% drag reduction from the baseline HV model) were measured at increased blowing rates.

- Variable slot combinations and blowing Cμ variations yielded drag decrease for fuel efficiency, or drag increase for braking and stability.

- Variable slot combinations and blowing Cμ variations yielded lift increases for reduced rolling resistance, or down force increases for additional traction and/or greater braking

- Blowing one side slot alone generated sufficient yawing moment to restore directional stability and offset side force due to gusts or side winds on large trailer side panels.

Thus all the original objectives for this Pneumatic Heavy Vehicle program have been experimentally confirmed: drag, lift, down force, side force and all corresponding moments can be significantly augmented (increased or decreased as needed) by blowing, and improved to the point where appreciable increases in Heavy Vehicle performance, economy, stability and safety of operation should result.

Prediction of on-the-road performance of a pneumatic Heavy Vehicle using blown drag reduction coupled with lift-enhanced reduced rolling resistance suggests that these aerodynamic improvements can result in 24% to 32% reductions in horsepower required to overcome drag plus tire rolling resistance. Even when the compressor power for blowing is factored in, savings of up to 43% are calculated in horsepower required to overcome the aerodynamic drag alone. The potential of pneumatic aerodynamic devices applied to Heavy Vehicles can be summarized as:

- Pneumatic devices on back of trailer, blowing slots on all sides and/or front top can yield dramatic improvement in aerodynamic performance, efficiency, stability, control, and safety of large commercial Heavy Vehicles
- Control of all aerodynamic forces and moments from the same pneumatic system using existing on-board air sources, which can be driver or system controlled
- Separation control and base pressure recovery = drag reduction; or base suction = drag increase
- Leading-edge (LE) suction on trailer = drag reduction
- Additional lift for rolling resistance reduction ($F_{Rolling} = \mu N$, where N = Weight - Lift), or reduced lift (increased download) for traction, braking and reduced hydroplaning
- Blowing slots and their corresponding effects can be instantaneously interchanged
- Partial slot blowing or differential blowing can yield roll control & lateral stability
- One-side blowing yields yaw control & directional stability
- Non-moving external components = all-pneumatic systems and components with very small (if any) component drag
- Very small-size aft trailer extension = no length limitations; minimal front or top add-ons
- Splash, spray & turbulence reduction accompanies drag reduction
- Use of existing on-board compressed air sources (exhaust, turbocharger, brake tank)
- Advanced pneumatic aerodynamic cooling systems can further reduce drag
- Fast response and augmented forces = safety of operation
- For safety, stability and/or economy, positive use can be made of aerodynamic forces/moments (lift, download, side force, yaw, roll) not currently employed in Heavy Vehicle operation, and drag can be used for braking as well as fuel efficiency

RECOMMENDATIONS

The above aerodynamic data confirm the Pneumatic Heavy Vehicle as a viable concept for improving the aerodynamic performance, economy, stability, handling and safety of operation of large tractor trailers. Data presented has exceeded the 35% drag reductions (previously demonstrated on streamlined cars) that the American Trucking Associations claim will result in savings of more than 1.2 billion gallons of diesel fuel per year for the US heavy trucking industry, and as much as 1.7 billion gallons per year can be saved at the 50% drag reduction level. The following recommendations are made to suggest a meaningful continuation of this program:

- Additional wind tunnel evaluations should be conducted to even further reduce the required blowing momentum which needs to be acquired from some air source on board the tractor-trailer rig. This might include slot height variation, improved blowing surface geometry, alternate jet turning characteristics, pulsed blowing, or other innovative means.

- Continued feasibility studies are needed, where the above results are transferred to the HV industry and interactions occur with tractor and trailer manufacturers, as well as with engine manufacturers, turbocharger builders, or other possible air-supply specialties.

- Preparation for a full-scale on-the-road demonstration of this technology should be begun, including further study of available air supplies and any associated penalties, plus design of a full-scale demonstrator configuration.

It is thus felt that the proof-of-concept has been successfully completed in smaller model scale, and it is recommended that a full-scale on-the-road demonstration of the Pneumatic Heavy Vehicle be undertaken.

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11. Englar, Robert J., “Development of Pneumatic Test Techniques for Subsonic High-Lift and In-Ground-Effect Wind Tunnel Investigations,” Paper #18, presented at the AGARD 73rd Fluid Dynamics Symposium, Brussels, Belgium, October 4-7, 1993.

12. “Transportation Energy Data Book: Edition 19,” DOE/ORNL-6958, September, 1999.

13. “EIA Annual Energy Outlook 2000,” DOE/EIA-0383(2000), December, 1999 and “AEO 2001”, Appendix A Table 11.

Ames Research Center

Experimental Physics Branch

Experimental Activities at Ames

Jim Ross
Dale Satran
Bruce Storms
JT Heineck
Steve Walker
Dave Driver

Heavy Vehicle Aerodynamic Drag
Working Group Meeting
3/29/01

CFD Validation Testing

- Report on 7x10 test of GTS model available
  - CD-ROM of complete data set included
- Second 7x10 test started 3/19
- Planning and prep work underway for test in 12’ Pressure Wind Tunnel

Current Test - Generic Truck in 7x10

- 1/8th scale generic truck model in 7x10
- CFD validation test
  - Pressure distributions
  - Unsteady pressures in gap area, cab extenders, and rear door
  - 3-D PIV in gap
  - Oil film skin friction (limited configurations)
  - Independent measurement of tractor and trailer drag

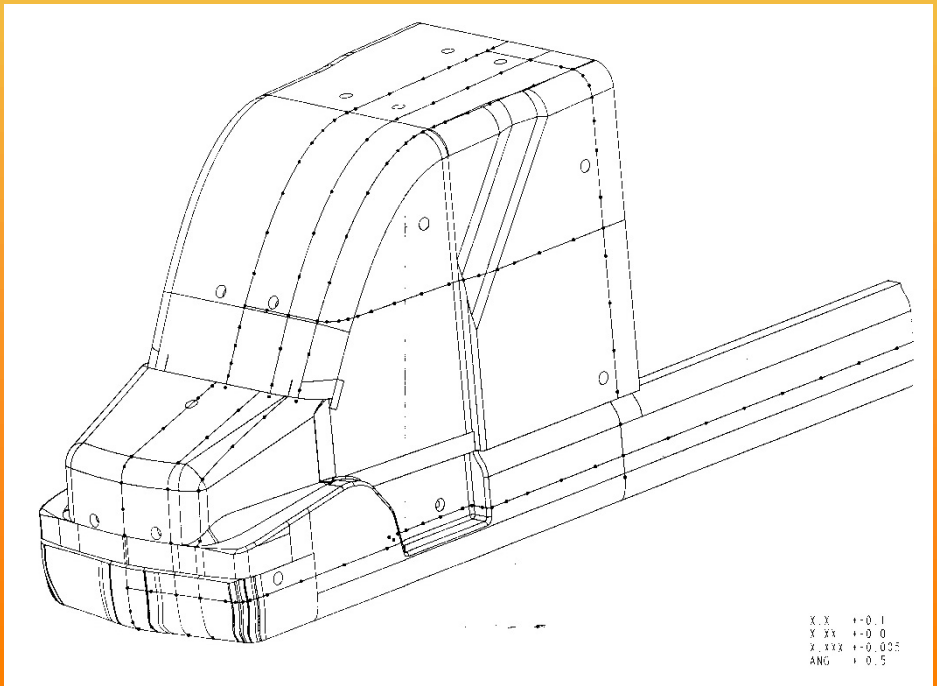
Also looking at flow changes at yaw angles where abrupt drag changes occur - possible cases to observe with PIV

Test Configurations

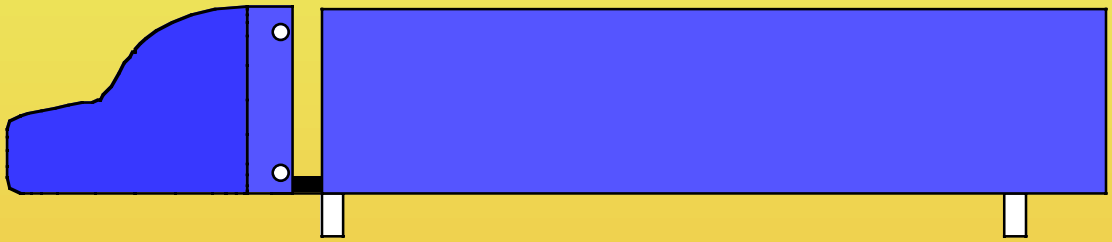
- Side extender and gap variations for drag
- CDI boat-tail plates (drag delta with simple geometry change)
- Trailer vortex generators
- Underslung cargo configuration

Surface Pressures

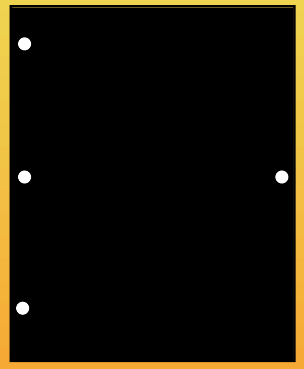
- 256 pressure taps
- No PSP - low absolute accuracy at test conditions
- Skin friction on tractor and trailer



Unsteady Pressure Locations



Unsteady transducers at rear of side extenders on inside surface

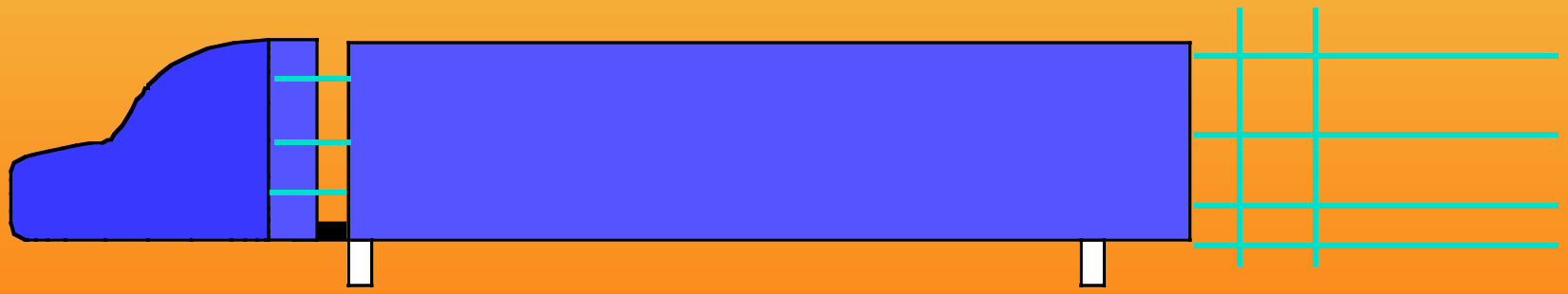


Pattern for unsteady transducers on back of tractor, front of trailer, and back of trailer

Will use Endevco 15psia transducers calibrated using piston phone

PIV Surveys

- Wake
  - 4 horizontal planes
  - 1 or 2 vertical cross planes
- Gap
  - With and without glass side extenders
  - 3 or 4 horizontal planes

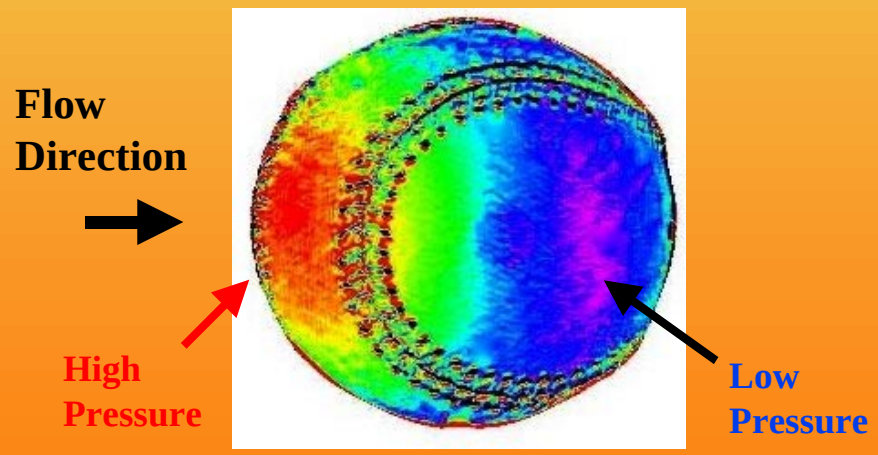


Test Status

- Aero data underway
- Tractor/trailer balance exceeding limits at high-q and yaw
  - Limited to 6 deg. at M = 0.27
  - 14 deg at M = 0.18
- PIV hardware fab done, installation next week
  - Modular mounting system will be used in 12’ PWT test
- Need accurate installation measurements
  - Pricing in-situ laser scan

12’ Experiment Objectives

- Generic tractor model
- Re effect on wind-averaged drag
  - Range from 0.5 to 5 million (based on width) at highway speed
- Re effect on drag components - *gap/side extenders*, mirrors, base-drag-reduction devices, etc. and associated flow physics
- CFD validation data
  - Skin friction
  - Pressure distributions
    - » PSP & electronic
  - Unsteady pressures
  - PIV



Pressure Sensitive Paint results on baseball at 120 mph at 1 atm. Much better at higher total pressure

USC Experiments

Inter-Wind Tunnel Validation

Cab-Trailer Forces and Moments

Cab-Trailer Gap Flow Field

Base Flaps with Oscillatory Perturbations

Participating Staff:

Mustapha Hammache, Staff

Al Knight, Graduate Student

Fred Browand, Staff

Mark Michaelian, Staff

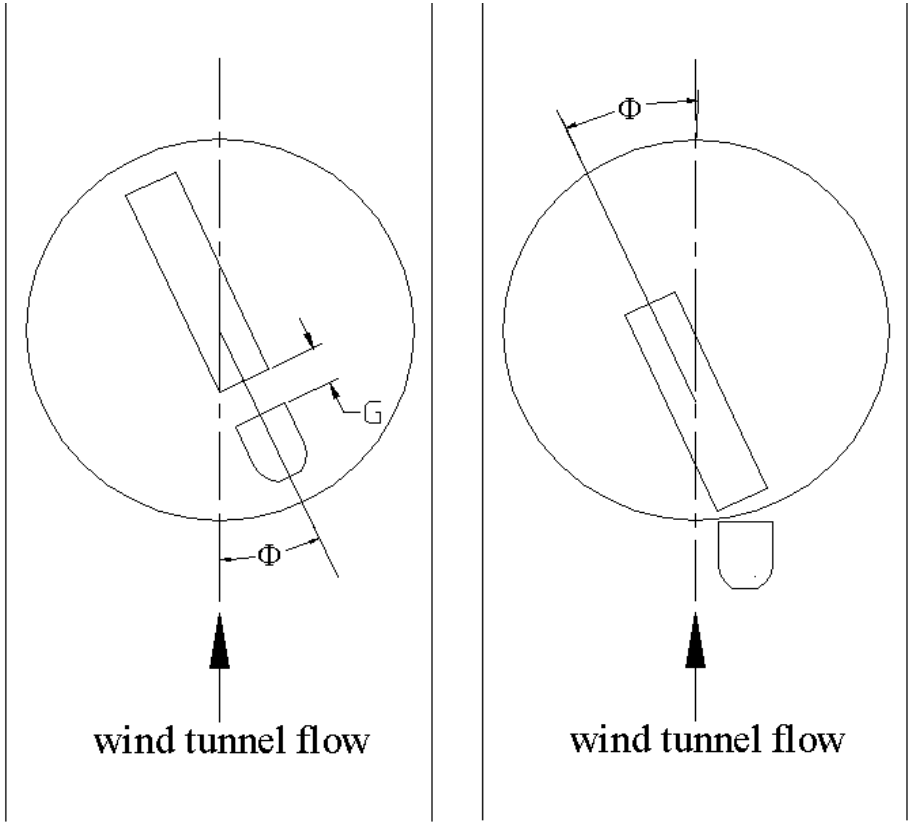
Phil Kassouf, Undergraduate

David Lazzara, Undergraduate

Cab-Trailer Forces and Moments

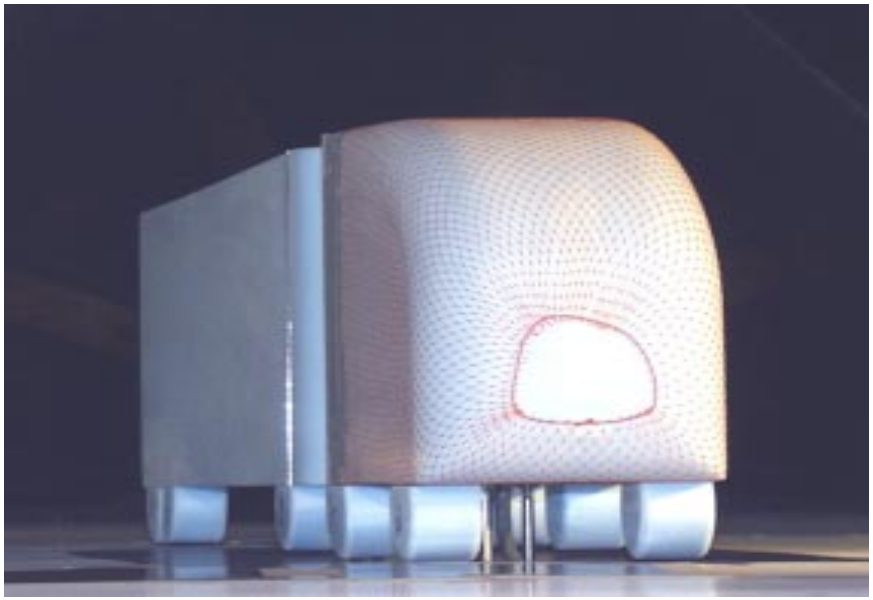
6-Components, 3 Forces, 3 Moments,

Separately on Cab and Trailer



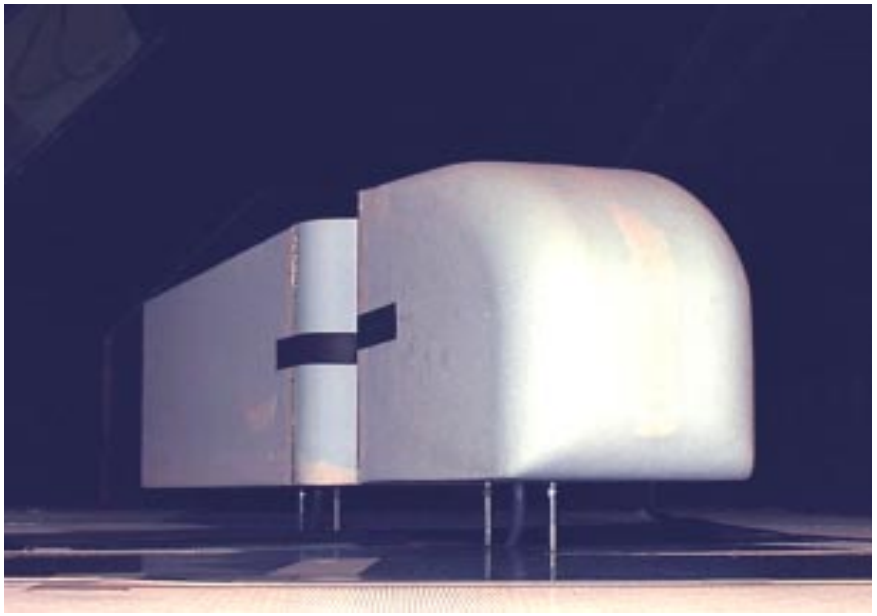
Aerodynamic Cab:Boundary Layer Trip, Wheels

Trailer : Rounded Verticals, Wheels



Aerodynamic Cab: No Trip

Trailer: Square Verticals

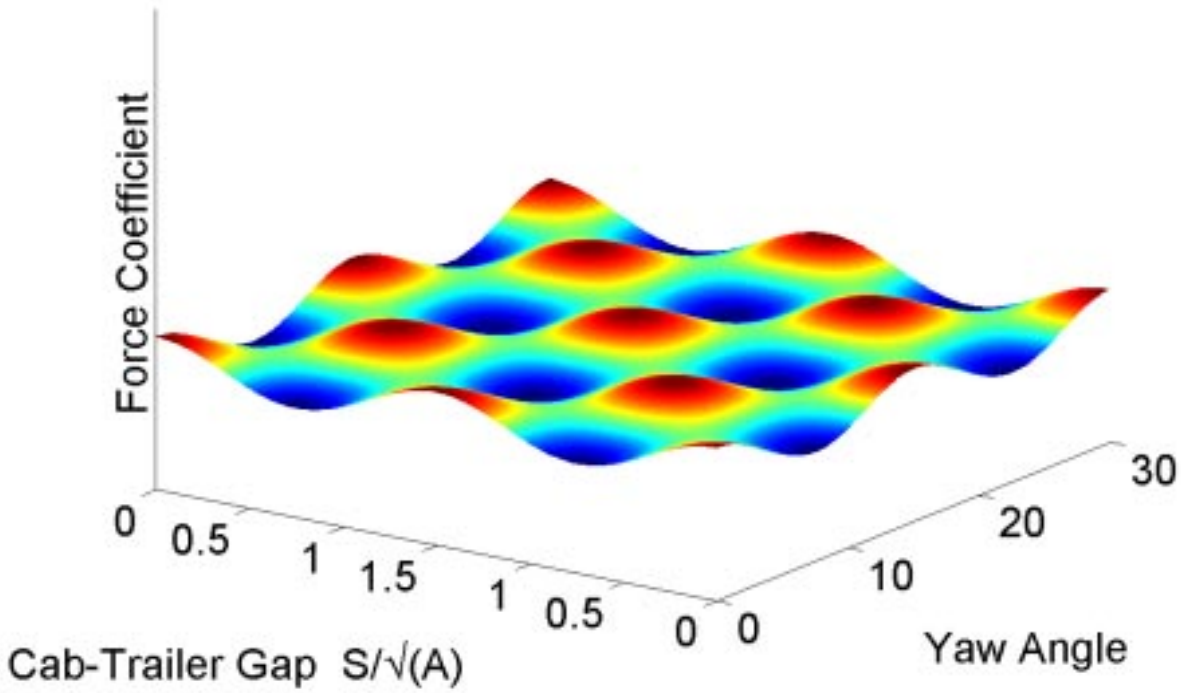


Aerodynamic Cab: No Trip

Trailer: Rounded Verticals

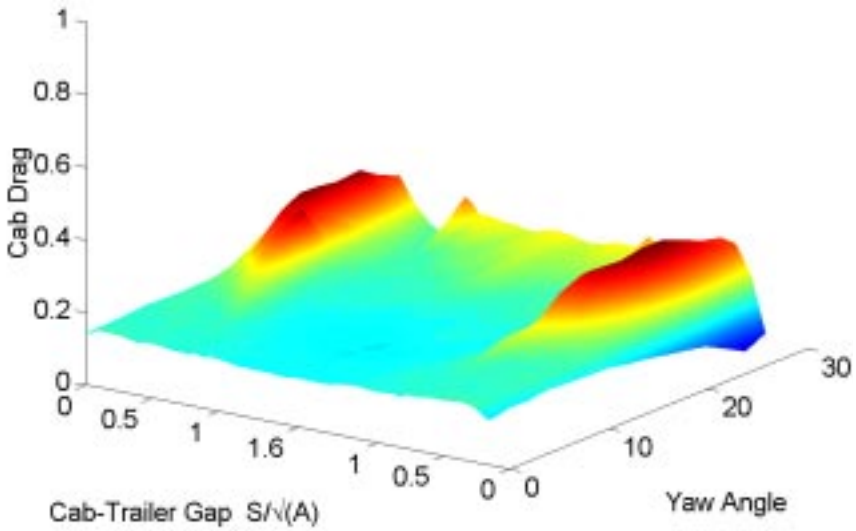
Force Coefficients as a function of Gap and Yaw Angle

Average Force (8-second average), and RMS Fluctuating Drag Force, Side Force, Yaw Moment

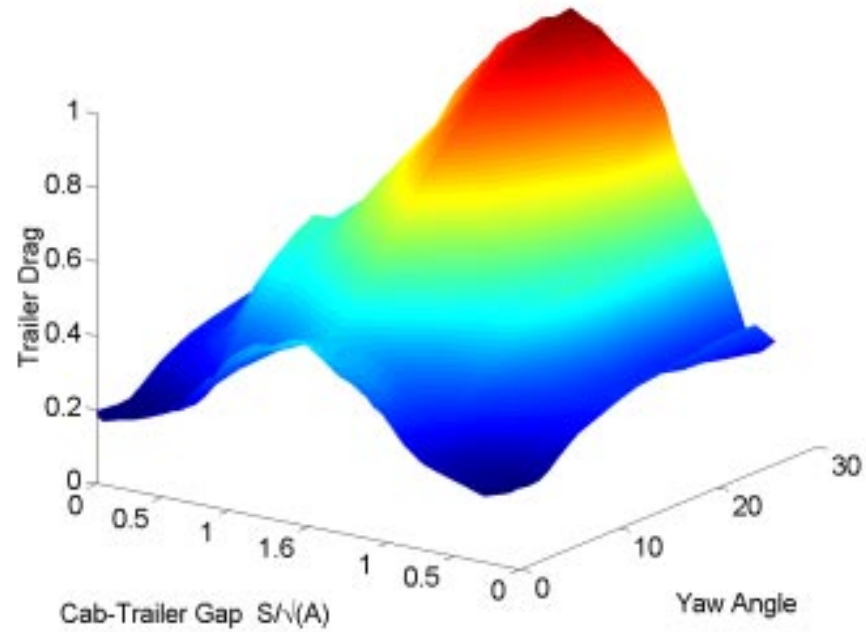


Drag: Cab & Trailer/w Square Verticals

Cab



Trailer



Cab: At small yaw angles, little variation in C_D

At larger yaw, there is a “critical” gap--C_D more than doubles

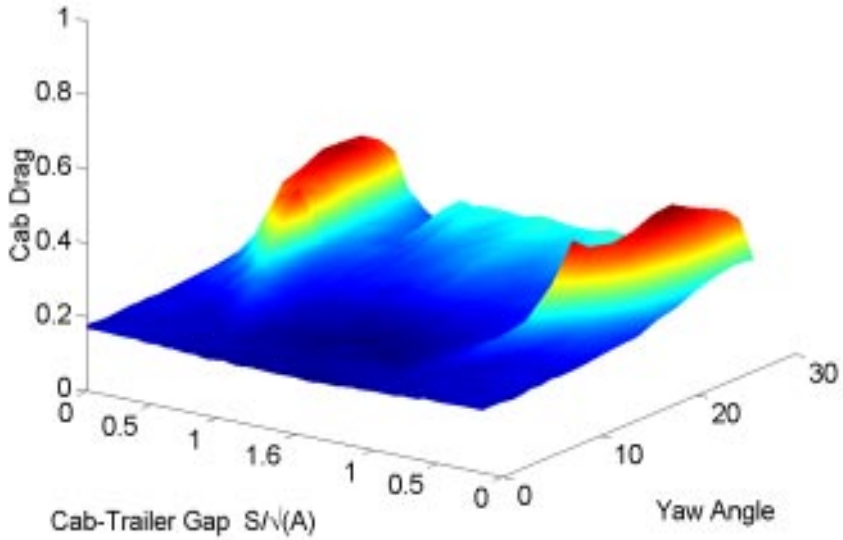
Trailer: At small yaw angles, C_D values more than double as gap varies

Weak influence of “critical” gap

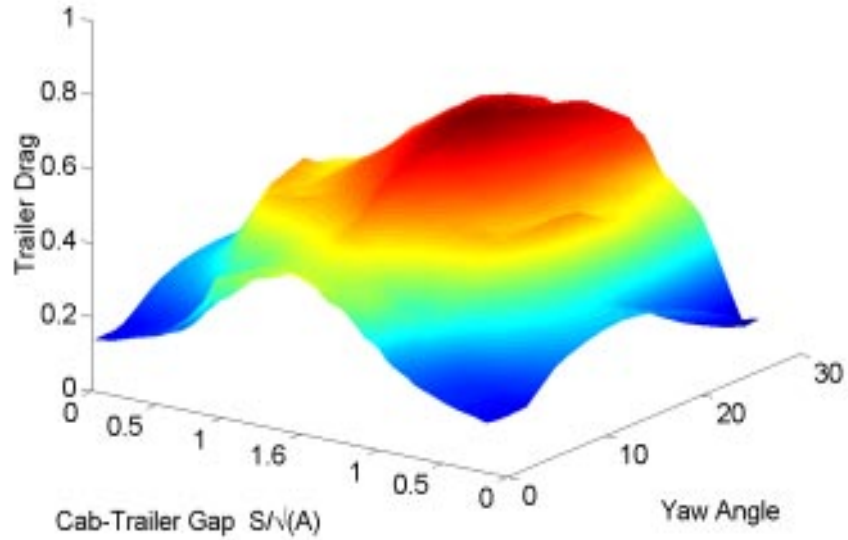
PRELIMINARY DATA

Drag: Cab & Trailer/w Rounded Verticals

Cab



Trailer



Cab: Rounded verticals on trailer produce higher C_D's on cab

"Critical" gap is present

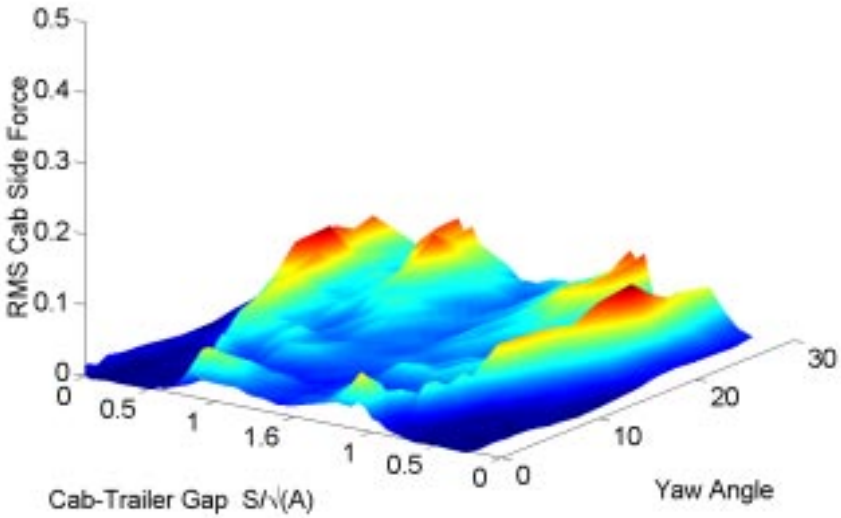
Trailer: Rounded verticals produce lower trailer C_D's

Greater influence of "critical" gap (yellow halo region)

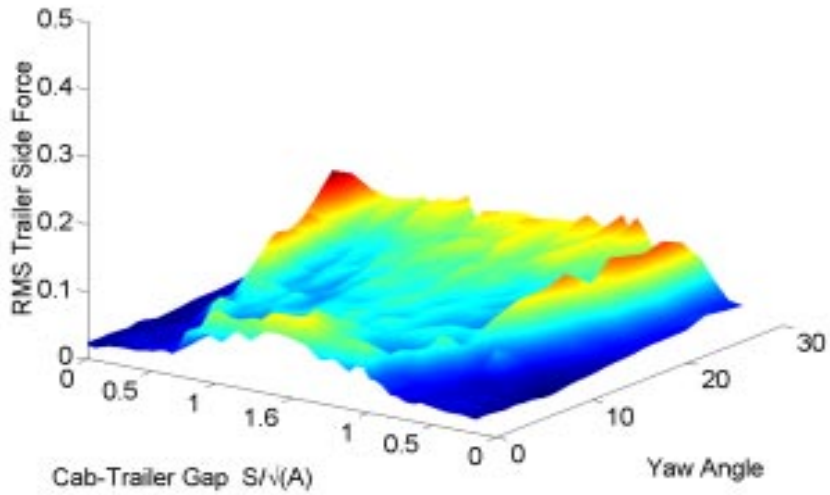
PRELIMINARY DATA

RMS Side Force: Cab & Trailer/w Rounded Verticals

Cab



Trailer



Additional evidence for “critical” gap--side force fluctuations are elevated

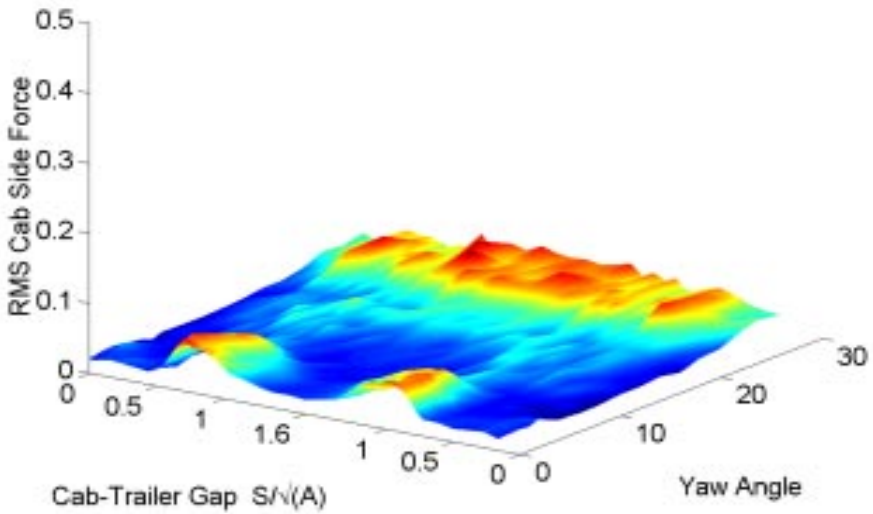
Evidence for a second “critical” gap at large yaw angles

