Ph.D. Course on *Vorticity, Vortical Flows and Vortex-Induced Vibrations*
Technical University of Denmark, Copenhagen, Denmark
vortex.compute.dtu.dk
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Vehicle Aerodynamics

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MONASH University

FLAIR
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Lecture Objectives

Learn:

Flow forces acting on vehicles

Flow around automobiles, cars, trucks, trains

Modifications to reduce drag forces

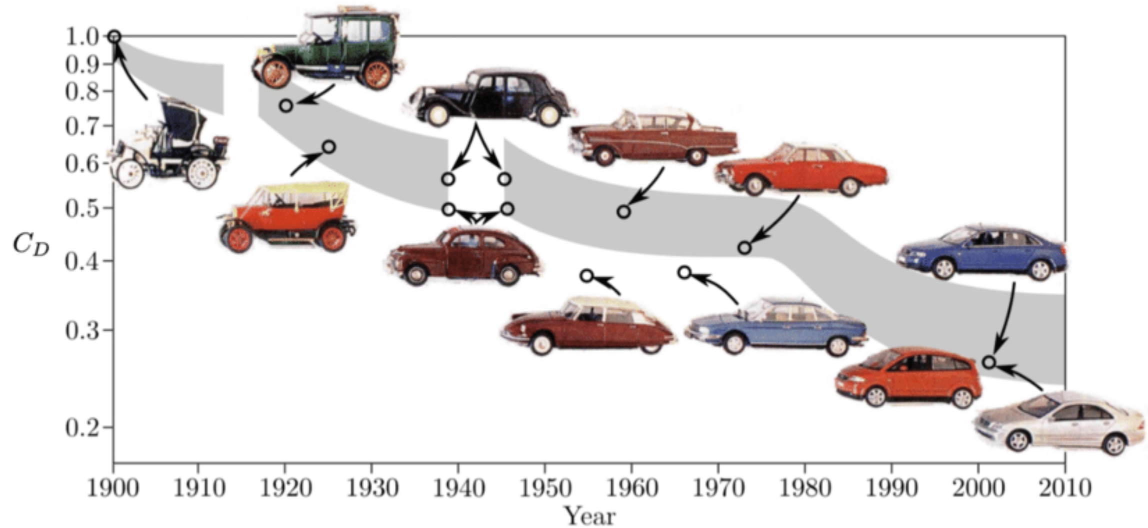
Introduction

Outline

Introduction
- History
- Motivation
- Previous Studies
- Applications to automotive vehicles

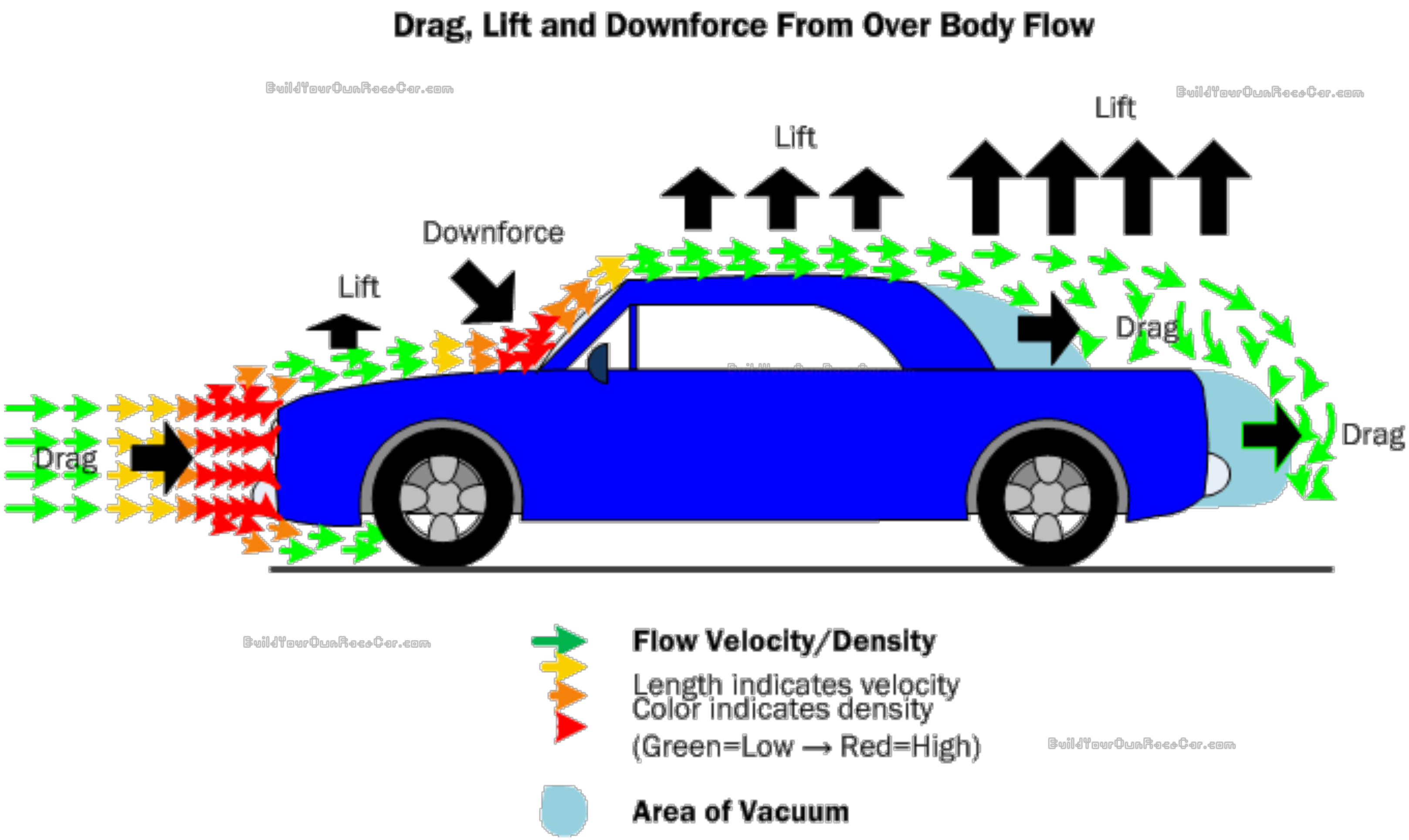
Current Research
- Automobiles
- Trains
- Cycling

Conclusions



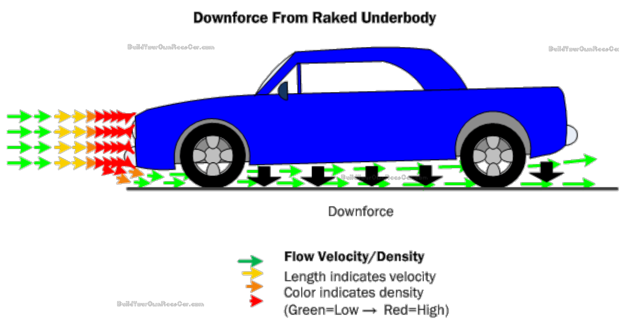
Feature	ΔC_D
Bodywork	0.050
Rearview Mirror	0.015
Rear Surfaces	0.085
Engine Bay	0.024
Cooling Drag	0.048
Underbody + Chassis	0.085
F Wheel + Suspension	0.025
R Wheel + Suspension	0.023
Total Drag Coefficient	**0.355**

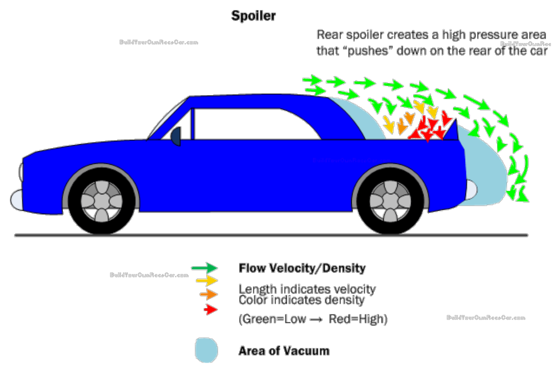
Aerodynamic Forces on Road Automobiles

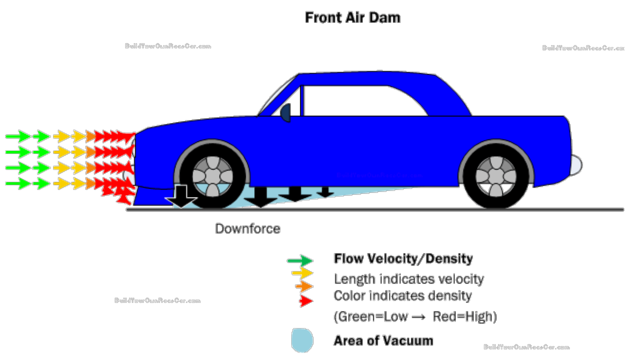


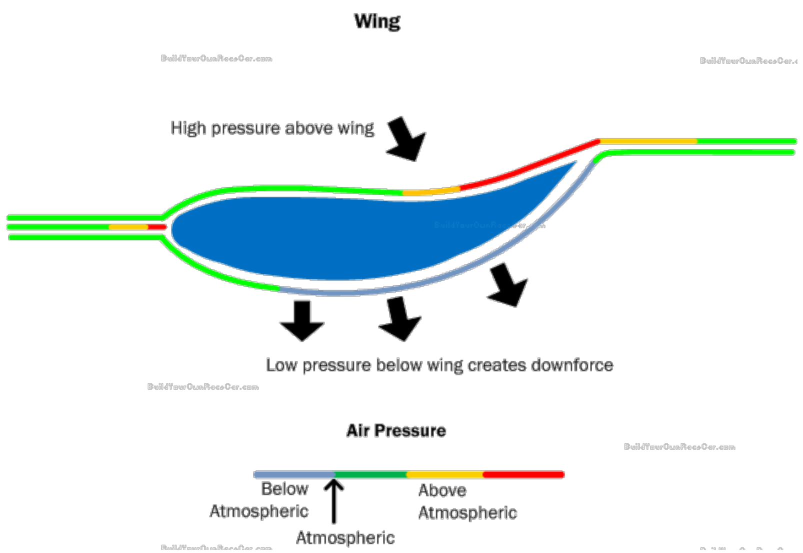
www.buildyourownracecar.com

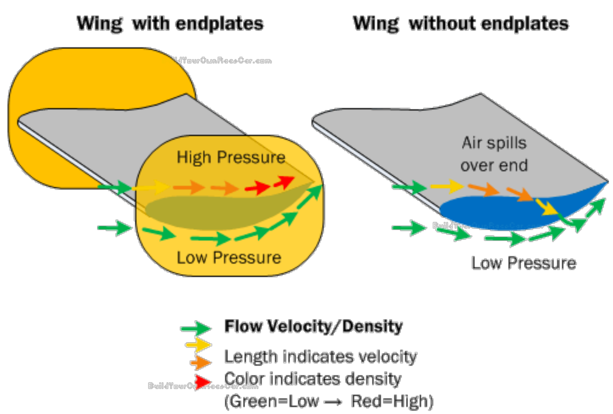
Some Controls of Aerodynamic Forces











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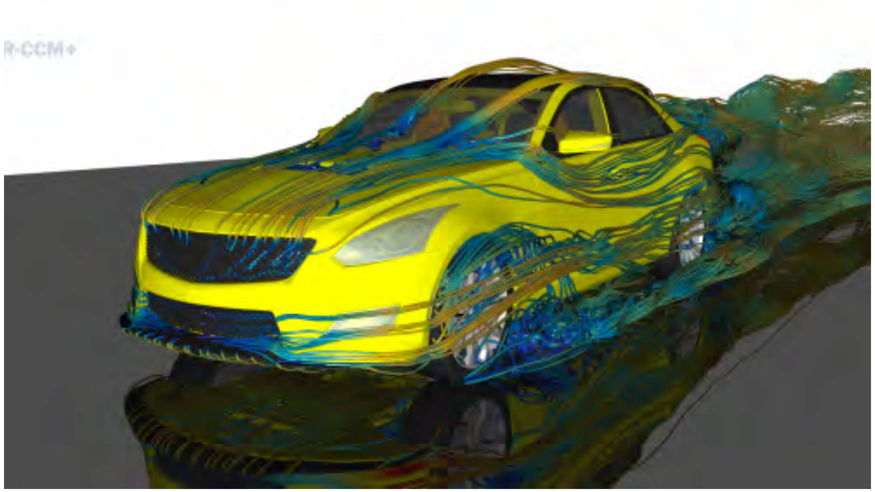
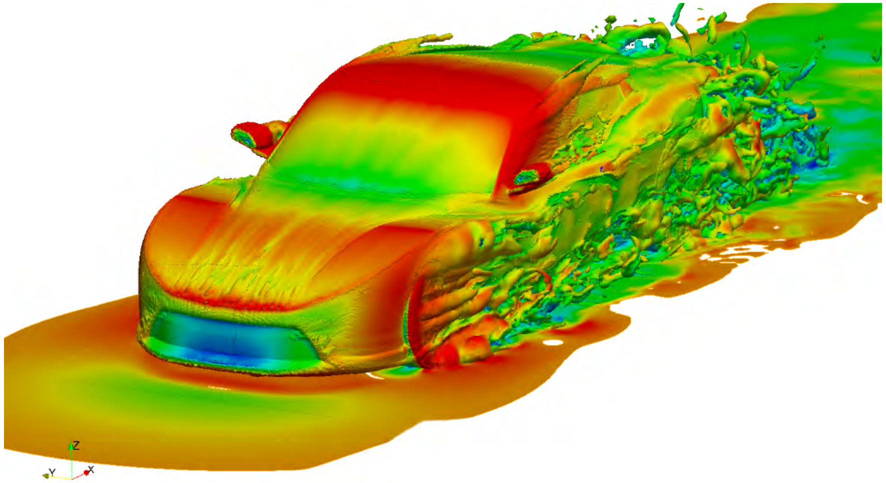
CFD Simulations

