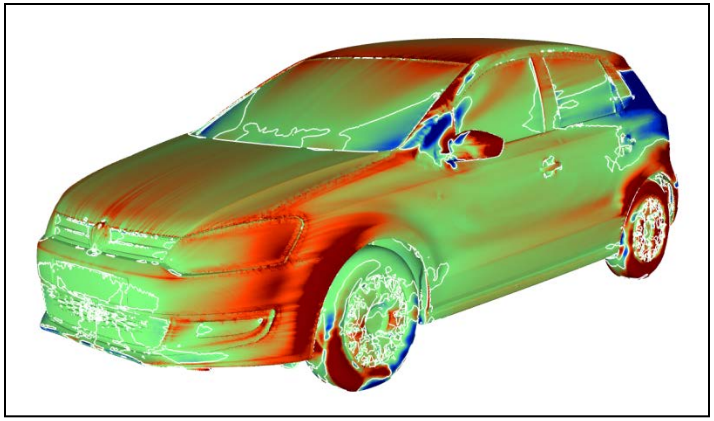
VOLKSWAGEN
AKTIENGESELLSCHAFT



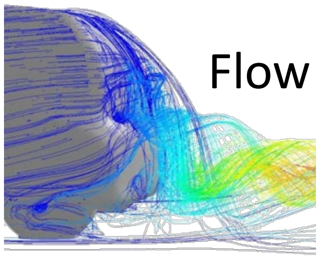
Symposium in Honor of Antony Jameson‘s 80th Birthday,
Stanford University 2014

The Adjoint Method Hits the Road: Applications in Car Aerodynamics

Dr. Carsten Othmer, Volkswagen AG, Corporate Research, Wolfsburg, Germany

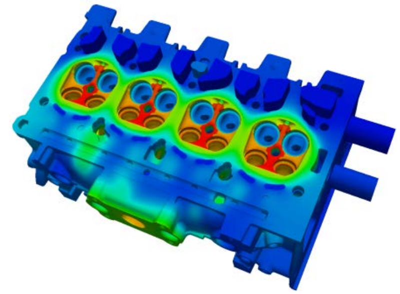
Adjoint-Based Optimization for Cars: Overview