Elevated fluctuations at small yaw may be unrelated to fluctuations at larger yaw angles

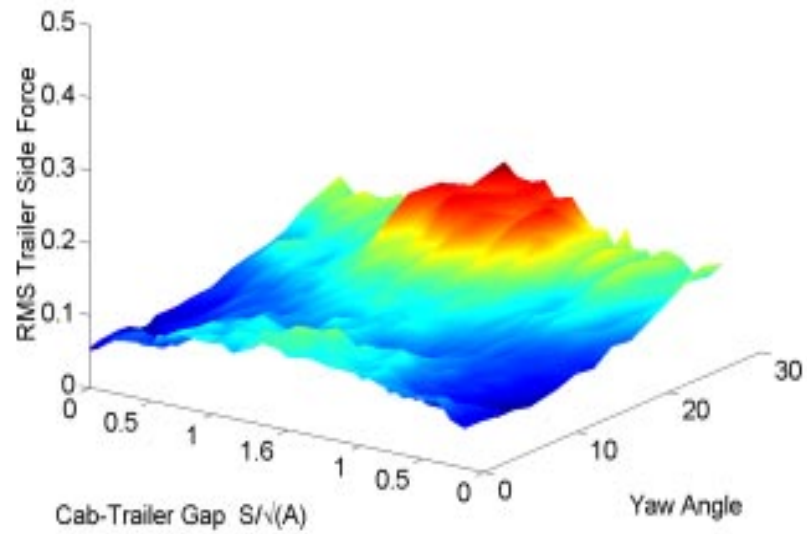
PRELIMINARY DATA

RMS Side Force: Cab/w Trip, Wheels & Trailer/w Rounded Verticals, Wheels

Cab



Trailer

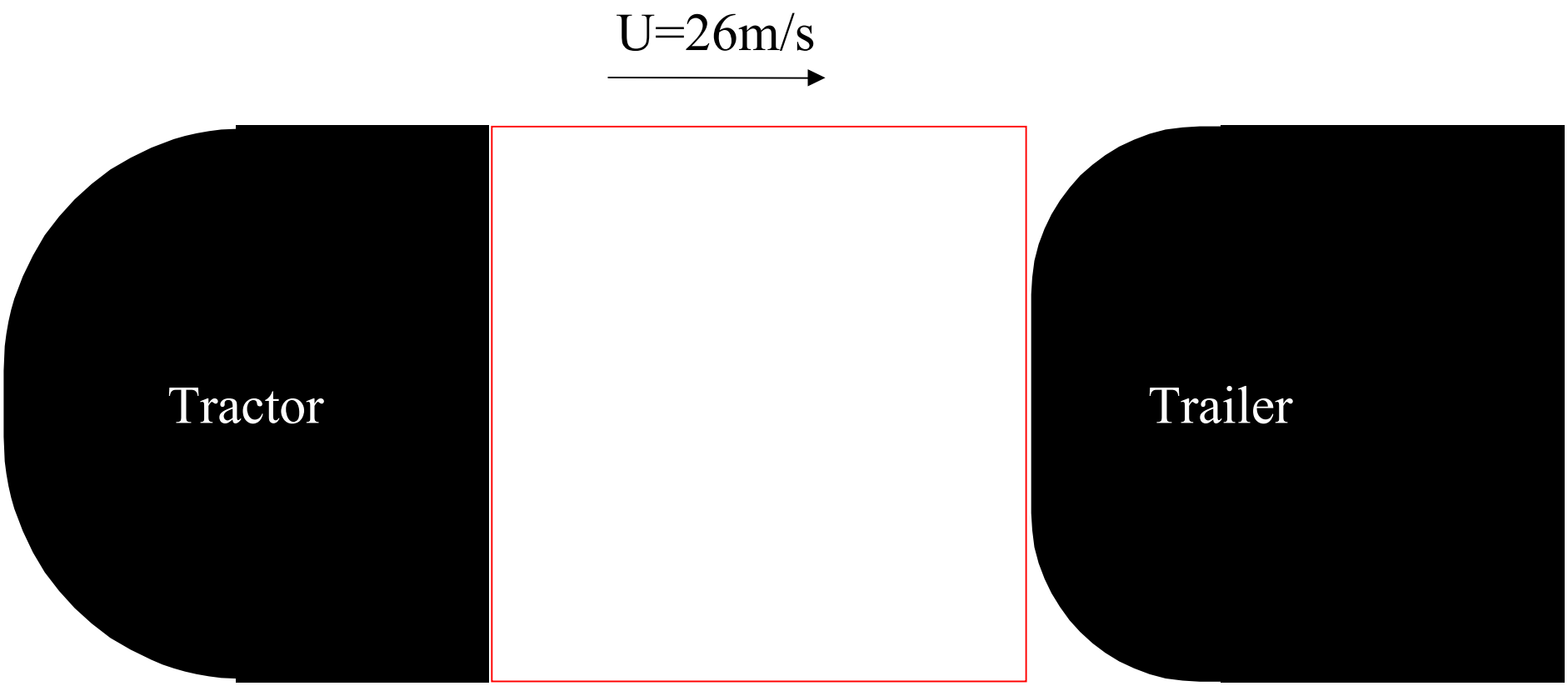


Wheels affect fluctuations at “critical”gap

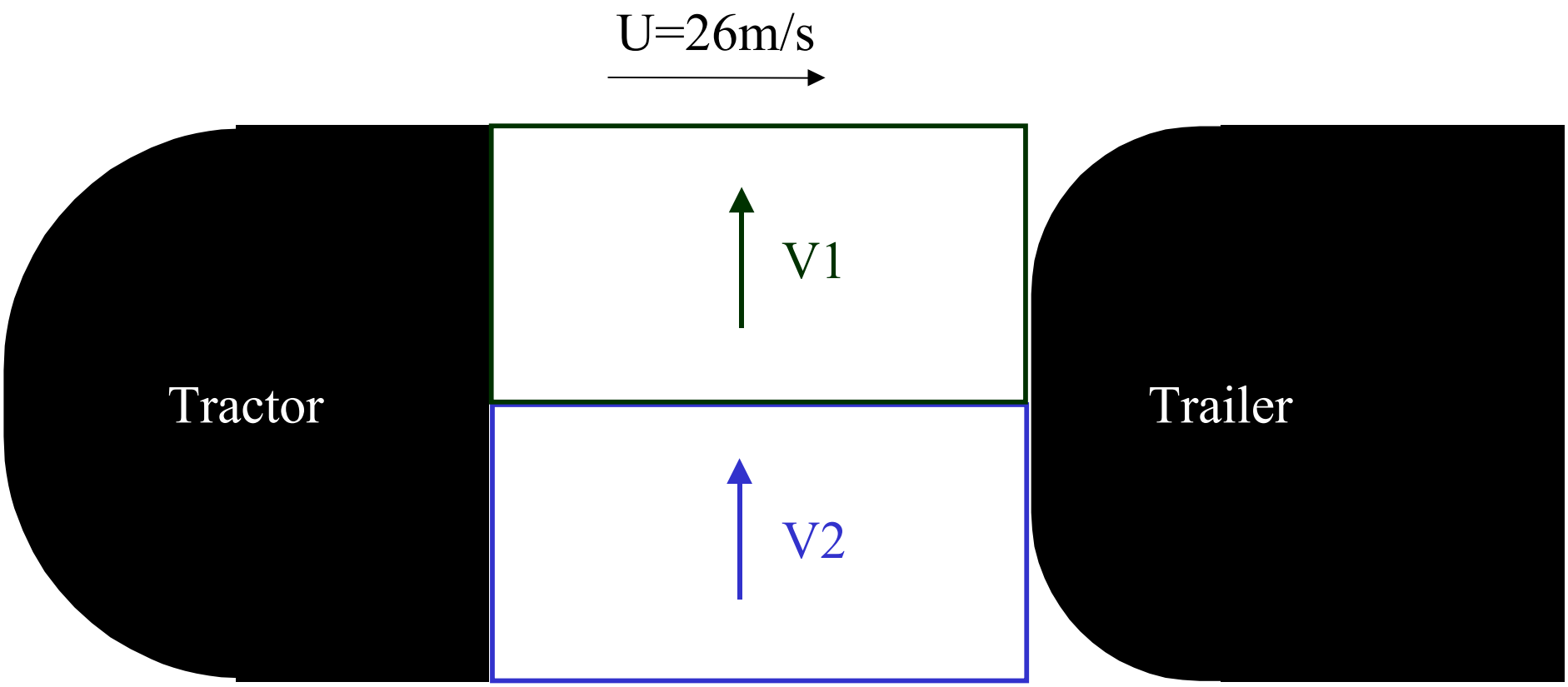
Note low fluctuation amplitude region separating small yaw and large yaw

PRELIMINARY DATA

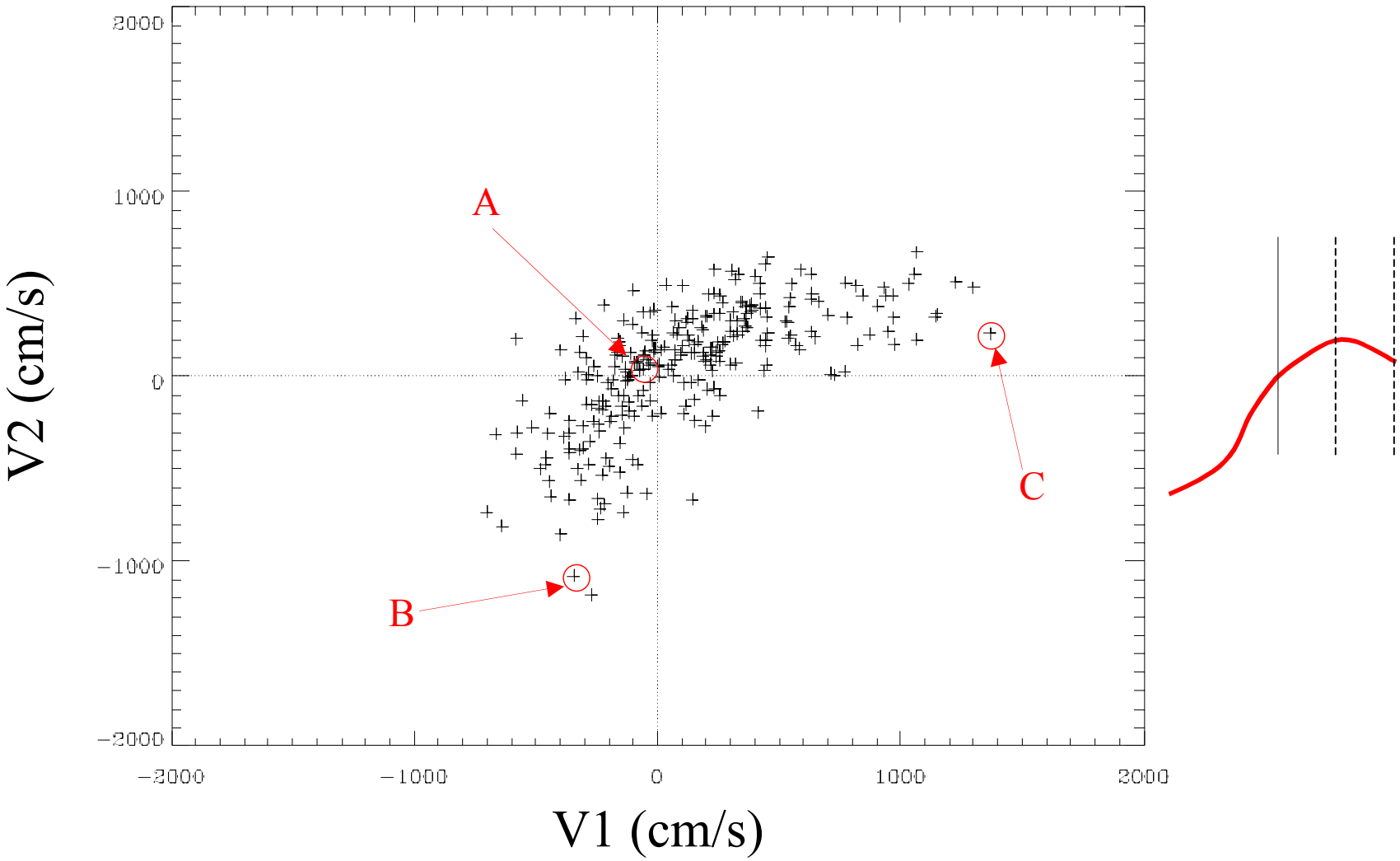
PIV data in horizontal mid-plane



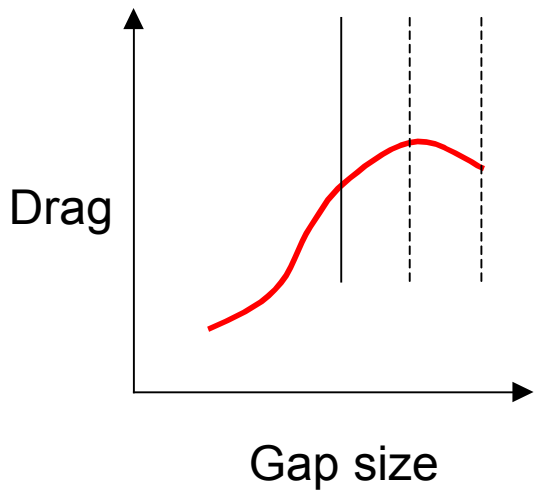
Characterizing gap flow

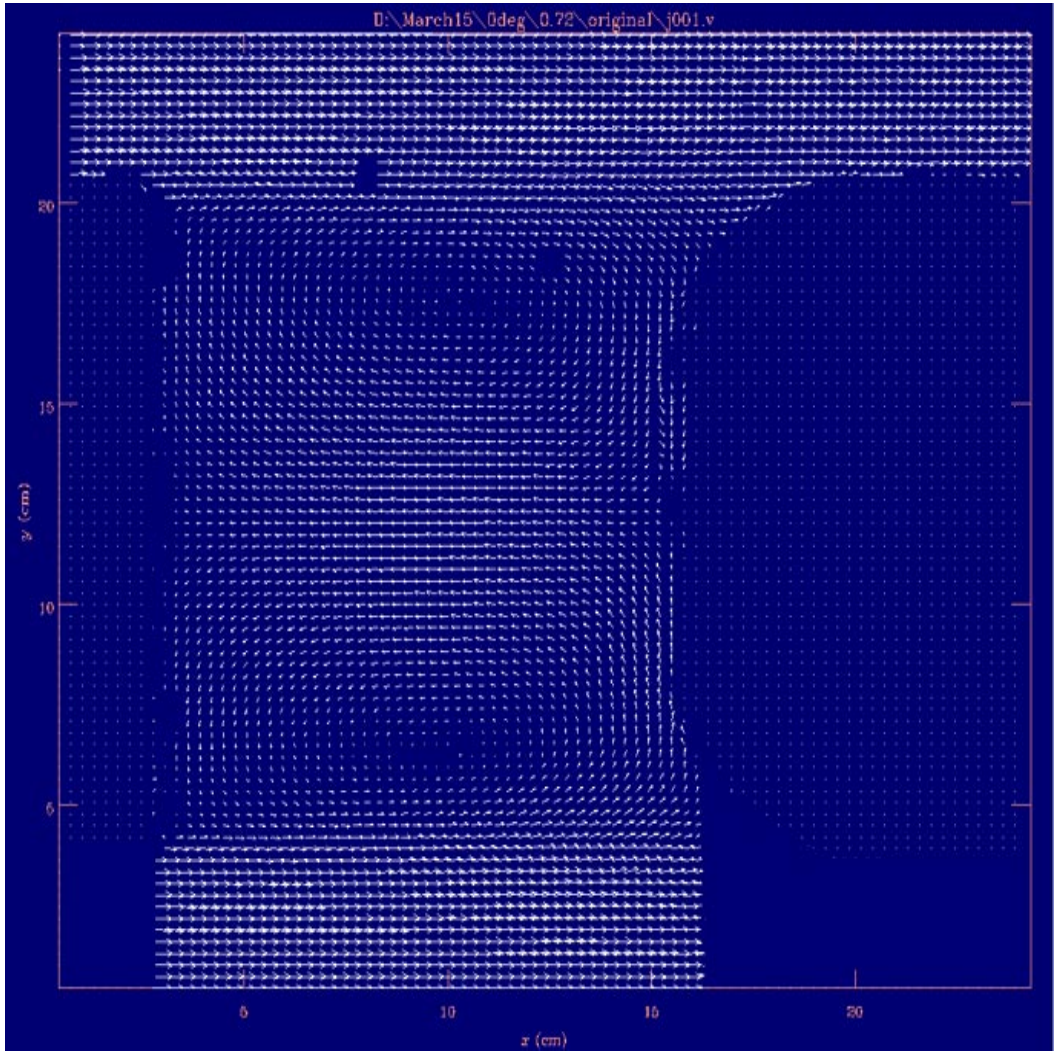


α=0, G/L= 0.72 - State space

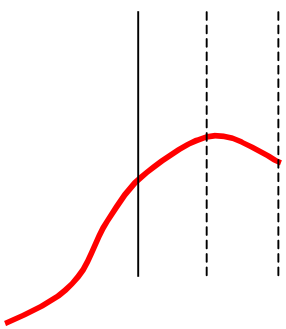


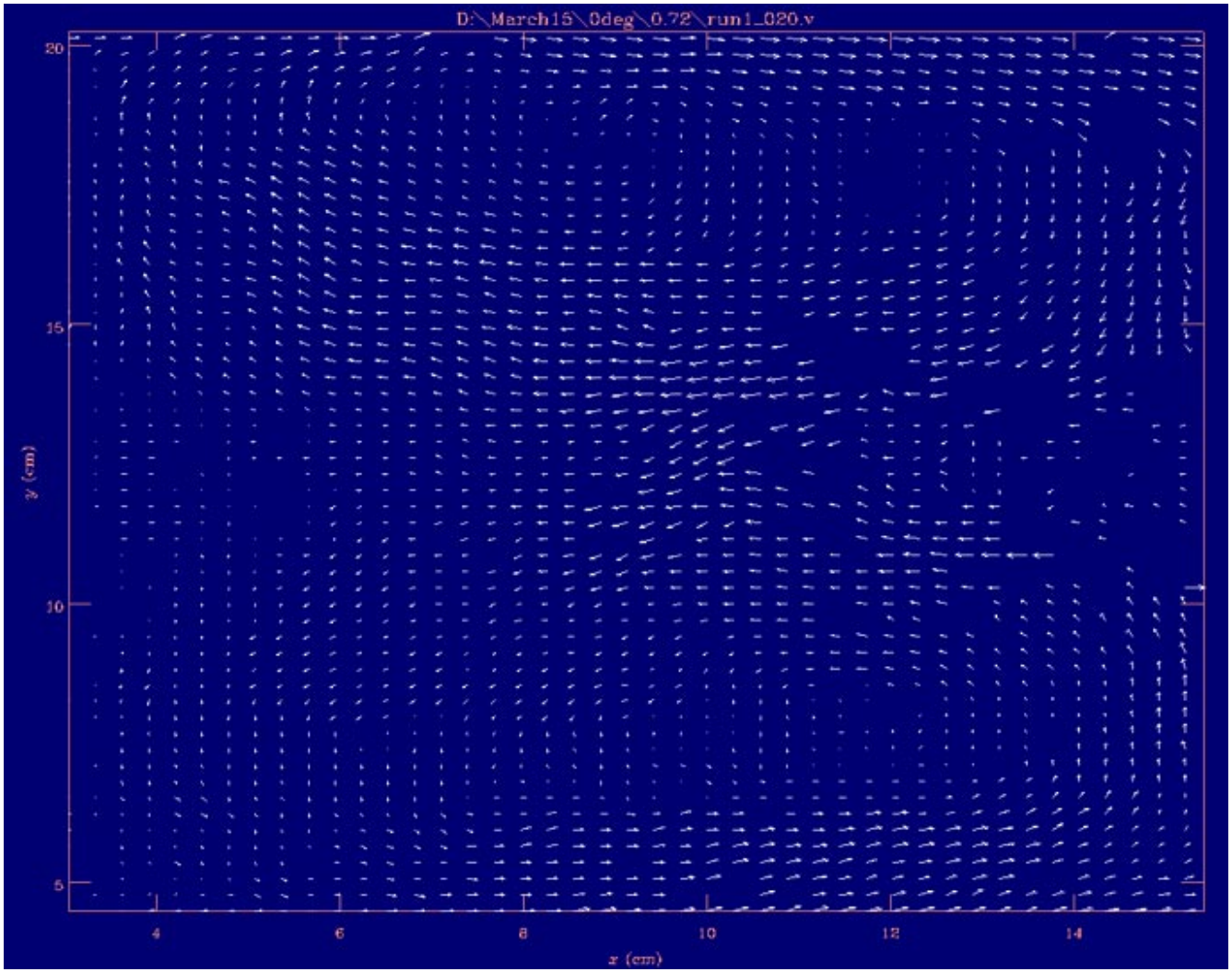
α=0, G/L= 0.72 (Average)



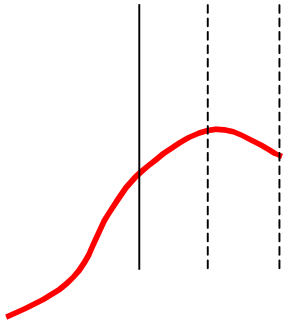


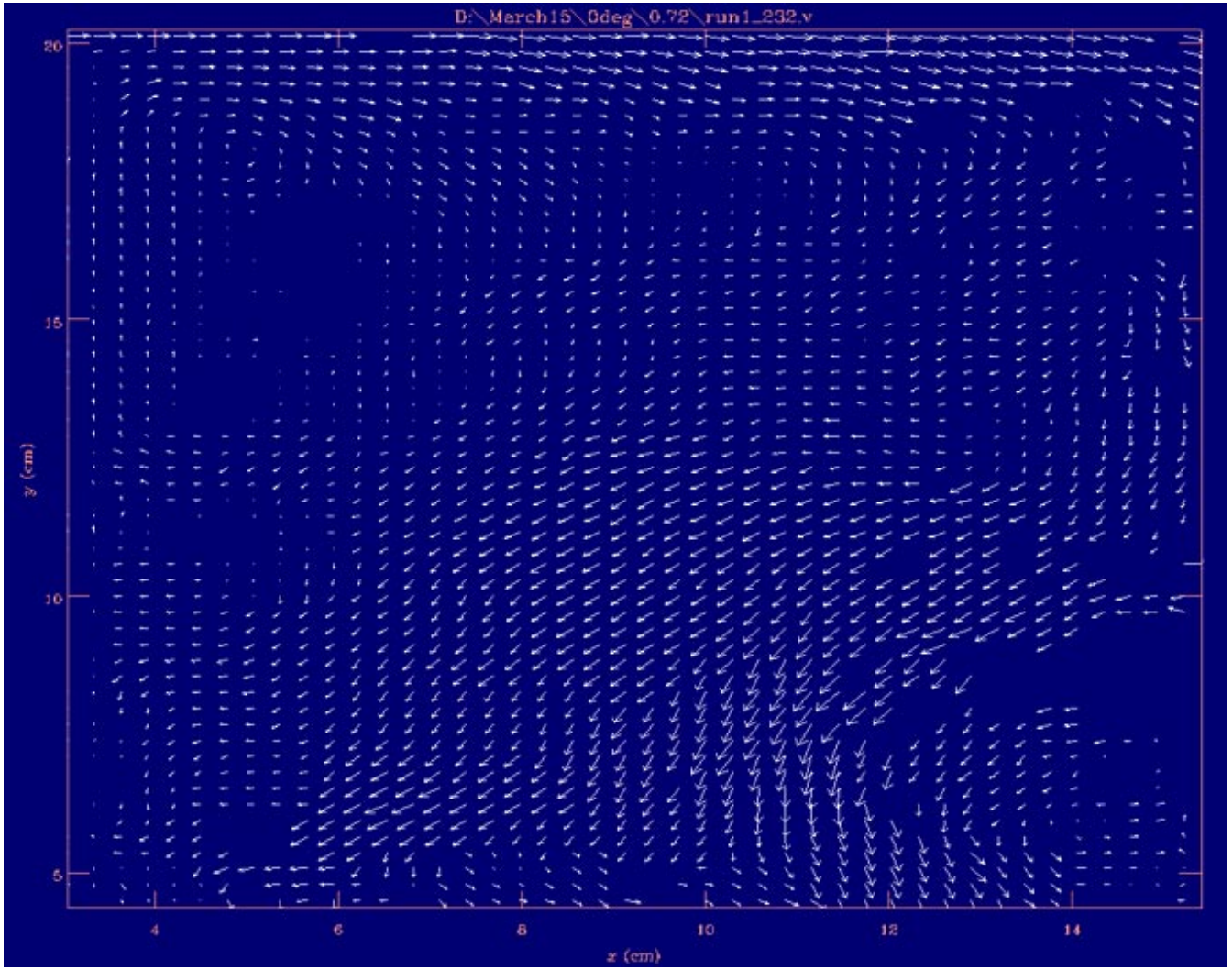
α=0, G/L= 0.72 (sample A)



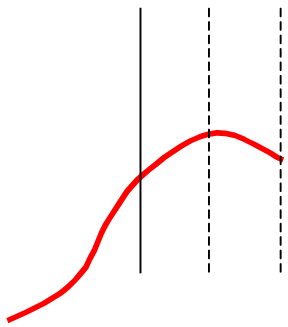


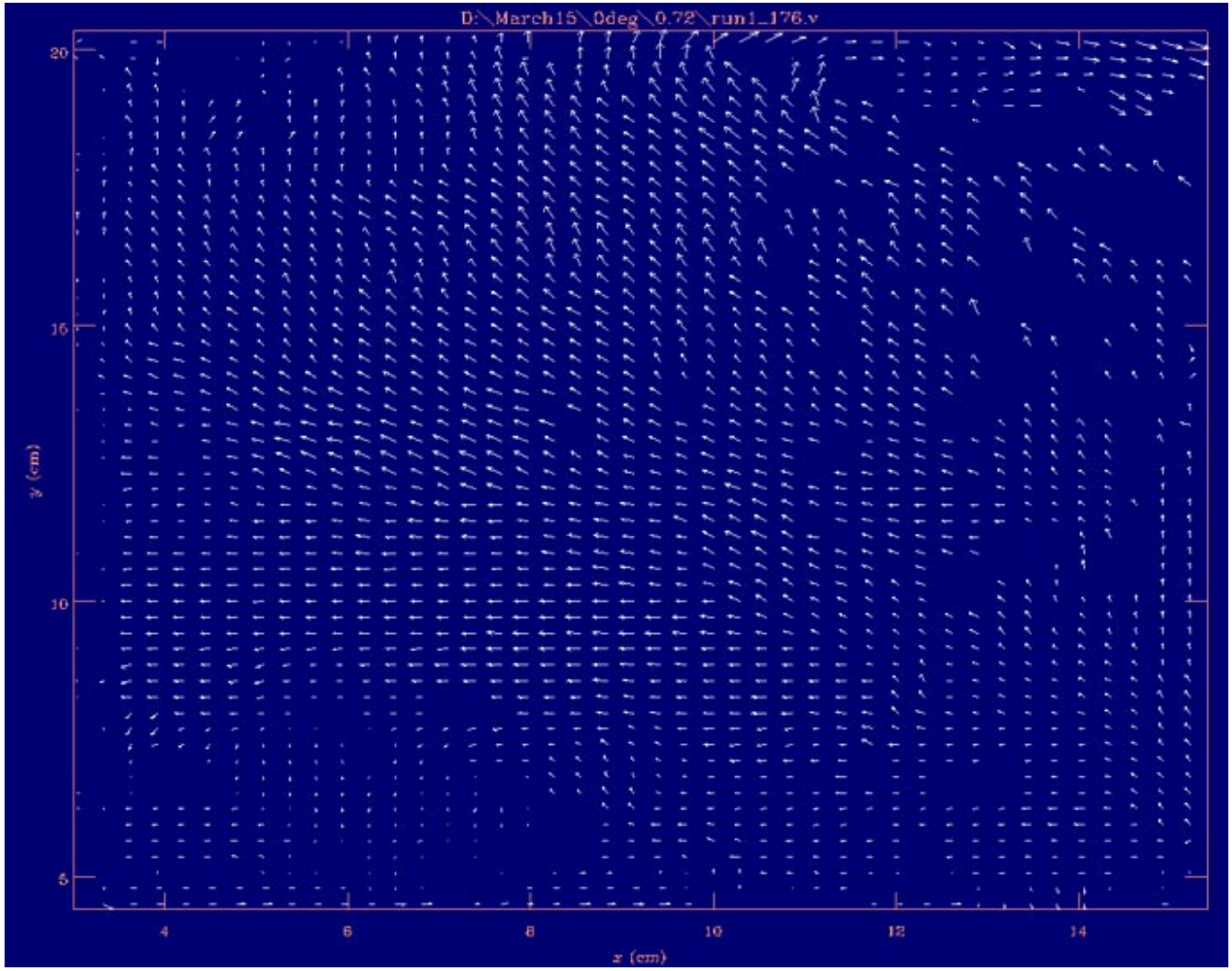
α=0, G/L= 0.72 (sample B)



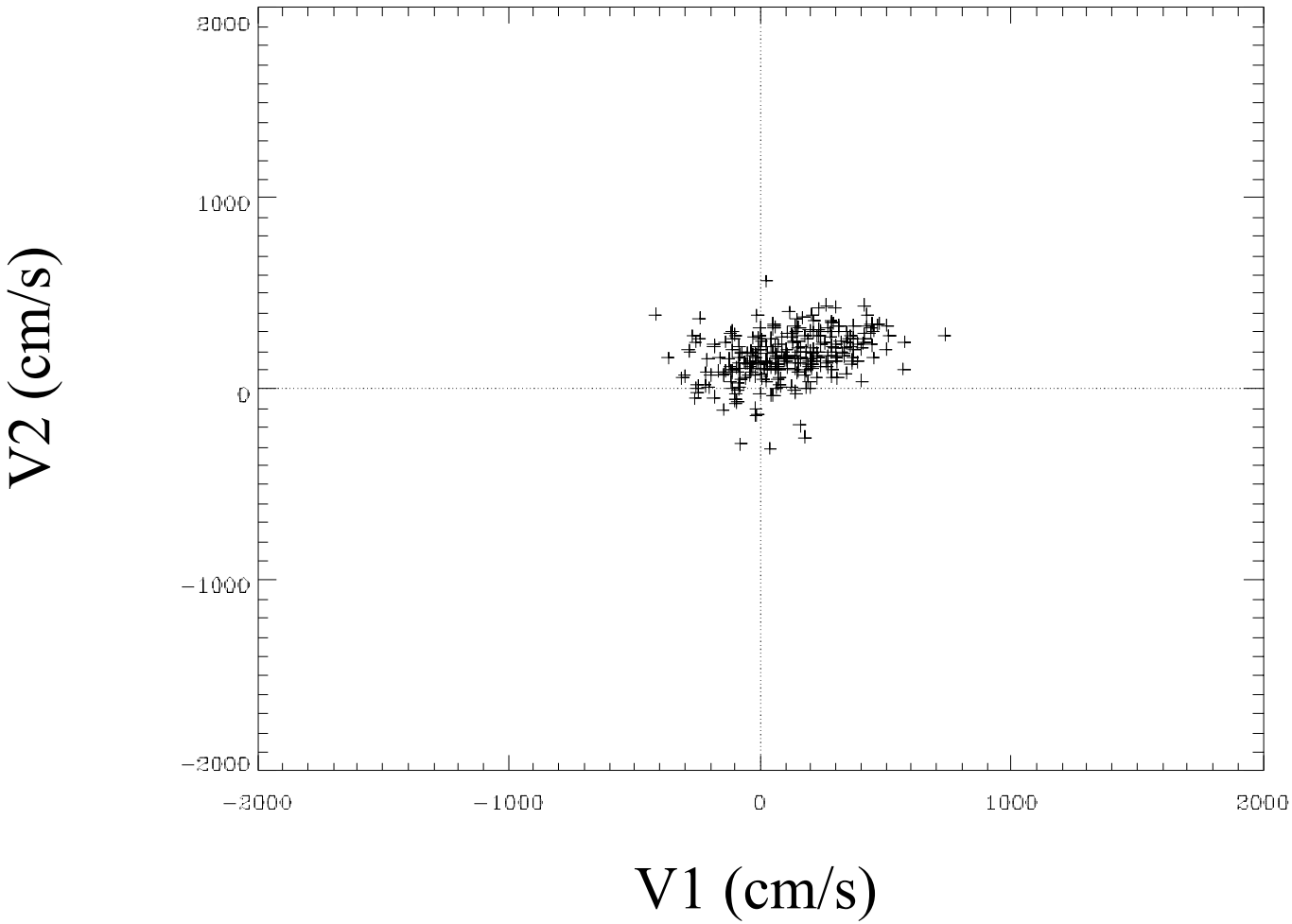


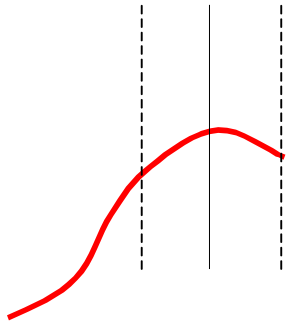
α=0, G/L= 0.72 (sample C)