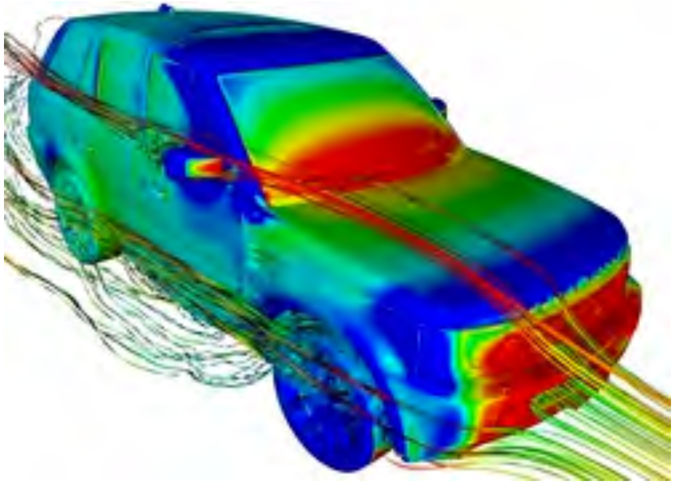


mdx2.plm.automation.siemens.com



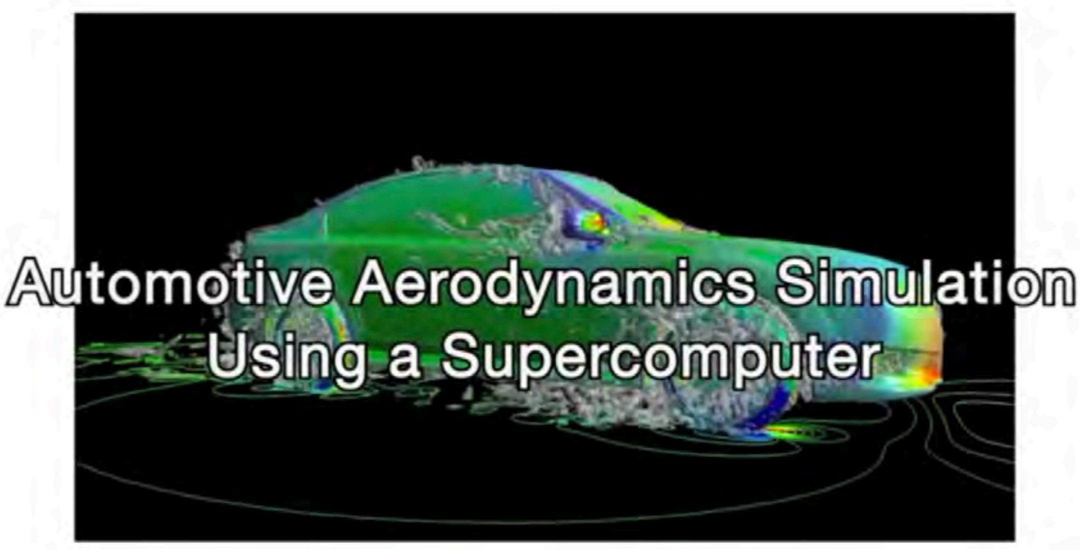
engys.com/applications/automotive

www.fortissimo-project.eu/experiments/417



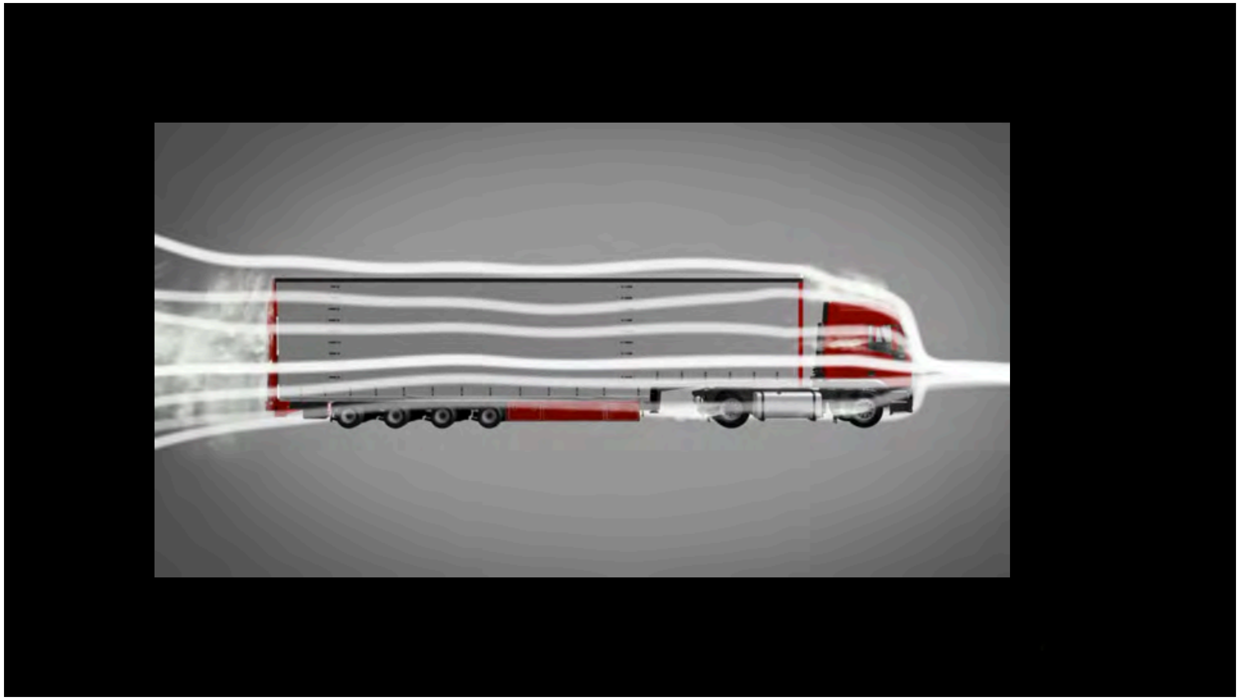
www.prweb.com/releases/cfd/simulation/

CFD Simulations of Flow around Automobiles



www.youtube.com/watch?v=HsUp0V_HqEY

Control of Drag on Trucks

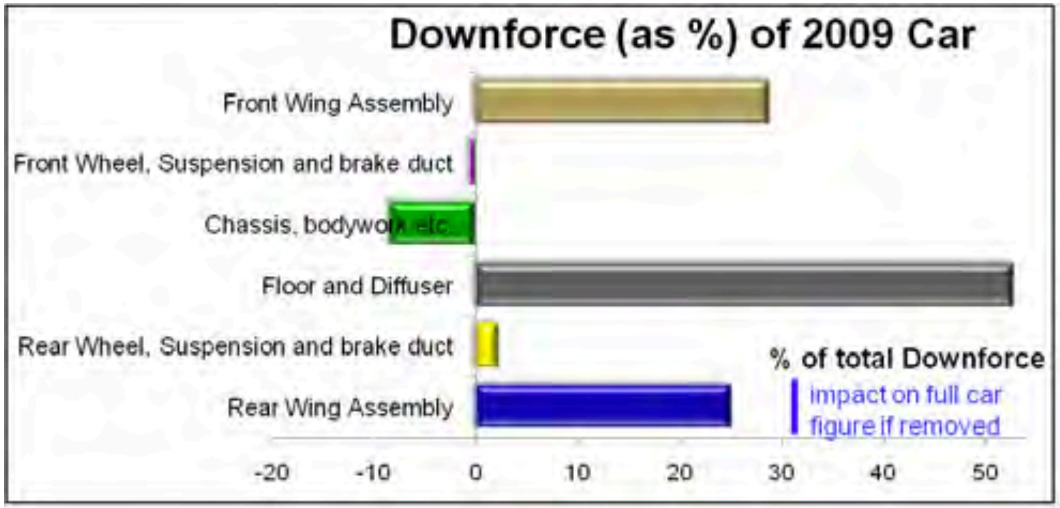


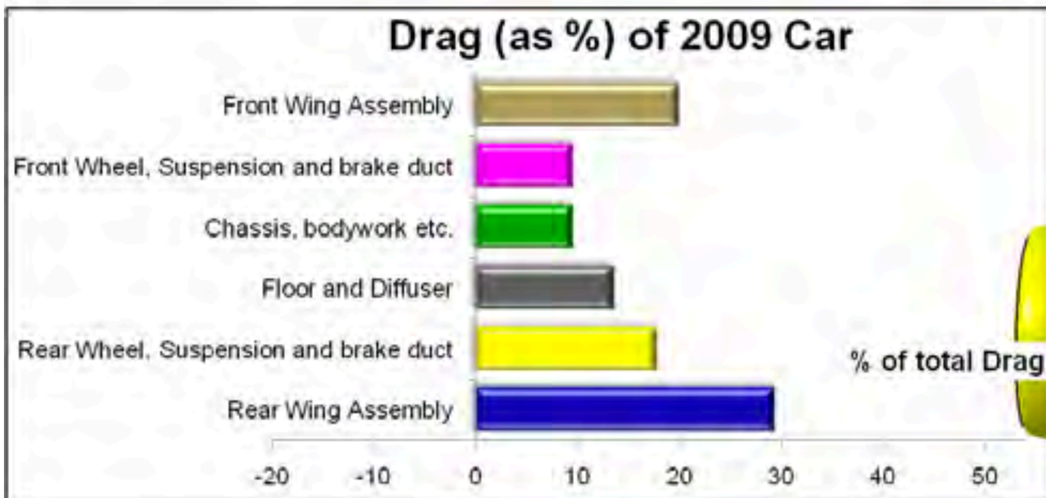
www.youtube.com/watch?v=jOG6RSjIEEs

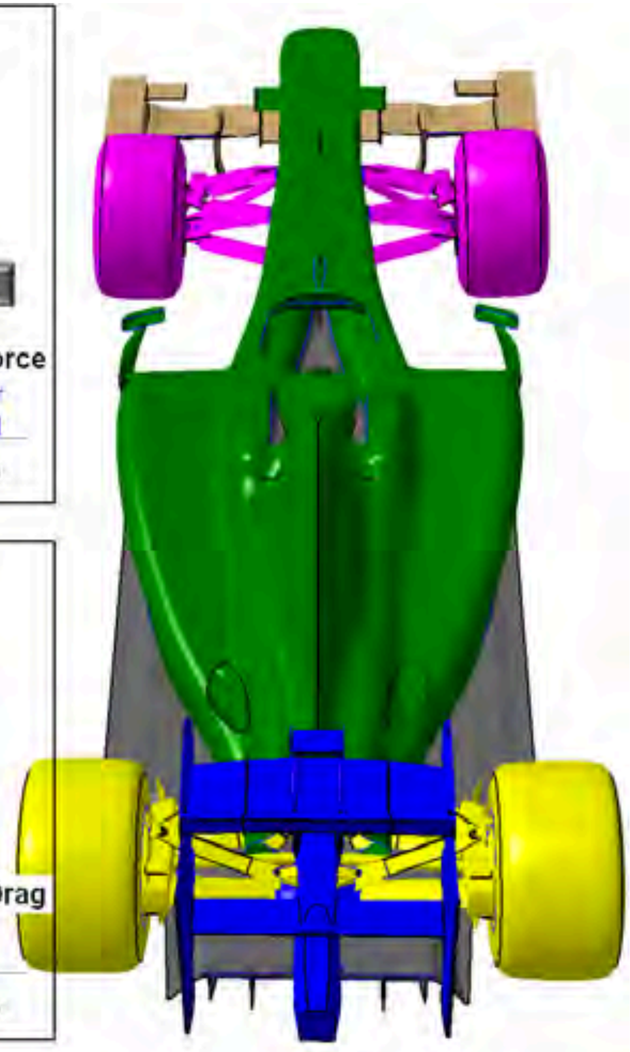
Control of Drag on Trucks

https://www.youtube.com/watch?v=_NPNiyR5cWo

Factors in Downforce and Drag on Racing Car

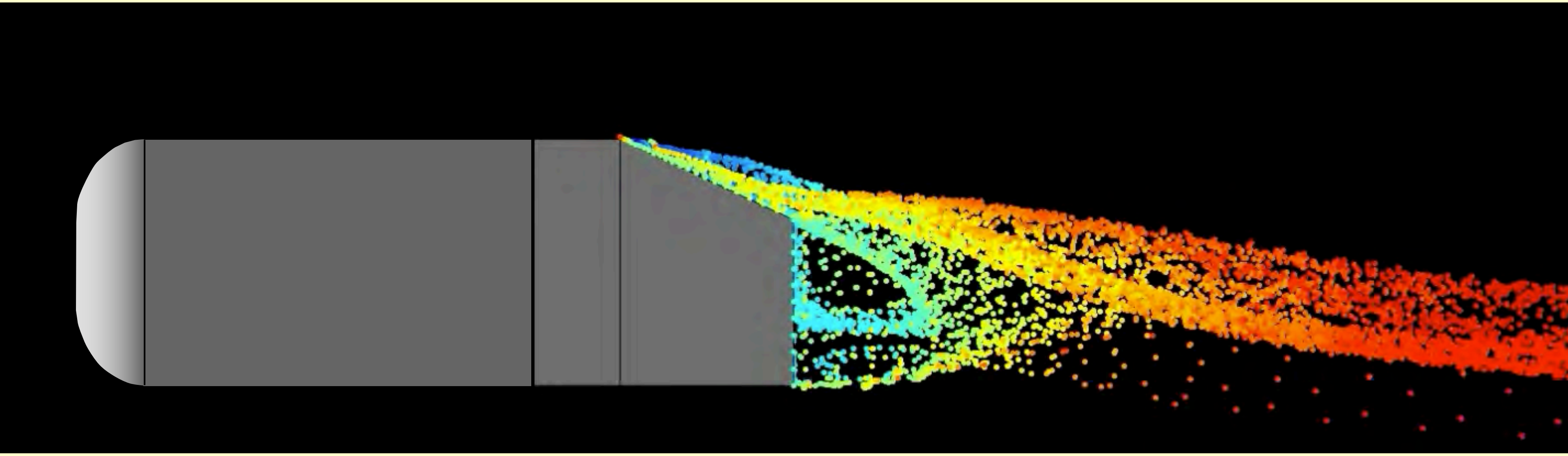






From "Aeronautical Journal Jan 2013

Effect of aspect ratio of the wake structures of simplified automotive geometries



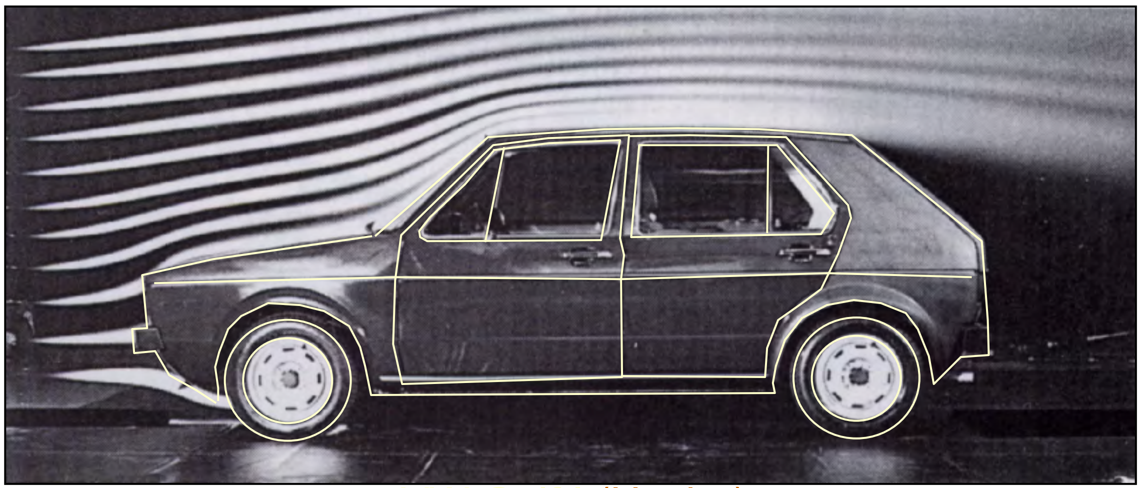
Introduction

History

Jannsen & Hucho (1975)

•Development of the VW Golf I

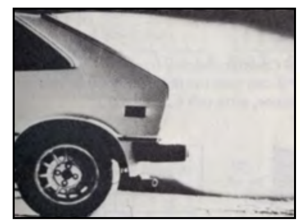
•Two different types of flow depending on slant angle (α) of the rear window



VW Golf I (Hucho)

Attached Wake

High Drag



Separated Wake

Low Drag

Led to many studies on the effect of the slant angle of the rear window on wake structures.

Introduction

Aspect Ratio Effects

- Main focus of research on the effect of slant angle (α)
- Effect of Aspect Ratio (AR) has not been seriously considered.

- AR of automotive vehicles too small to separate drag components

  "C_{Do} (profile drag) and C_{Di} (induced drag) do not interfere with one another, which only occurs with wings of high aspect ratio. However, because the aspect ratio is very small for vehicles, a breakdown of the flow field into 2D and 3D components is not possible." – Hucho.

  Previous research hasn't considered how vehicle width will effect drag.

- AR effects have been considered to have a proportional effect on drag and wake structures.

  "As AR increases, the effect of side-edged vortices on the overall flow patterns gets progressively smaller, as only a relatively small portion of the base is exposed to them (side-edged vortices)." – Morel.

Previous Research

Ahmed, Ramm & Faltin

Investigated the effect of α on drag and wake structures

Low drag regime

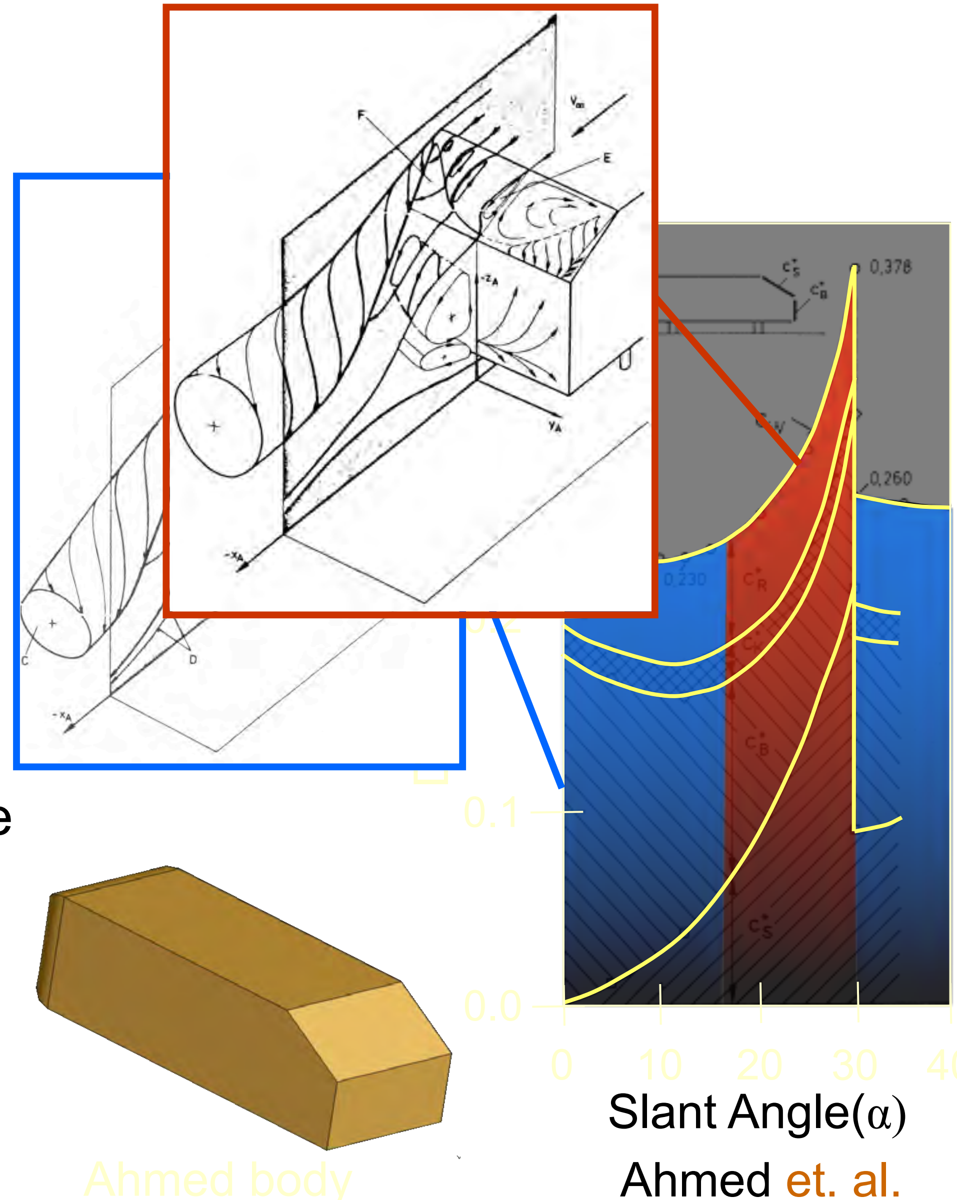
-Flow is attached to slant surface
-Two streamwise vortices developing from C-pillars
-Separation bubble on rear end base

High drag regime

-Strong streamwise vortices
-Separation bubble on slant surface
-Separation bubble emanating from the vertical rear end base

Low drag regime

-Wake fully separated
-Absence of streamwise vortices



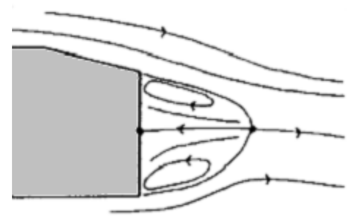
Previous Research

Gillieron & Chometon

Numerical simulations on the Ahmed body

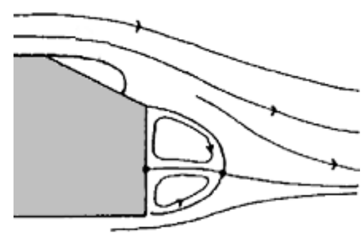
2D Base Flow (0°–12°)

-Flow is attached to slant surface
-Two recirculation zones on the rear surface
-Two counter rotating vortices



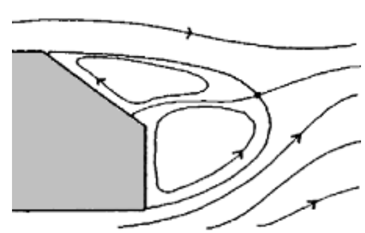
3D Hatchback Flow (12°–30°)

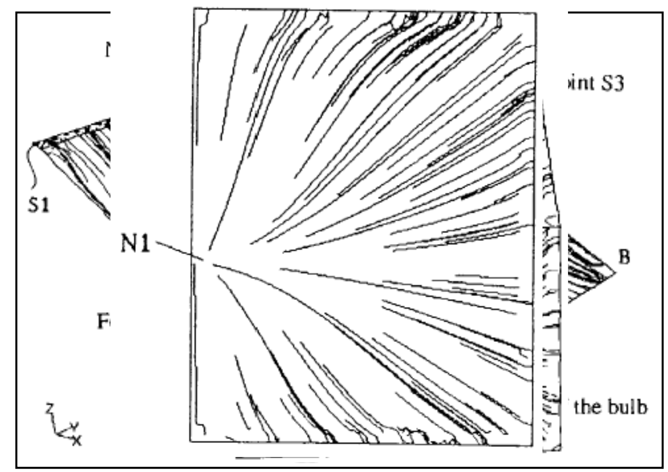
-3D structures on slant surface
-Flow reattached on the slant surface
-Two counter rotating vortices



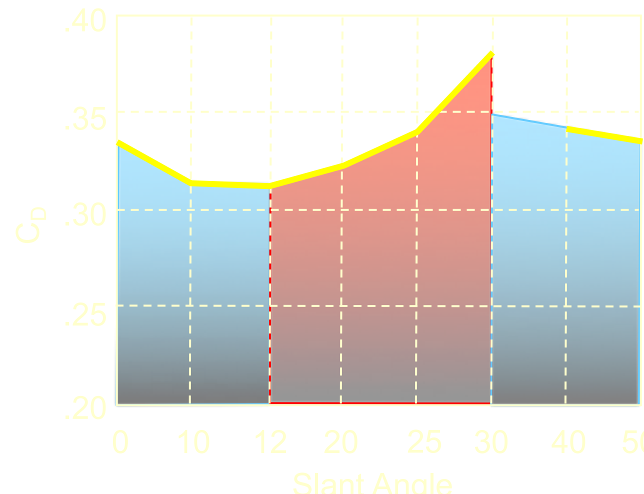
2D Base Flow (30° -)

Flow separated from top of slant surface





Friction lines for slant surface for angle = 30°

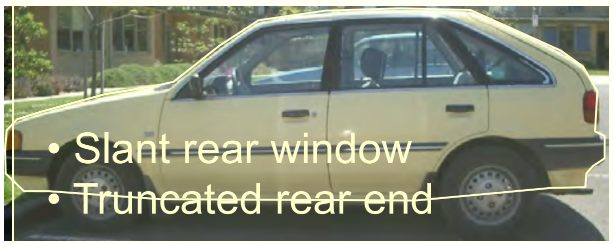


Applications

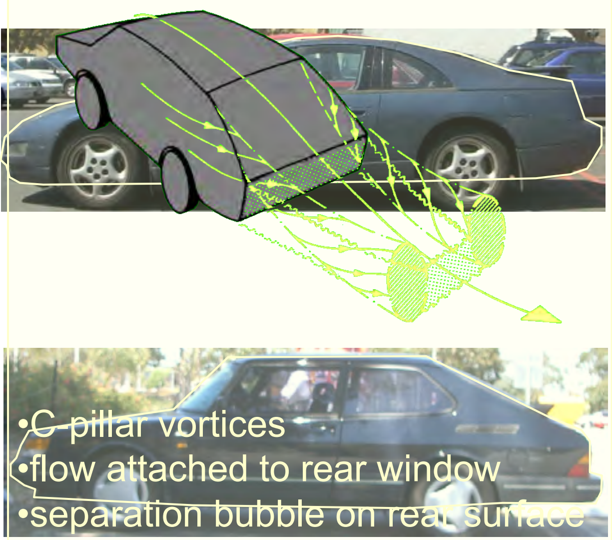
Vehicle Geometry

How does wake structure compare to other vehicle geometries

Fastback



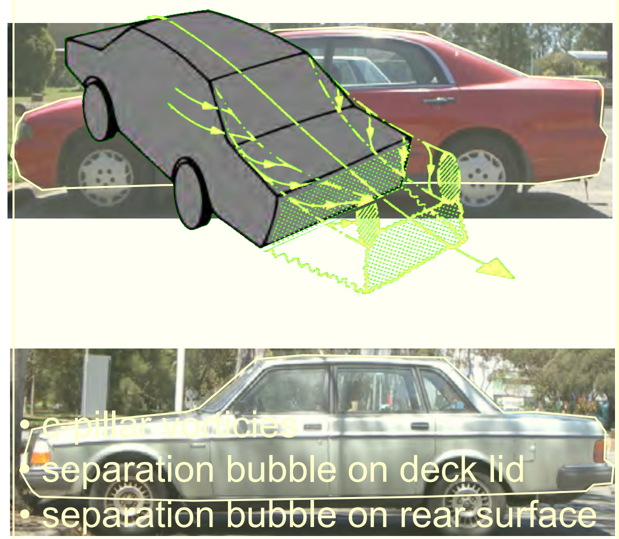
- Slant rear window
- Truncated rear end