Continuous Adjoint Method

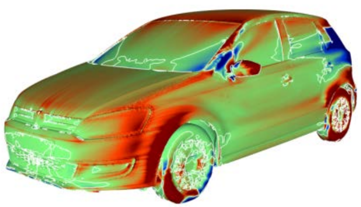


Flow Control

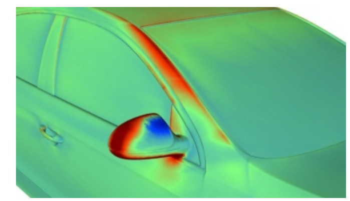
Cooling Optimization



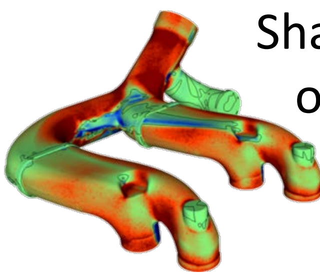
Vehicle Shape Optimization



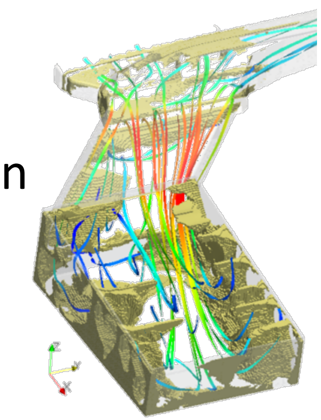
Aeroacoustic Optimization



Shape Optimization of Ducted Flows



Topology Optimization



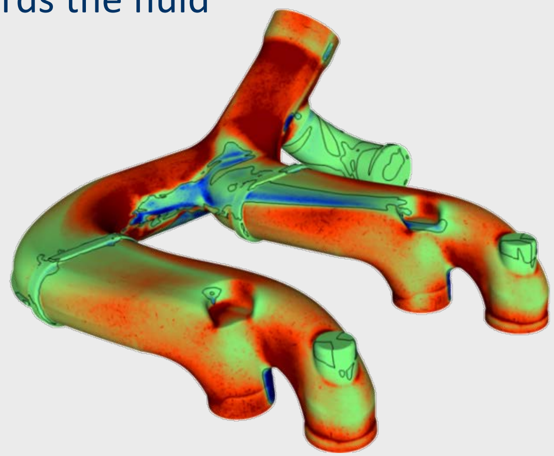
Acknowledgements

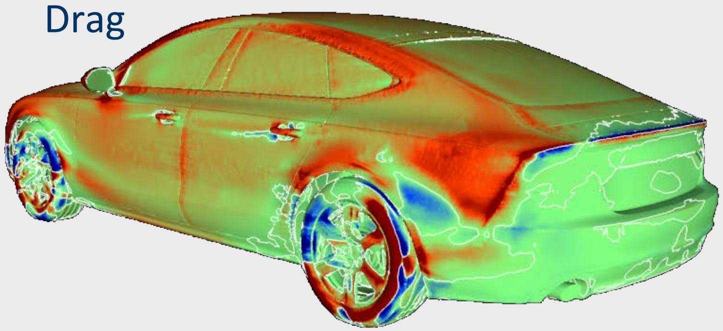
- Prof. Giannakoglou‘s team at the National Technical University of Athens
- Eugene De Villiers and Thomas Schumacher from Engys, London
- E. Stavropoulou, M. Hojjat and Prof. Bletzinger from TU Munich
- The Adjoint team at Volkswagen: S. Baumbach, K. Brandes, M. Gregersen, F. Kunze, N. Magoulas, J. Müller, H. Narten, D. Schräder and other supportive colleagues

The Adjoint Method: Computation of Sensitivity Maps

Surface Sensitivities = $\partial J/\partial \beta$

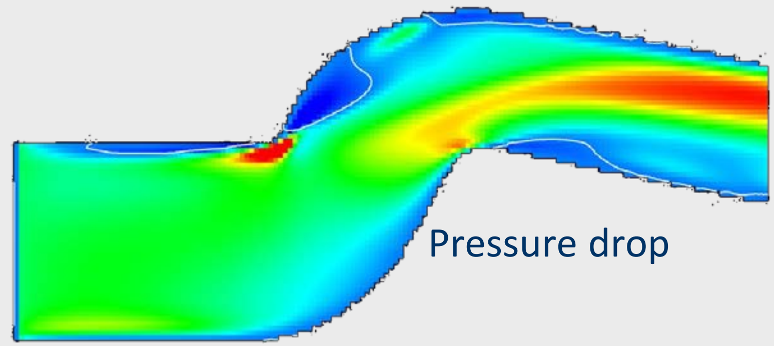
red: push away from the fluid
blue: push towards the fluid

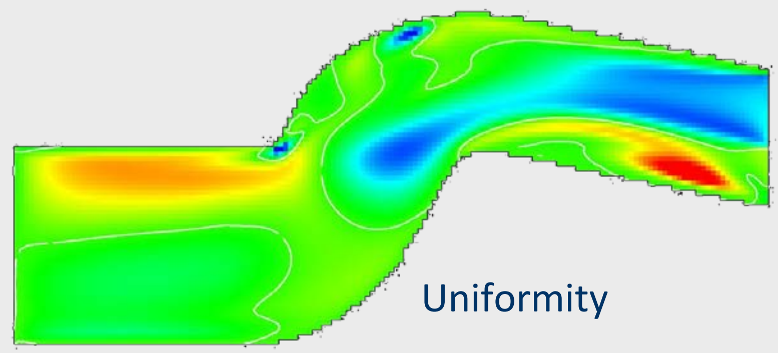




Volume Sensitivities = $\partial J/\partial \alpha$

red: important areas
blue: counterproductive areas

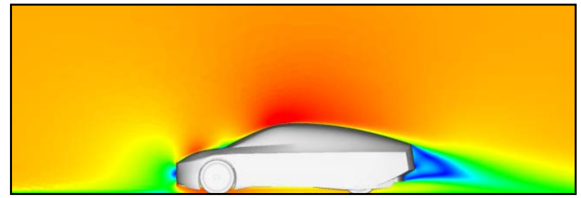




The Adjoint Method: Computational Process

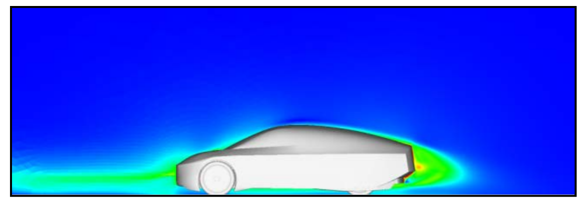
1. CFD computation: v , p ("primal field")

$$\begin{aligned} (\mathbf{v} \cdot \nabla)\,\mathbf{v} &= -\nabla p + \nabla \cdot (\nu\, \nabla \mathbf{v}) - \alpha \mathbf{v} \\ \nabla \cdot \mathbf{v} &= 0 \end{aligned}$$



2. Adjoint CFD computation: u , q ("dual field")

$$\begin{aligned} -(\nabla \mathbf{u})\,\mathbf{v} - (\mathbf{v} \cdot \nabla)\,\mathbf{u} &= -\nabla q + \nabla \cdot (\nu\, \nabla \mathbf{u}) - \alpha \mathbf{u} \\ \nabla \cdot \mathbf{u} &= 0 \end{aligned}$$