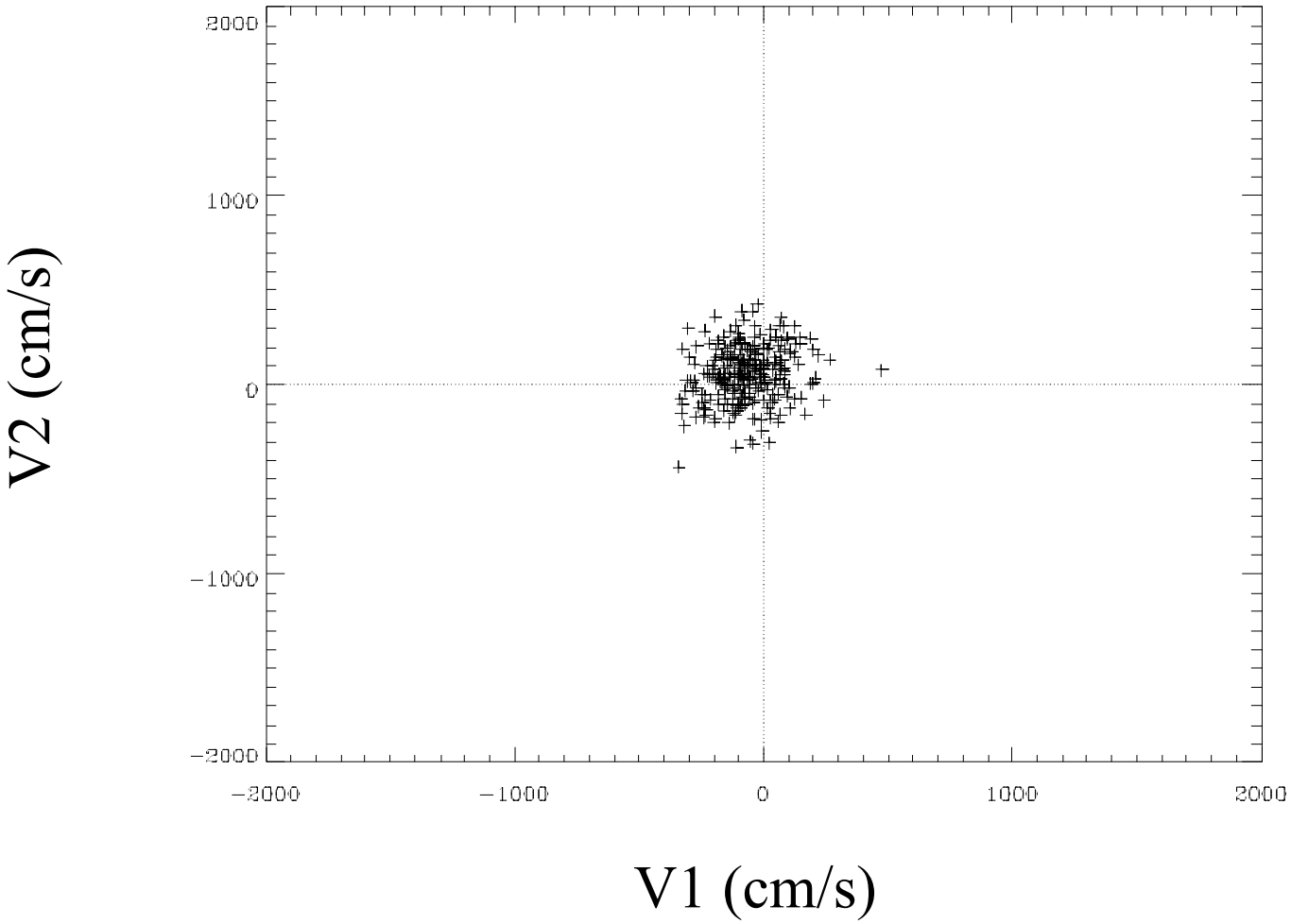


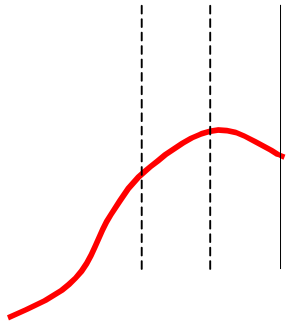
α=0, G/L= 0.94 - State space



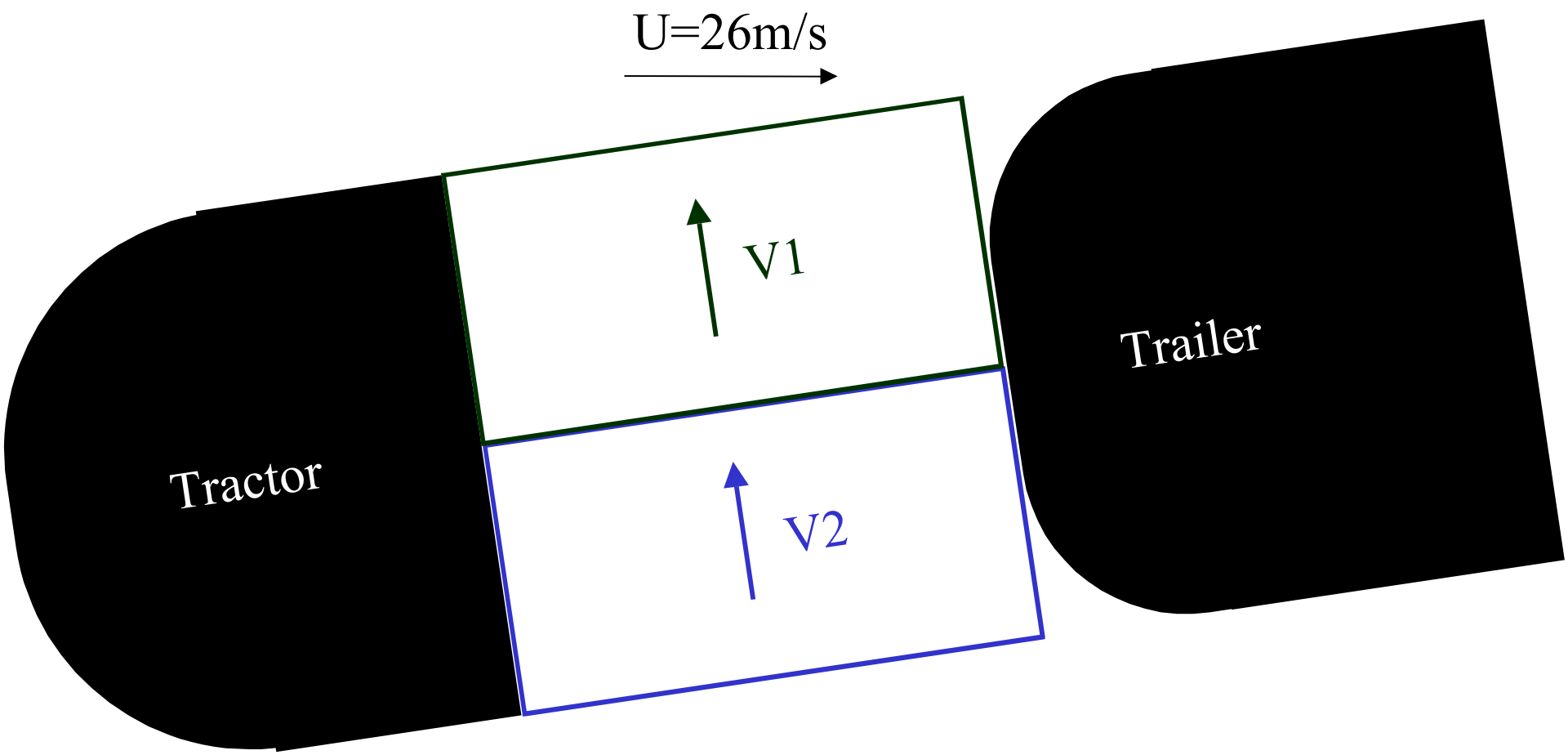


α=0, G/L= 1.22 - State space

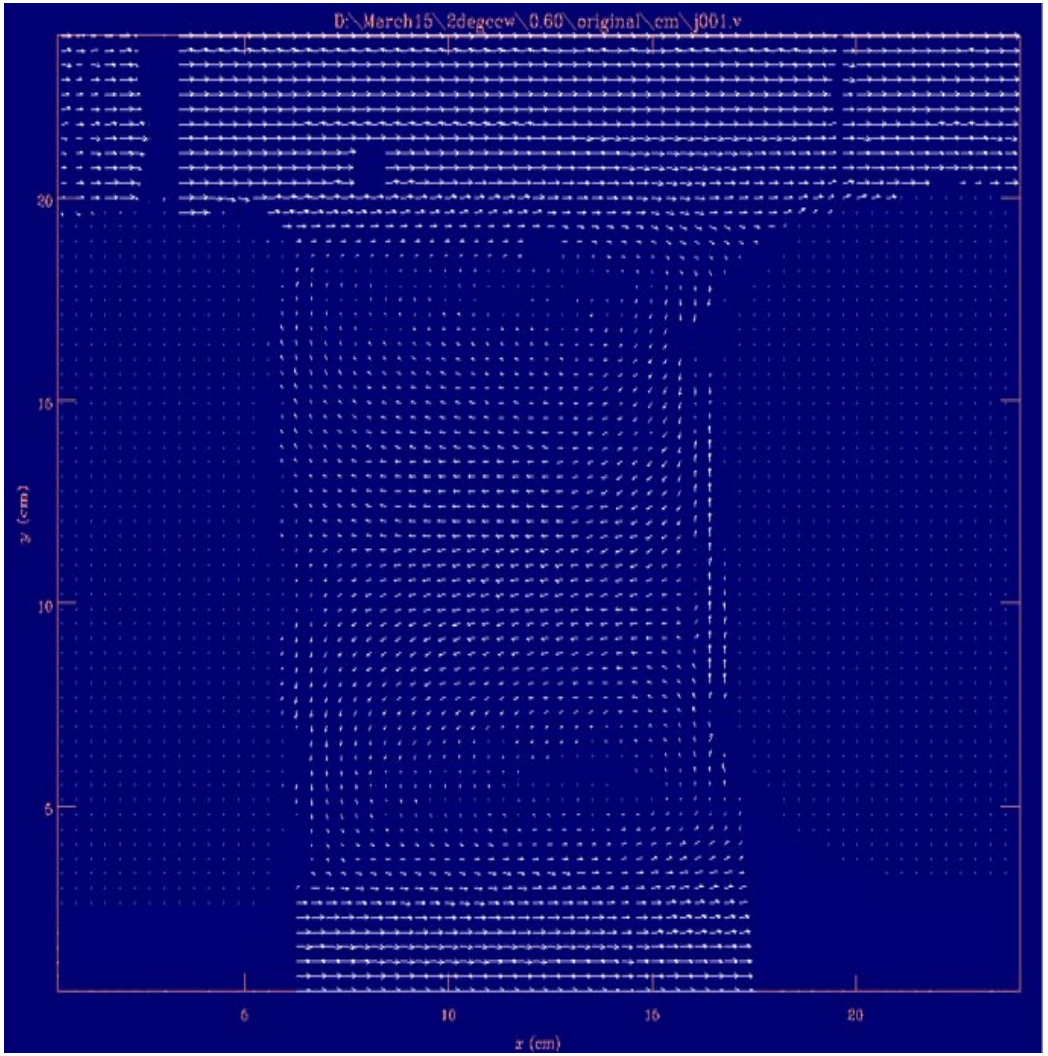


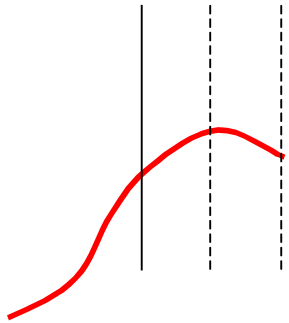


Finite yaw

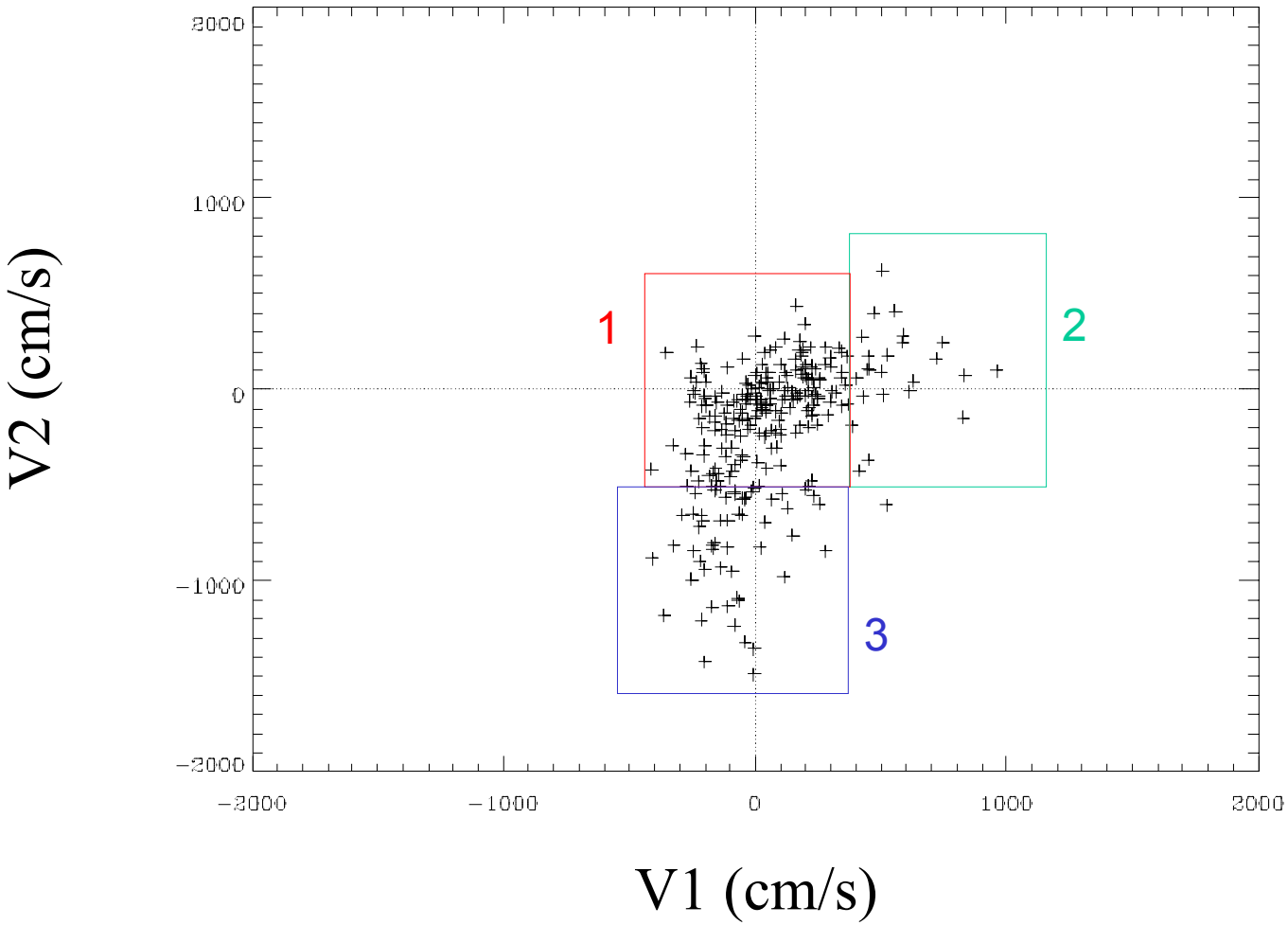


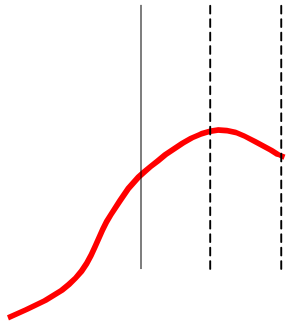
α=2deg, G/L= 0.60 (Average)



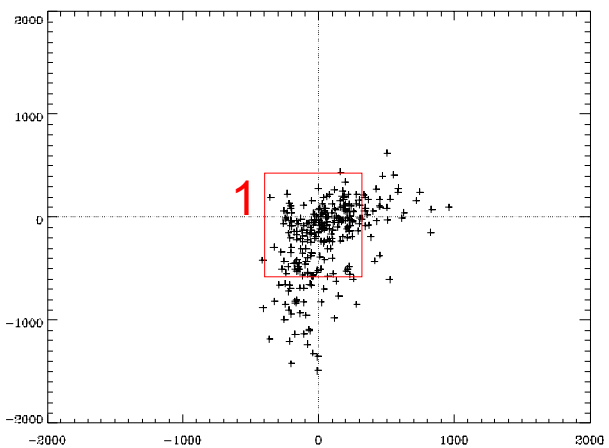


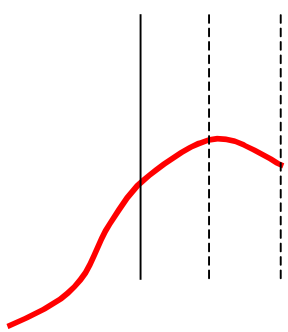
α=2deg, G/L= 0.60 - State space

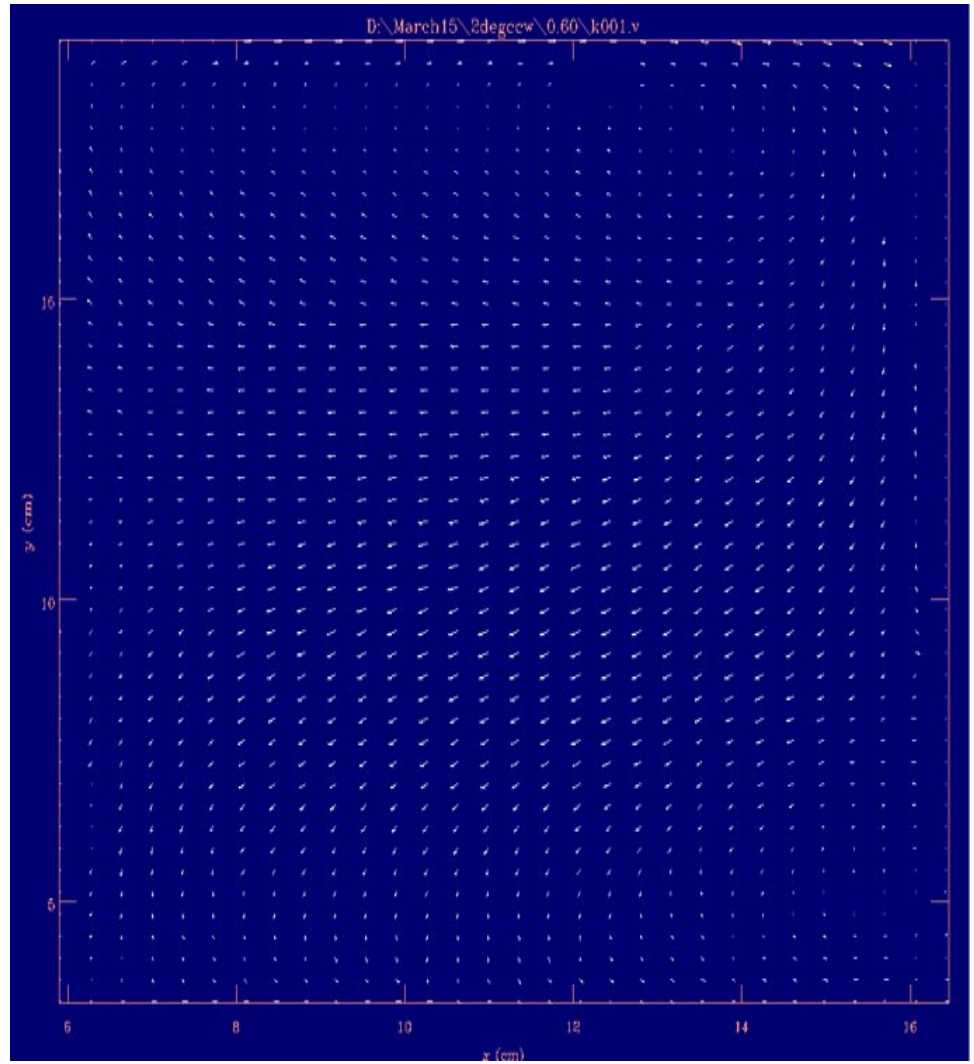




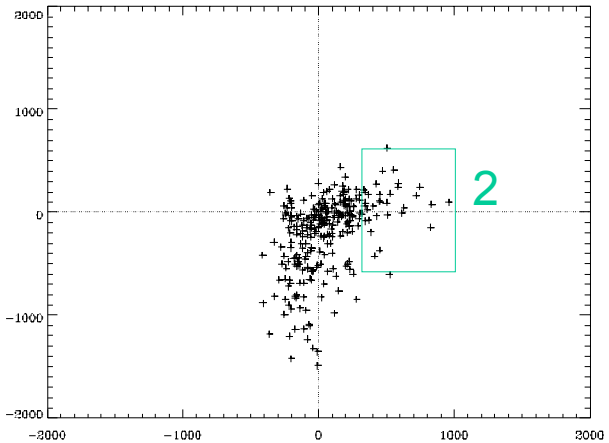
α=2deg, G/L= 0.60 (ensemble average 1)

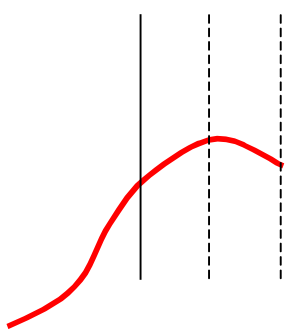


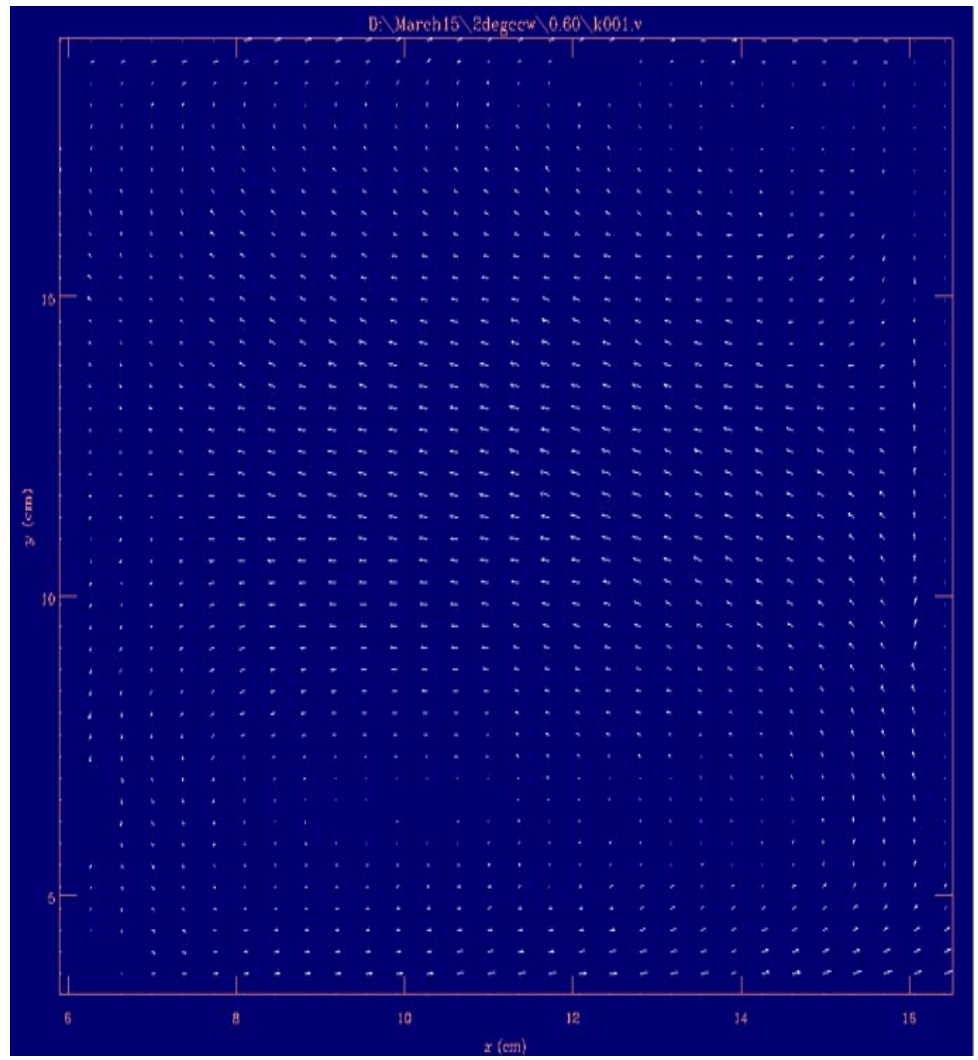




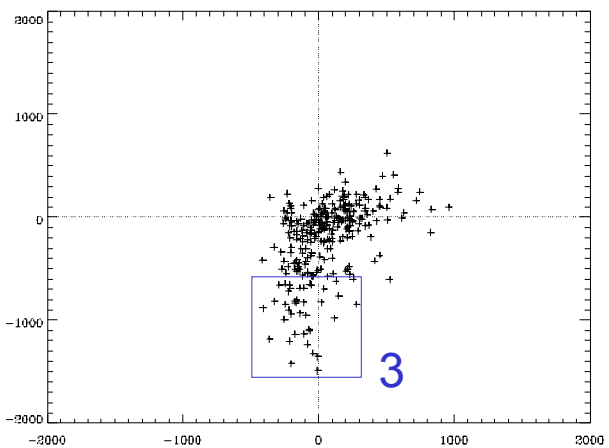
α=2deg, G/L= 0.60 (ensemble average 2)

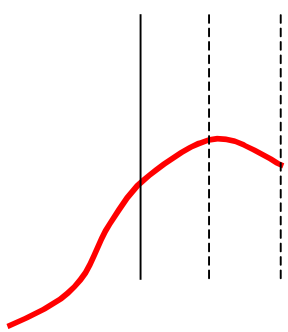


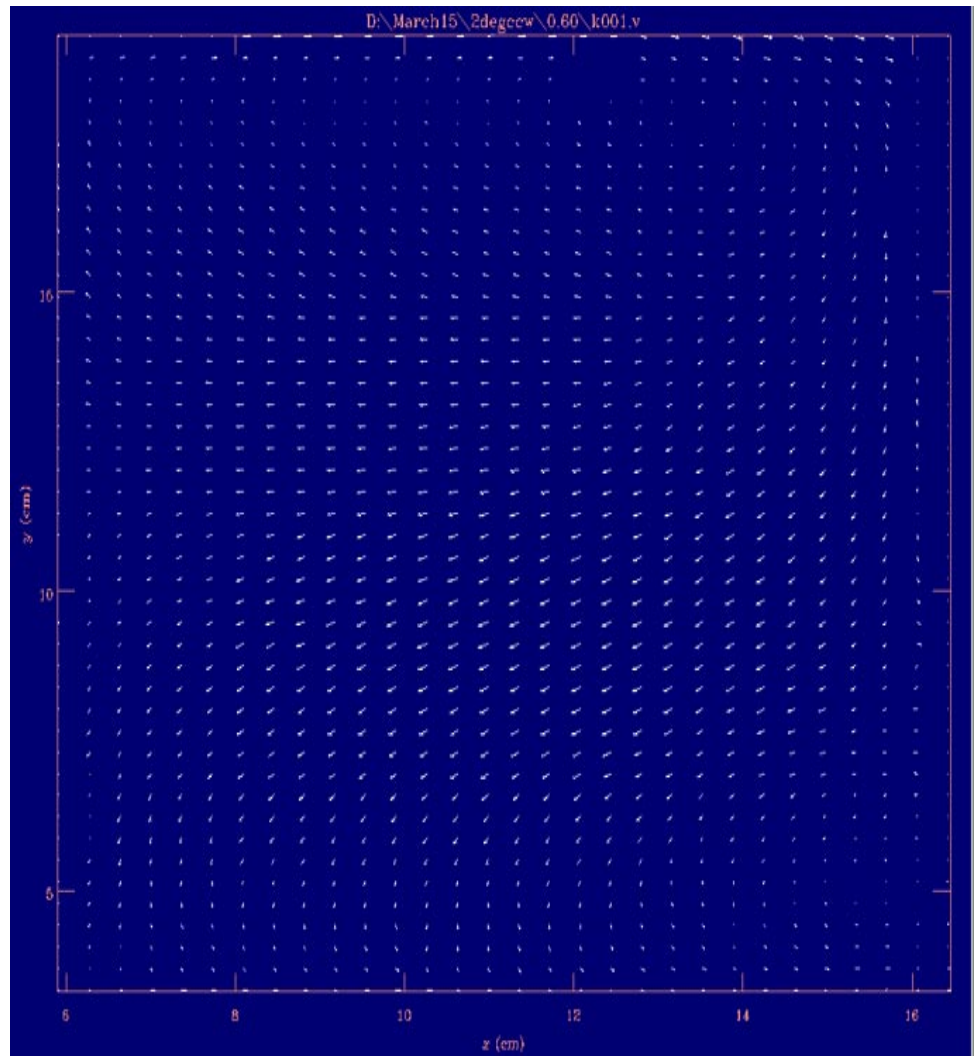




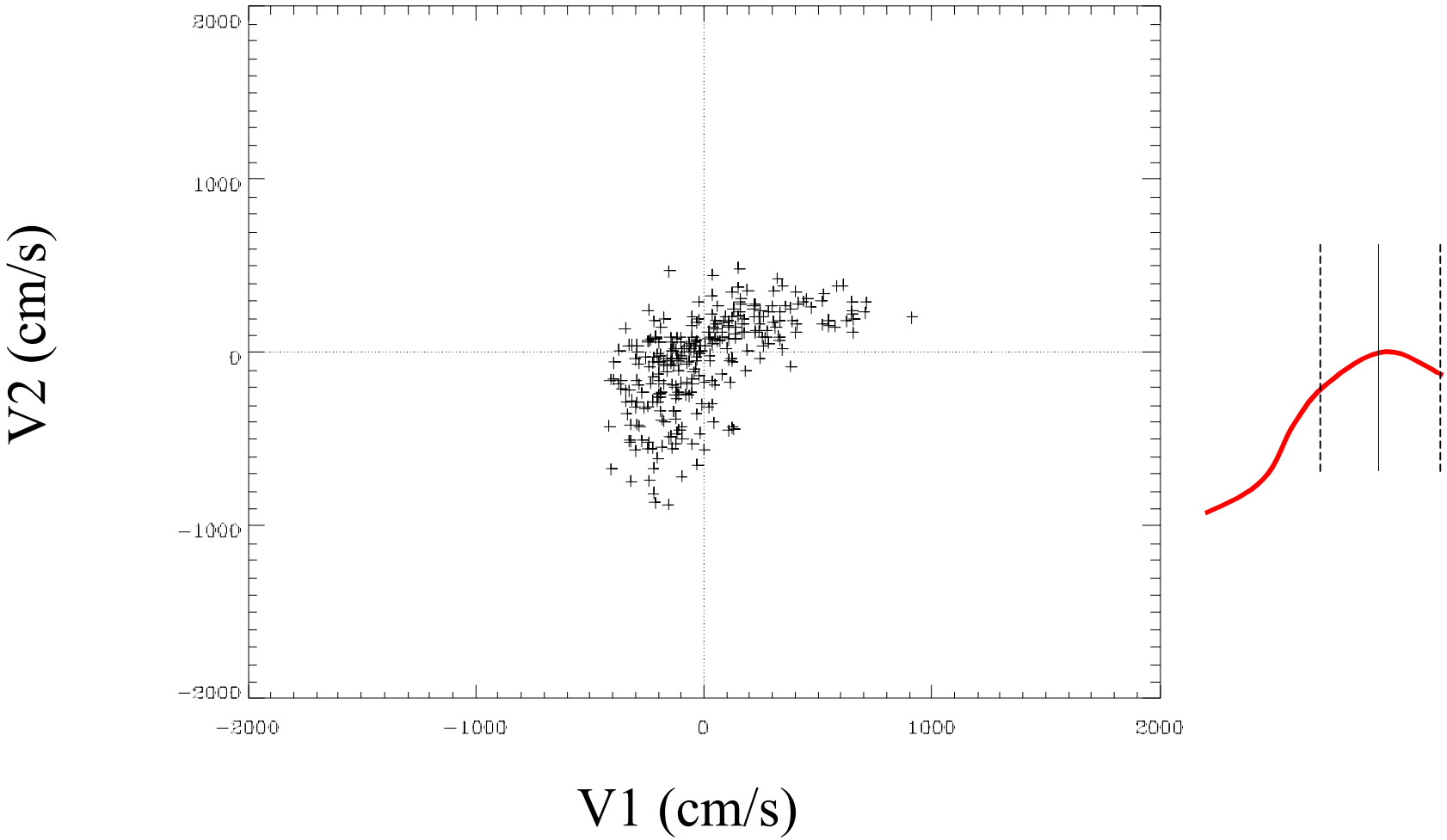
α=2deg, G/L= 0.60 (ensemble average 3)