- C-pillar vortices
- flow attached to rear window
- separation bubble on rear surface

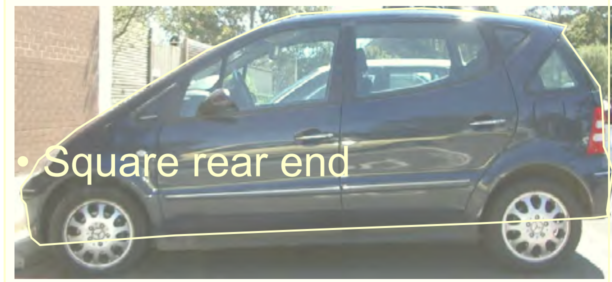
Notchback

- Slant rear window
- Deck Lid
- Truncated rear end



- c-pillar vorticies
- separation bubble on deck lid
- separation bubble on rear surface

Squareback



- Square rear end

- flow separated on
- no strong C-pillar vortices

Vehicle Geometry

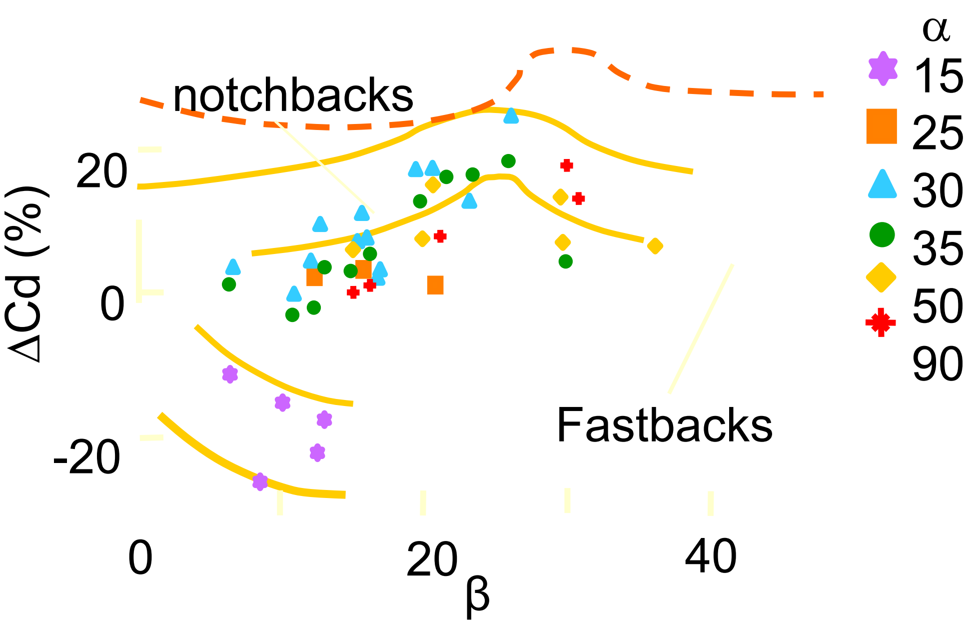
Fastback ↔ Squareback

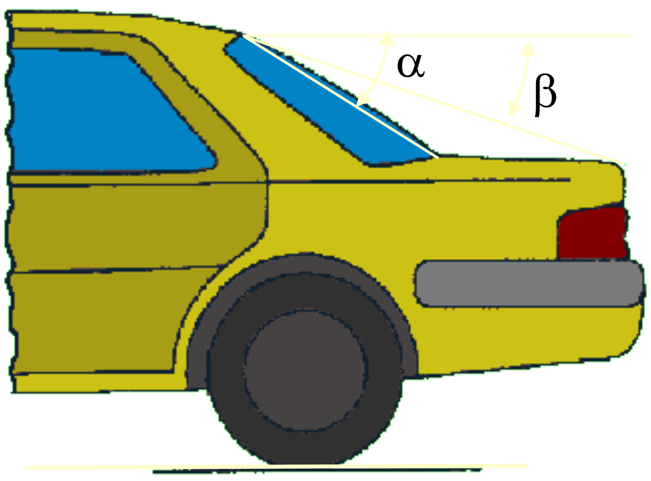
Squareback = Fastback @ α=90^o

Fastback ↔ Notchback

Geometry simplified by determining characteristic angles

Nozarawara et. al. (from Hucho)





Similar drag characteristic by changing β

Parameters and Simulations

Parameters

Slant Angle (α)
Range: $0^o - 40^o$

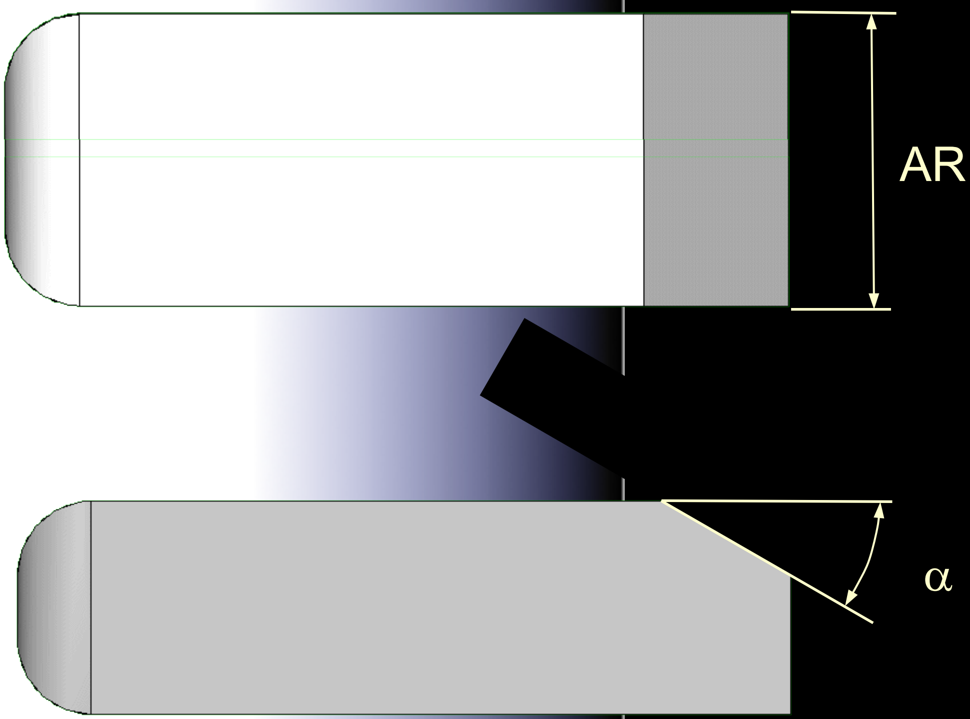
Aspect Ratio (AR) (W/SL)
Range: 1.297 to 2.631

Simulations

V=40m/s

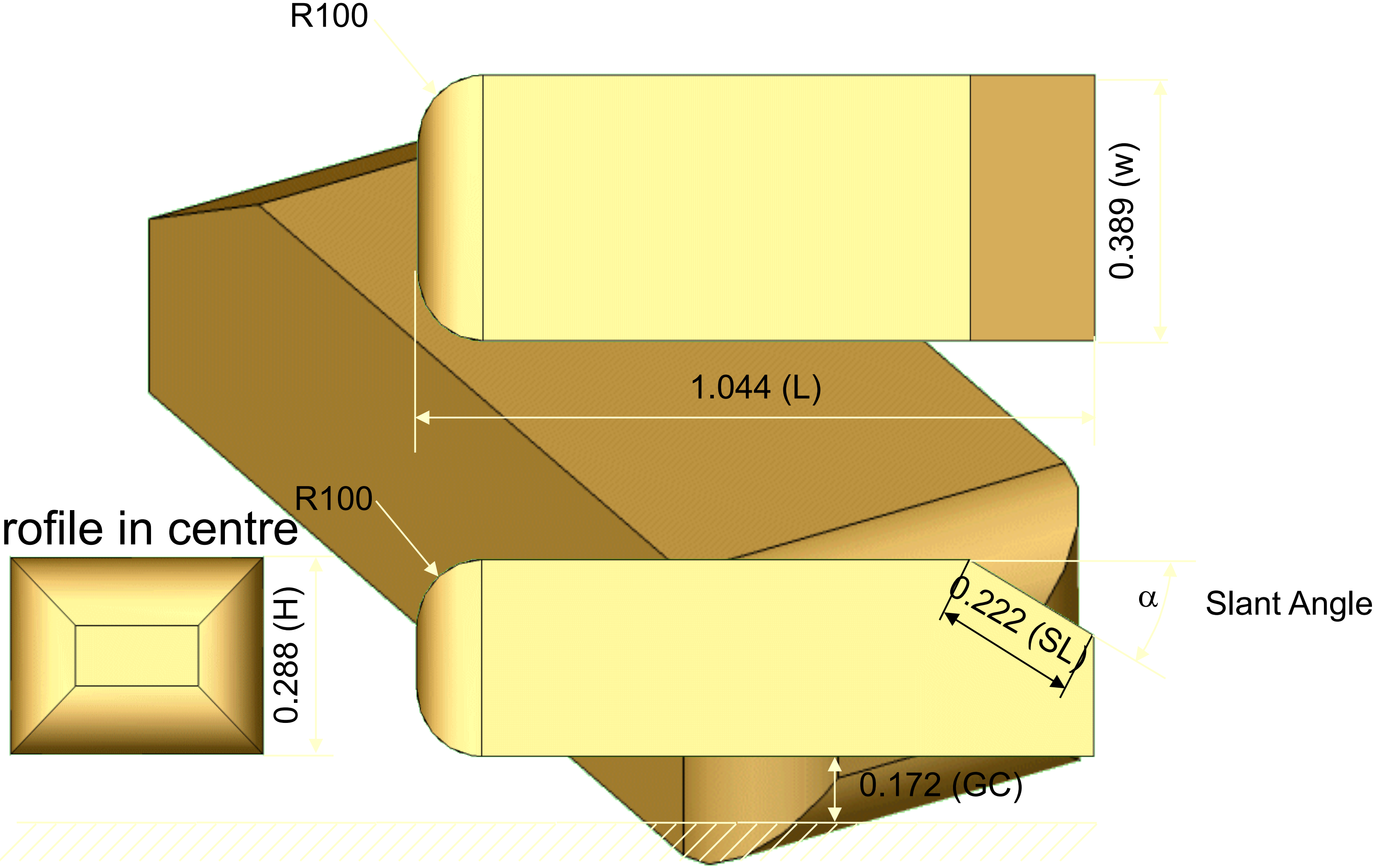
Re=2.86×10^6
Length Scale = 1.044 (L)

kω-SST Turbulence model



Ahmed Body Geometry

Creates large structures in the wake



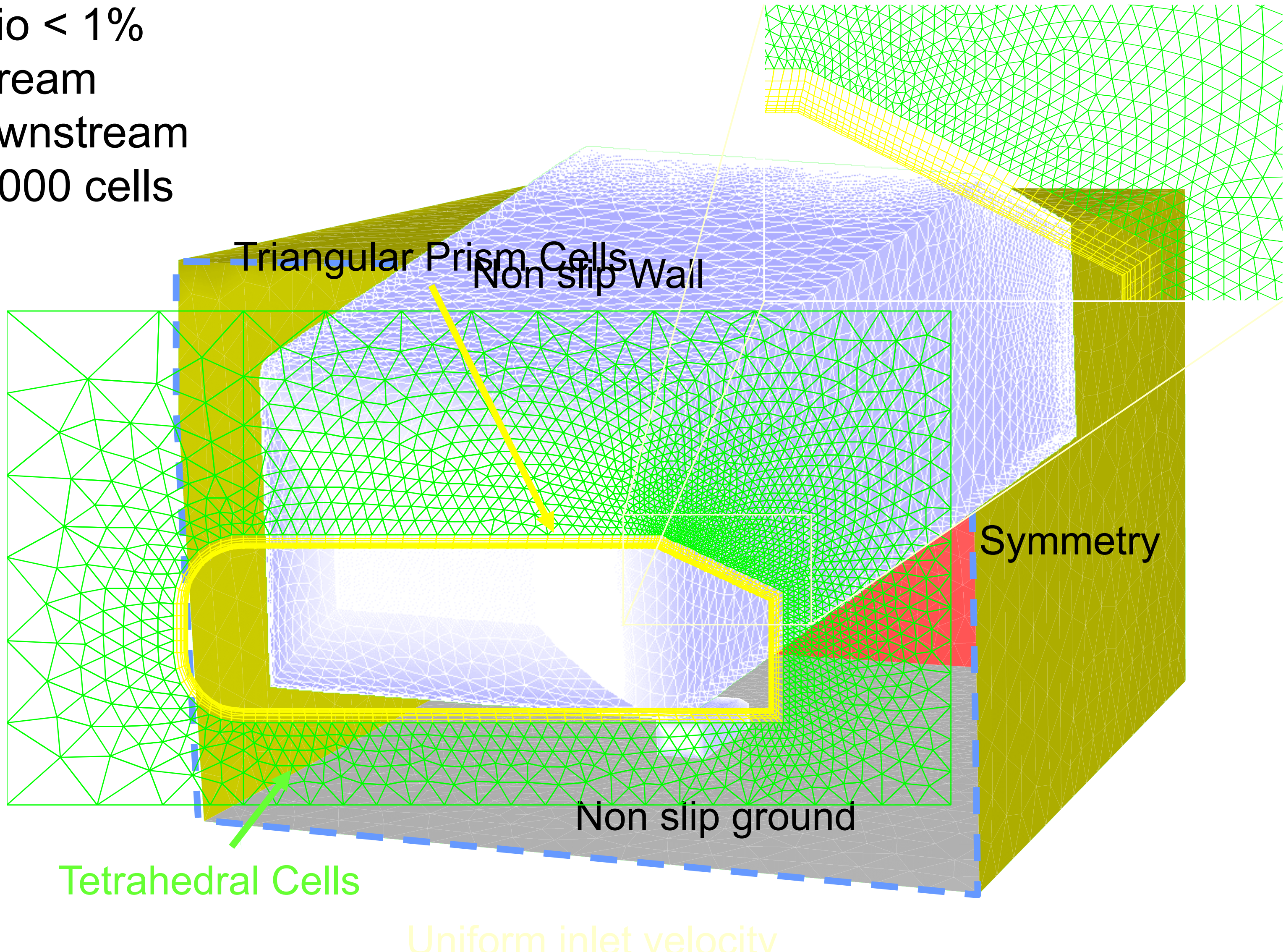
Uniform profile in centre

Ahmed Body Dimensions

Strong 3D displacement at front

Grid setup

Blockage Ratio < 1%
Inlet 14L upstream
Outlet 10L downstream
Minimum 634000 cells
Y+<5



Comparison with other Experiments

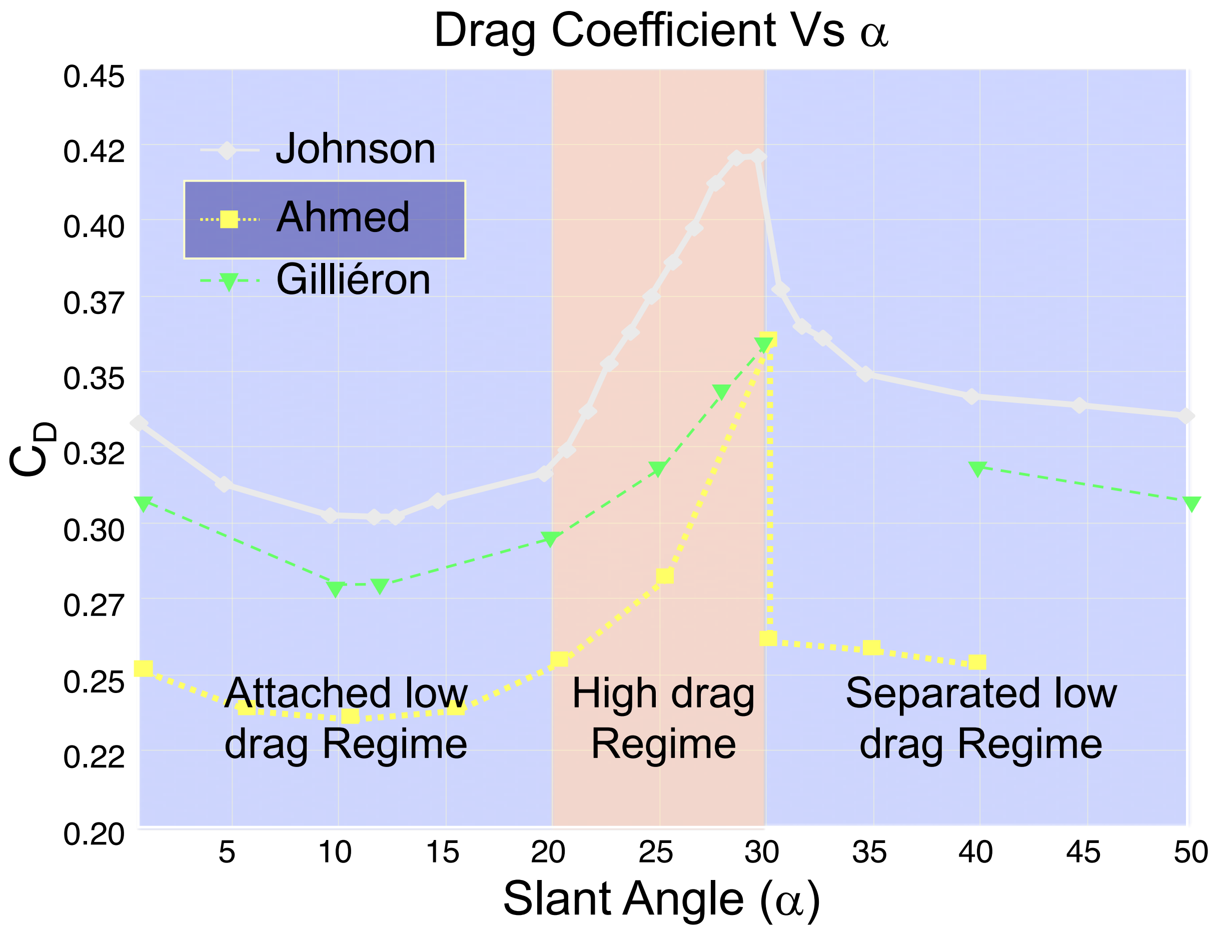
Drag coefficients over predicted for α.

Same trend in C_D as α is varied.