3. Computation of sensitivities:

- Volume sensitivities: $\dfrac{\partial J}{\partial \alpha} \sim \mathbf{v} \cdot \mathbf{u}$
- Surface sensitivities: $\dfrac{\partial J}{\partial \beta} \sim \dfrac{\partial \mathbf{v}}{\partial n} \cdot \dfrac{\partial \mathbf{u}}{\partial n}$

Implementation of an Adjoint Solver for Automotive Applications

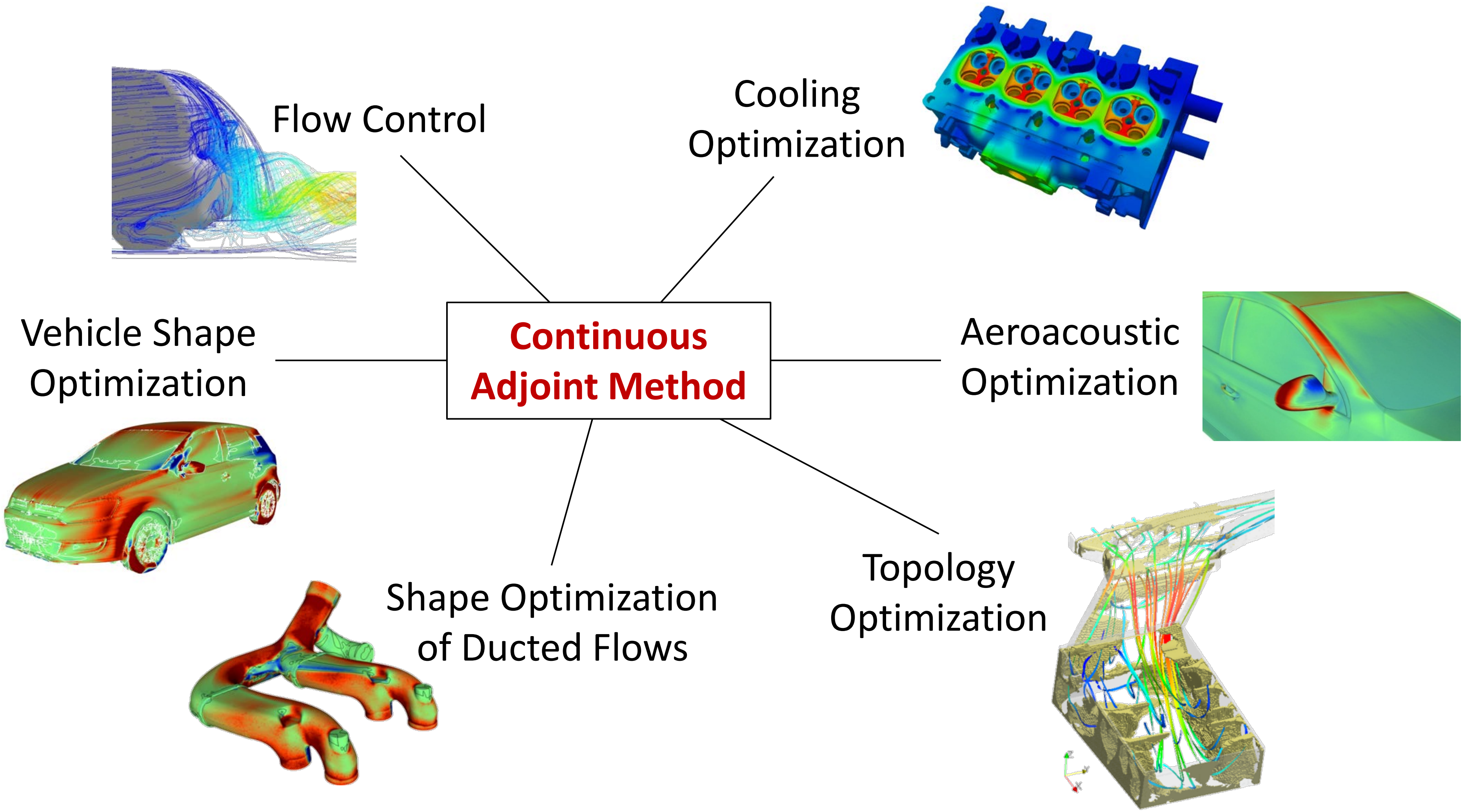
- Platform: Open source code OpenFOAM® chosen in 2006

```
solve ( fvm::ddt(rho, U) + fvm::div(phi, U) - fvm::laplacian(mu, U)
        == - fvc::grad(p) );
```