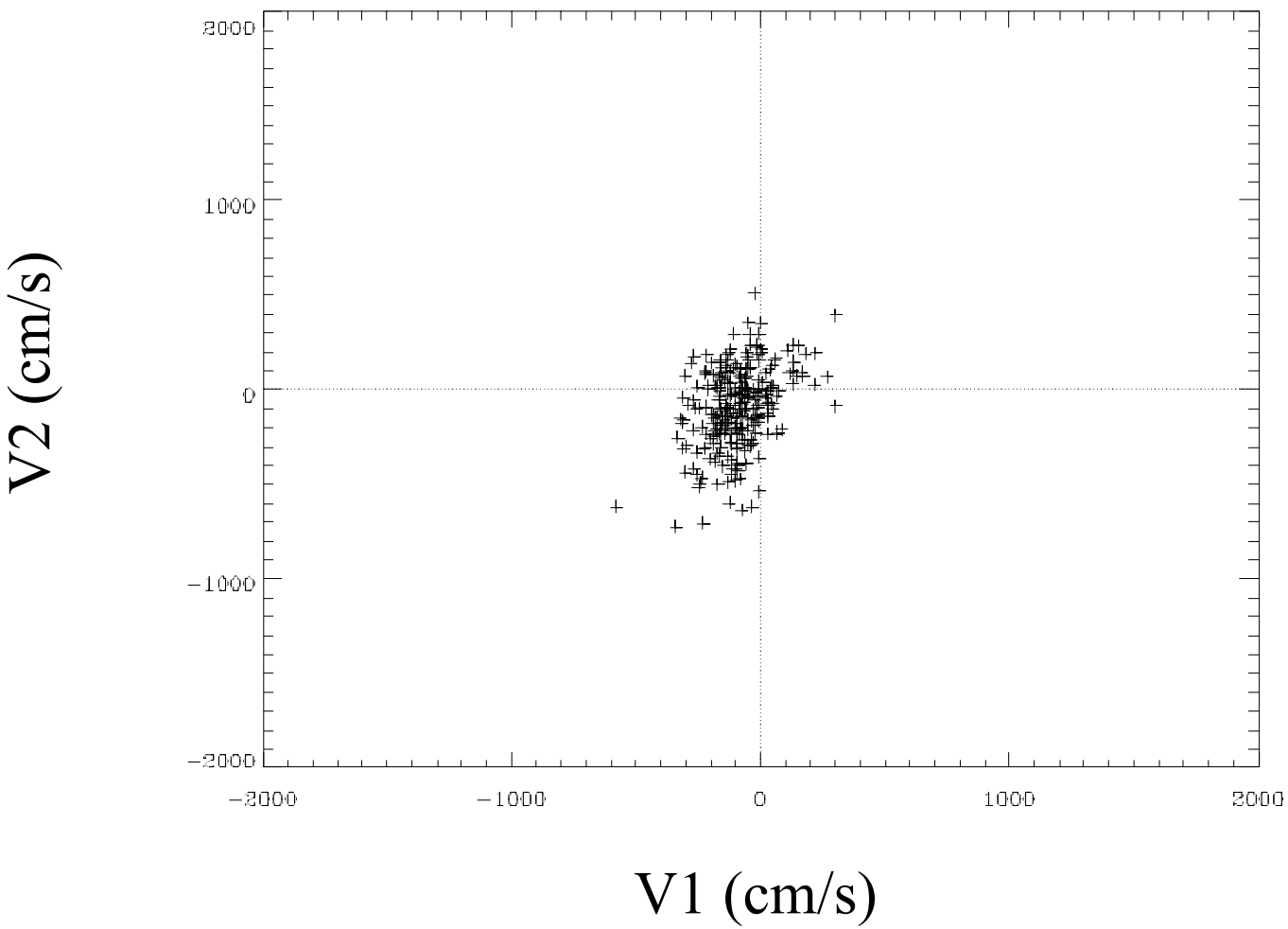


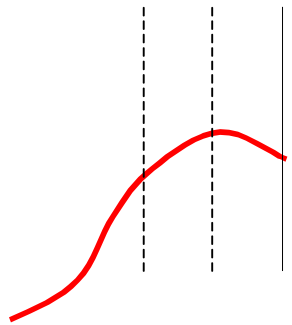


α=2deg, G/L= 0.80 - State space

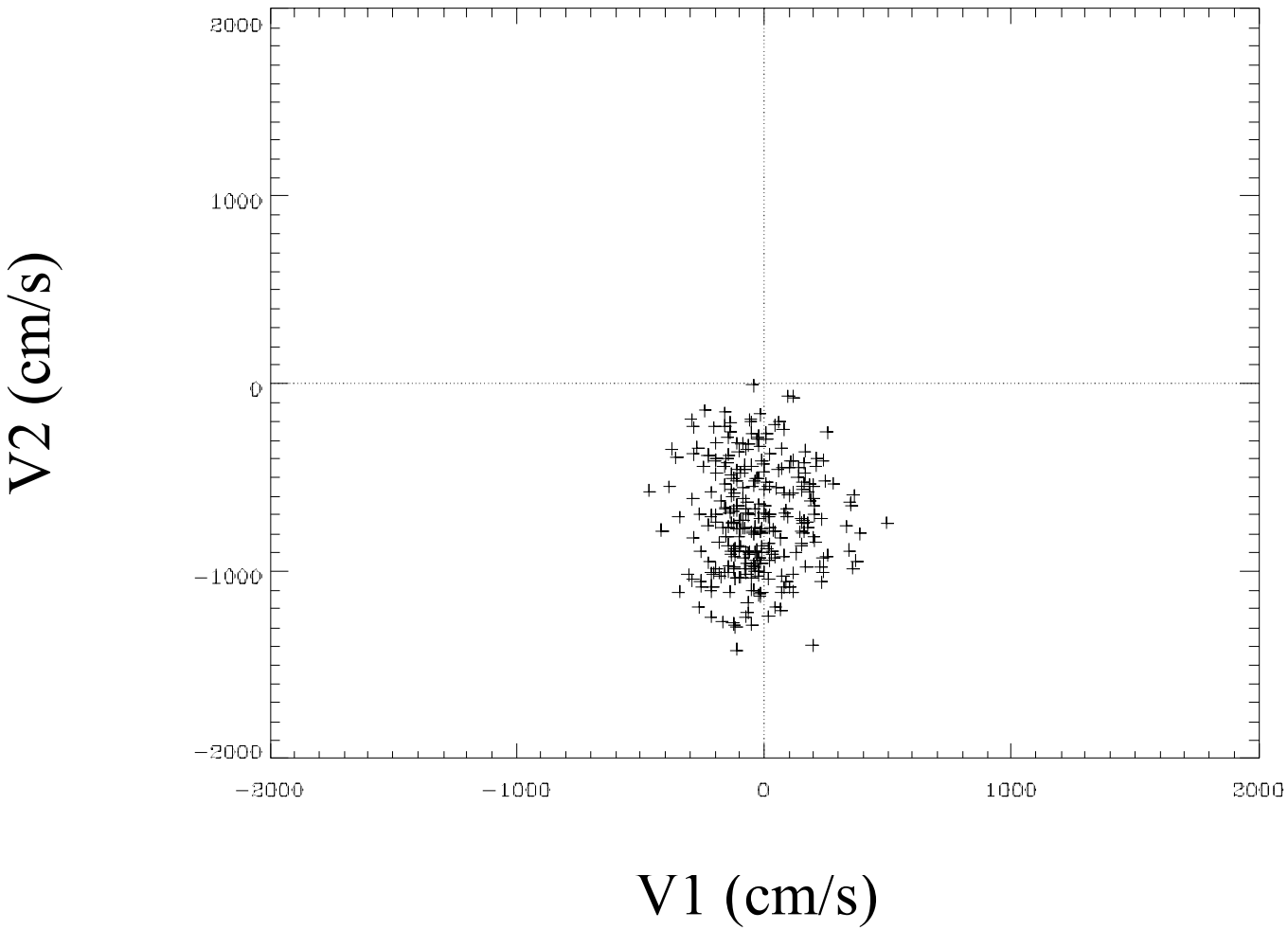


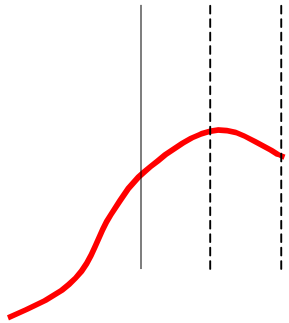
α=2deg, G/L= 1.00 - State space



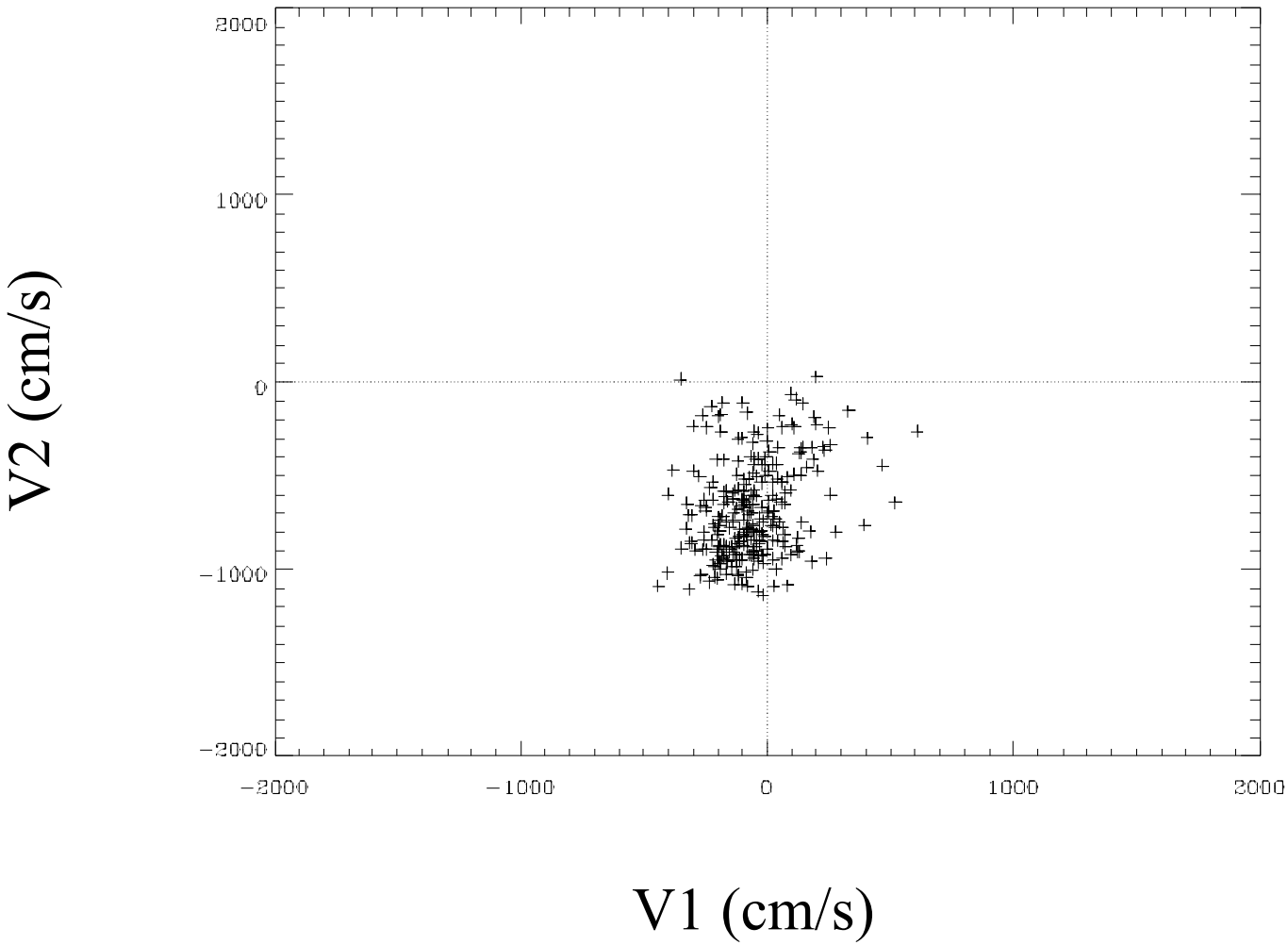


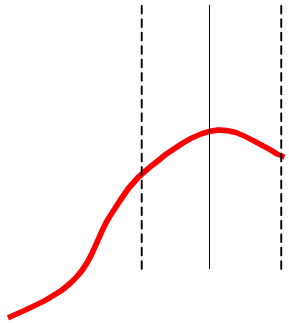
α=6deg, G/L=0.50 - State space



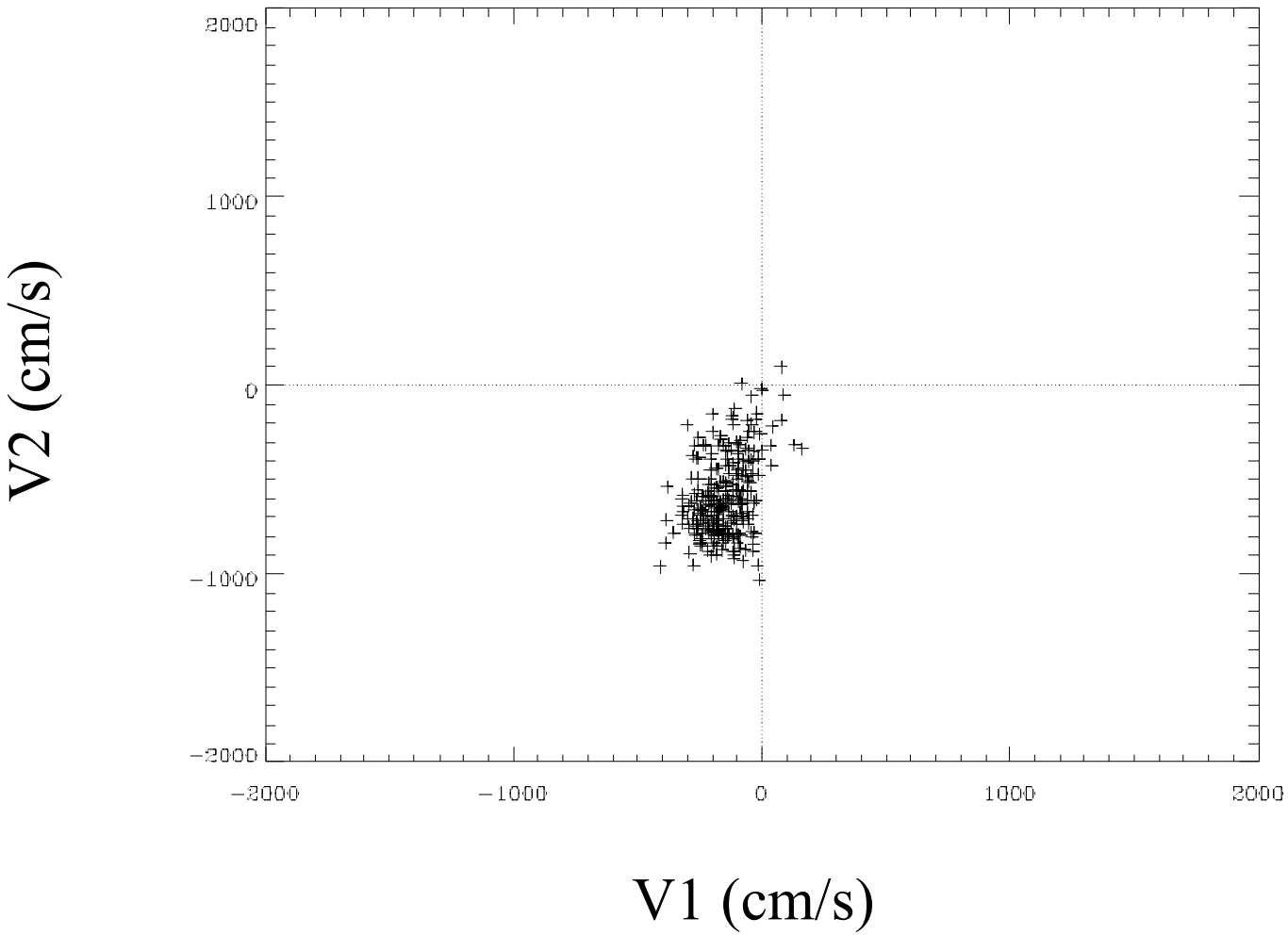


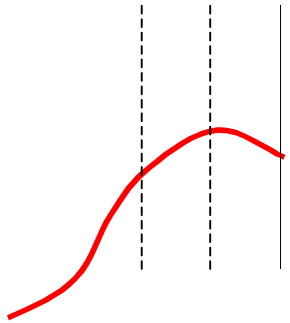
α=6deg, G/L=0.65 - State space



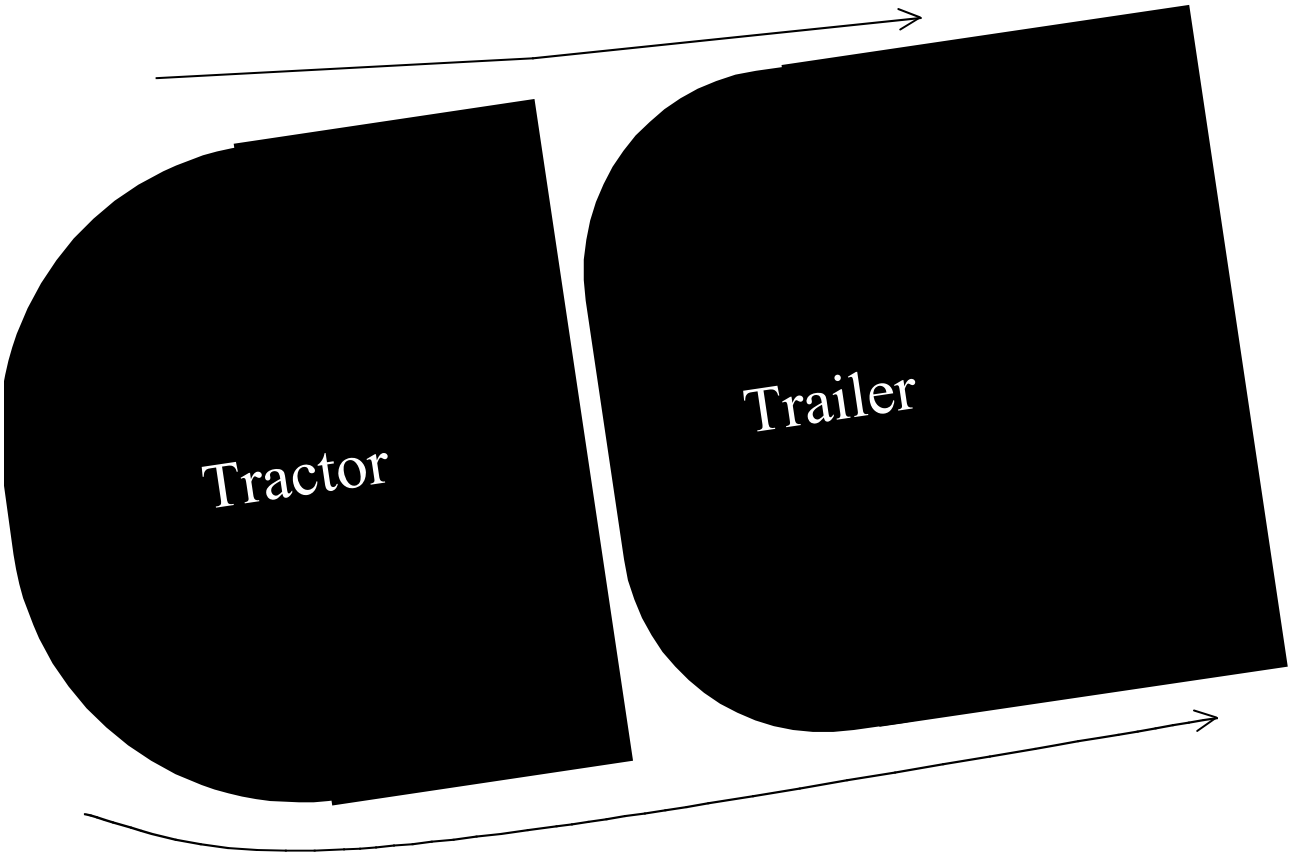


α=6deg, G/L=0.80 - State space





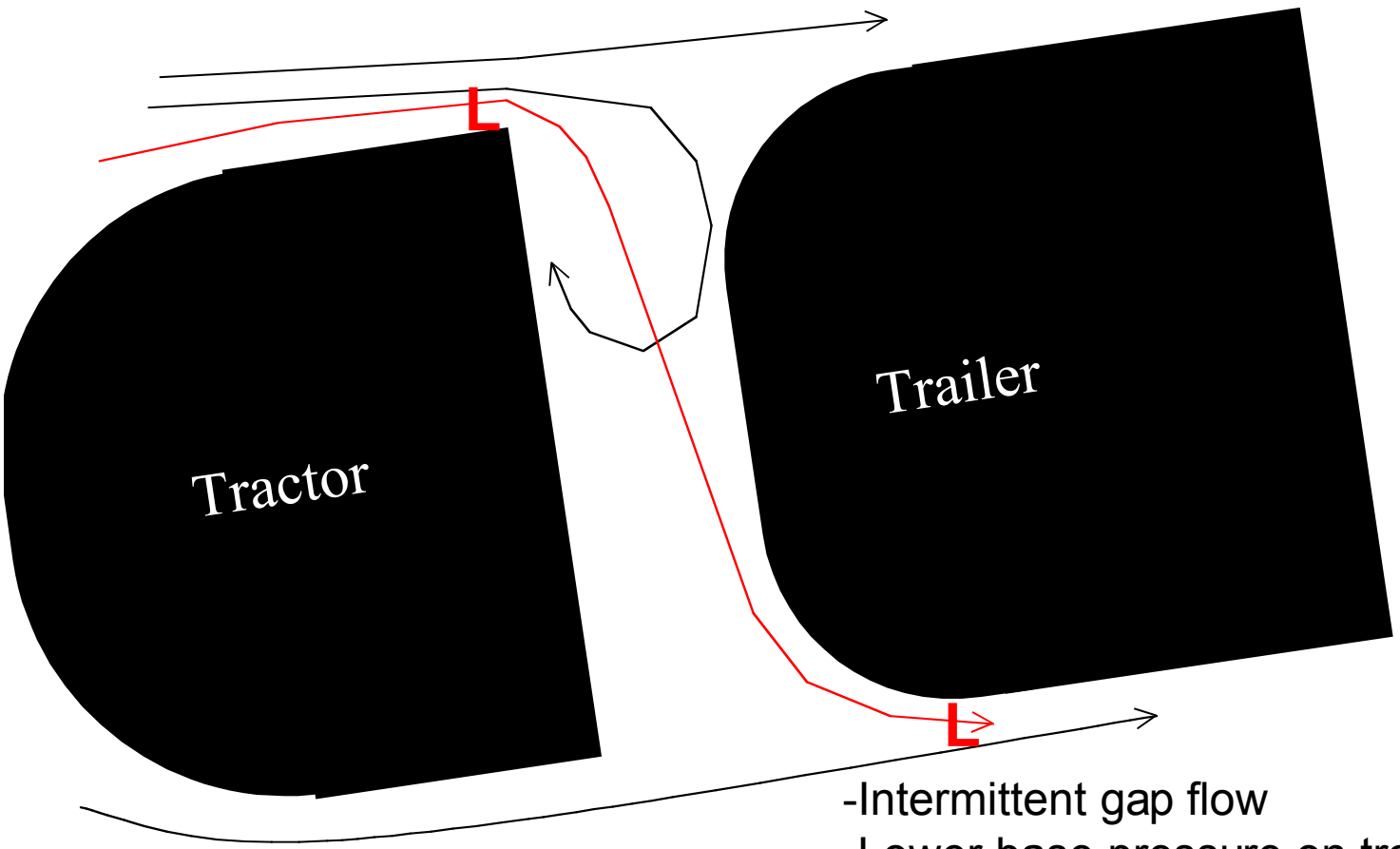
Effect of Gap spacing on drag (1/3)



Small gap

-No gap flow
-Trailer shielded

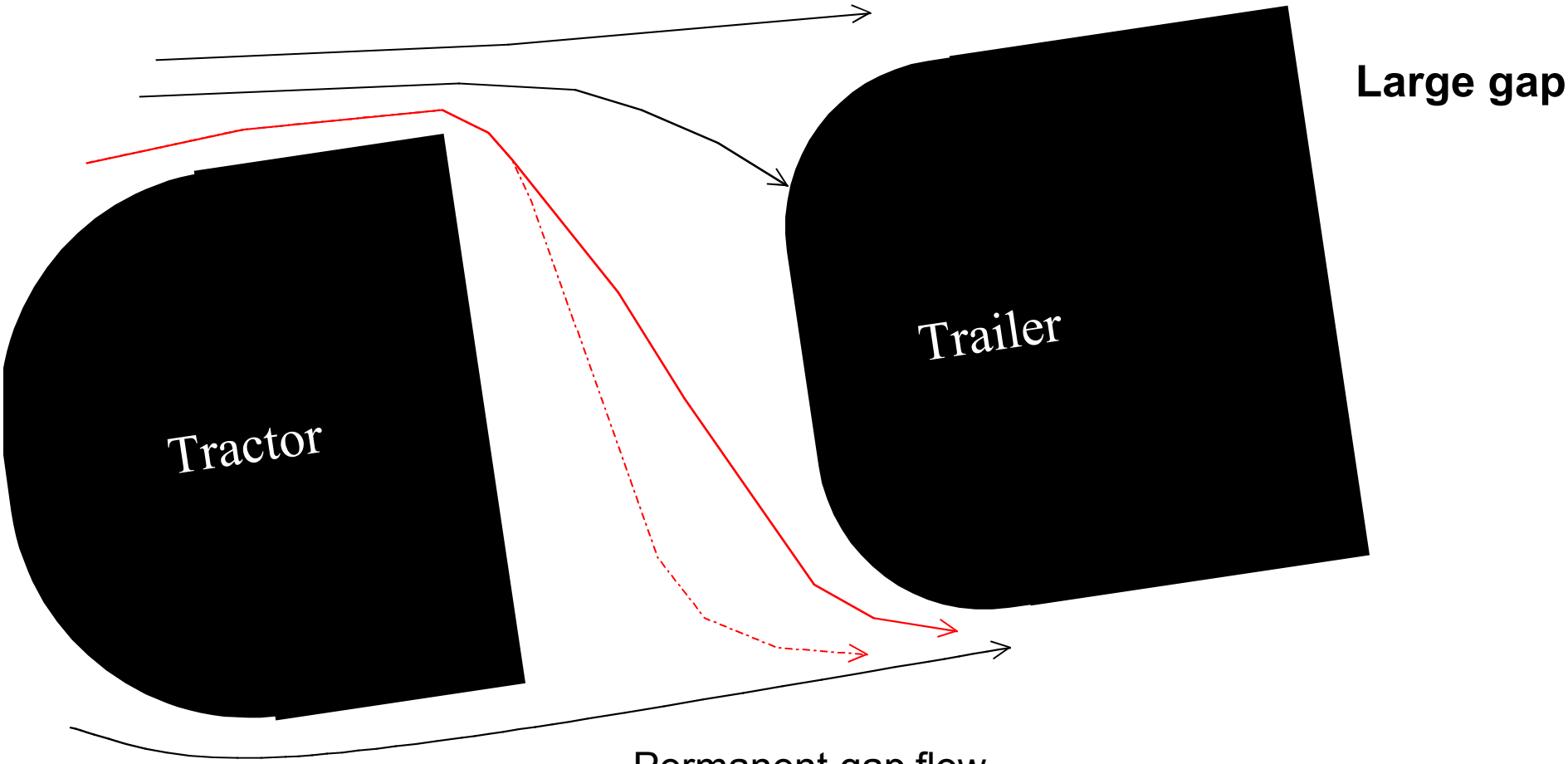
Effect of Gap spacing on drag (2/3)



Critical gap

-Intermittent gap flow
-Lower base pressure on tractor --> drag rises
-Less shielding on trailer --> drag rises
-Peak side force r.m.s. on tractor and trailer

Effect of Gap spacing on drag (3/3)

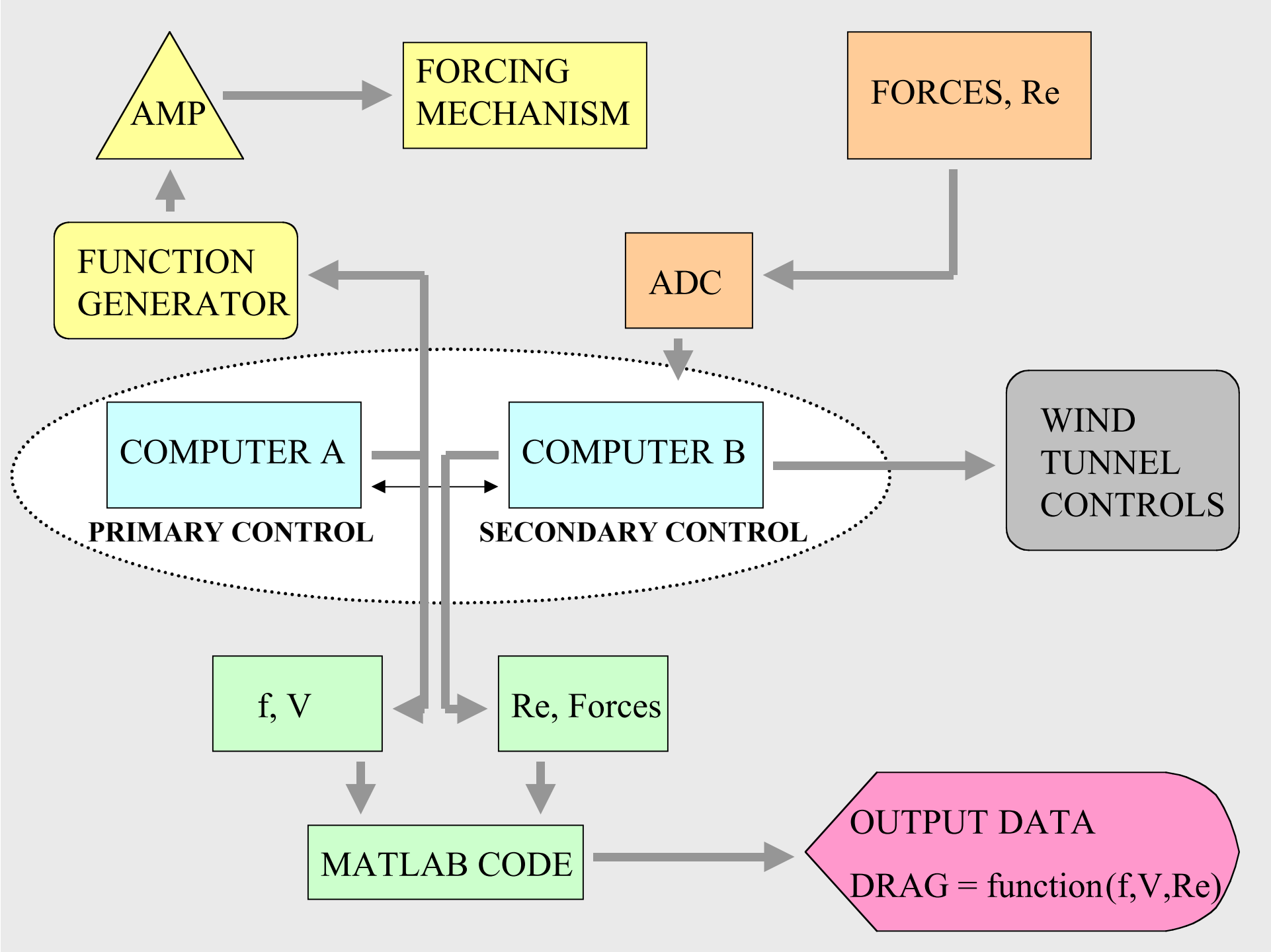


-Permanent gap flow
-Base pressure on tractor increases--> drag drops
-Less shielding on trailer --> drag keeps rising

ACTIVE BOUNDARY LAYER CONTROL RESEARCH

PROJECT OBJECTIVES

- Reduction of drag exerted on a bluff body.
- Identification of energy savings as a function of forcing parameters: amplitude and frequency.
- Comparison of ❮ c_μ ❯ to other energy saving mechanisms; i.e. c_μ or passive devices.
- Development of a system which can be efficiently applied at full scale.