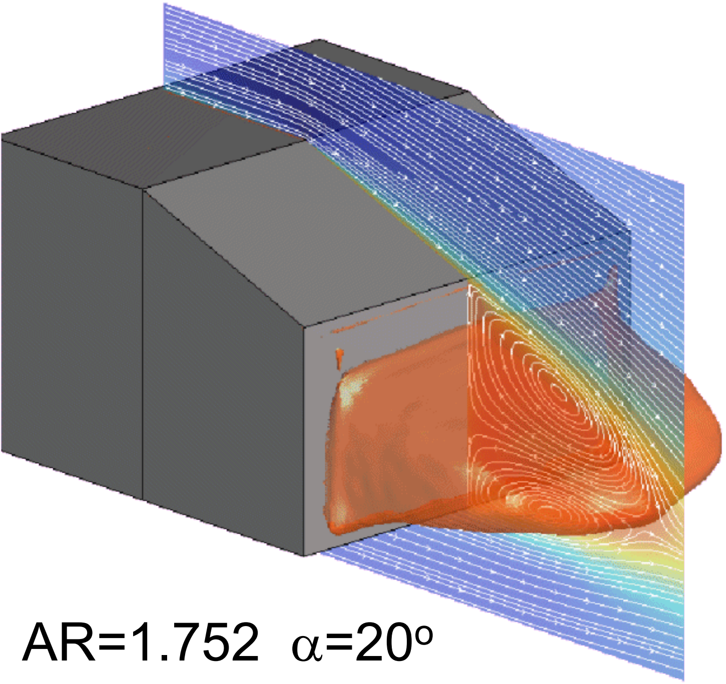
Gilliéron results same for α=30°.

Same trends as α is varied indicates that essential flow structures are captured.

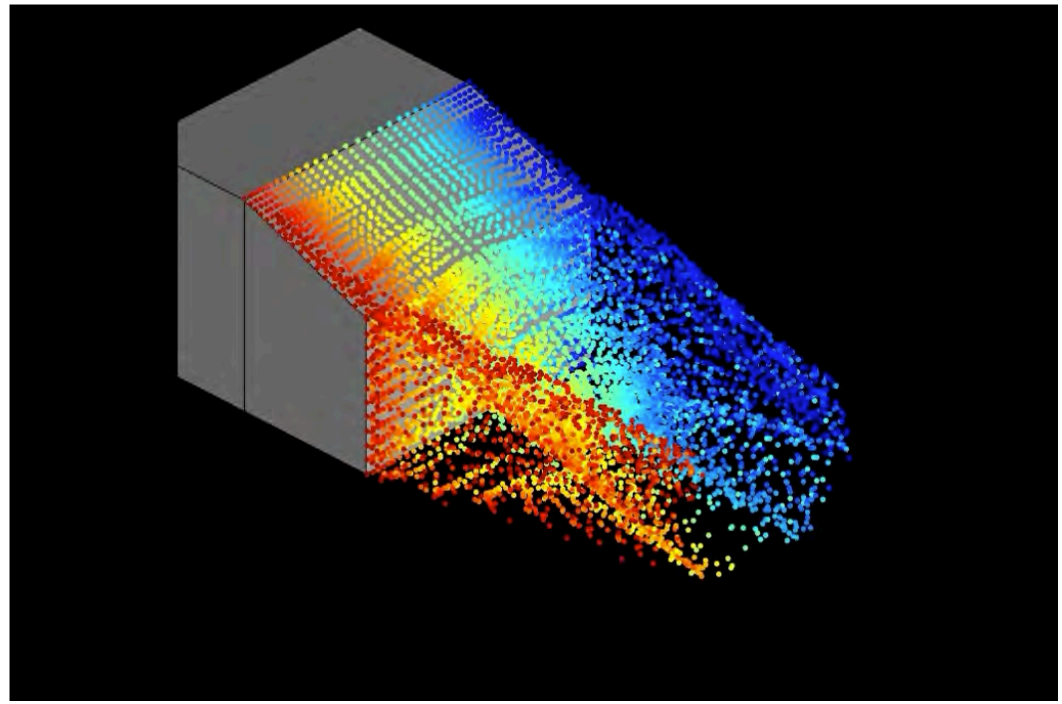
Three regimes identified



Attached Low Drag Regime



AR=1.752 α=20°

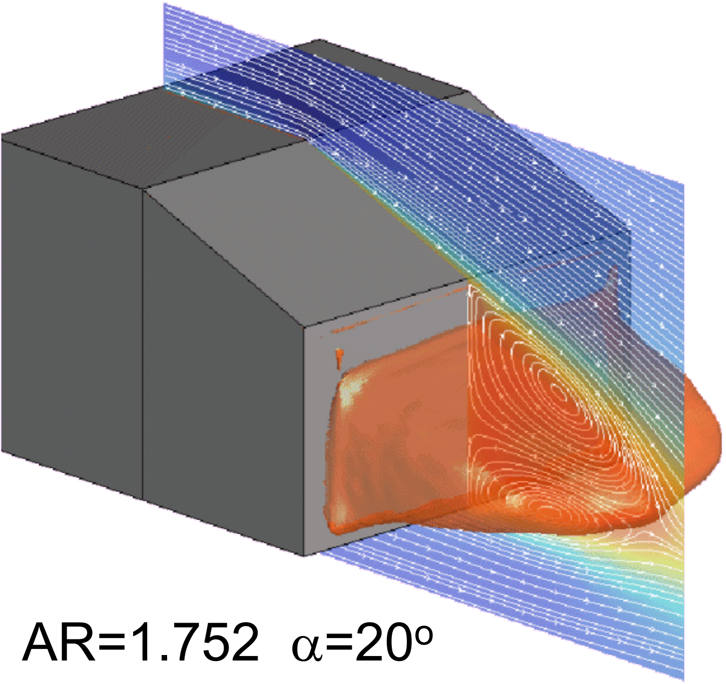


Particles coloured by release position

Attached Low drag regime

- Flow attached to slant surface.
- Two parallel sets of flows (from top and bottom and from sides) create two counter-rotating vortex flows.
- Above α=12°, vorticies roll up from C-pillar.

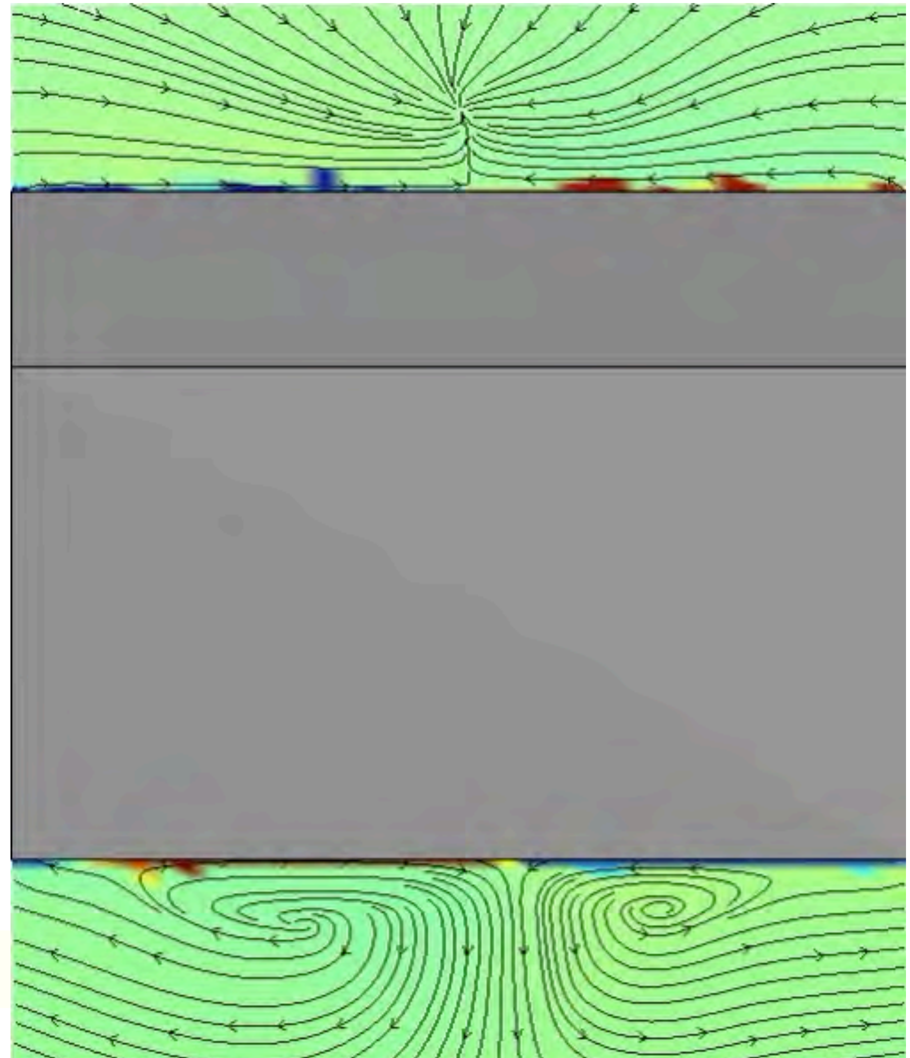
Attached Low Drag Regime



AR=1.752 α=20^o

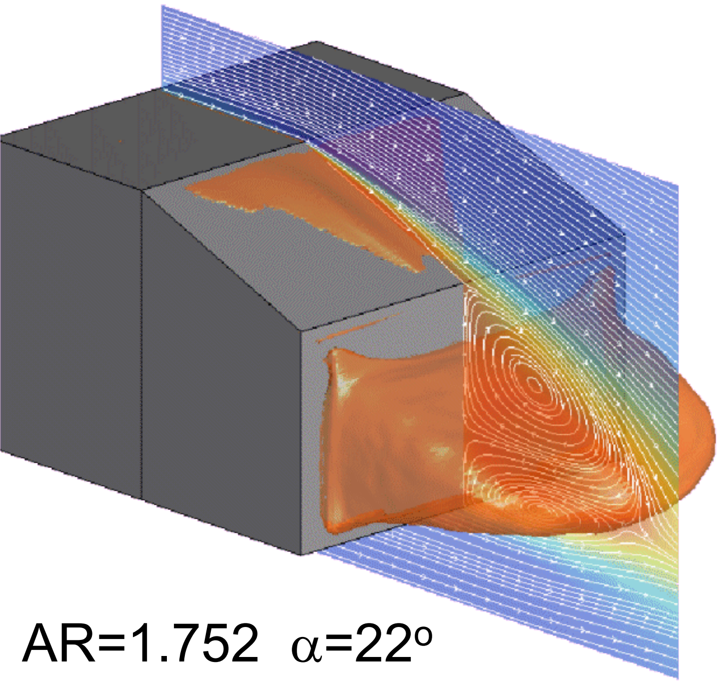
Attached Low drag regime

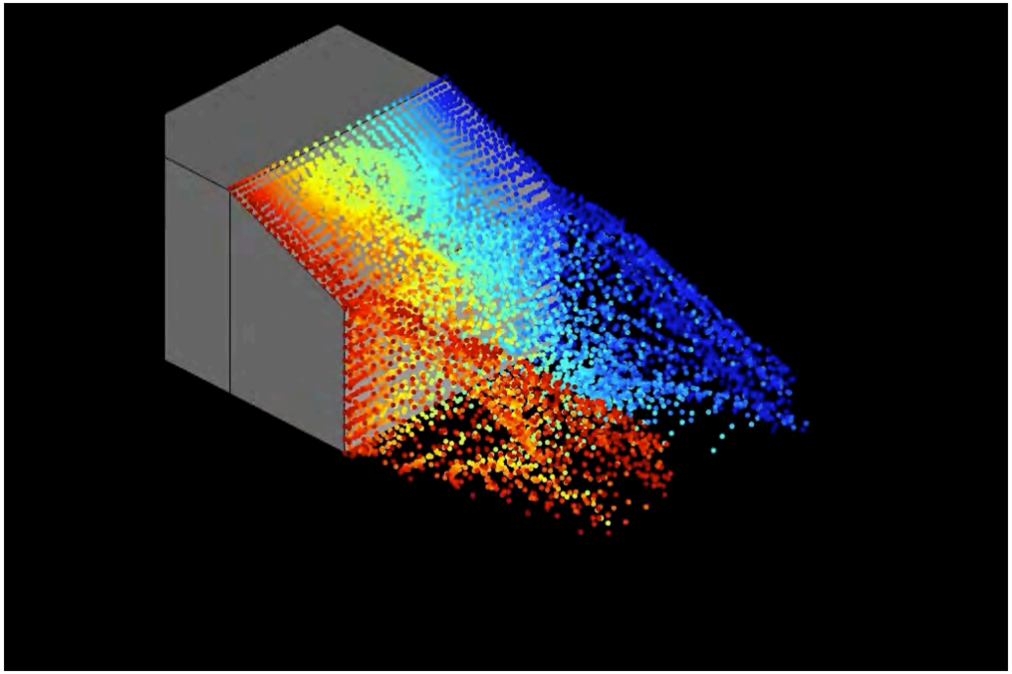
- •Vortices roll up from C-pillars
- •No separation bubble on centreline



Streamwise vorticity

High Drag Regime



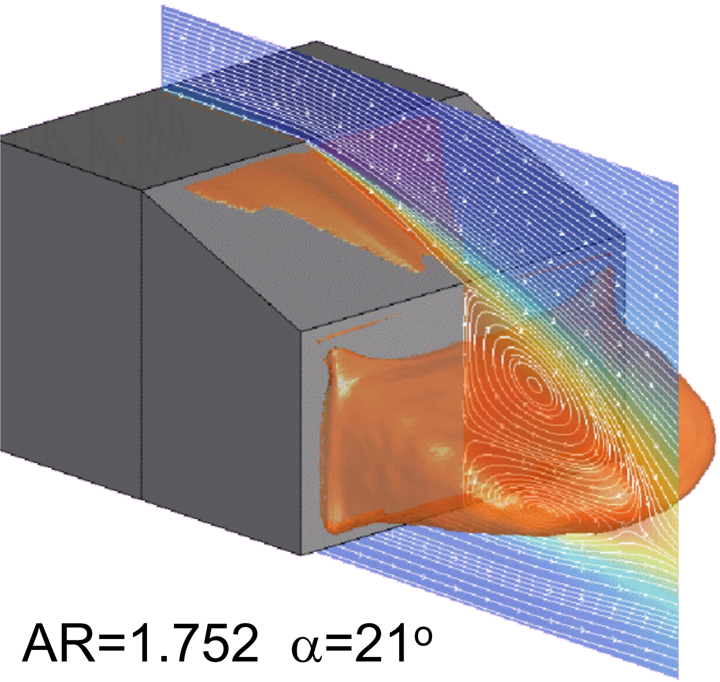


Particles coloured by release position

High drag regime

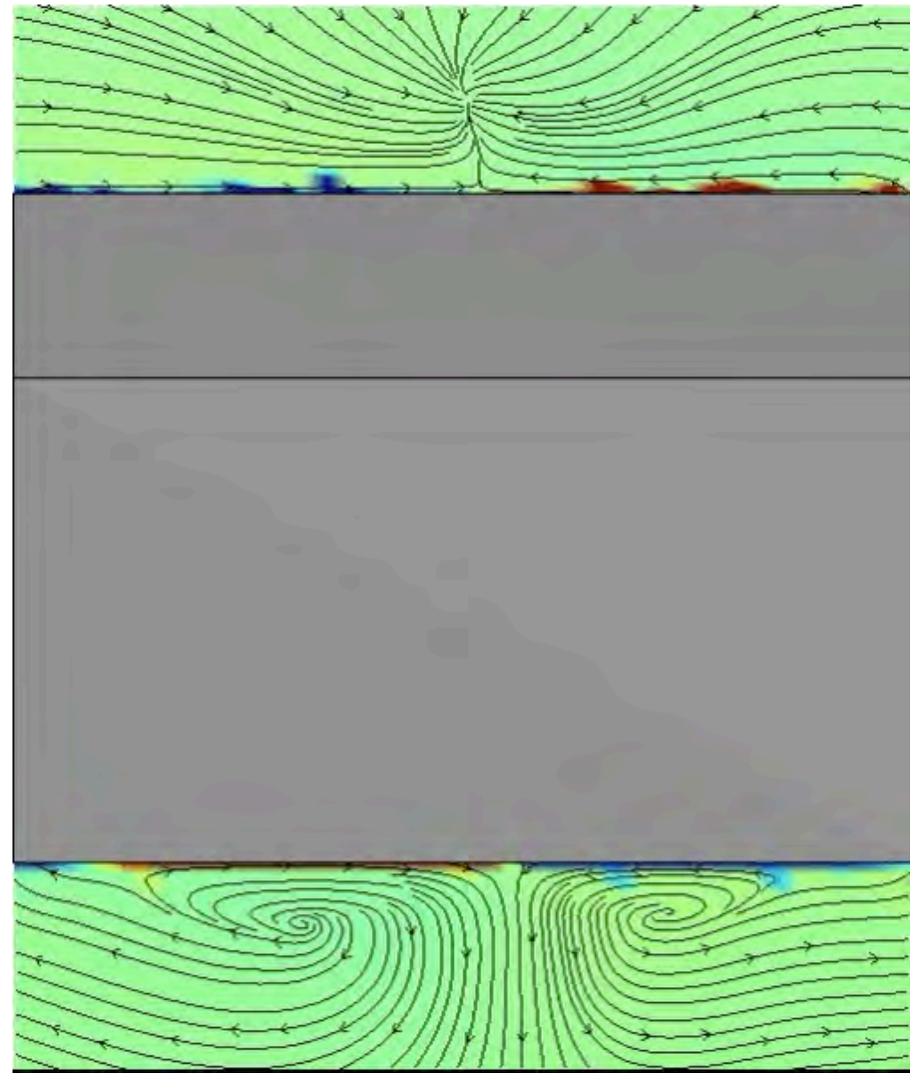
- Flow separates from slant surface in centre
- Two counter rotating flow structures in separation bubble

High Drag Regime



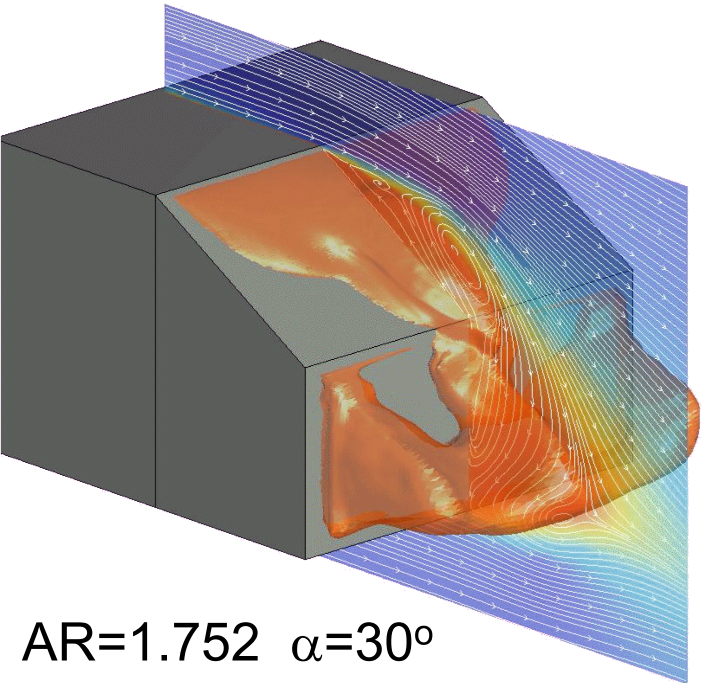
High drag regime

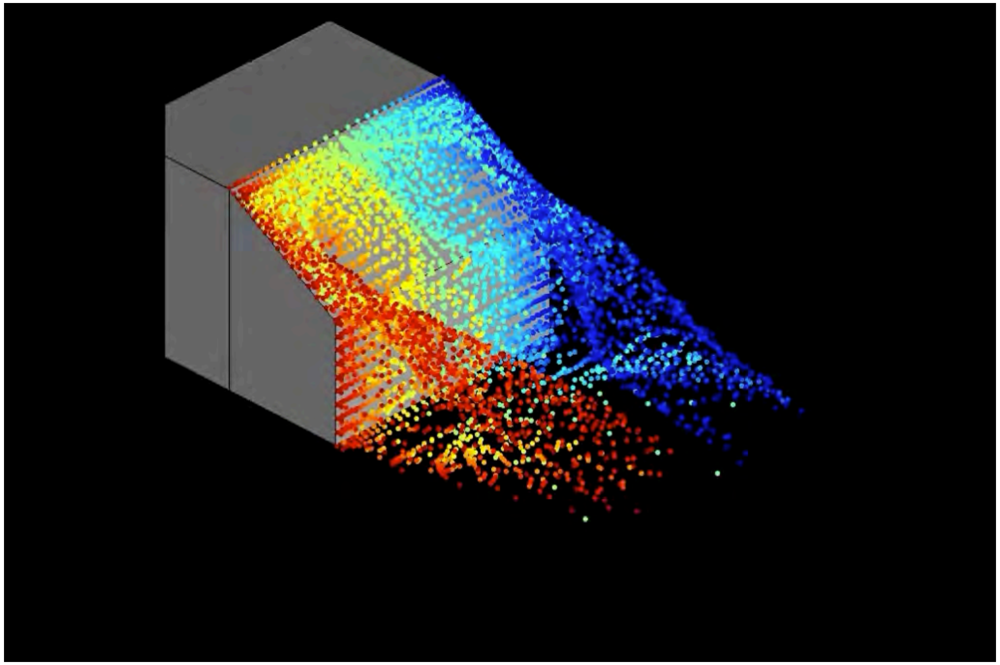
- Separation bubble visible on centerline
- C-pillar vortices stronger
- Vortices keep flow attached on the sides of slant surface