AMP
FORCING MECHANISM
FORCES, Re
FUNCTION GENERATOR
ADC
COMPUTER A
COMPUTER B
WIND TUNNEL CONTROLS
PRIMARY CONTROL
SECONDARY CONTROL
f, V
Re, Forces
MATLAB CODE
OUTPUT DATA
DRAG = function(f,V,Re)

CURRENT RESEARCH

- Use of thermal anemometry to determine jet exit velocities, $\langle c_\mu \rangle$.

- Flow diagnostics under consideration – PIV and base pressure measurements.

- Development of new data acquisition procedure. Drag is to be determined as a function of forcing parameters, flow parameters, and model geometry.

- Measure the energy input versus the energy savings for variations in forcing and geometrical arrangements.

Computational Prediction for a Simplified Truck Geometry

Kambiz Salari

Mary McWherter-Payne

Walter H. Rutledge

Aerosciences and Compressible Fluid Mechanics Department

Sandia National Laboratories

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

Lawrence Livermore National Laboratory

March 29, 2001

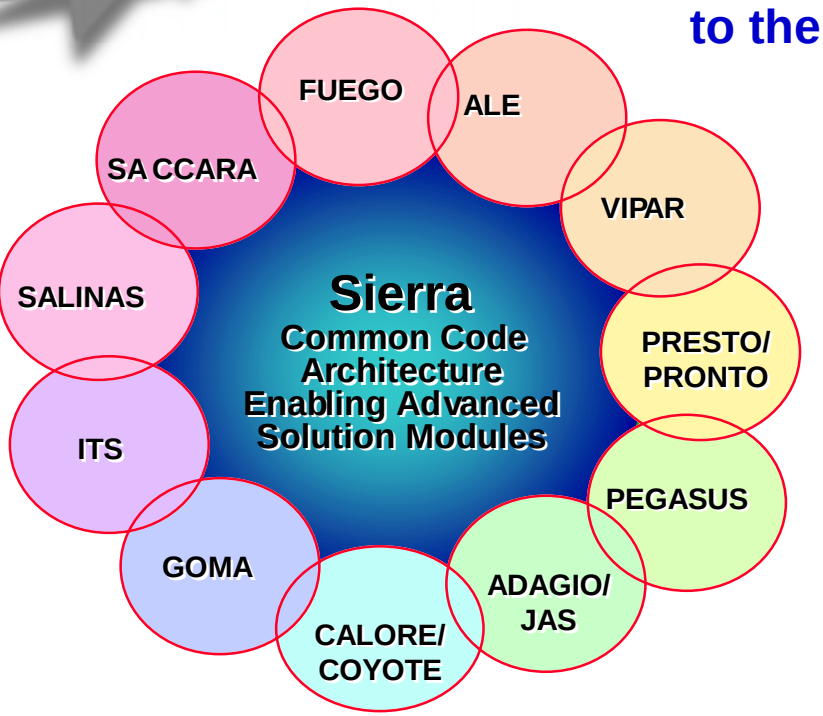
Sandia National Laboratories

Outline

- ASCI Overview
- V&V issues
- Overview of Sandia Accomplishments
- Sandia FY01 Tasks and Budget
- Current status of activities
- Grid Patching issues
- Predictive Capability of RANS
- Status of DES
- Added visualization capability for unsteady flow simulations (with Bob Haimes, MIT)
- Conclusions

Mission

Provide trusted engineering analysis codes to the nuclear weapon complex.



Finite-element services shared among codes

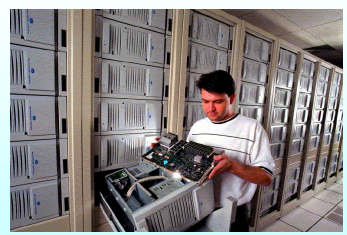
- software quality support
- extensive finite element library
- adaptive meshing
- fully parallel on NWC computers
- dynamic load balancing
- linear solvers
- code coupling

LLNL Blue Pacific

SNL Red Janus

LANL Blue Mountain

SNL CPLANT



codes for the complex

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SACCARA Code Capabilities

Sandia Advanced Code for Compressible Aerothermodynamics Research and Analysis

- Multi-block, structured grids for 2-D, Axisymmetric, and 3-D flows
- Solution of the Full Navier-Stokes equations for compressible Flows (RANS/DES/LES)
- Finite volume spatial discretization (steady and unsteady)
- MP implementation on a variety of distributed parallel architectures (IBM, Intel, etc.)
- Implicit time advancement schemes
- Subsonic → Hypersonic flows
- Zero-, one-, and two-equation turbulence models
- Ideal, equilibrium, and thermo-chemical nonequilibrium finite-rate gas chemistry
- Ablation boundary conditions
- Rotating coordinate system

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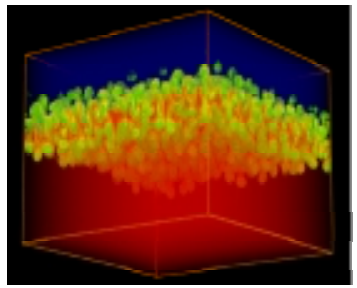
ASCI Program Elements

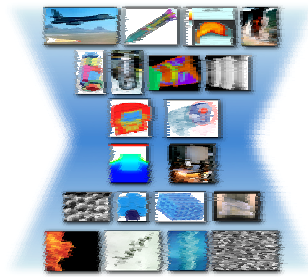
Computers

Develop massively parallel, high performance computers to achieve the ASCI 100 TeraOps computing goal by 2004



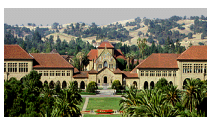
Applications Codes

Modify and develop codes to achieve the speedup's and improvements necessary to perform full physics simulation



Verification and Validation

- Provide the tools methodologies and data to ensure that high-end simulation capabilities reflect reality
- Establish confidence in the predictive capabilities of ASCI tools



Alliances

Problem Solving Environments

Make the full-physics codes user friendly to weapons analysts including set-up of large scale problems, transferring and storing tera-byte size files, and 3D visualization on the desktop of these tera-byte size files

isCom²

- Implements secure Tera-scale computing across 1000s of miles
- Integrate information and simulation
- Install distributed security and resource management
- Demonstrate high capacity distributed computational plant

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ASCI Red Platform

ASCI INTEL "RED"
TeraOp Computer
Sandia National Laboratories
1.8 TeraOps

Tightly Coupled
Distributed Memory
HP Interconnect, 9000
200MHz Processors
2 processors/node
MPI Programming Model
600 Gbytes Memory

ASCI Red is:

- **Providing outstanding performance and stability**
- **Transitioned to a production mode**
- **Doing important work for the Stockpile Stewardship program**
- **Effectively saturated**

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Understanding the Solution

- Because of the influence from the ASCI program, Sandia is very concerned about the following issues (and these are big issues!):
  - Verification
  - Validation
  - Uncertainty Quantification, including:
    - Solution Accuracy Assessment
      - Grid Resolution Studies
    - Sensitivity to input parameters
    - Other sources of error or uncertainty
    - AIAA 2000-2549 paper provides further guidance on V&V and uncertainty quantification for CFD

What is a Validation Experiment?

Based on: "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations" (AIAA-G-077-1998)

1) A validation experiment should be jointly designed and executed by experimentalists and code developers.

- **Teamwork and candor are essential**

2) A validation experiment should be designed to capture the relevant physics, all initial and boundary conditions, and auxiliary data.

- **Leave no loop-holes in the comparison**

3) A validation experiment should utilize any inherent synergisms between experiment and computational approaches.

- **Offset strengths and weaknesses of each approach**

What is a Validation Experiment? (cont'd)

4) The flavor of a blind comparison of computational results with experimental data should be a goal.

   – It should be a "true prediction," not a calibration

5) A hierarchy of complexity of physics should be attacked in a series of validation experiments.

   – Identify levels of complexity and difficulty of prediction

6) Develop and employ experimental uncertainty analysis procedures to delineate and quantify systematic and random sources of error.

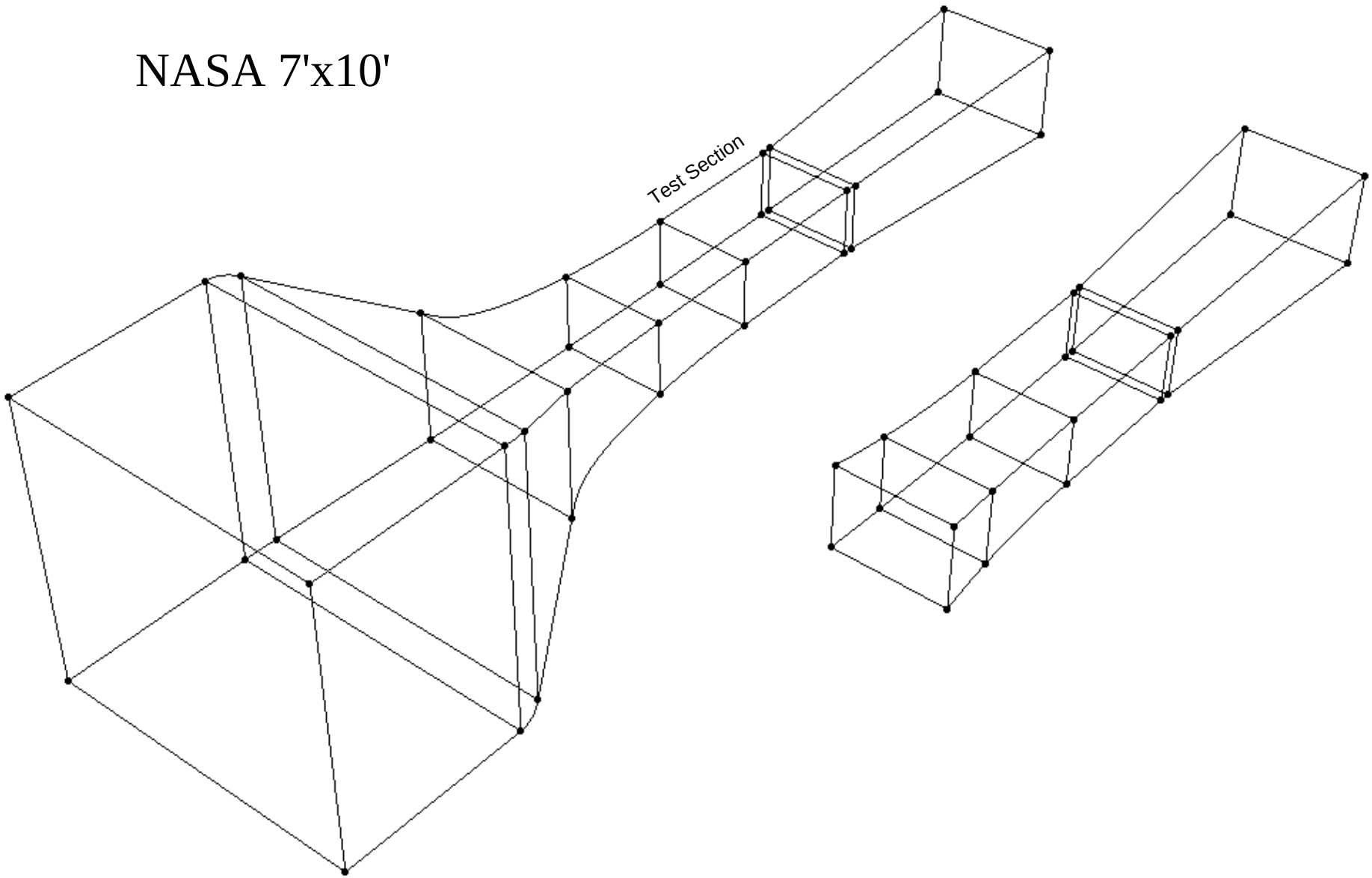
   – Use symmetry arguments to help identify systematic errors

– Validation experiments are new types of experiments.

Levels of Validation

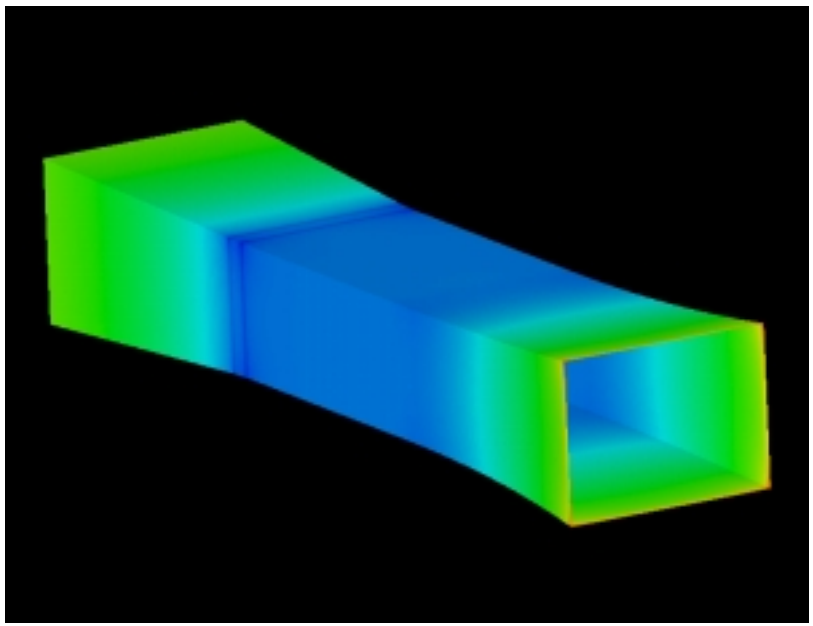
- Increasing levels of complexity…. (applied to both experiments and computations)
  - Unit Level
  - Benchmark Level
  - Sub-System Level
  - System Level
- Refer to AIAA-G-077-1998 for more clarification on Validation Levels

NASA 7'x10'

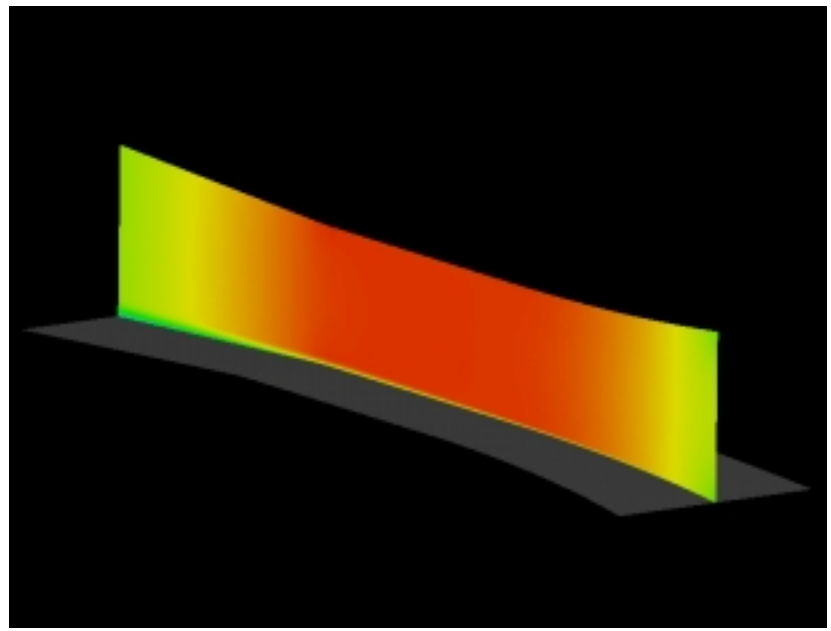


NASA 7'x10' Tunnel, Flow Simulation

Pressure contours

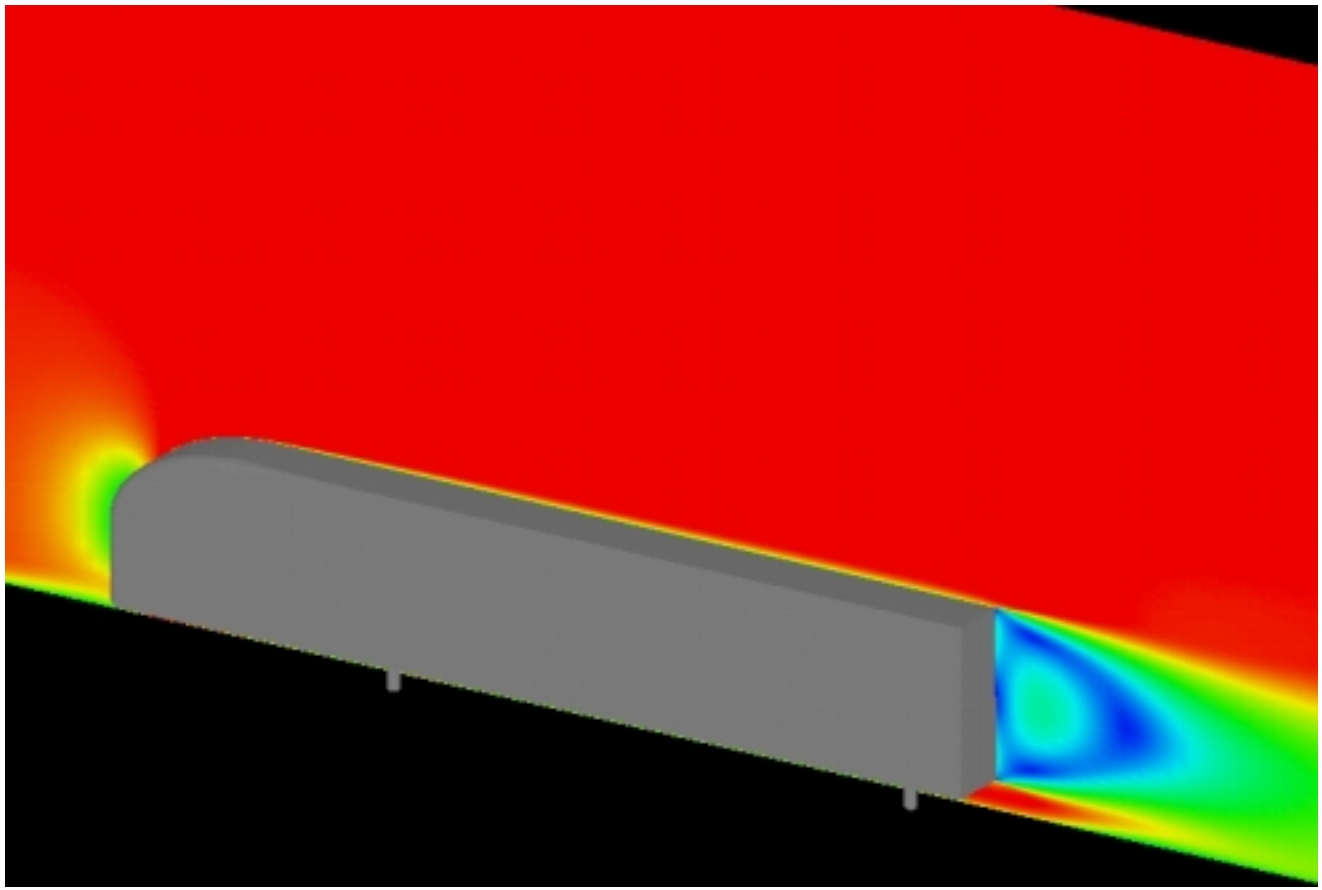


Mach contours (centerline)



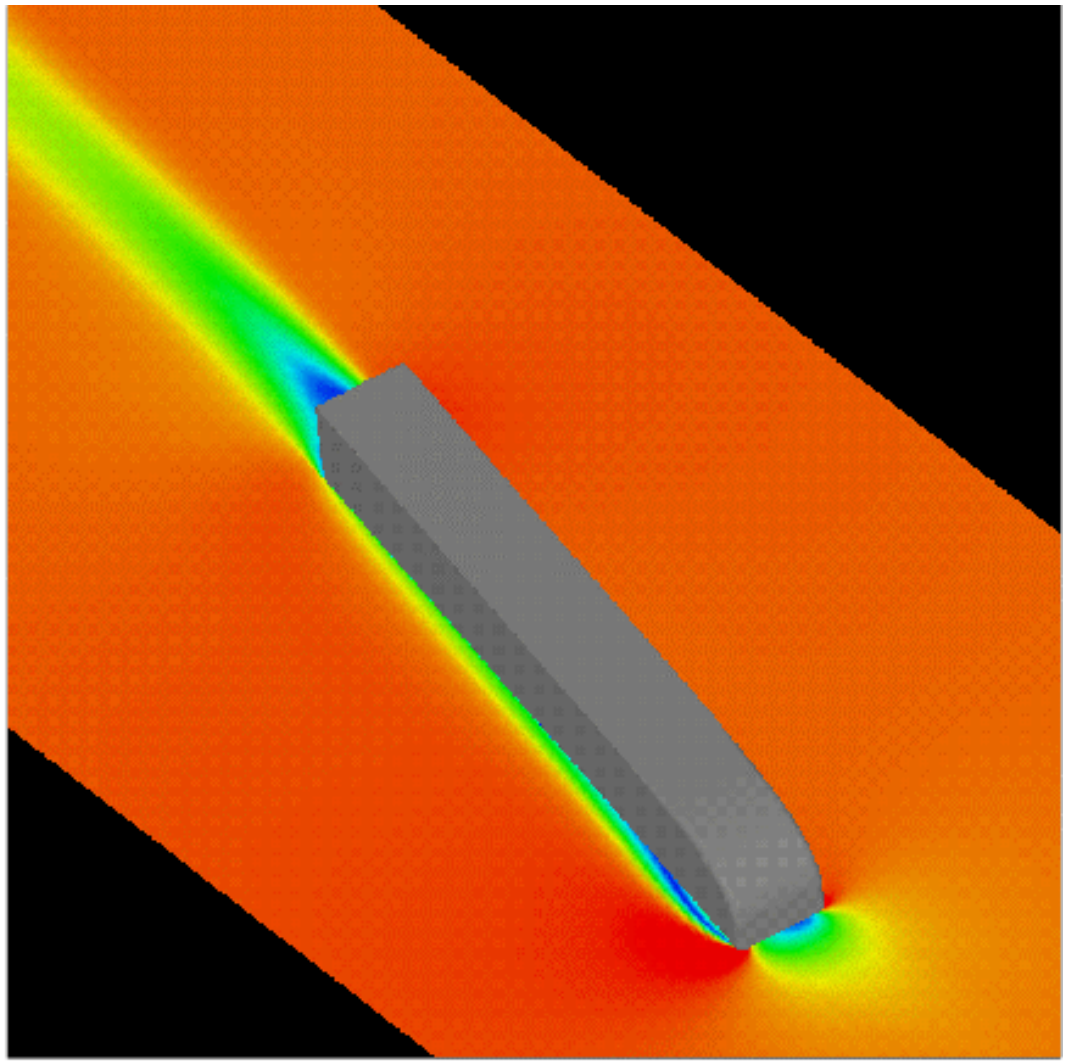
Steady RANS Solution, 0° yaw

Mach contours (centerline)



GTS Flow Simulation, 10 yaw

10° yaw
y-plane cut
Mach contours



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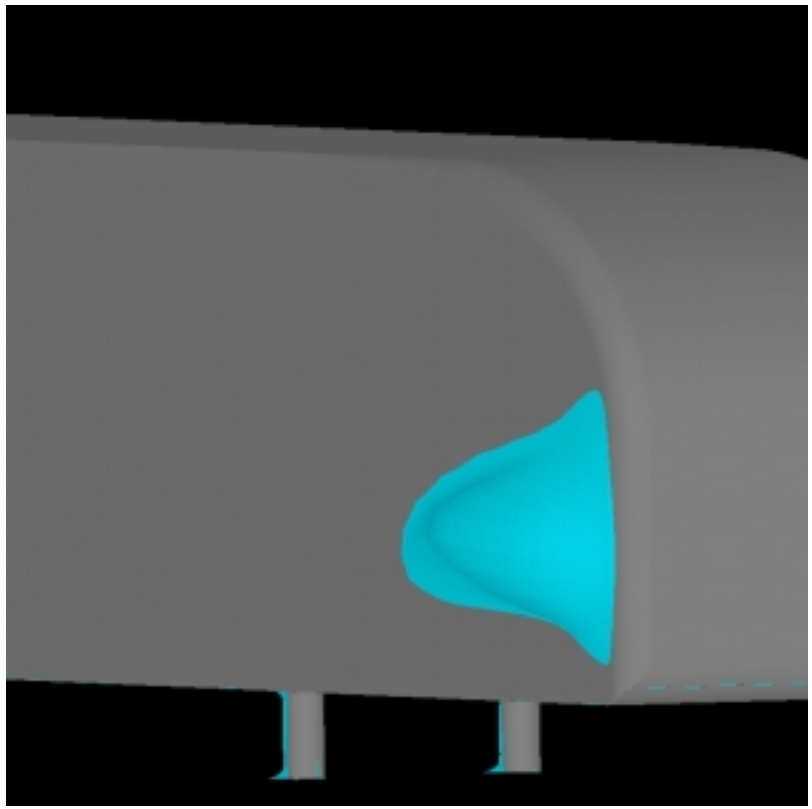
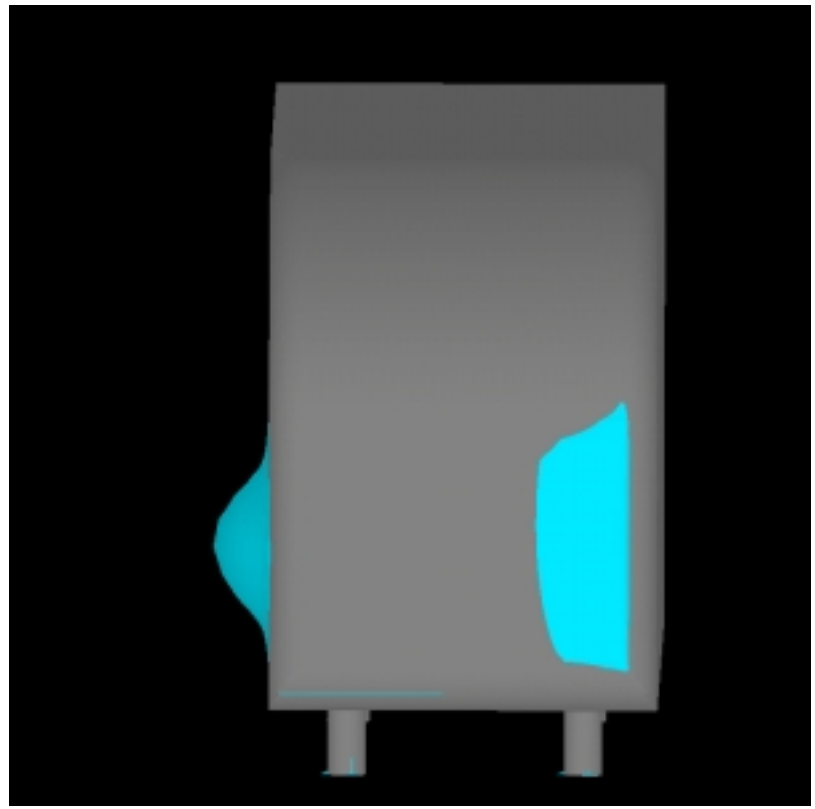
Separation Bubble, Leeward Side, 10° yaw

Iso-Surface u = -0.001 (m/s)





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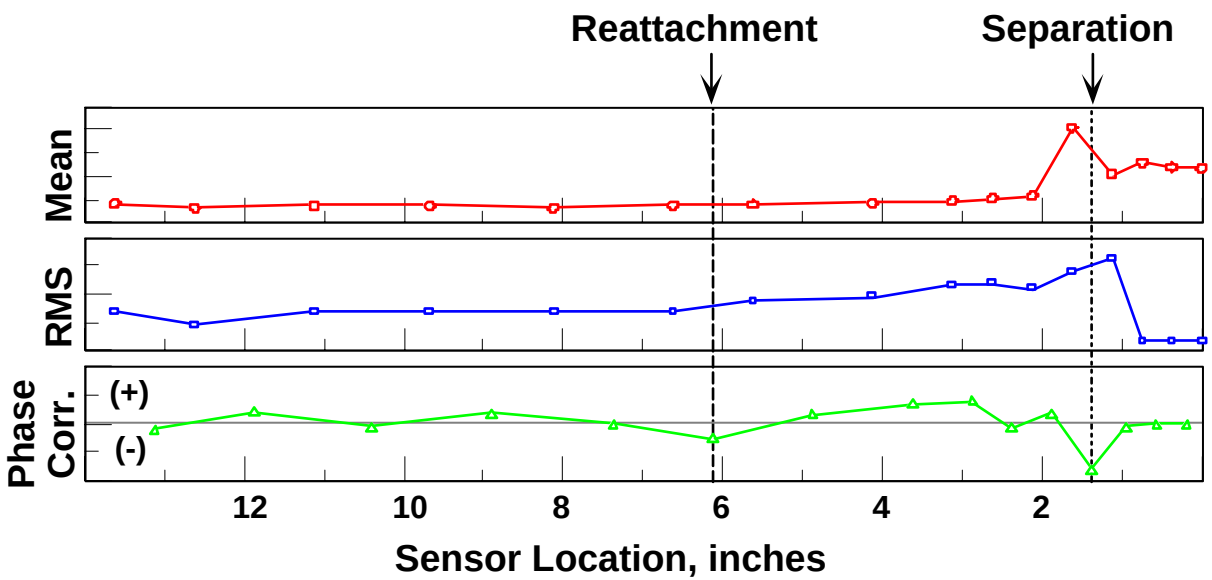
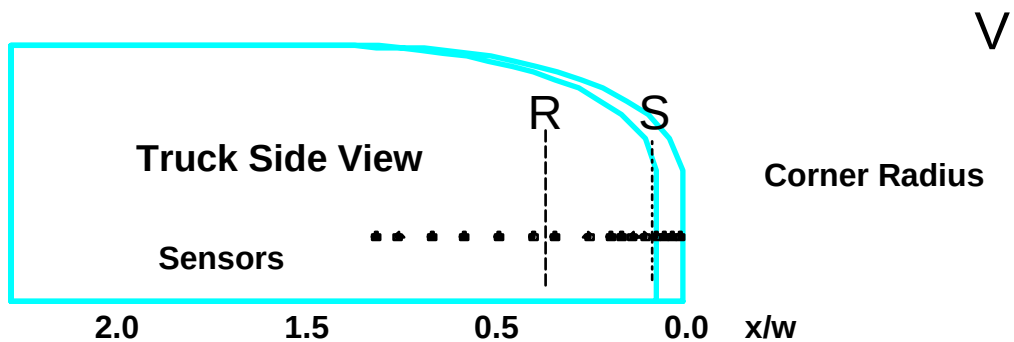
Hot Film Results





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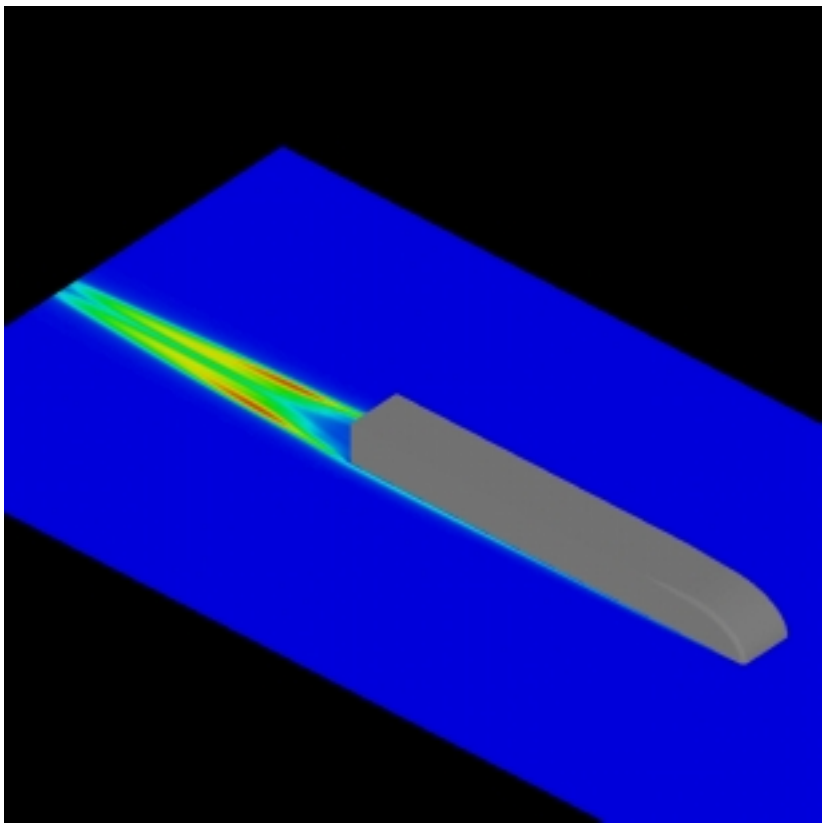
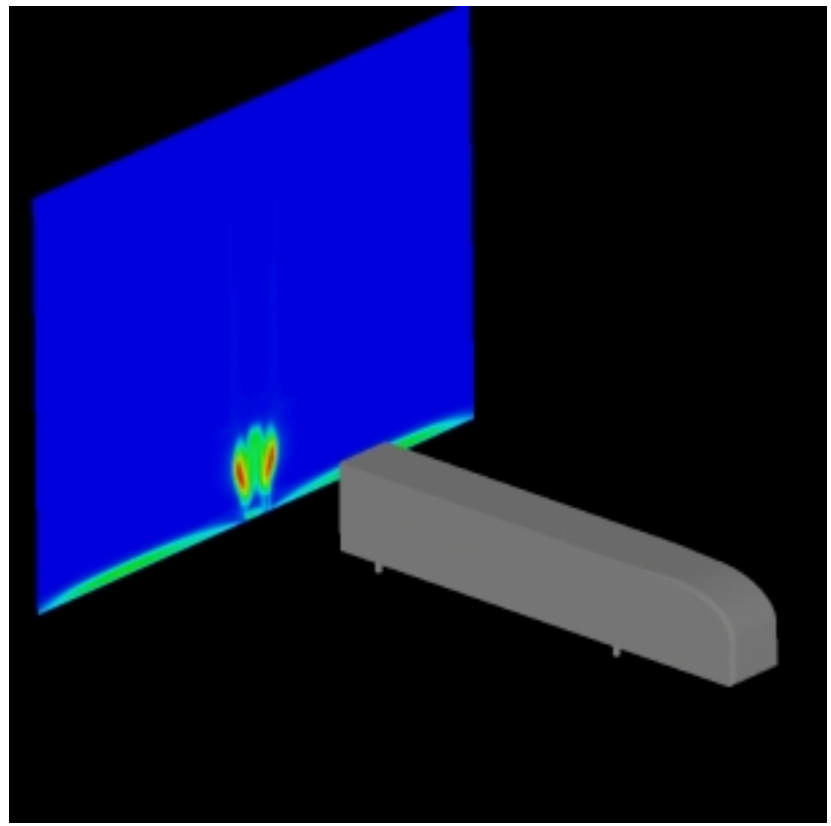
GTS Flow Simulation, DES Result

Contours of turbulent viscosity, xy and yz cutting planes





Sandia Tasks for FY01

1. Complete March 2002 SAE paper that documents RANS solutions for 0° and 10° yaw angles (NASA 7'x10')
2. Perform grid resolution for RANS calculations
3. Construct grids for DES simulations
4. Perform DES calculation 0° yaw angle
5. Document the DES results in a March 2002 SAE paper
6. Investigate the capability of RANS eddy viscosity models (SA,k-ε,k-ω,k-ζ) to predict the wake flow of the GTS and document in a SAE paper (this task is very important for evaluating accuracy of RANS)
7. Help design and participate in future NASA wind tunnel experiments (task currently unfunded)
8. Improve visualization for unsteady flow simulations (Real-Time feature extraction for RANS/DES/LES)

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Sandia Funding Status

- Funding request for all tasks was $330K (Aug. 00)
- FY01 Project Funding Decision: $225K
  - All funding has been received
- Year-to-Date Spending: $69K
  - All tasks (except Task 7) expected to be completed this year ($285K tasks accomplished for $225K)
- Leveraging
  - Eng. Sci. Research Foundation funding for DES research
  - ASCI Sub-Grid Physics funding:
    - RANS Turbulence Modeling
  - ASCI Code Development, University Alliance funding for boundary layer transition research
  - ASCI Red Teraflop Computer (9000 processors)

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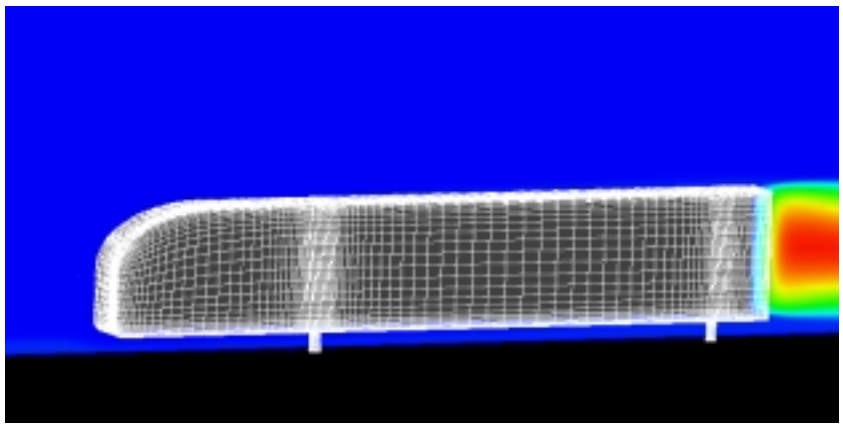
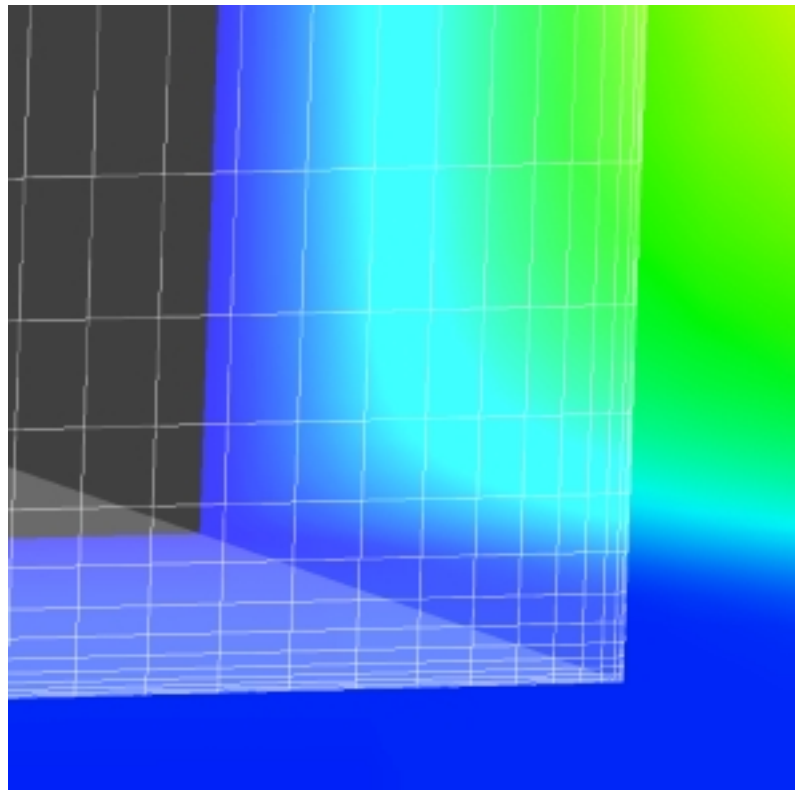
Current status of activities

- GRIDGEN – new version of GRIDGEN has a bug in providing block patching information for SACCARA and had to revert back to older version
- SACCARA – have uncovered a bug in the k-ω turbulence model (now fixed)
- DECOMP – This code provides decomposition of the grid for parallel runs. Uncovered a bug for the inter-zone patching
- Janus – Lack of availability since December due to OS/hardware stability issues (this has severely affected our productivity)

Boundary Condition: Inter-Zone Patch



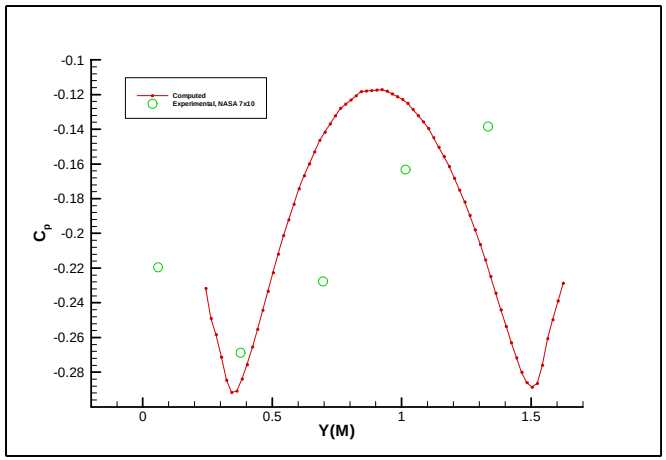


RANS Solutions

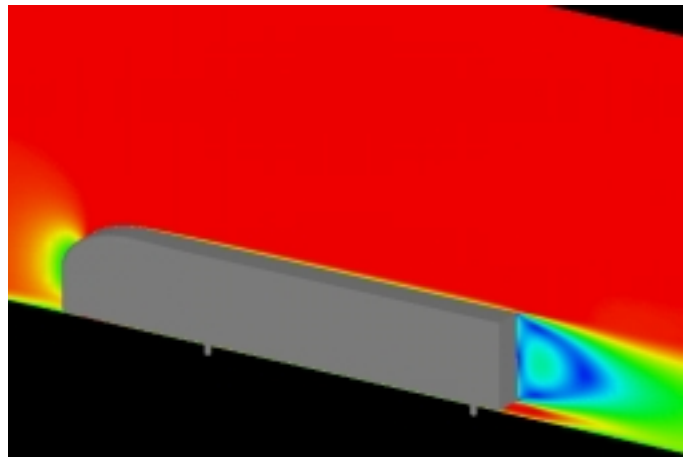
- Simulate truck model in the tunnel for “validation exercises”
- Good agreement over the entire truck except in the base region
  - RANS code appears to be useful for design tradeoff studies (but not absolute numbers)
- RANS code (at least with one-equation SA model) does not appear to capture the right wake structure
  - New FY01 task will assess newer and more advanced turbulence modeling based on eddy viscosity models (e.g., k-ω, k-ζ)

Steady RANS Solution, 0° yaw

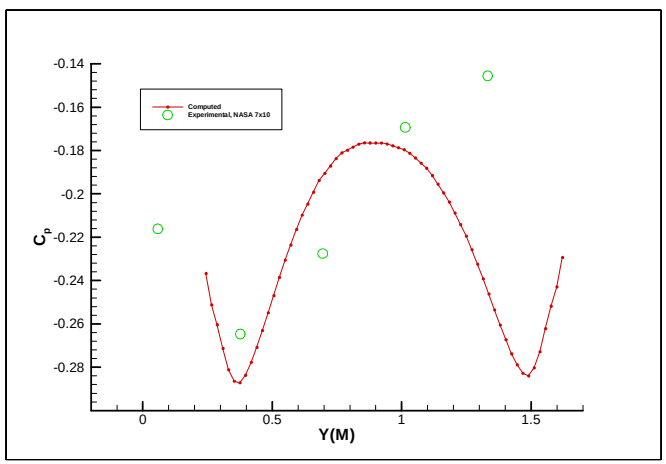
Z = 0.0 (centerline)



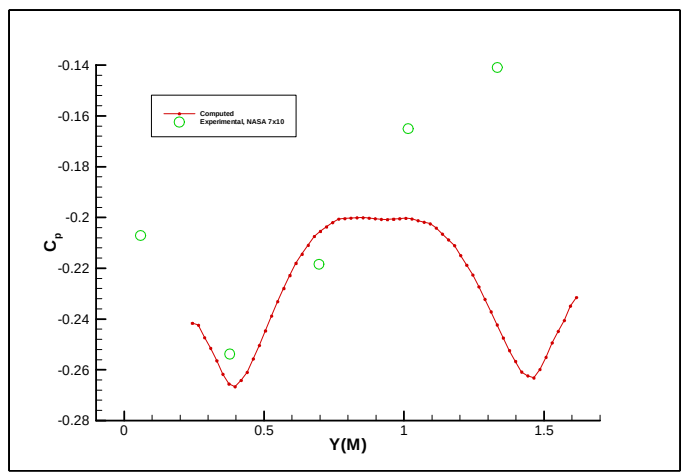
Mach contours



Z = 0.22



Z = 0.44



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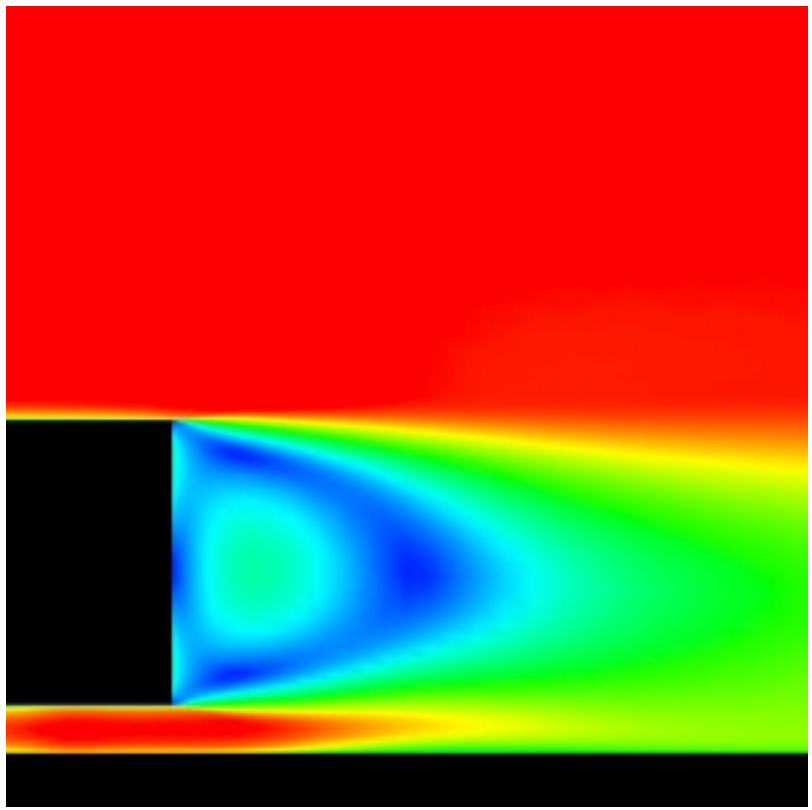
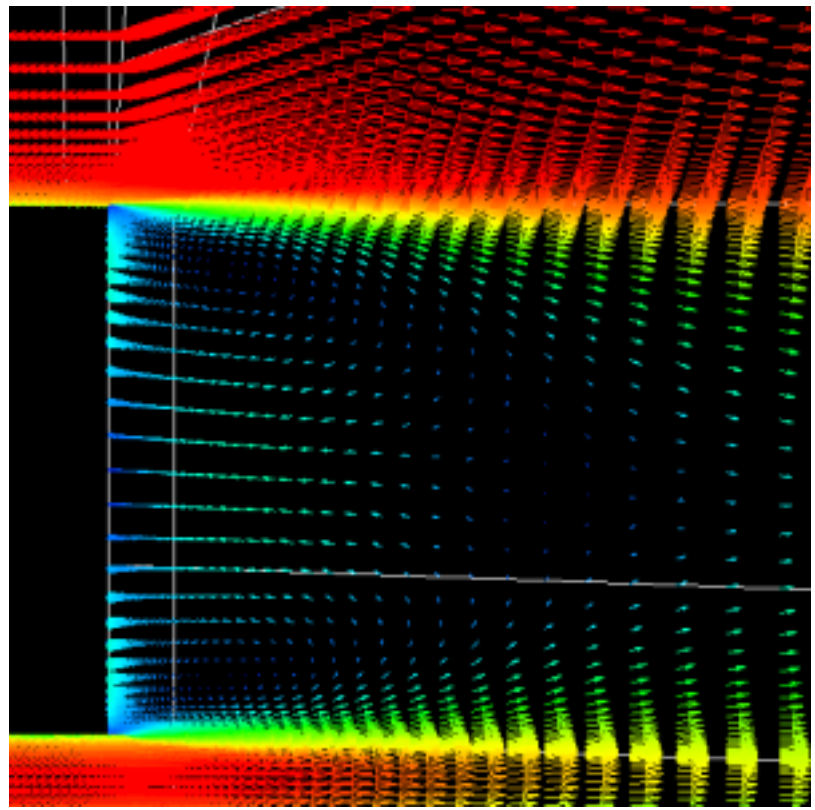
Steady RANS Results , 0° yaw, …

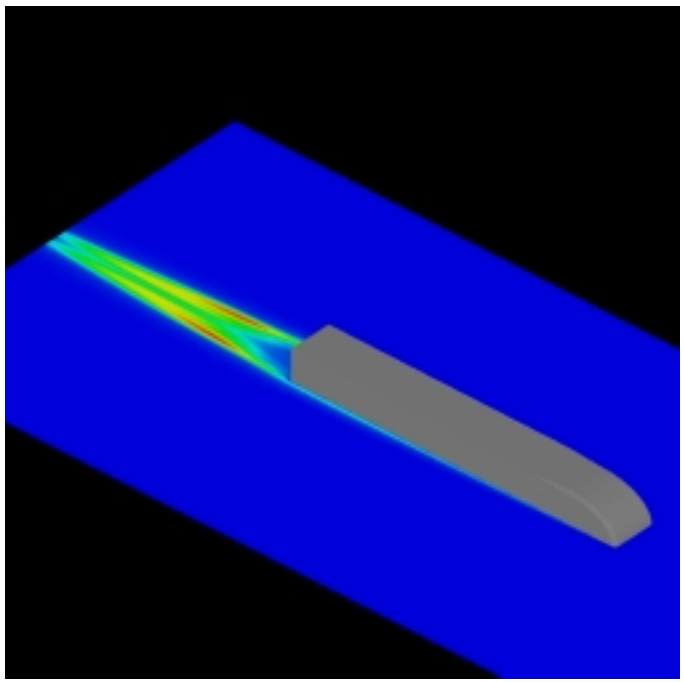


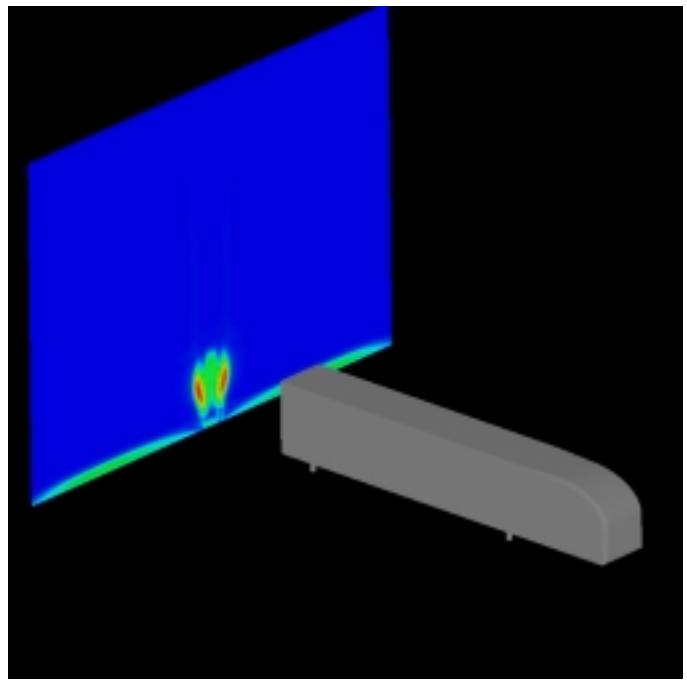


Sandia National Laboratories

Status of DES

- DES simulation of the GTS model in the NASA 7'x10' tunnel that has been on going is on hold because of the block and inter-zone patching and boundary condition issues (hope to resume in April)





Added Capability to Visualize Large Dataset

- DES/LES unsteady simulations produce very large datasets
- Feature extraction, real-time on MP machine (vs. post-processing)
  - Vortex core
  - Surface cutting plane
  - Particle traces
  - Separation and reattachment lines
  - Significant reduction in storage
- For the circular cylinder coarse grid example, 250 MB of storage was required as opposed to 20 GB of storage for the entire volume to be stored for proper post-processing

Movie time

Concluding Remarks

- Due to the uncovered bugs, all the calculations that have been performed so far are suspect and need to be investigated for the sensitivity of the solutions to the inter-zone patch difficulties (on-going)
- Documentation of previous RANS simulations are on hold until we have a better understanding of the impact of the patching issues on these solutions (should pick back up in April)

Concluding Remarks, …

- The uncovered bugs in block patching and inter-zone patching have been corrected
- All previous grids for GTS model have been modified to eliminate the inter-zone patching problem
- Currently, we are rerunning our calculations with different turbulence models with the above corrections
- All scheduled tasks should be completed and documented by the end of FY01

Simulation of Complex, Unsteady Flows Using a Grid-Free Vortex Method

A. Leonard, P. Chatelain, M. Rubel
Graduate Aeronautical Laboratories
California Institute of Technology

March 28-29, 2001

Vortex Code: *Essentials*

- Numerical technique to solve the Navier-Stokes Equations
- Suitable for Direct Simulation and Large-Eddy Simulation
- Uses vorticity (curl of the velocity) as a variable
- Computational elements move with the fluid velocity

Vortex Code: *Advantages*

- Computational elements only where vorticity is non-zero
- No grid in the flow field
- Only 2D grid on vehicle surface
- Boundary conditions in the far field automatically satisfied

Large-Eddy Simulation

Direct Simulation not Sufficient (1990s)

- Direct Simulation possible for Reynolds no.=10^3 to 10^4
  (at parking speeds – 0.01 mph)

- $N = 10^{12}$ elements (approx. 20 Terabytes) required for Reynolds no.=5×10^6
  (at highway speeds)

Large-Eddy Simulation Required

- Treatment of small-scale (subgrid-scale) turbulence in the wake

- Treatment of small-scale turbulence in the boundary layers

- Treatment of fluidic actuators, blowing/suction, vortex generators and other flow control devices

Numeric Time Integration by Dead Reckoning

A Tool-In-Progress for Accelerating Heavy-Vehicle Aerodynamic Computation

Mike Rubel

Tony Leonard

Graduate Aeronautical Laboratories · California Institute of Technology

March 29, 2001

Fully-Resolved DNS of Flow Around a Truck at Re 10^7

. . . just kidding

- Luckily, we know the equations
- We can even solve them sometimes
- The problem is speed
- Searching for pockets of inefficiency or redundancy
- An observation . . .

next: equations as an ODE in time

Time Integration of the Flow Equations

Discretizing the flow equations (vorticity equation, in our case) gives a system of the form:

$$\frac{dX}{dt} = A(X) \qquad\qquad X(0) = X_0$$

where:

- X is the *state vector*
- A is a (dense) nonlinear operator

In vortex particle methods, X contains the strength and position of each particle and the boundary panel strengths. In finite-difference methods, it contains values of the fields at grid points.

next: integrating the equations numerically

Timestepping: A Truly Brief Overview

Solve:

$$\frac{dX}{dt} = A(X) \qquad\qquad X(0) = X_0$$

$$X = \{x_0, x_1, \ldots, x_N\}$$

Take a “small” Δt, move a “small” ΔX. Small is relative!

Fast Big Steps	$\Longleftrightarrow$	Accurate Small Steps

How do we choose Δt when X is a vector with many components?

The CFL Condition: Astronomical Analogy

. . . or, Why We Can't Just Scale Each Variable's Timestep Independently

Solution: limit timestep by fastest relative speed, smallest distance $\longrightarrow$ the CFL (Courant, Fredrichs, Lewy) condition.

Next: what does this mean for truck aerodynamics?

CFL Condition: A Step In The Fluids Direction

$$\Delta t_{max} \propto \min(\frac{\sigma^2}{\Gamma}, \frac{\sigma^2}{\nu})$$

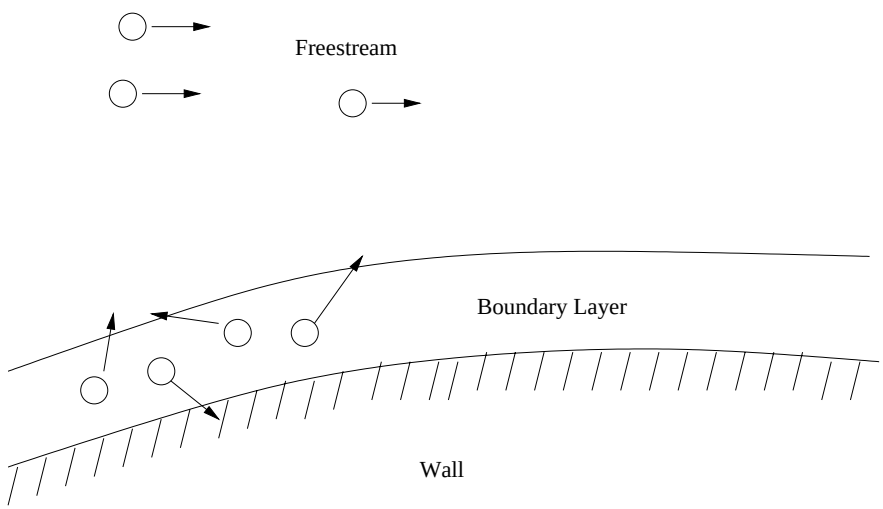
Γ is the largest relative velocity times the largest physical scale in the problem; σ is a grid spacing or particle core size.

The effect of using too large a CFL number depends on the timestepper and the problem. Sometimes the calculation becomes inaccurate; sometimes an instability develops.

$$\boxed{\text{CFL too big}} \longrightarrow \boxed{\text{inaccurate / unstable}} \longrightarrow \boxed{\text{NaN, inf}}$$

next: how using a single Δt leads to redundancy . . .

Possibly Redundant Computation



Most of the particles move roughly with the freestream, and they're timestepped *very* slowly. That's because the *largest* relative speed controls the time step, and in many flows of interest, there is some small region with a lot of activity. A few particles spoil it for everyone.

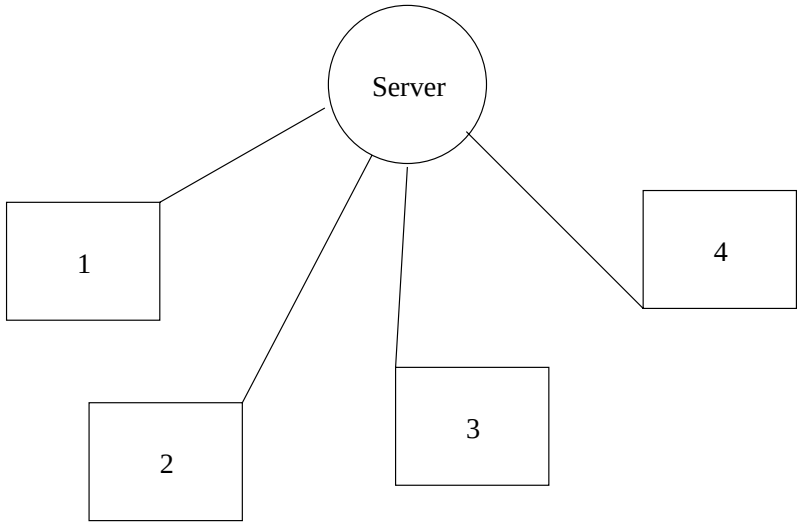
next: sometimes we do take different steps

When May We Use Different Timesteps?

- Astrophysical simulation
- Bubbles
- Multiple grids
- Chemical reactions

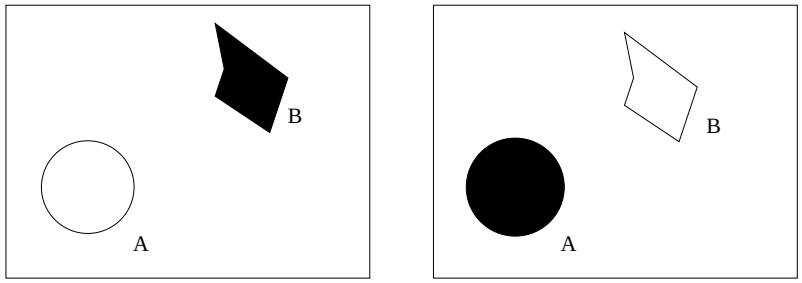
Often problem-dependent. Is there a better way?

A Slight Detour: Network Games



- server insures each version is the same
- reduce the effect of network lag
- use *dead reckoning*.

The Dead Reckoning Algorithm



- player A sends position and velocity to player B
- B extrapolates A's position until further notice
- A performs the same extrapolation; sends new position and velocity to B when the error reaches some predefined threshold

next: integration by dead reckoning

Integration by Dead Reckoning: Algorithm

Choose a flexible form for each element of X:

$$X(t) = \{x_1(t)\ x_2(t)\ \ldots\ x_n(t)\}^T \qquad\qquad x_i(t) = a_i t + b_i$$

then solve:

$$Y(t) = \int_0^t A(X(\tau))\, d\tau + X_0 \qquad\qquad \|X(t) - Y(t)\| < \epsilon$$

Assume that at time t_0, locally-valid coefficients are known for all x_i. Sleep until one of the following:

- *Continue*: It is not known how much longer $x_i(t)$ will be a valid approximation to $y_i(t)$. Timestep forward a small amount; schedule a *repost* or another *continue*. Go back to sleep.
- *Repost*: Revise the coefficients of this $x_i(t)$ based on new information. Wake all x_j that depend on x_i through A immediately with a *continue*.

Let's Try An Example

Solve the (scalar) equation:

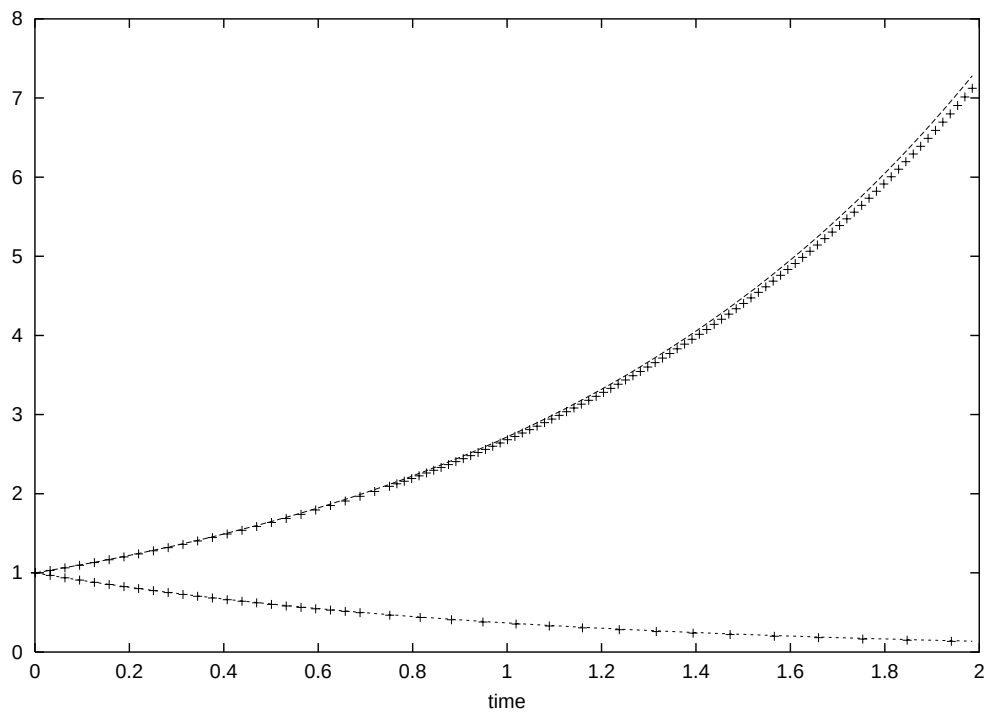
$$\frac{dx}{dt} = 2x \qquad\qquad x(0) = 1$$

Exact solution $x(t) = exp(2t)$.

next: so . . . how does it work?