Streamwise vorticity

High Drag Regime



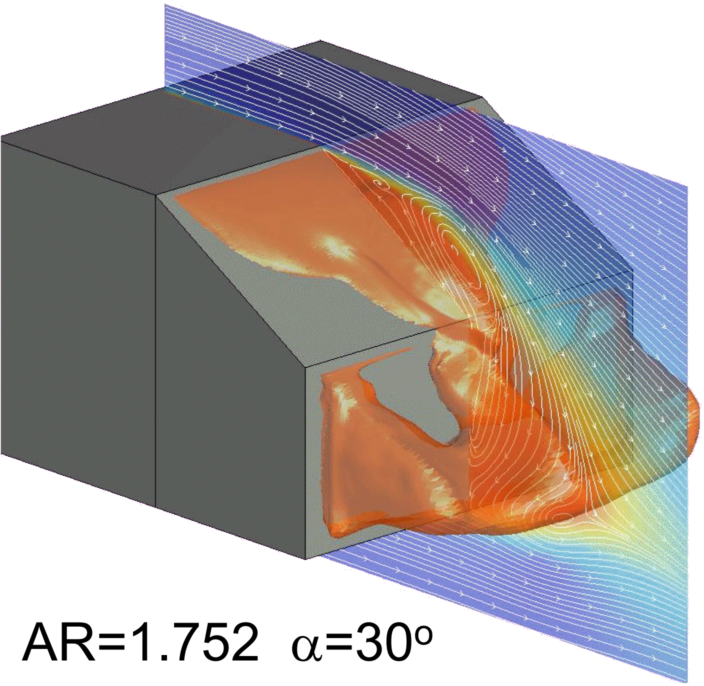


Particles coloured by release position

High drag regime

- Flow still attached on edges of slant surfaces.
- Larger structures in shear layer
- Slant separation bubble feeding C- pillar vortices.

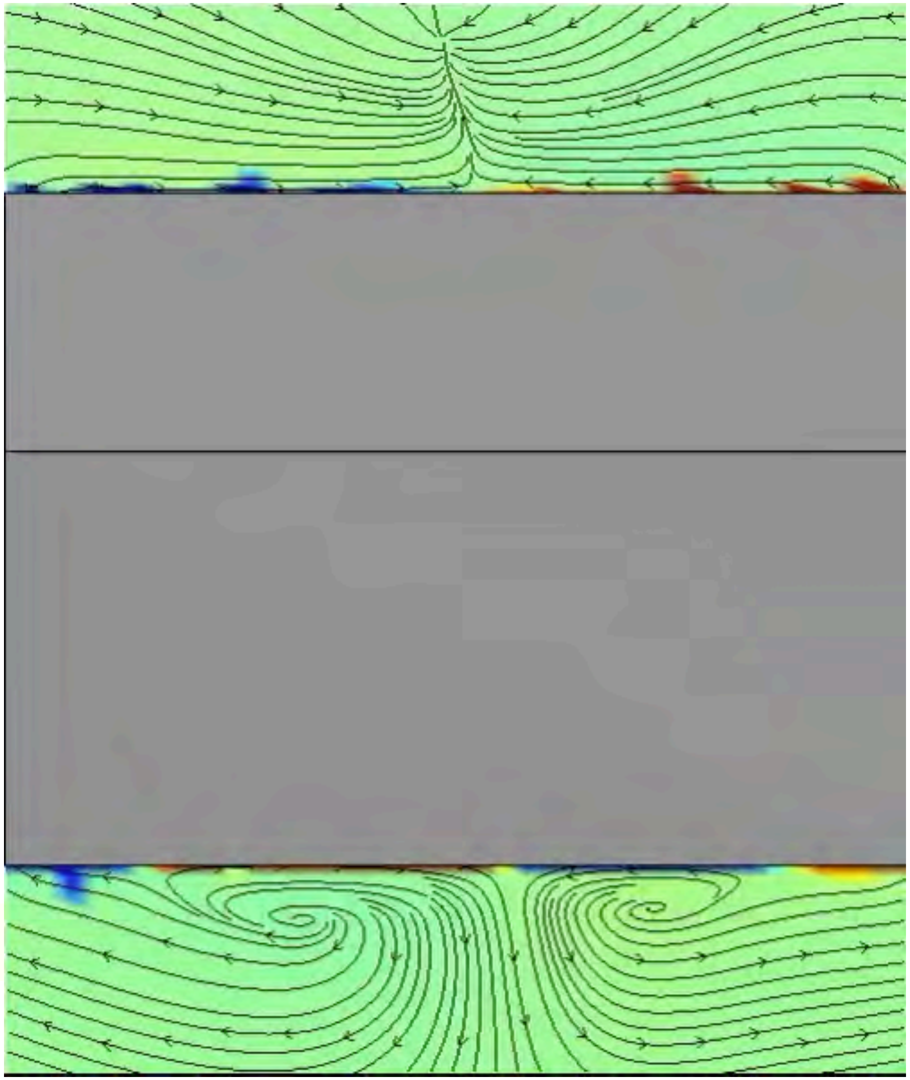
High Drag Regime



AR=1.752 α=30^o

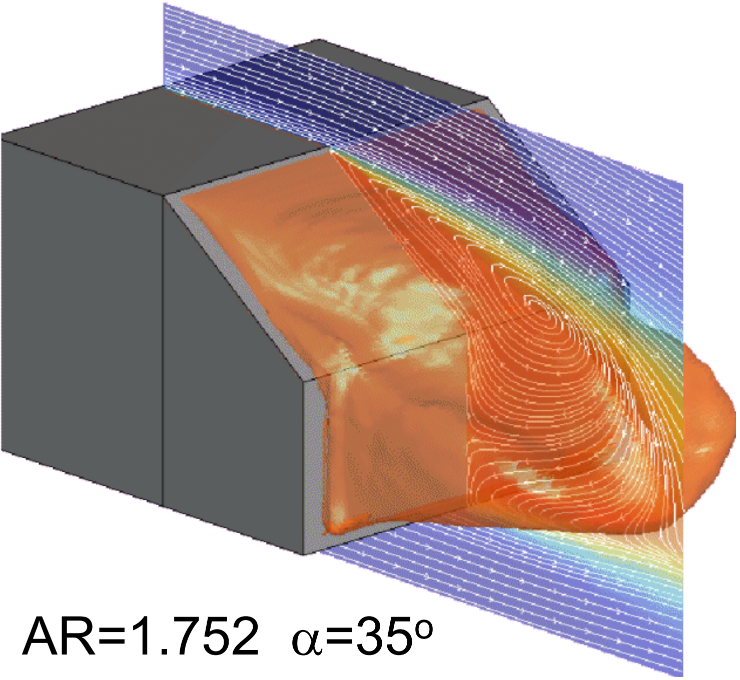
High drag regime

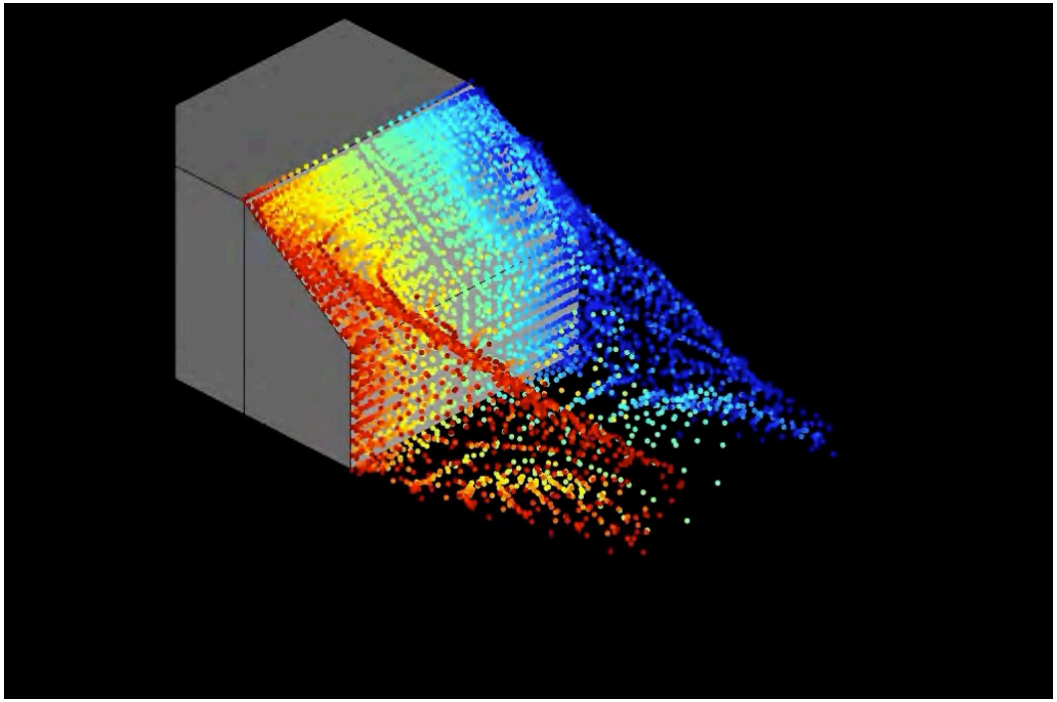
- C-pillar vortices feeding two streamwise counter rotating vortices, causing large downwash.



Streamwise vorticity

Separated Low Drag Regime



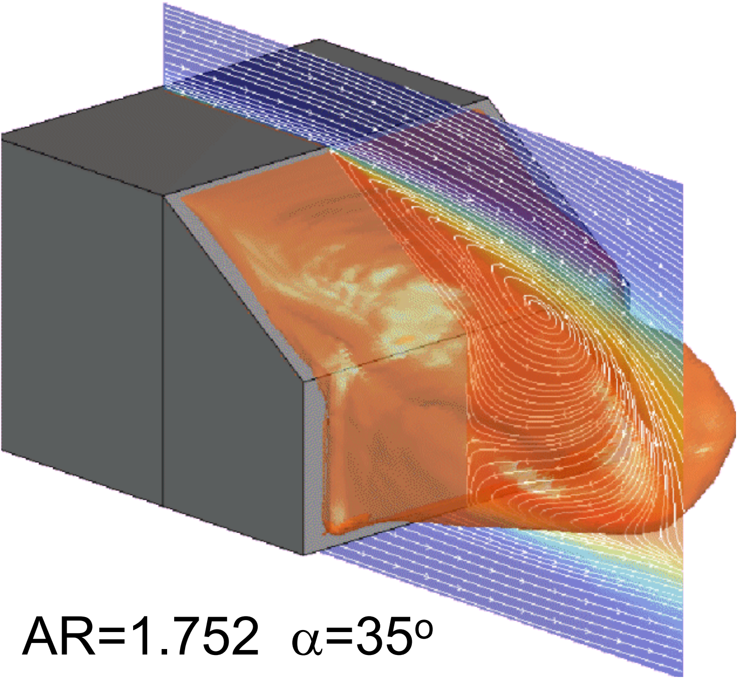


Particles coloured by release position

Separated low drag regime

- Flow separated from the top of the slant surface.
- Separation bubbles from slant surface and rear end combine to form larger region behind body.

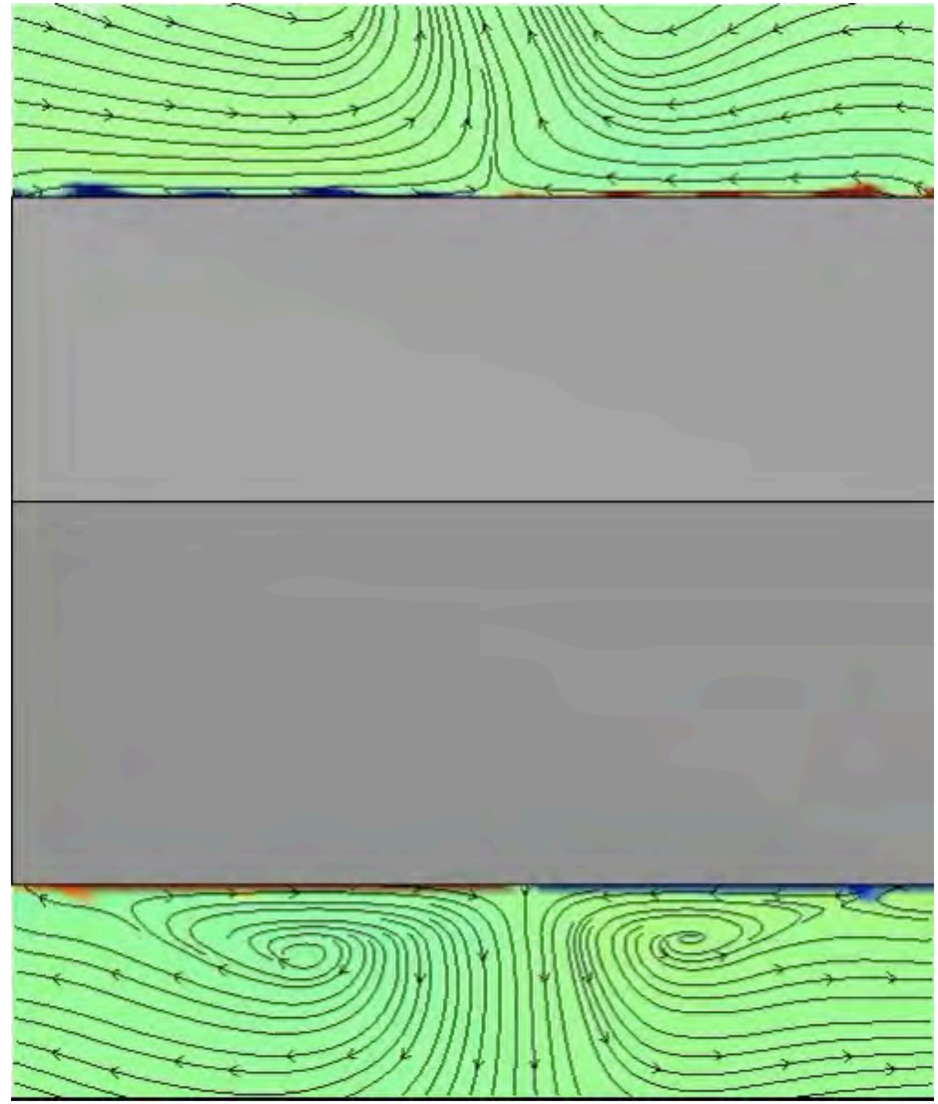
Separated Low Drag Regime



AR=1.752 α=35^o

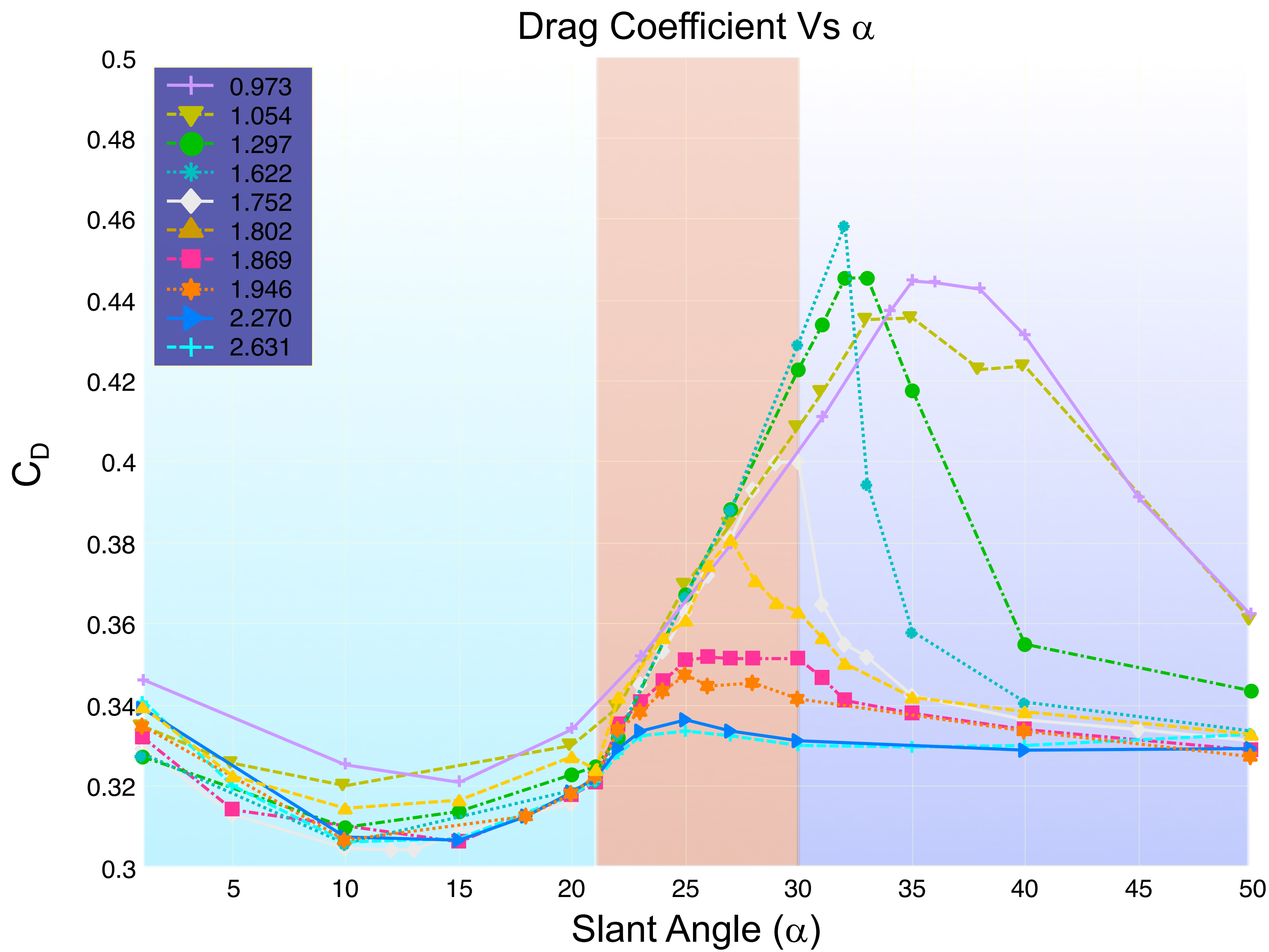
Separated low drag regime

- C-pillar vortices seen at lower α not sustained due to separation bubble dominating the wake.