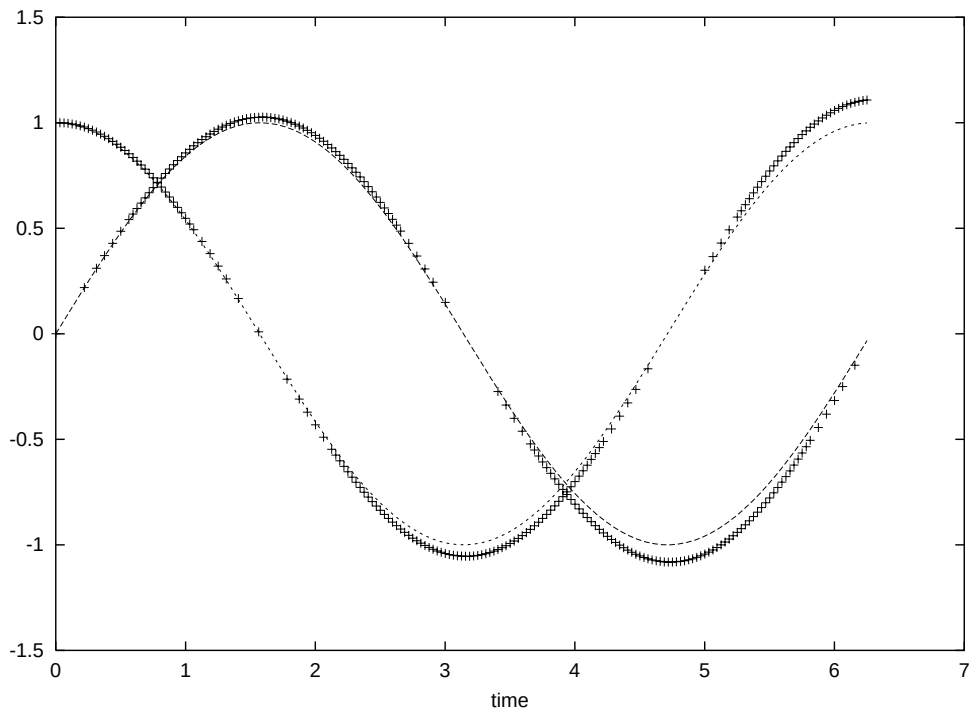
Results: a Diagonal System

$$\dot{X} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} X \qquad X_0 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$



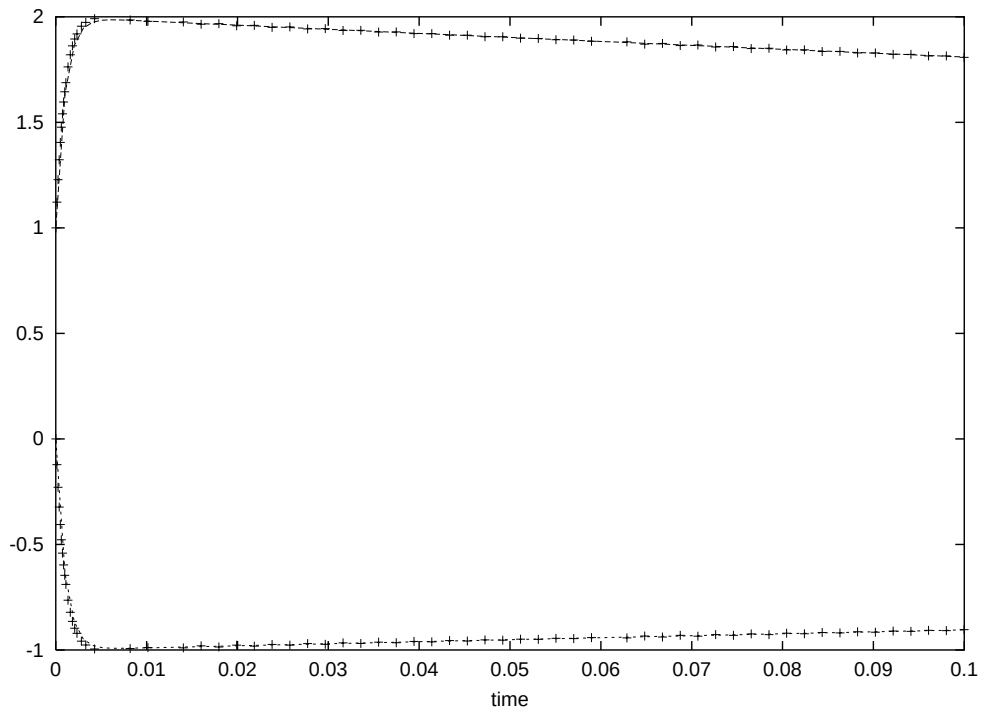
Results: a Not-Diagonal System

$$\dot{X} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} X \qquad X(0) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$



Results: a Stiff System

$$\dot{X} = \begin{bmatrix} 998 & 1998 \\ -999 & -1999 \end{bmatrix} X \qquad X(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

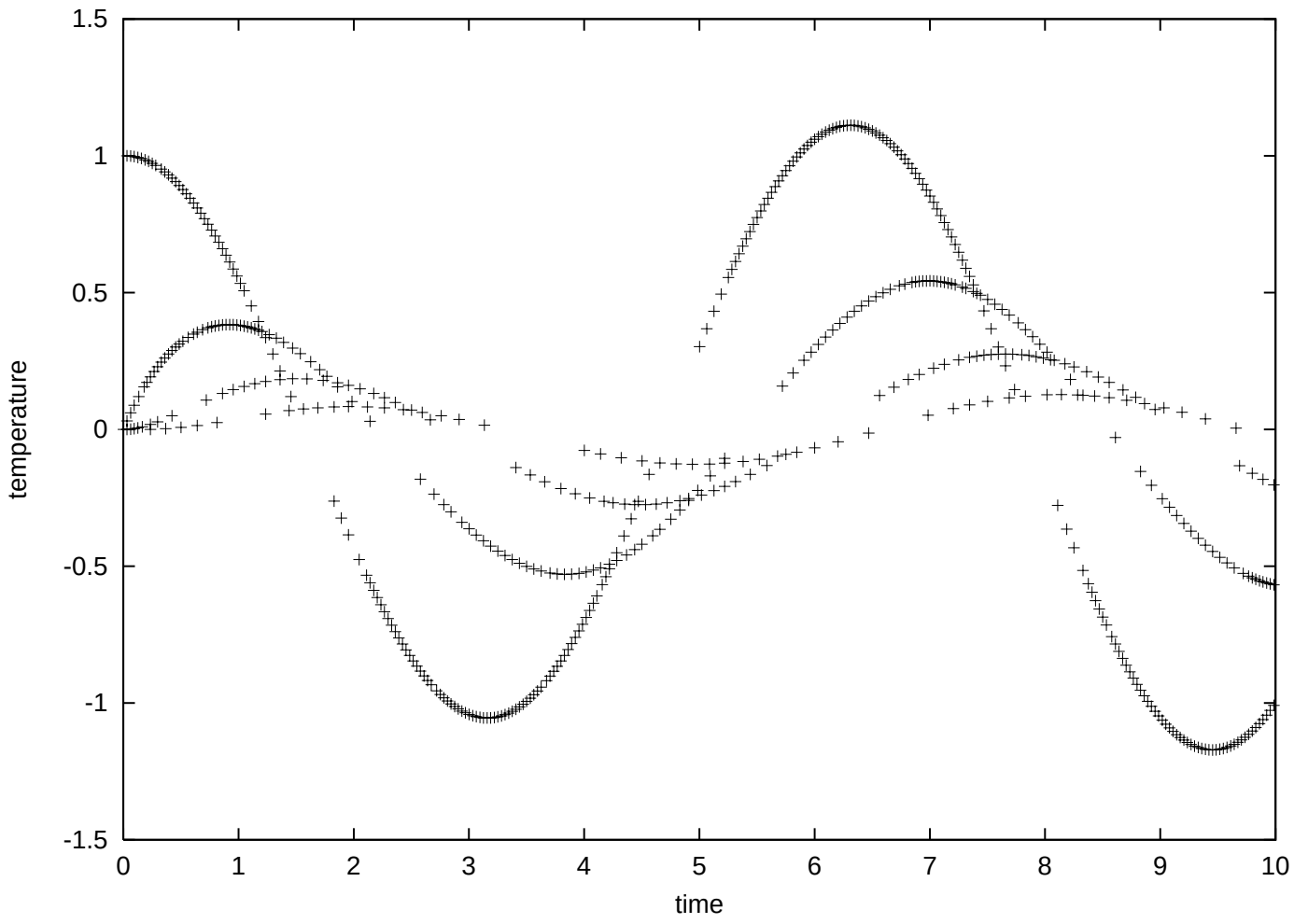


Results: a Larger System–the Wine Cellar Problem

$$\dot{X} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} X \qquad X(0) = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

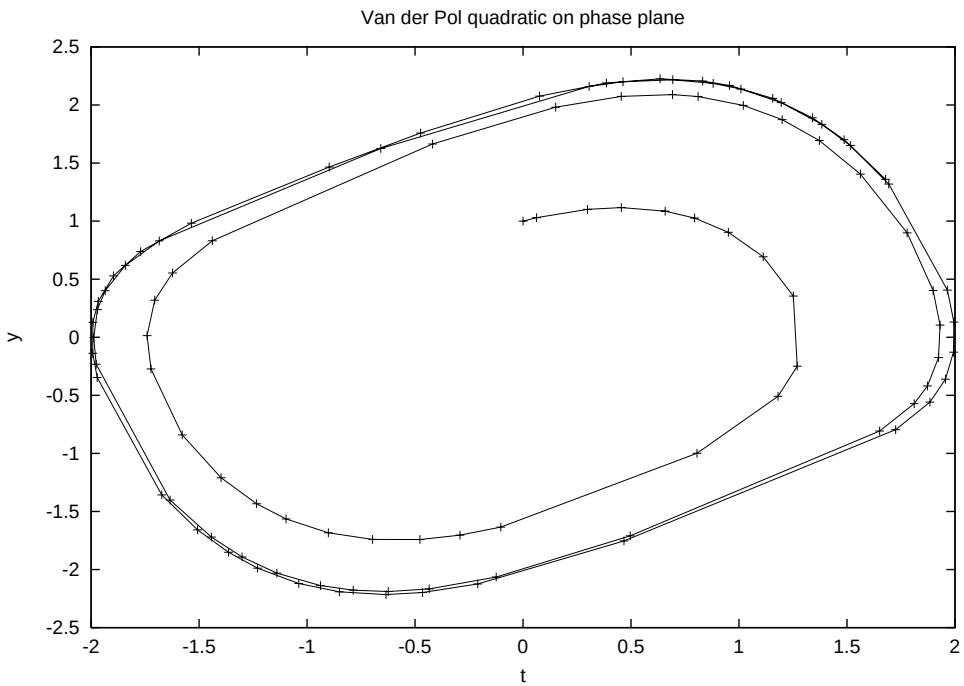
This is a simple discretization of the *wine cellar problem*; a sinusoidal temperature source (from the first two equations) sits on the end of a semi-infinite 1-D heat conductor. Here $\infty = 4$. The large daily temperature swing on the surface is damped by the earth; only small oscillations make their way to the cellar.

Results: the Wine Cellar Problem, continued



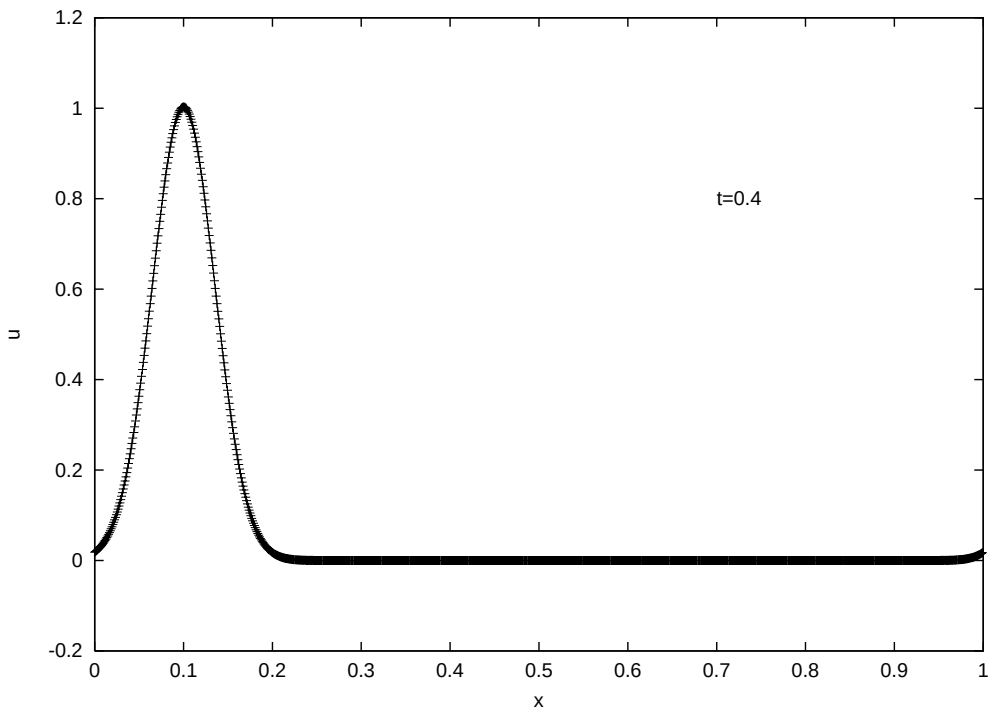
Results: Van der Pol oscillator

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} y \\ -x - \epsilon(x^2 - 1)y \end{bmatrix}$$



Results: Periodic Convection on $x \in [0, 1)$

$$u_t = u_x \qquad\qquad u(0,t) = u(1,t)$$



All Wind and No Tunnel?

So just how fast is it? . . . not very!

- Actually runs several times *slower* than RK2
- Turns out small oscillations are over-compensating, causing short–time repost of every single element
- Oscillations *do* decrease in magnitude as $\epsilon \longrightarrow 0$, but remain present
- Suspect that improving prediction method will fix
- If we can fix it, may provide several-fold improvement

Stepping in to the Future: Our Plans

- Fix the incessant reposting problem
- Incorporate into our hashed oct-tree vortex particle code
- Model, instead of stepping, certain small-scale motions. A different way to incorporate subgrid models?
- Multiple-pass solutions? Richardson extrapolation?

Questions?

LES/DES Incompressible Flow Computations/Analysis & Development

Rose McCallen, Tim Dunn, Roxana Greenman,
Greg Laskowski, Dan Flowers, Jerry Owens

Lawrence Livermore National Laboratory
Livermore, CA

March 29, 2001

University of California
Lawrence Livermore National Laboratory

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

The project focus is on a validated simulation capability

Goal

To identify and develop simulation methods which can accurately predict the flow-field of heavy vehicles

Application of methods to investigate drag reduction strategies

Approach

Carefully validate the simulations with experimental data

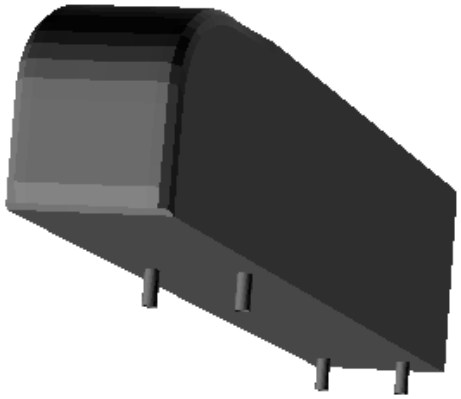
Model

Incompressible/compressible model

Finite element method (FEM)

Large Eddy/Detached Eddy Simulation (LES/DES)

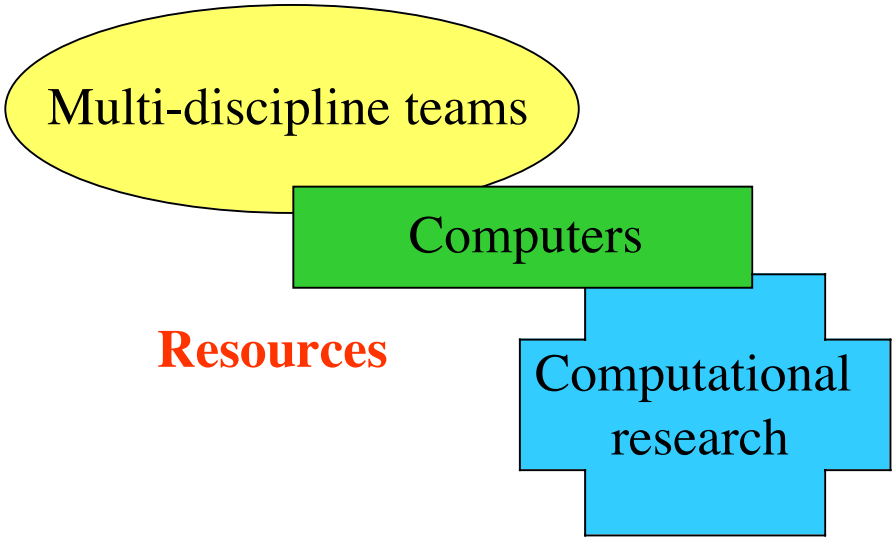
Parallel computing



In-house tools provide flexibility and access to internal resources to investigate modeling issues

Numerical and Modeling Issues

- Spatial discretization
- Time integration
- Turbulence modeling
- Parallelization
- Solvers
- Meshing
- Visualization



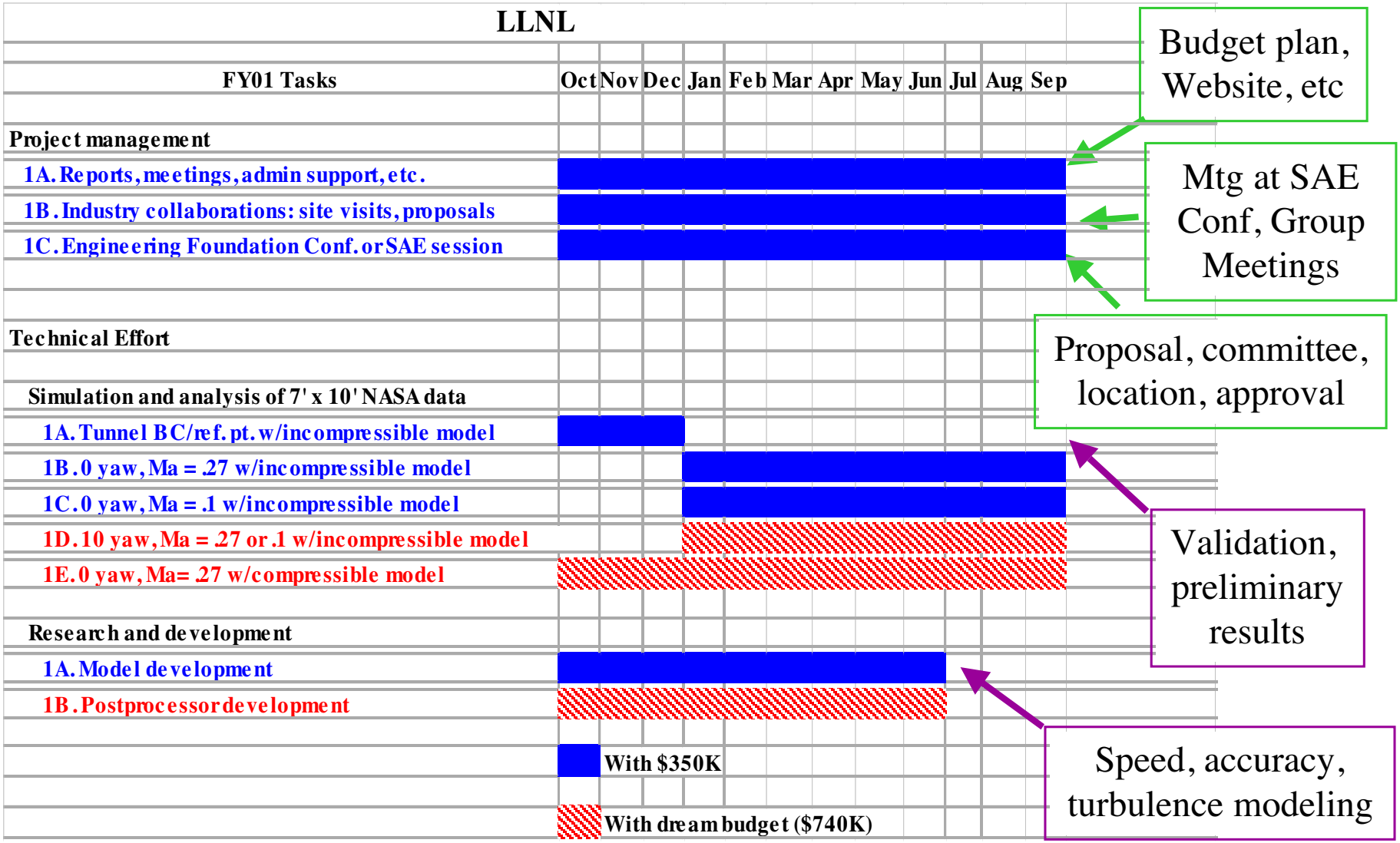
Benefits

- Provides a flexible testbed
- Allows the simulation of large-scale, unsteady, 3-D complex geometry
- Access to advanced research and development

Disadvantage

- Some options not available - implementation required

The LLNL effort is divided between Project Management and Technical efforts



The LES challenges are related to physical as well as numerical modeling

Wide range of scales	**Can't resolve wall regions - problem gets too big** **Grid is Reynolds number dependent** **DES/LES/RANS methods - in development**
Runtime very long	**Evolution is over long time scales** **Small time steps required** **Fast/Parallel computations required - in development**
Analysis	**Huge data sets** **Visualization required - in development** **Methods for testing convergence (V&V) in development**

Significant development being done by LLNL programs.

Incompressible Flow Modeling and Development

Rose McCallen, Tim Dunn, Roxana Greenman,
Greg Laskowski, Dan Flowers, Jerry Owens

University of California
Lawrence Livermore National Laboratory

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

Solving the Time-Accurate, 3-D, Incompressible Navier-Stokes Equations

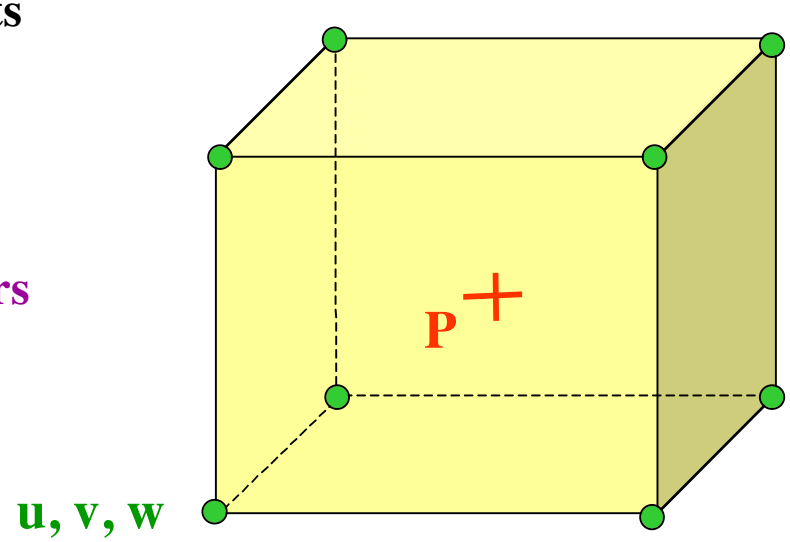
Using methods developed at LLNL

- **Similar formulation is used in the commercial codes FIDAP and LS-DYNA**

Galerkin Finite-Element Method, Q1Q0 Element

- **8-node Hexahedral Brick Elements**
- **Tri-linear Velocity**
- **Piecewise Constant Pressure**

Runs on Massively Parallel Computers



The Discretized Incompressible Momentum and Continuity Equations

Matrix Form

$$M\dot{u} + \left(K + N(u)\right)u + CP = f$$

$$C^T u = 0$$

With explicit forward Euler time integration

$$\begin{bmatrix} M_L & C \\ C^T & 0 \end{bmatrix} \begin{pmatrix} v \\ P \end{pmatrix} = \begin{pmatrix} F \\ 0 \end{pmatrix}$$

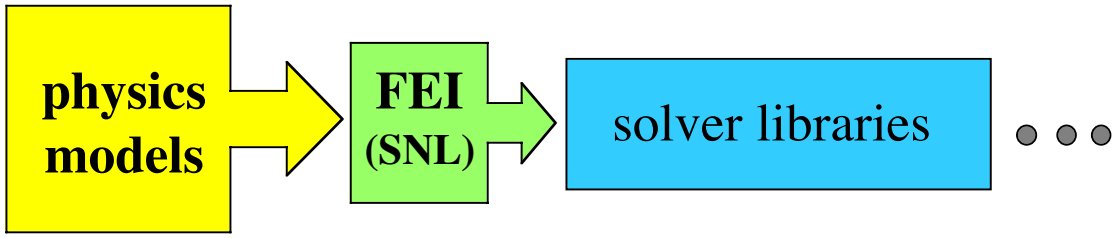
coupled system is too big

The above system is NOT Positive Definite and it is more efficient to use the Schur reduced form of the matrix

$$\left(C^T M_L^{-1} C\right) P = RHS$$

$$u_{n+1} = u_n + \ldots$$

The Finite Element Interface (FEI) is used to assemble and solve the matrix



Advantages: **many Krylov solvers and preconditioners become available**

Advanced Solvers: **HYPRE libraries developed at LLNL CASC**

- **Solvers**
  - **Generalized minimal residual (GMRES)**
  - **Conjugate gradient (CG)**
- **Preconditioners**
  - **Incomplete LU**
  - **Sparse approximate inverse**
  - **Algebraic multigrid (AMG)**

Recent code development efforts have focused on speed-up, accuracy, and turbulence modeling

Code speedup (supported in part by internal funding)

- Reuse of matrix with FEI
- Stabilization
- Minimum residual or A-Congugate acceleration
- Implicit/Semi-Implicit (in progress)

Accuracy

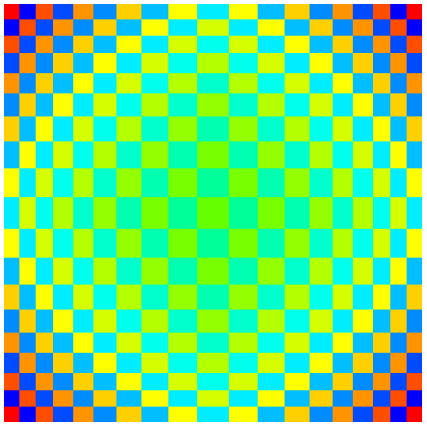
- Flexibility (algorithm reformulation)
- Full spatial integration
- Higher order time integration (in progress)

Turbulence Modeling

- LES
- RANS
- DES

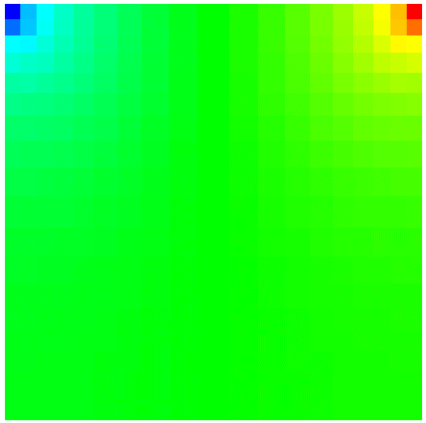
Pressure stabilization has been added to improve solver convergence

Without Stabilization



Pressure Coupling

With Stabilization



Lid Driven Cavity

- **Stabilization adds coupling between neighboring elements**
  - **Global – coupling between all elements**
  - **Local – coupling between elements within macro-elements**
- **Can improve speed by factor of 2**
  - **Reduces number of iterations**
  - **Allows use of faster solvers (AMG)**

Improving the initial guess

Minimum Residual Projection / A-Conjugate Projection

$$\begin{bmatrix} x_1^{(-n)} \\ x_2^{(-n)} \\ \vdots \end{bmatrix} \cdots \begin{bmatrix} x_1^{(-2)} \\ x_2^{(-2)} \\ \vdots \end{bmatrix}, \begin{bmatrix} x_1^{(-1)} \\ x_2^{(-1)} \\ \vdots \end{bmatrix} \Rightarrow \begin{bmatrix} x_1^{(0)} \\ x_2^{(0)} \\ \vdots \end{bmatrix}$$

Previous "n"
Solution Vectors

Initial Guess

Can improve speed by factor of 2

Turbulence Modeling

DNS

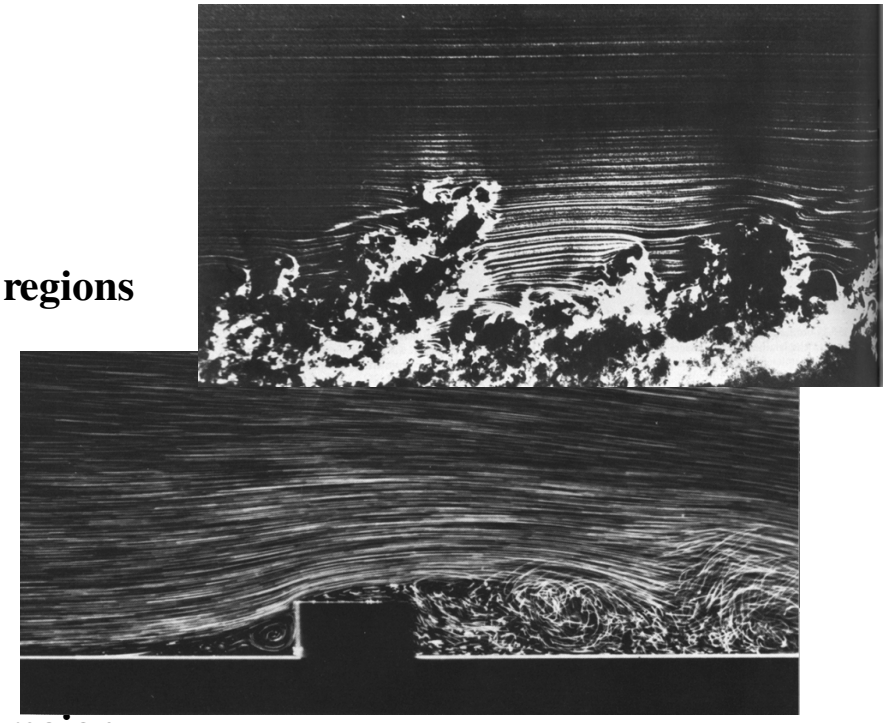
- **Resolve all scales of turbulence**
- **Impractical for even moderate Re**

LES

- **Resolve 'large' scales of turbulence**
- **Resolve near wall region or model near wall regions**
- **Model 'small' scales**
  - **Smagorinsky model**
  - **Dynamic model**
  - **Filtered Structure Function Models**
- **Challenging for high Re**

RANS

- ***Model* all scales of turbulence**
- **Resolve near wall region or model near wall region**
- **Model for 'turbulent viscosity'**
  - **Reynolds stress models**
  - **2-equation: 'k-l', 'k-ε','k-ω'**
  - **1-equation: Baldwin-Barth, Spalart-Allmaras**
  - **Algebraic Models**



VanDyke, Album of Fluid Motion

How about a hybrid model?

Choice between LES or RANS

LES

- **Time accurate**
- **Sacrifice computational cost for greater accuracy**
- **Issues concerning near wall modeling for separated flow**

RANS

- **Time averaged**
- **Sacrifice accuracy for faster run times**

Detached Eddy Simulation (DES)

- **RANS near wall and LES away from wall**
- **Maintain time accuracy while approximating some 'small' scales**

Turbulence modeling status

Current turbulence modeling capabilities

- Smagorinsky model
- No near-wall correction terms (i.e., van Driest damping)

Development strategy

- Implement the Spalart-Allmaras model to allow for:
  - RANS simulations
  - DES simulations

Progress

Model implemented

Currently conducting small test cases to verify implementation

Short term goal

- **Plane channel flow simulations**
- **Re_τ=2000**
- **Compare with Spalart (“*An Approach to Wall Modeling in Large-Eddy Simulations*”, Physics of Fluids, Vol. 12 no. 7, July 2000, pp. 1629).**
- **Compare with VKI report 1998-21**

Long term goal

- **Three-dimensional, unsteady truck simulations**

Incompressible Flow Computations and Analysis

Rose McCallen, Tim Dunn, Roxana Greenman,
Greg Laskowski, Dan Flowers, Jerry Owens

University of California
Lawrence Livermore National Laboratory

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

Verification & validation and scaling & timing for the incompressible model

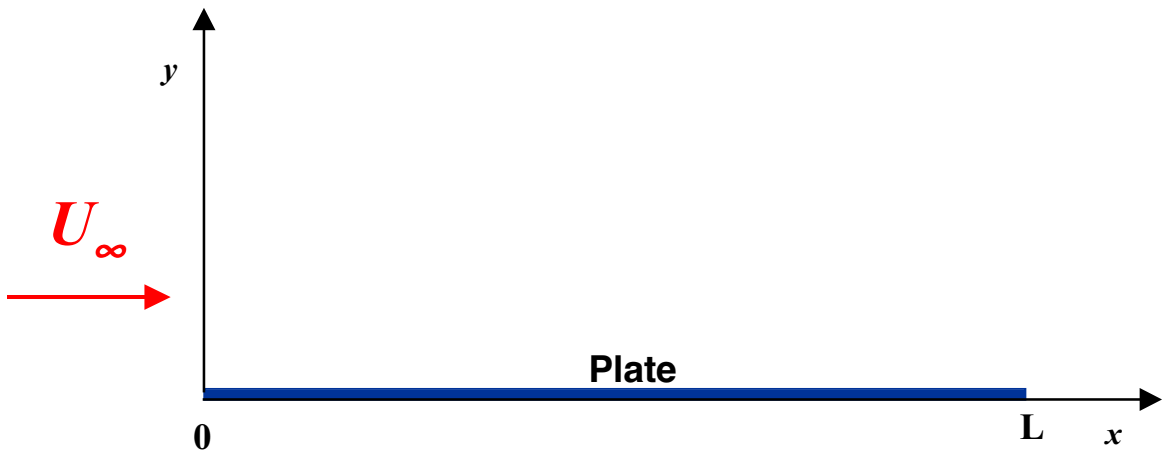
V&V cases provide guidance for wind tunnel simulations

- **Laminar Flat Plate**
  - **Compared with theoretical Blasius solution**
  - **Speed-up and scaling results**
- **Channel Flow**
  - **Comparison of laminar case to theory**
  - **Turbulent case (*in progress*)**
- **Sphere**
  - **Comparison to experiment (*in progress*)**

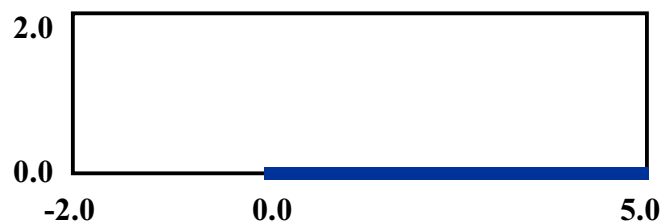
Simulations for NASA 7x10 Wind Tunnel with GTS

- **Determining inflow/boundary conditions**
  - **Empty tunnel calculations (*in progress*)**
- **Estimating grid/runtime**

Laminar incompressible flat plate -- flow and geometry description

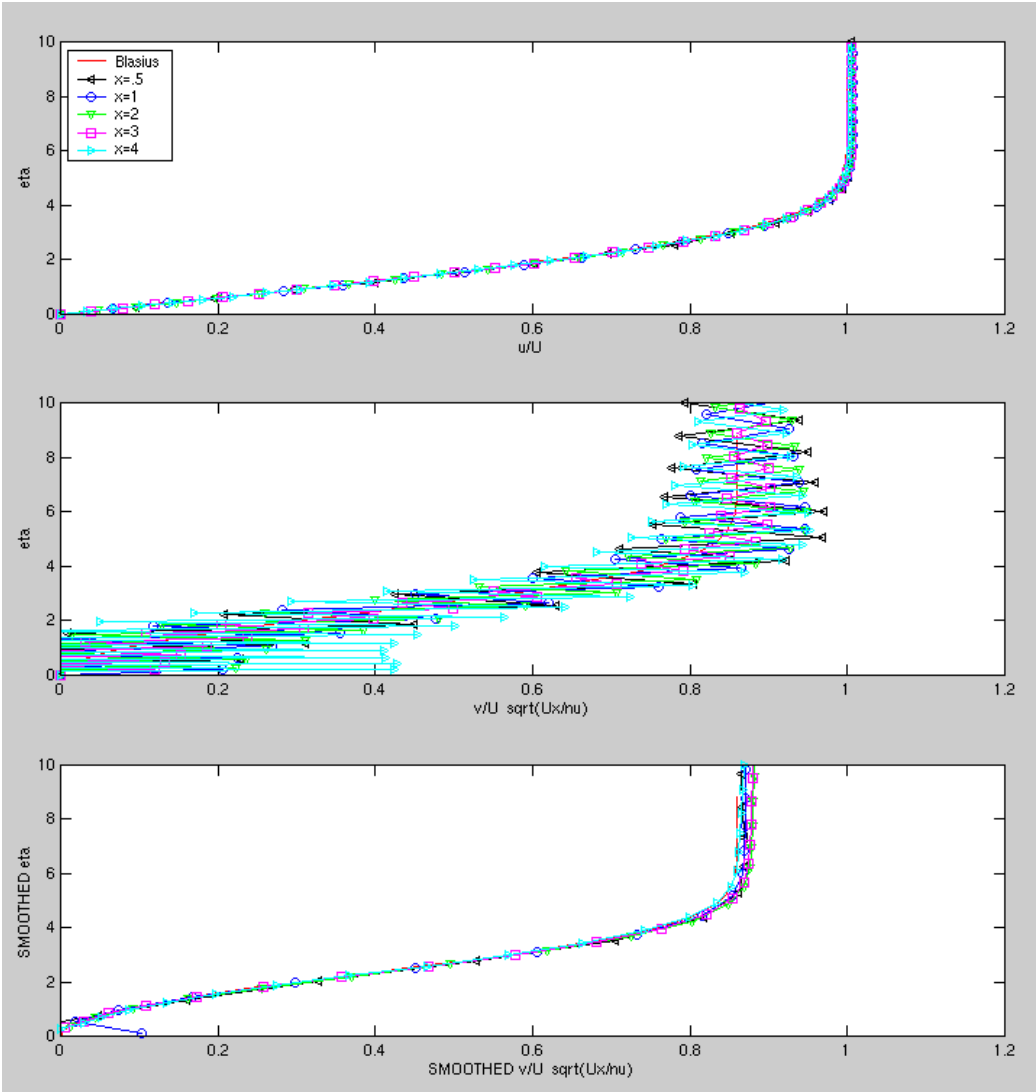


Computational domain



A leading-edge singularity makes this a challenging problem.