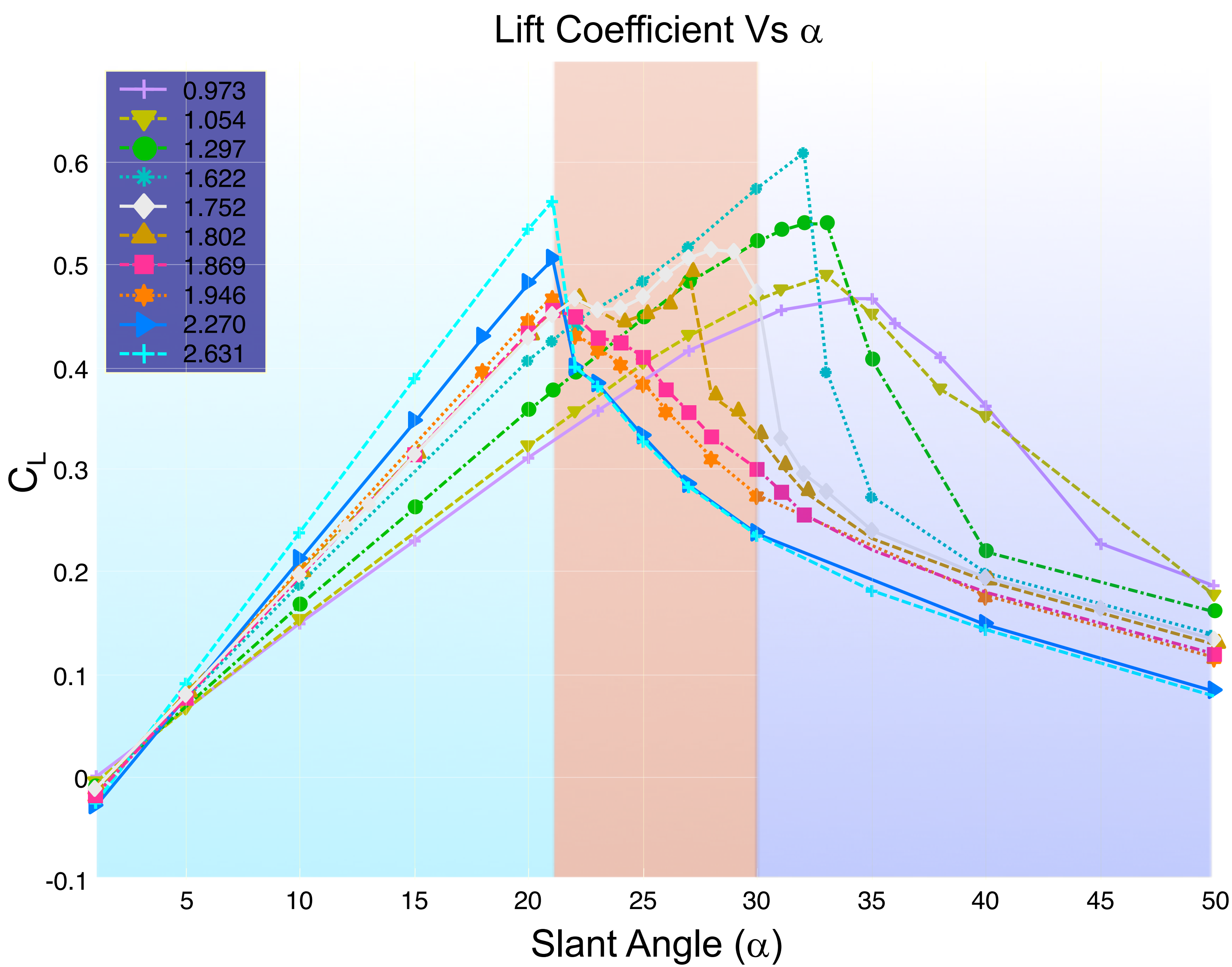


Streamwise vorticity

Body Forces - Drag



Body Forces - Lift



AR effects

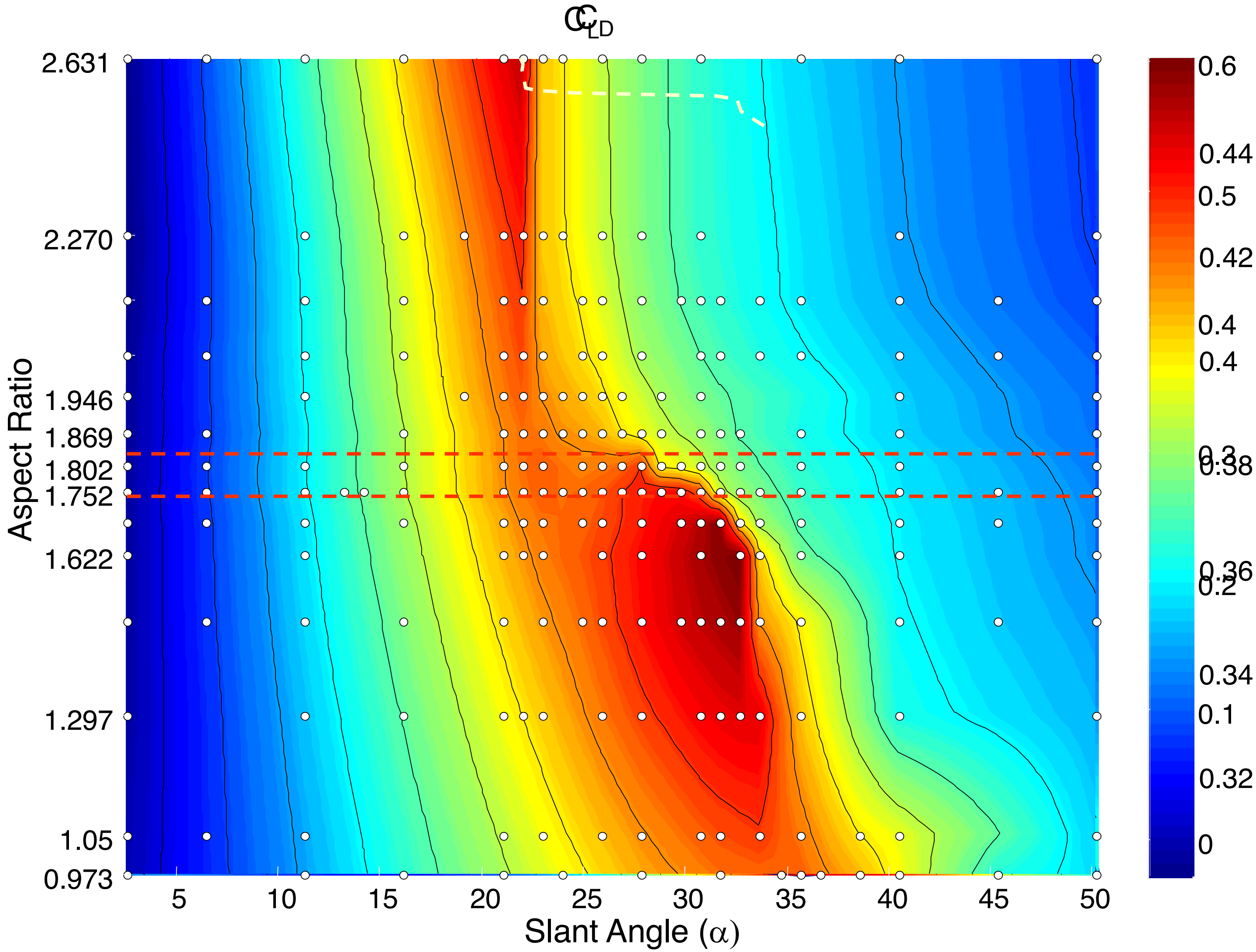
Peak drag at α=30° for AR=1.752

Critical AR

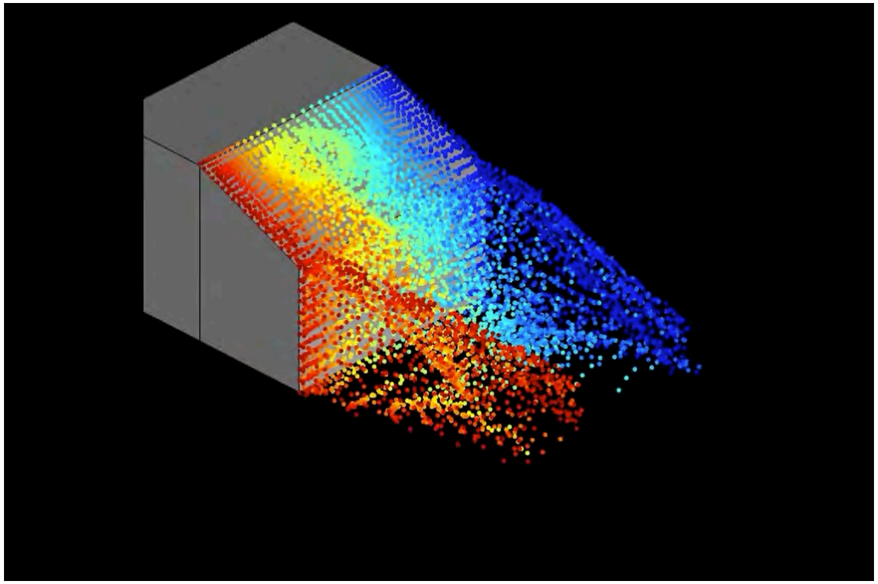
1.802>AR>1.869

Below AR_C
Peak Lift: $\alpha\approx$32°

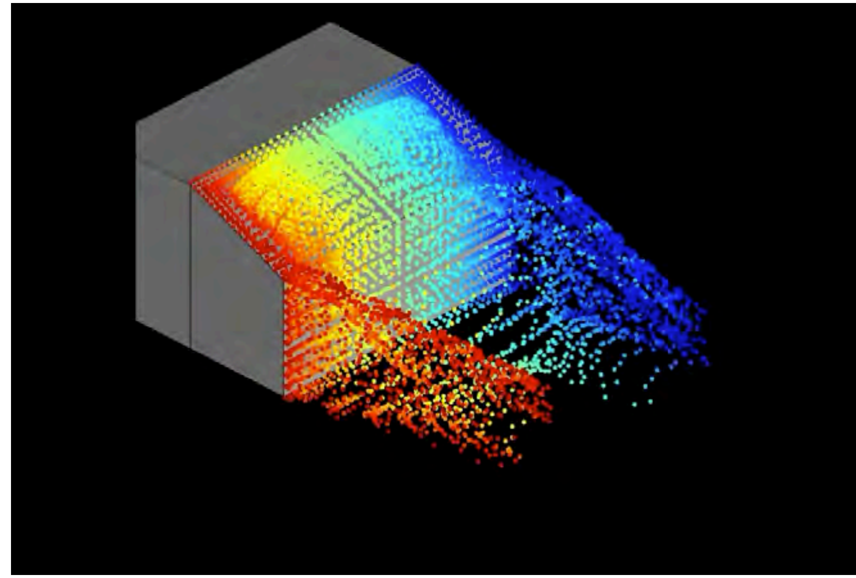
Above AR_C
Peak Lift: $\alpha\approx$20°



Aspect Ratio Effects



AR=1.752 α=22˚



AR=2.270 α=22˚

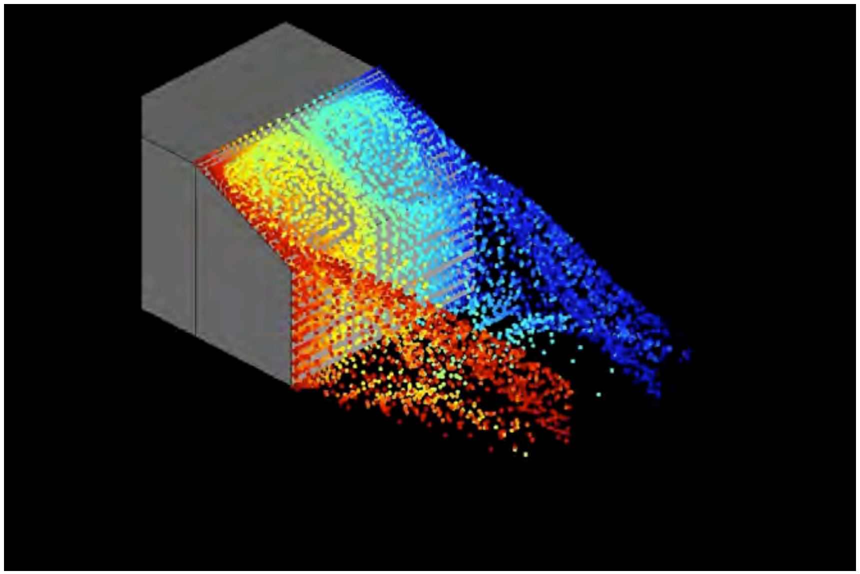
Below AR_C

- Small separation bubble formed on slant surface.
- Downwash from vortex forming from C-pillar causing flow to attach on side of slant surface.

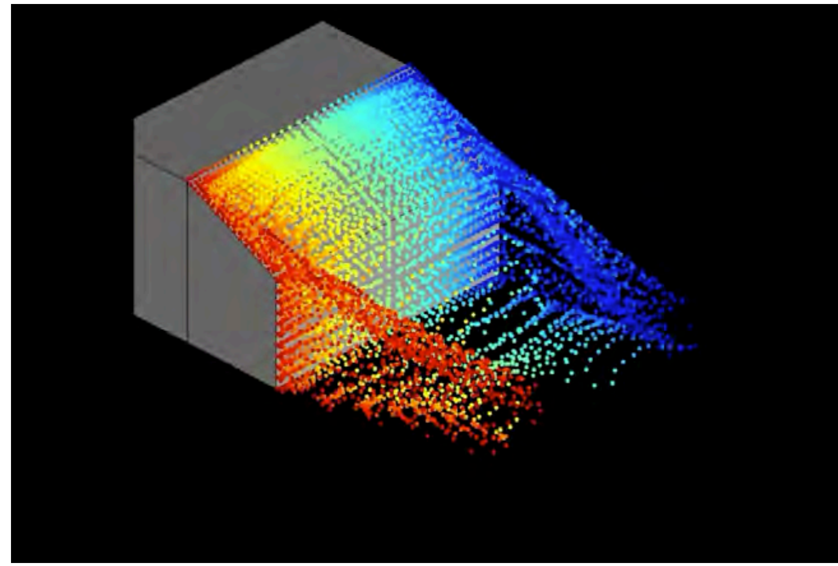
Above AR_C

- Wider separation bubble covering majority of slant surface.
- Vortices from C-pillar similar strength as those below AR_C.
- Rear separation bubble larger.

Aspect Ratio Effects



AR=1.752 α=25˚



AR=2.270 α=25˚

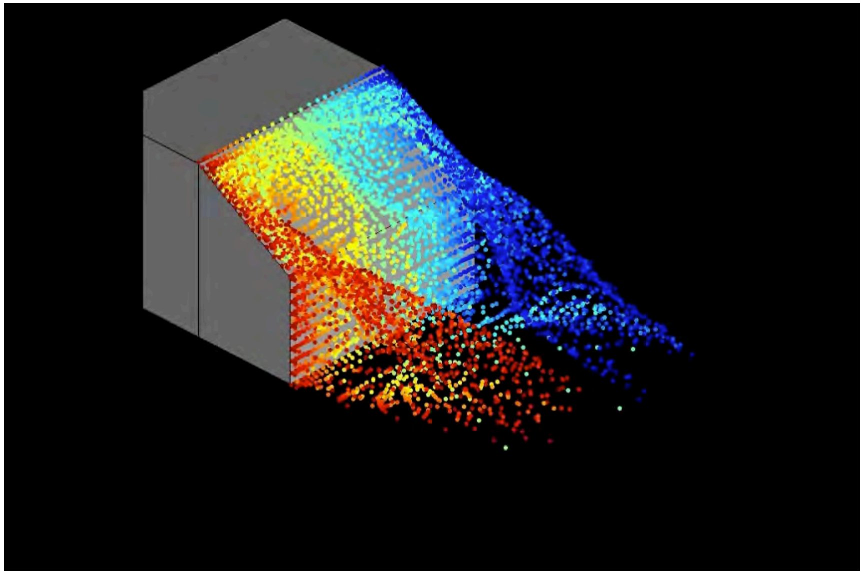
Below AR_C

- Separation bubble larger with two counter rotating vortices inside.
- Separation bubble containing toroid vortex system shorter due to net downwash from slant surface.

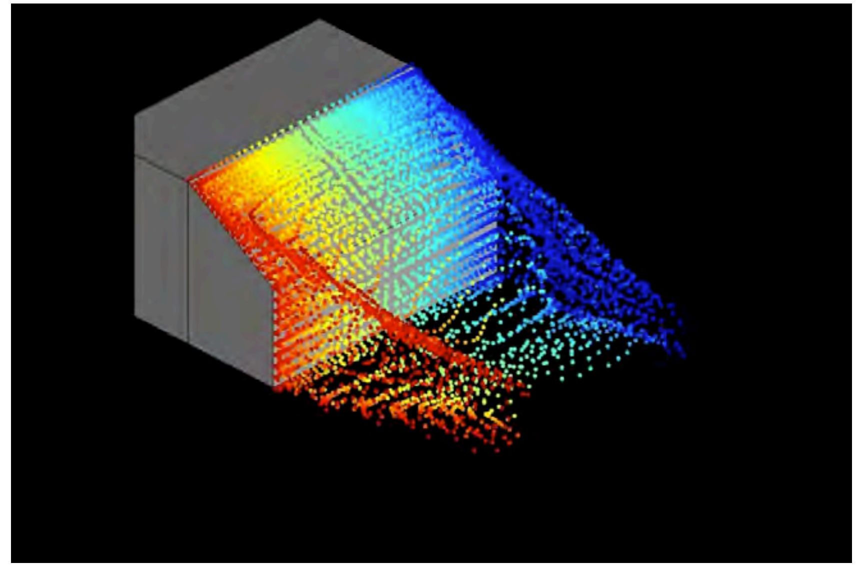
Above AR_C

- Wake separated from top of slant surface.
- Slant separation bubble and rear separation merged together.
- C-pillar vortices still present but decreased in strength.

Aspect Ratio Effects



AR=1.752 α=30˚



AR=2.270 α=30˚

Below AR_C

- C-pillar vortices feeding two streamwise counter rotating vortices causing large downwash.
- Slant separation bubble feeding C-pillar vortices.

Above AR_C

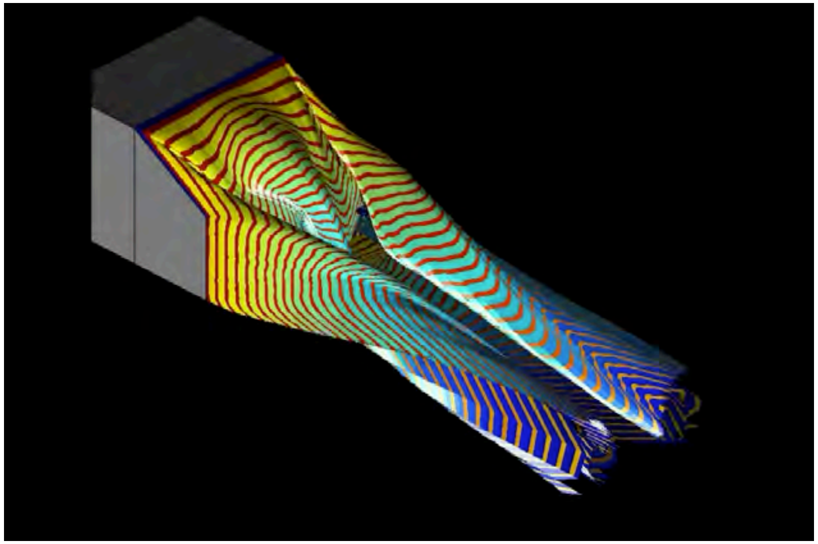
- Flow detached from the top of the slant surface.
- Larger separation bubble at rear.
- C-pillar vortex and downstream vortices no longer present.