Predicted velocity compares with Blasius boundary layer theory for laminar flat plate



U-velocity agrees with theory

strict divergence free condition results in oscillatory V-velocity

smoothed V-velocity (averaged every other point) agrees with theory

Mesh 235 x 100 = 23,500 elements

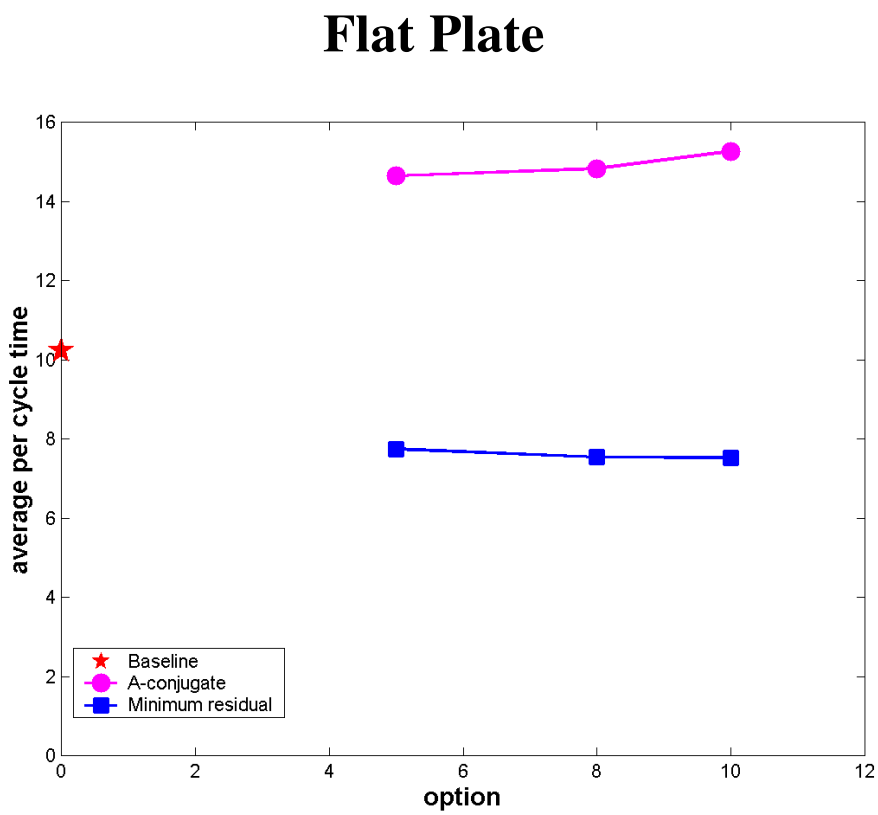
Projection method can improve solution speed

Baseline

- Conjugate gradient solver
- Parallel sparse approximate inverse preconditioner
- Schur reduction
- No projection method

A-conjugate or minimum residual projection methods

- Option to choose how many previous answers for next guess



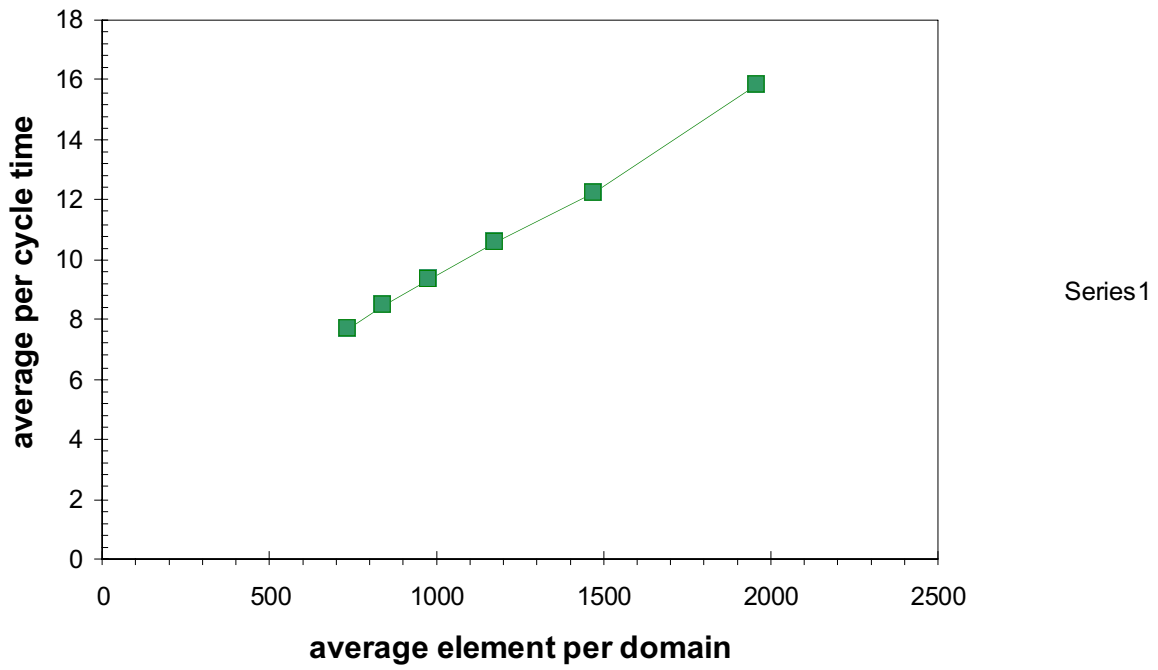
Preliminary results show linear scaling

Flat Plate

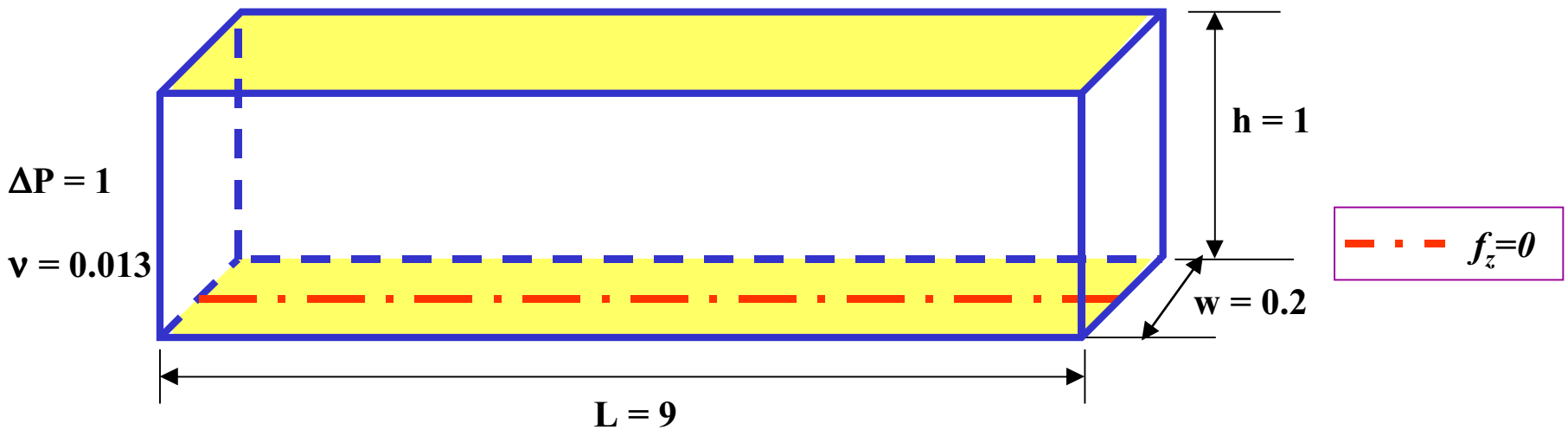
1 domain per processor

Minimum residual projection method with option 10

4 processors/node



Laminar channel flow is accurately predicted



Channel Theory

$$U_{max} = -\frac{dp}{dx}\frac{h^2}{8\nu}$$

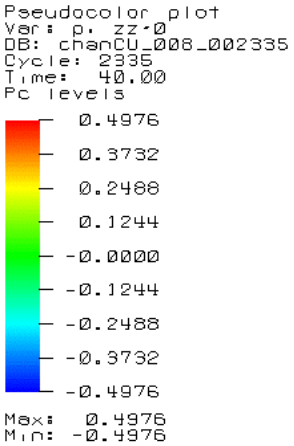
Computational Results

$P_{calc} = 0.9952, P_{theo} = 1.0$, error = -0.48%

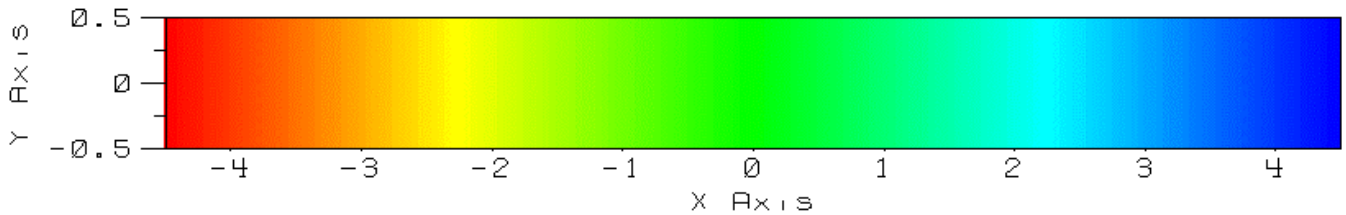
$Umax_{calc} = 1.0427, Umax_{theo} = 1.0417$, error = 0.096%

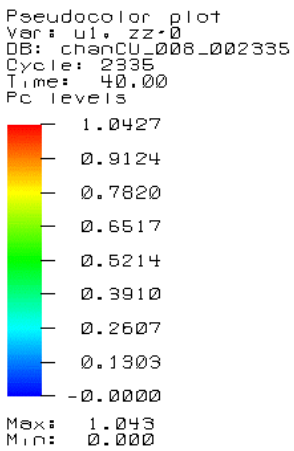
$Uavg_{calc} = 0.6934,\ Uavg_{theo} = 0.6945$, error = -0.15%

Computational results of laminar channel flow with uniform mesh

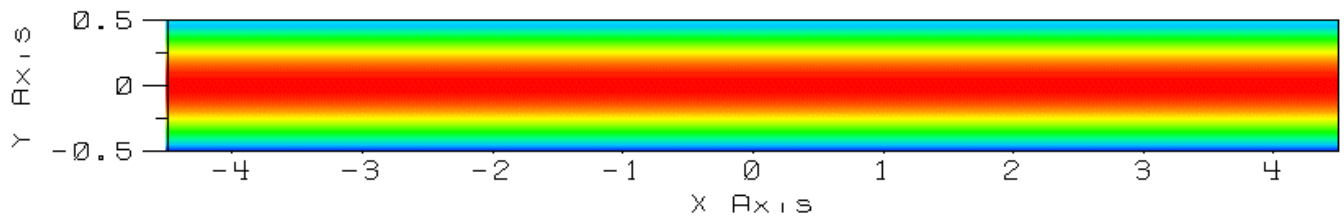


PRESSURE





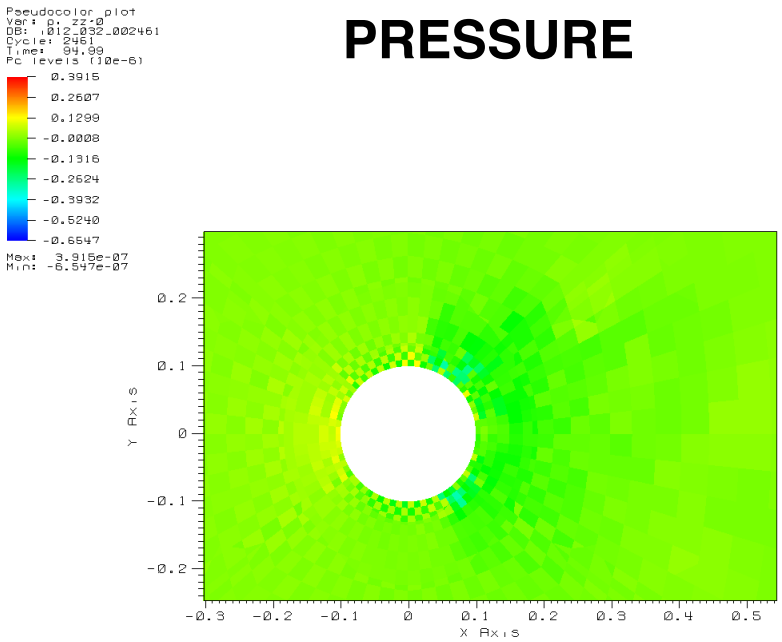
U-VELOCITY



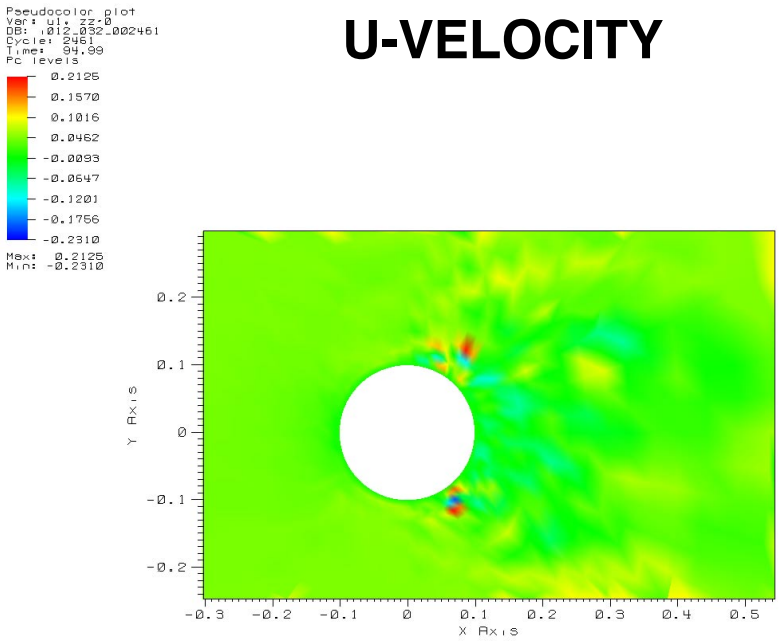
Mesh: 180 x 20 x 4 = 14,400 elements

Incompressible laminar sphere (in progress)

PRESSURE

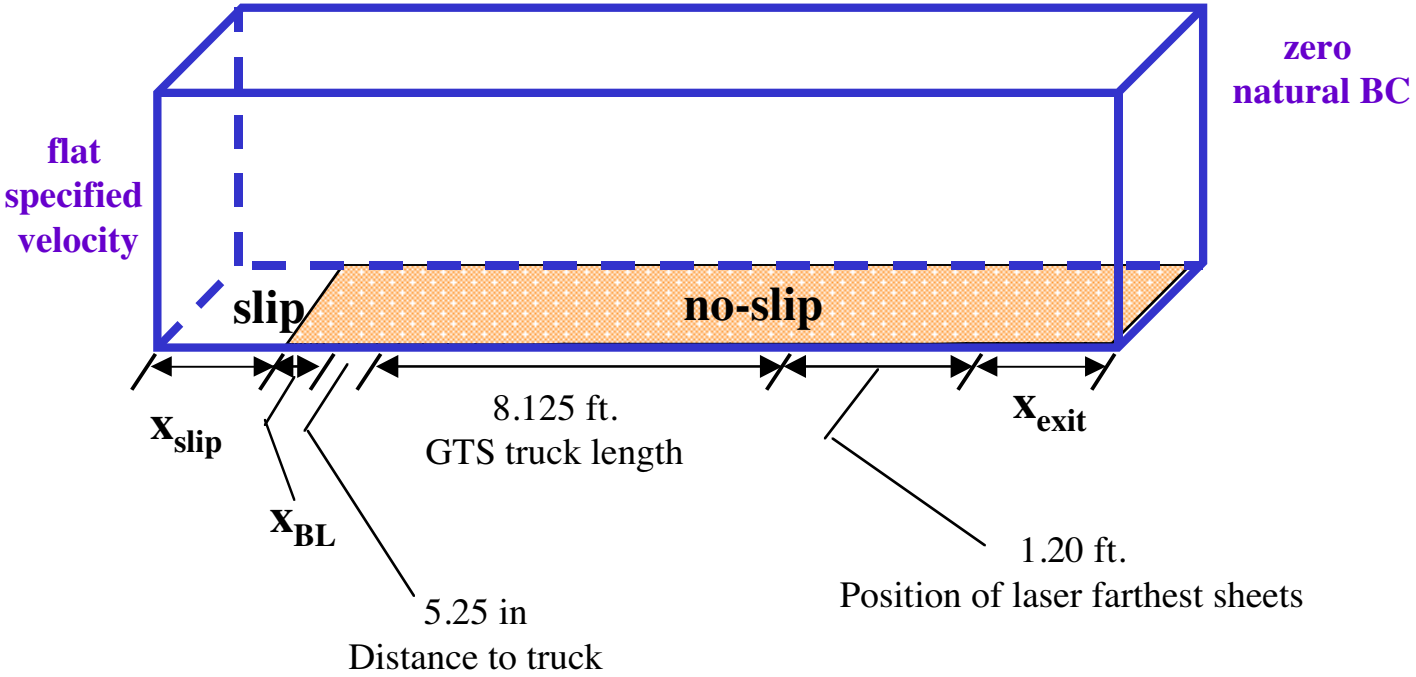


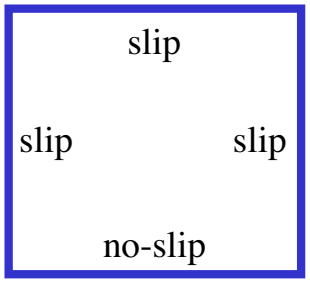
U-VELOCITY



Empty wind tunnel calculations to establish correct inflow and boundary conditions

- **Determine tunnel inlet length and conditions to capture correct inlet velocity profile at test section entrance**
- **Assumptions**
  - **Tunnel walls are parallel and flat**
  - **Cross-section matches test section entrance**



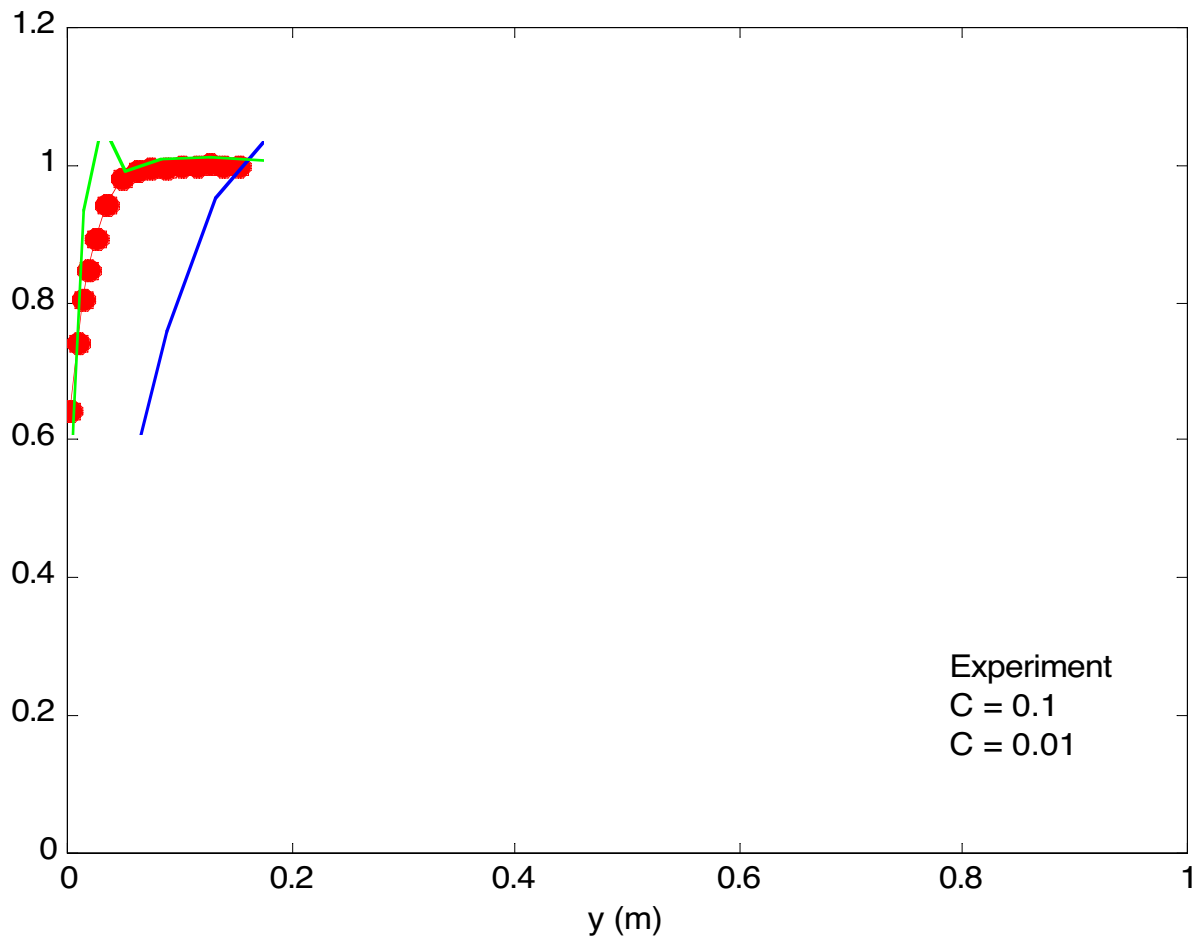


x_{slip} = 1 m

x_{BL} = ?

Preliminary calculations for empty tunnel provide expected entrance length, $x_{BL} \sim 3.5$m

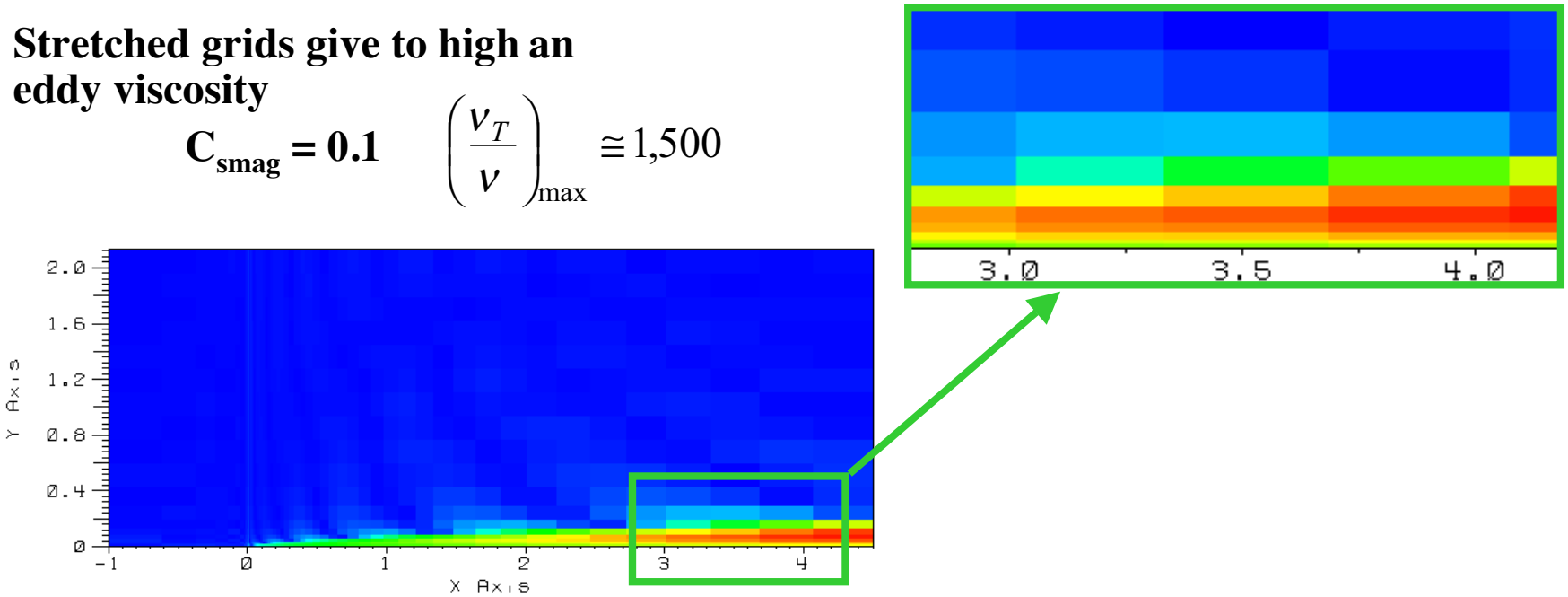
Time-averaged velocity profile



Eddy viscosity is too high for stretched grids near the wall

Stretched grids give to high an eddy viscosity

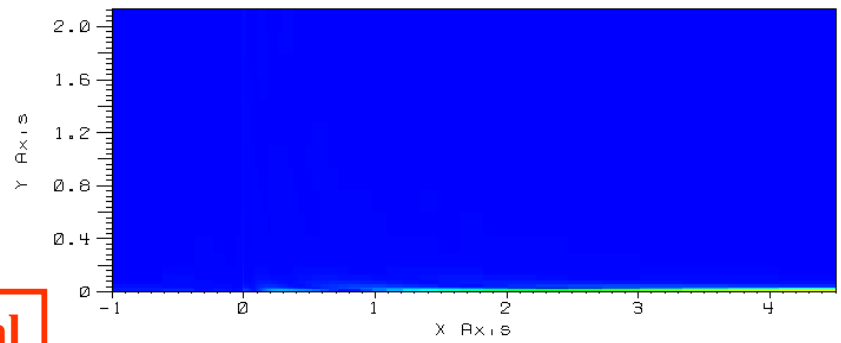
$$C_{smag} = 0.1 \qquad \left(\frac{\nu_T}{\nu}\right)_{max} \cong 1{,}500$$



Lowering model coefficient lowers eddy viscosity

$$C_{smag} = 0.01$$

$$\left(\frac{\nu_T}{\nu}\right)_{max} \cong 50$$



Grid refinement is essential

Preliminary timings for empty tunnel calculations provide estimates for solutions speed requirements

Empty Tunnel Calculation

Time step is controlled at the noslip leading edge

Current solution time with 16 processors

~ 10 sec/cycle for 33,000elements

~ 300 microsec/element/time step

Parallel computing is essential

Can refine stretched grid and maintain solution speed by adding processors

Evaluation of problem run times for GTS using empty tunnel results

Assuming :

8m domain length

Ma = 0.1 or U ~ 30m/s

Time step O(10^{-5}) with Δ = 0.005m - may not be reasonable

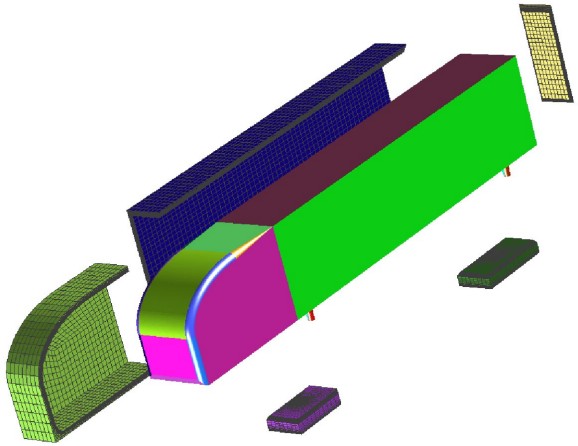
10 sec/cycle with 2000 elem/proc - may not be reasonable

Estimated problem run time :

For fully explicit scheme => diffusion limited time step O(10^{-5}) => 12 days

May need factor of 10 speed-up in solution time.

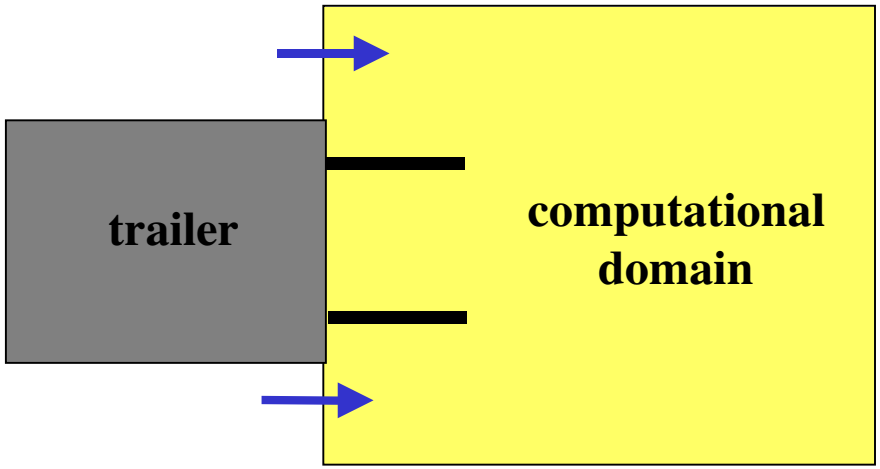
Semi-implicit schemes are being considered.



Suggested alternate plan, if GTS requirements exceed solution speed and resources

Focus on base pressure predictions

- **Area in need of advanced space/time-accurate modeling**
- **Reduced problem size**



Visualization

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Greg Laskowski, Dan Flowers, Jerry Owens

University of California
Lawrence Livermore National Laboratory

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New transient analysis capability

Transparent (see through) contour plots

Alpha composite of 3 movies

Moving plane with transparent contours

Movies

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