Conclusion

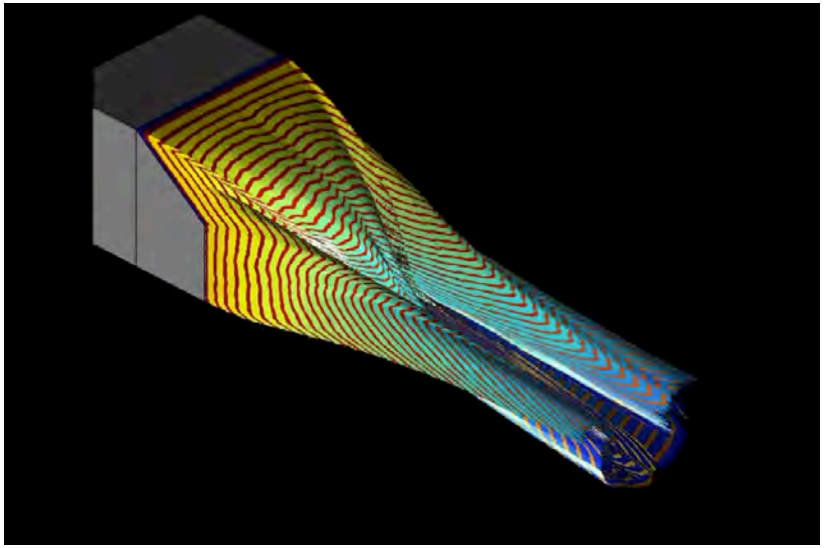
Numerical modelling captures the significant flow structures.

Beyond a critical AR (AR≈1.802) for automotive geometries, high drag wake structures are not sustained.

Important implications as it demonstrates that the vehicle AR has a critical effect on reducing drag.

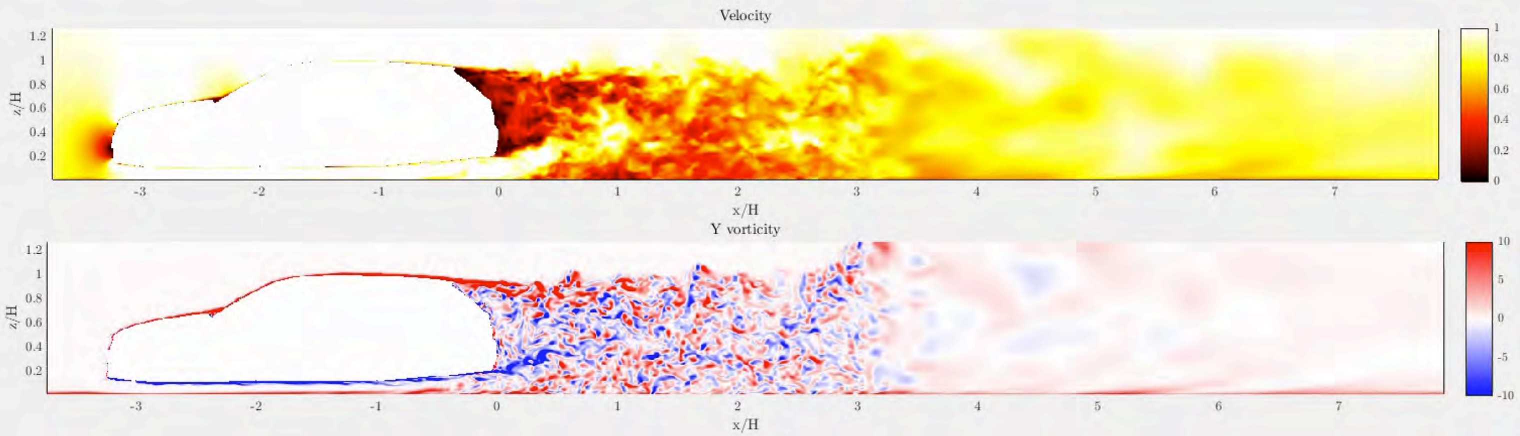


AR=1.752 α=30°

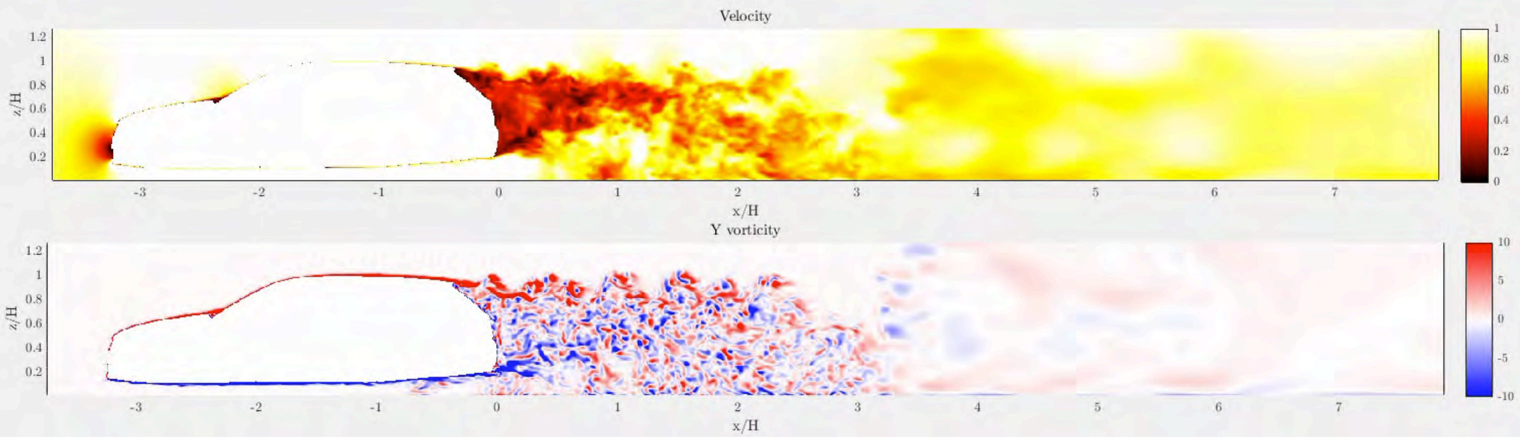


AR=1.752 α=35°

Effect of Moving Ground (Shibo Wang)



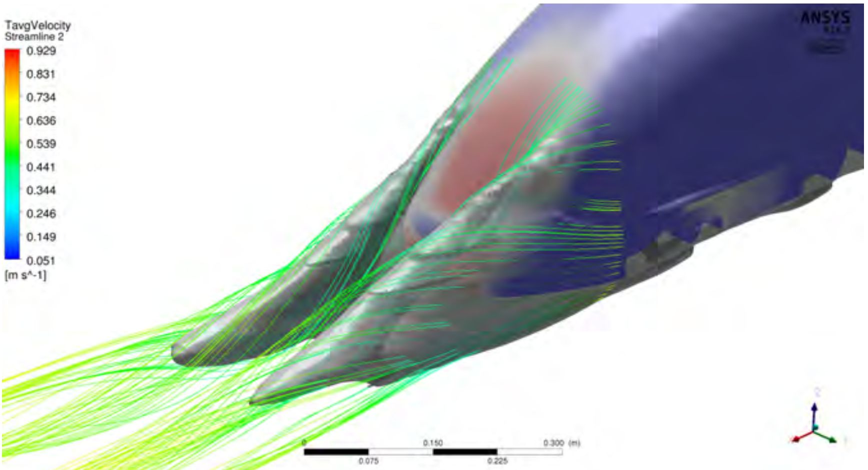
Stationary Ground

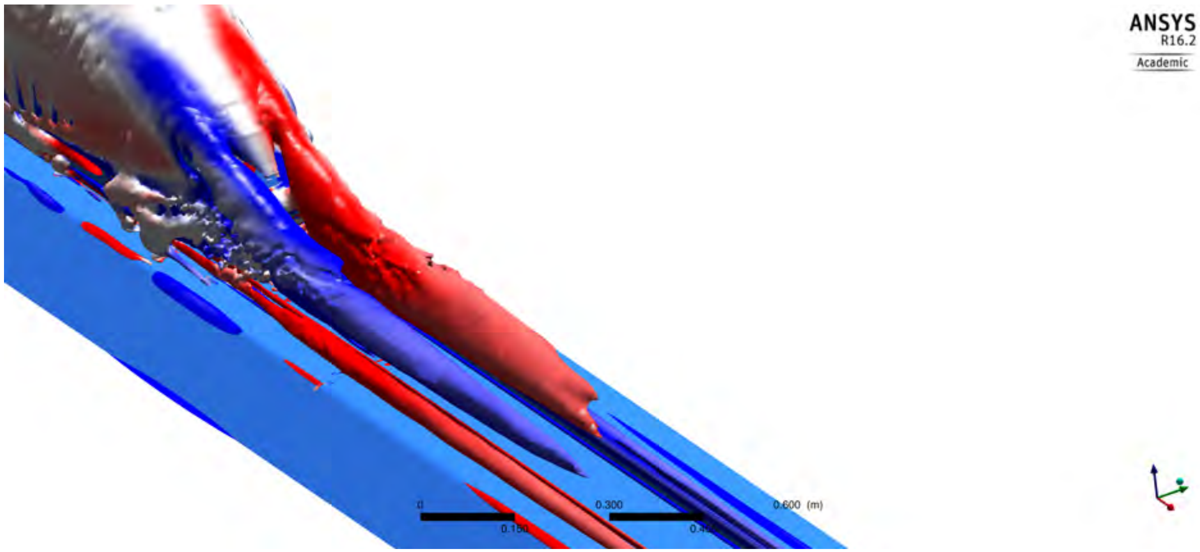


Moving Ground

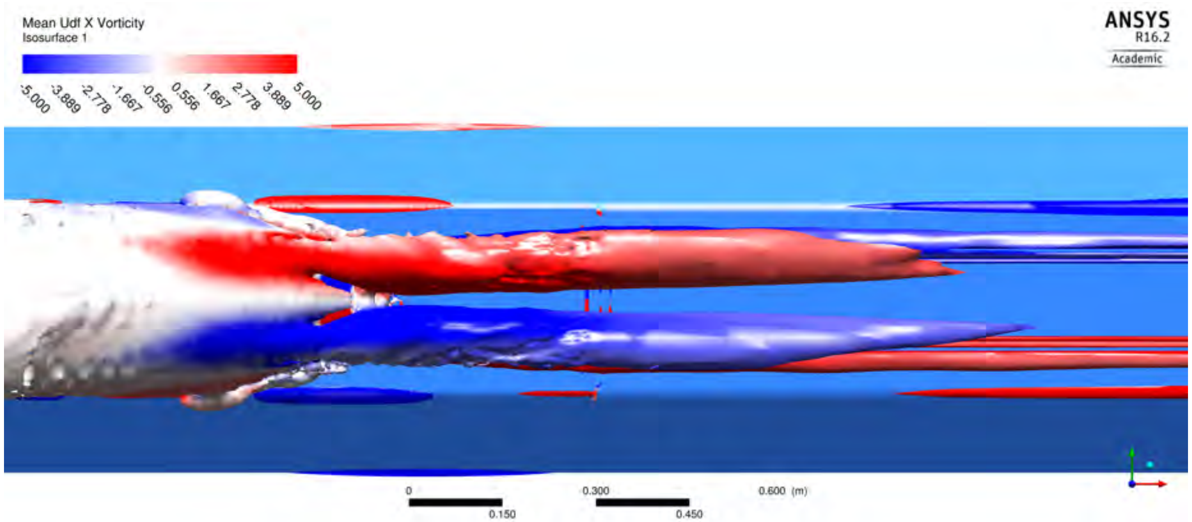
Shibo Wang, FLAIR

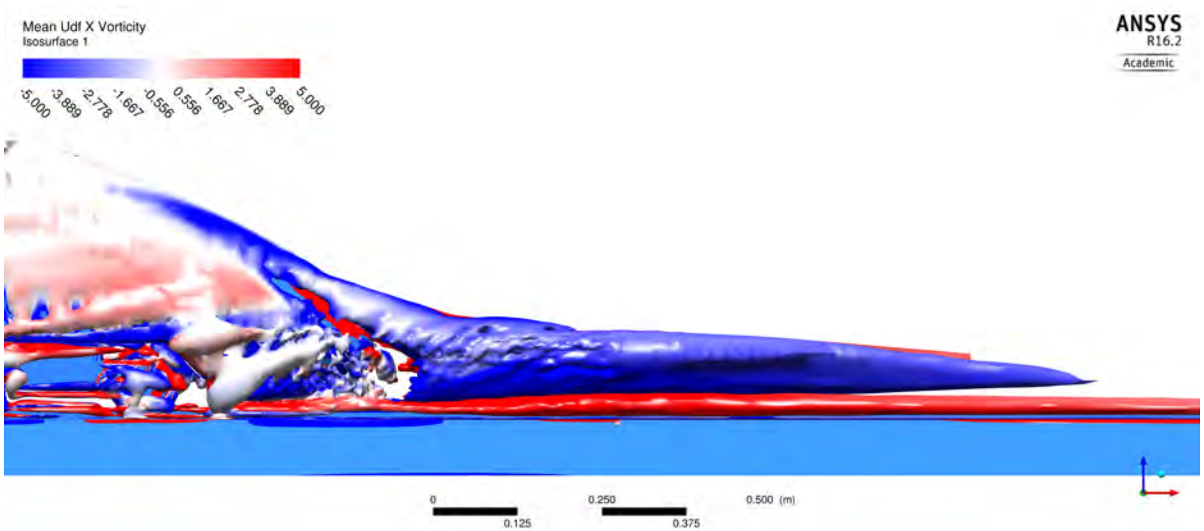
Train: Trailing vortex(Shibo Wang)



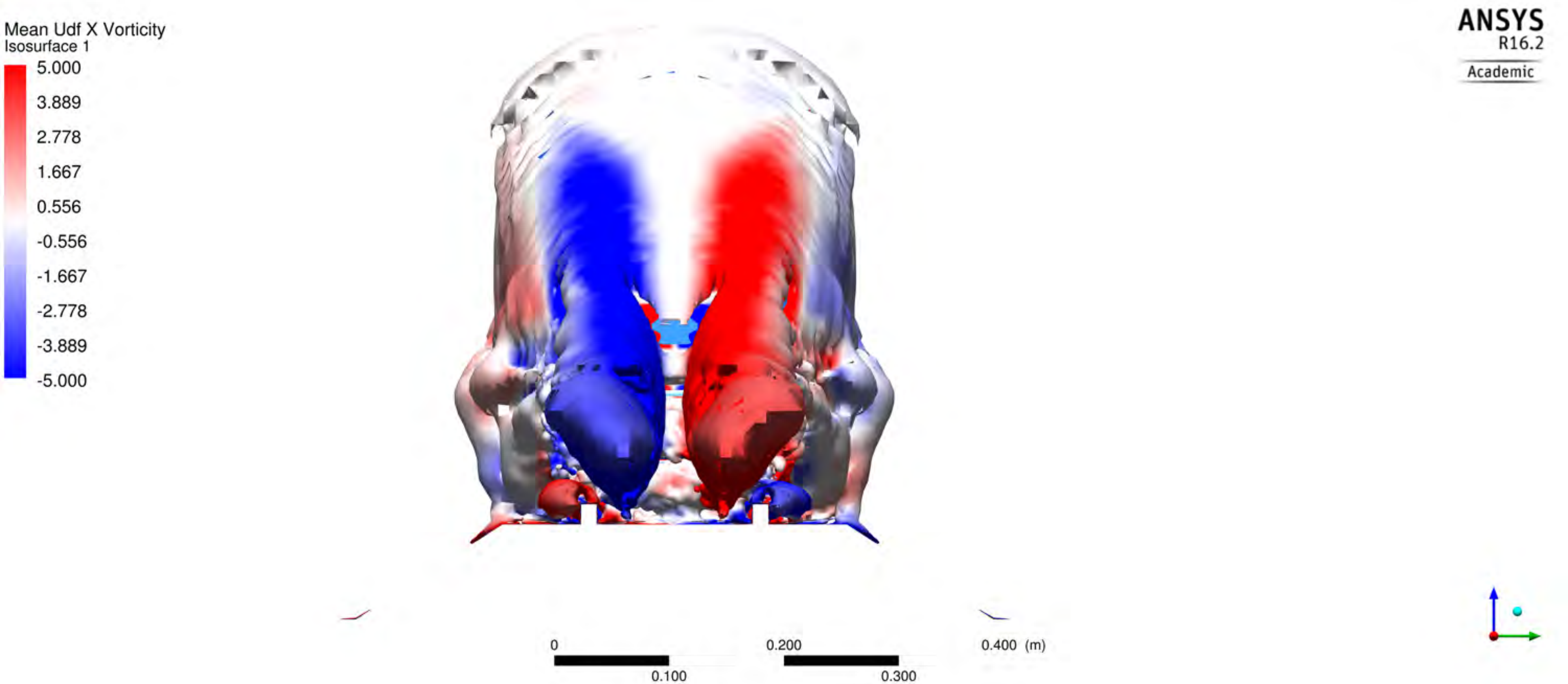


Trailing vortex behind train

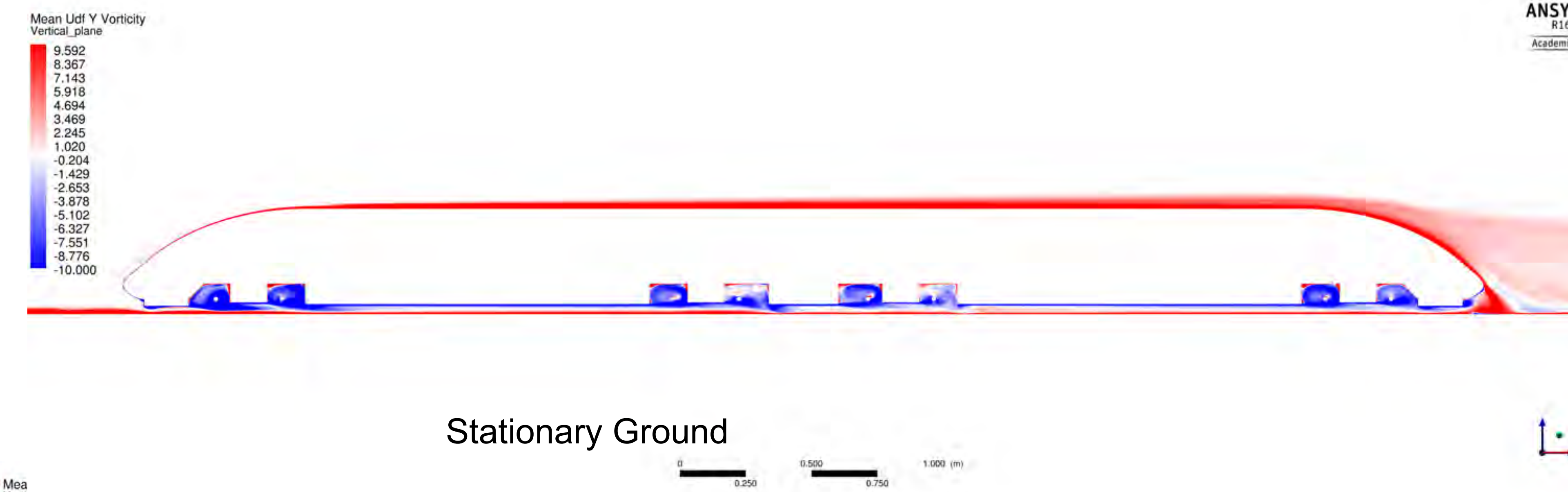




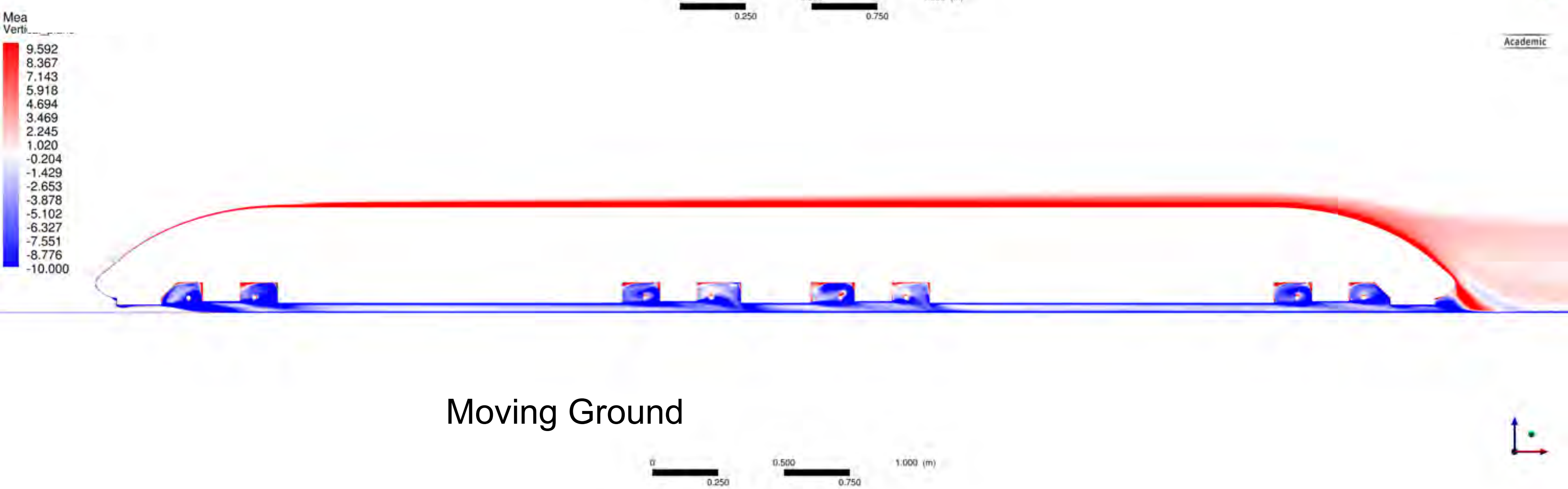
Trailing vortex behind train



Effect of moving ground

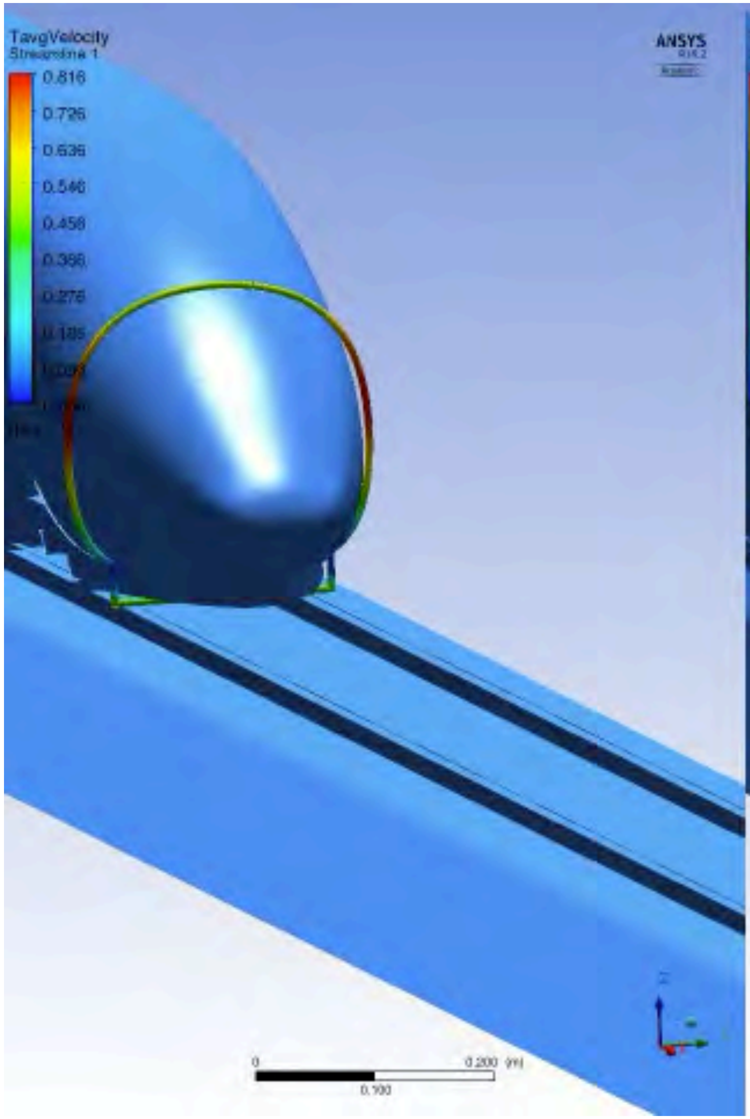


Stationary Ground

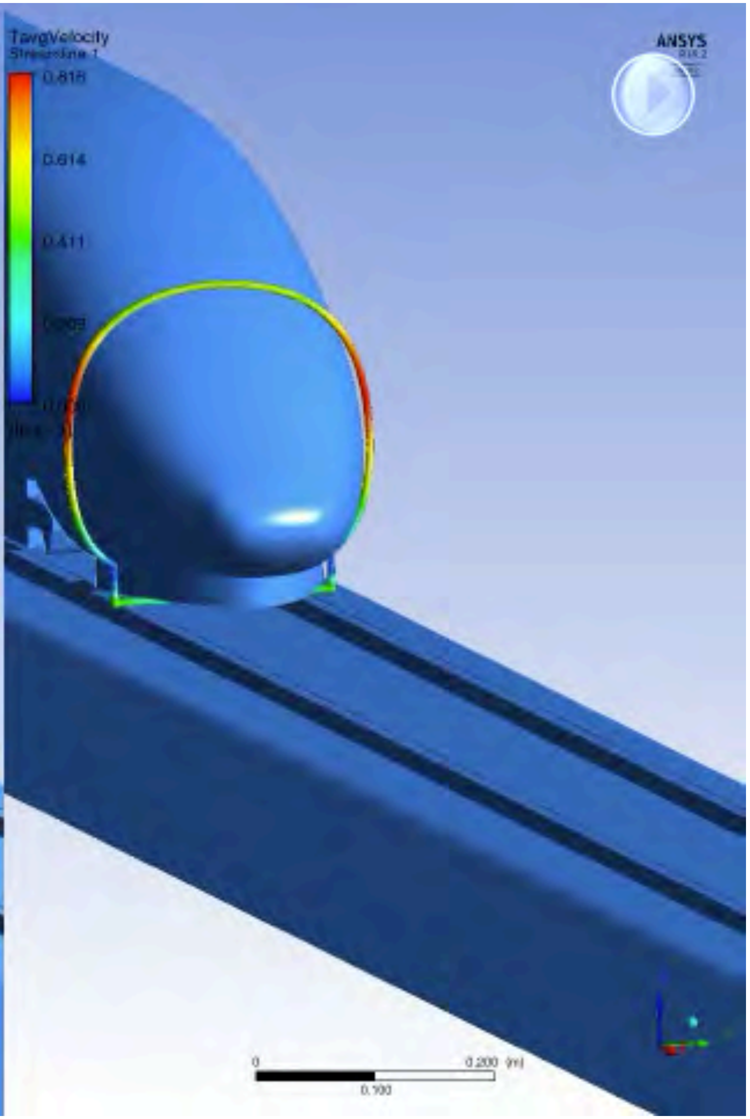


Moving Ground

Effect of moving ground

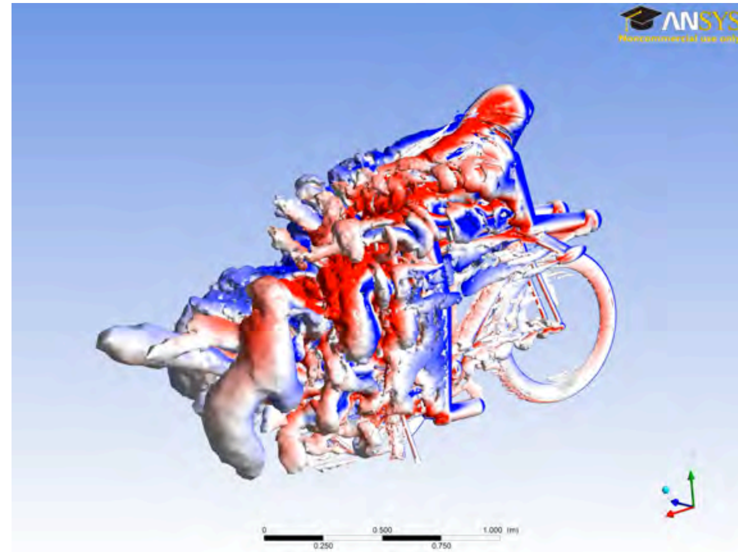


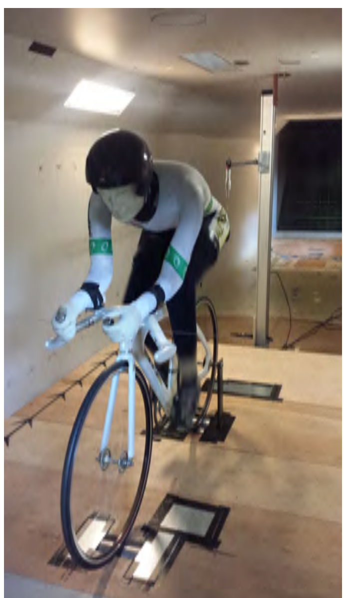
Moving Ground

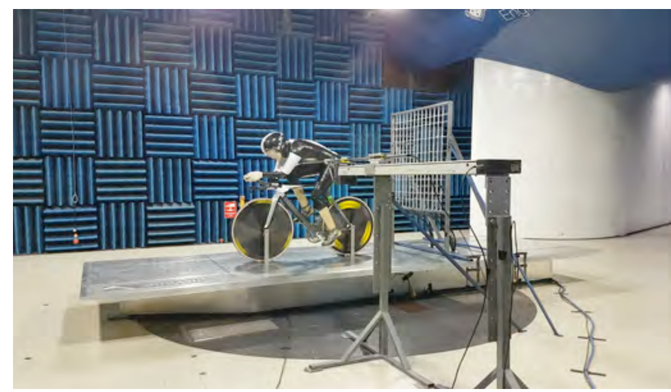


Stationary Ground

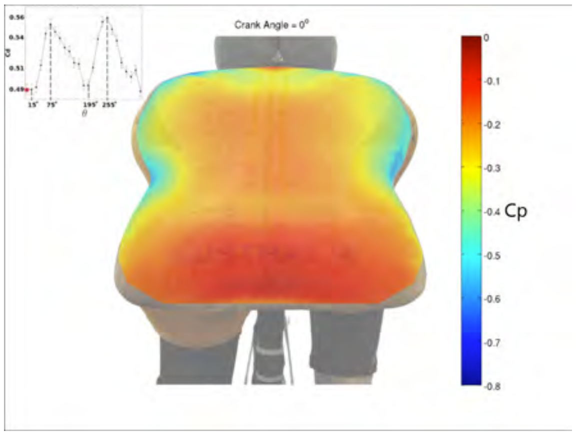
Cycling Dynamics

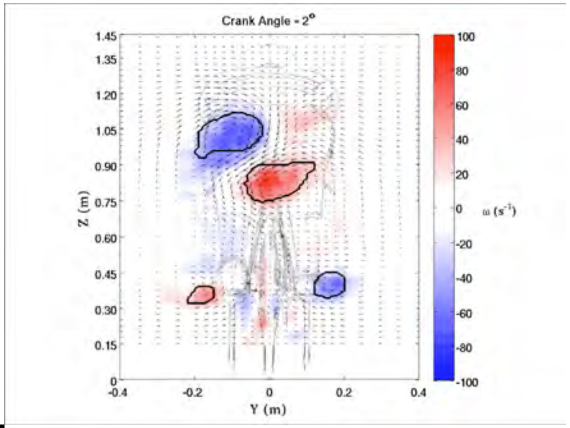


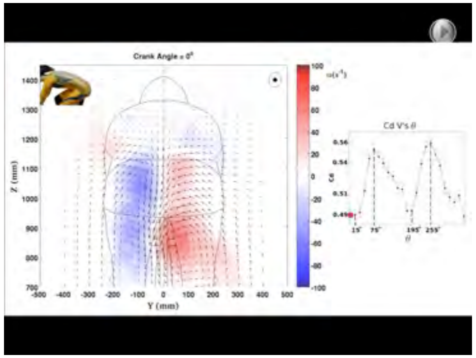


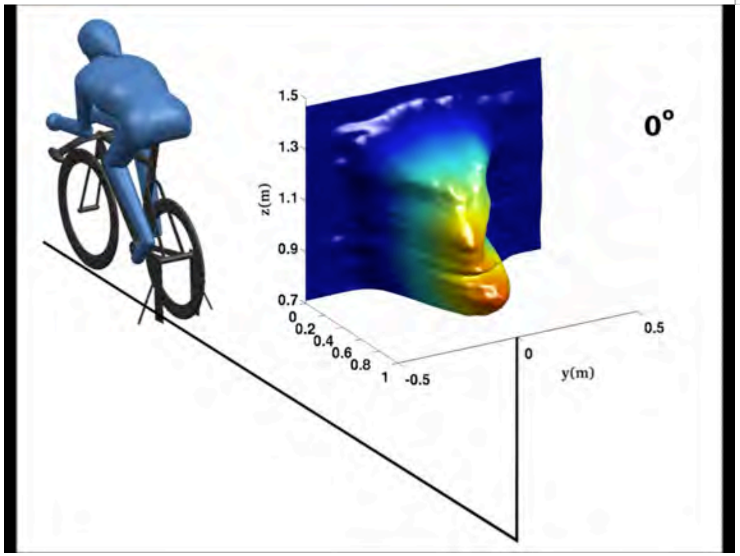


Omega 3

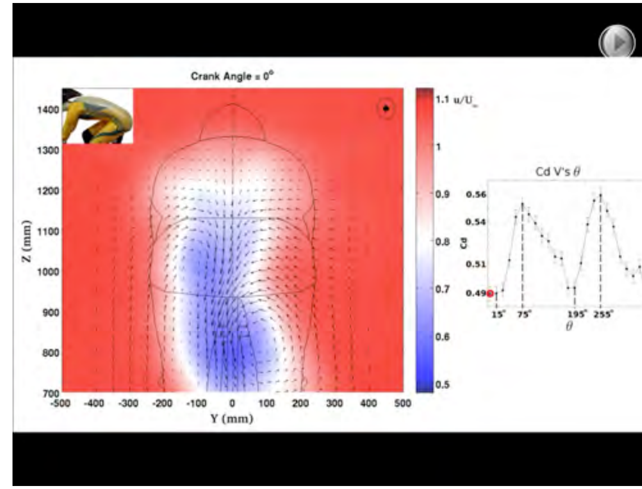

Crank Angle = 0°
Cp
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8


Crank Angle = 2°
Z (m)
Y (m)
ω (s⁻¹)
100
80
60
40
20
0
-20
-40
-60
-80
-100


Crank Angle = 0°
Cd V's θ
Z (mm)
Y (mm)

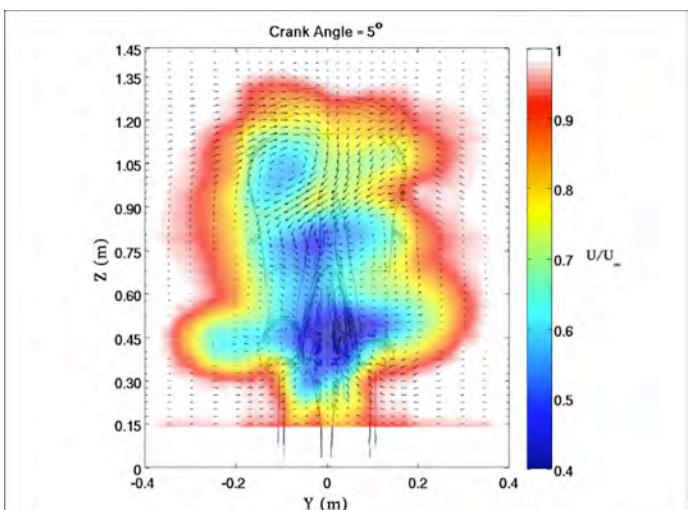

0°
z(m)
y(m)
1.5
1.3
1.1
0.9
0.7

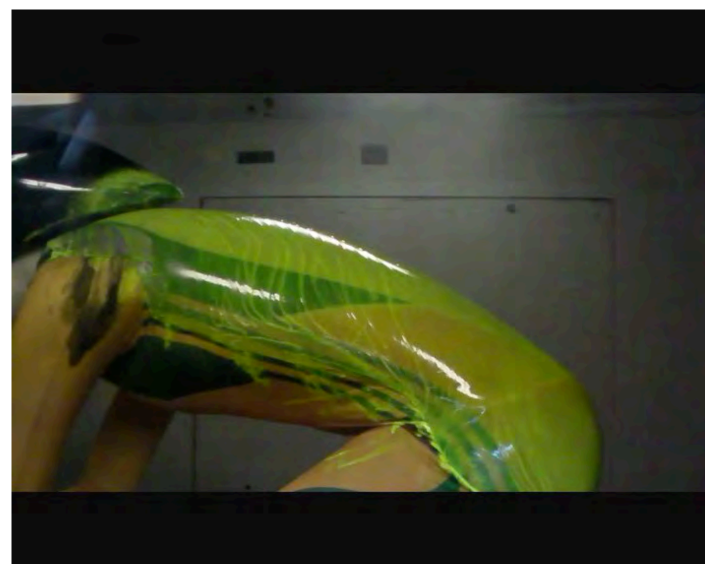
U3



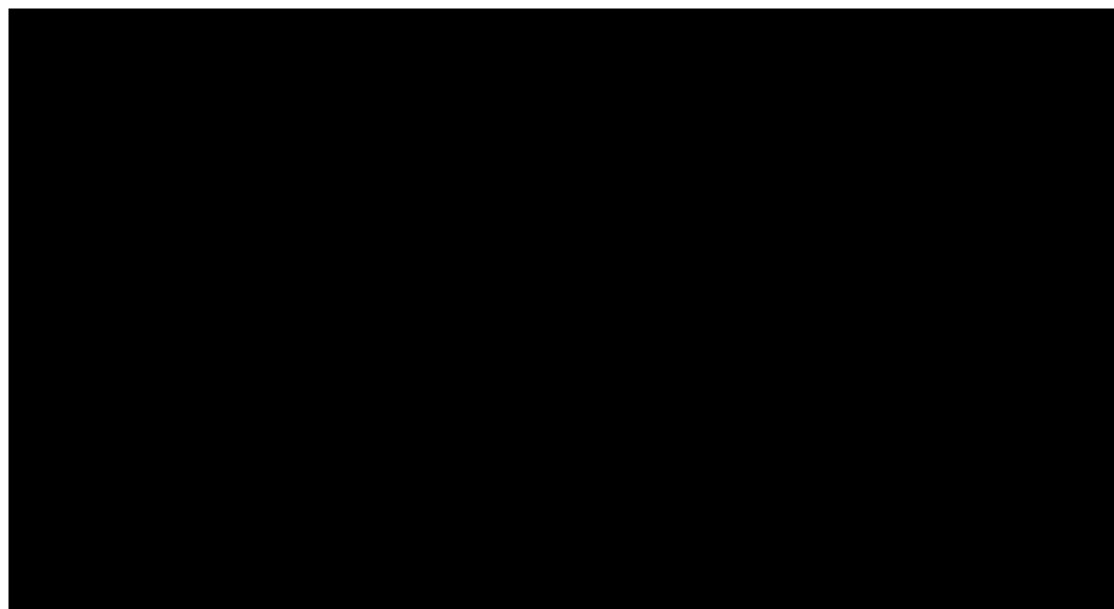
Skin Friction

Phase-averaged 100 RPM





Water Channel



Conclusions

Many types of bluff vehicles require streamlining

Wakes of vehicles important in determining drag and lift forces

Surface treatment (roughness, ribs, etc) modify skin friction and flow separation