- Topology optimization [VW, AIAA 2007]
- Shape sensitivities [VW, IJNMF 2008]
- Low-Re Adjoint turbulence [NTUA + VW, C&F 2009]
- Adjoint wall functions [NTUA + VW, JCP 2010, ECCOMAS 2014]
- Packaging and further industrialization by Engys [since 2011]
- Uptake and improvements by Helgason, Hinterberger, Jakubek, Lincke, Towara, …

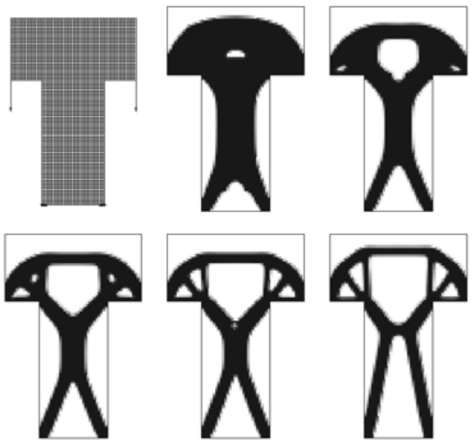
→ Versatile continuous adjoint solver “adjointFoam“ for incompressible steady-state RANS

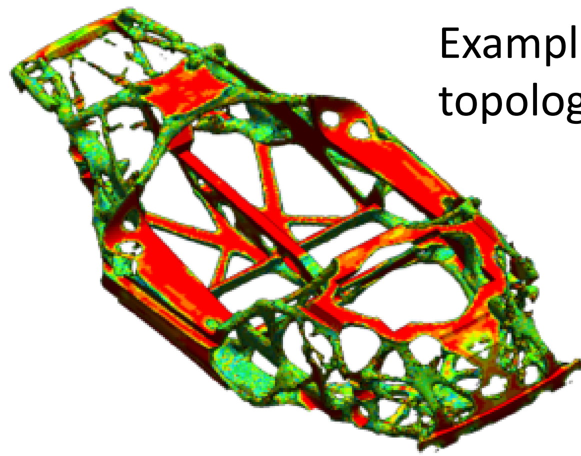
Adjoint-Based Optimization for Cars: Overview



Topology Optimization

- Well-developed tool in structure mechanics, wide-spread industrial use



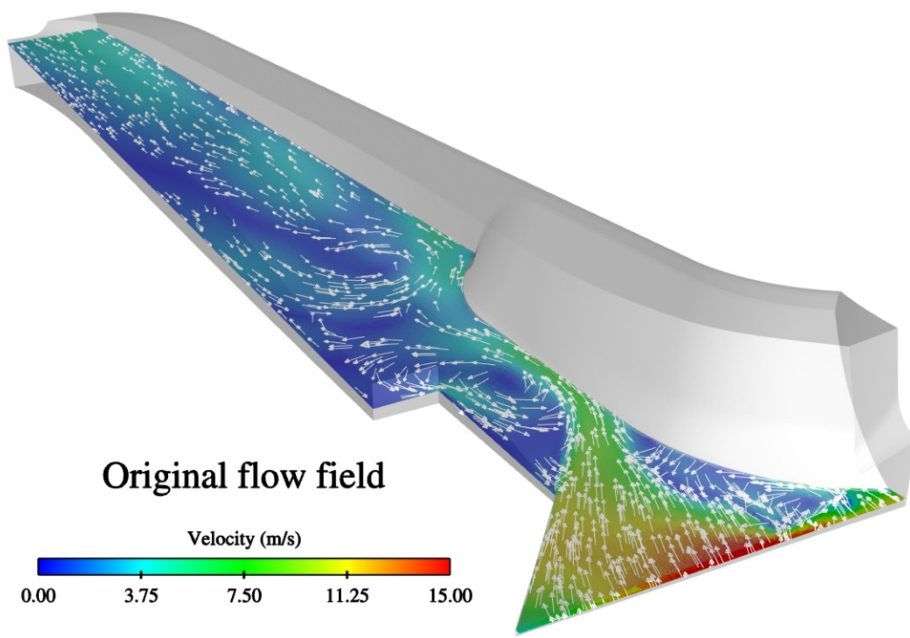


Example: Optimal car body topology [Conic, VW]

- Transfer to fluid dynamics: Klimetzek [Daimler, 2003], Borrvall and Petersson [2003]

Topology Optimization for Fluid Dynamics

- Starting point: **Entire installation space**
  - Flow solution
  - Identification of “counter-productive“ cells via a **local criterion** ($\underline{v} \bullet \underline{u}$)
  - Punishment of counter-productive cells with porosity
- Result: Optimal topology



Topology Optimization for Fluid Dynamics

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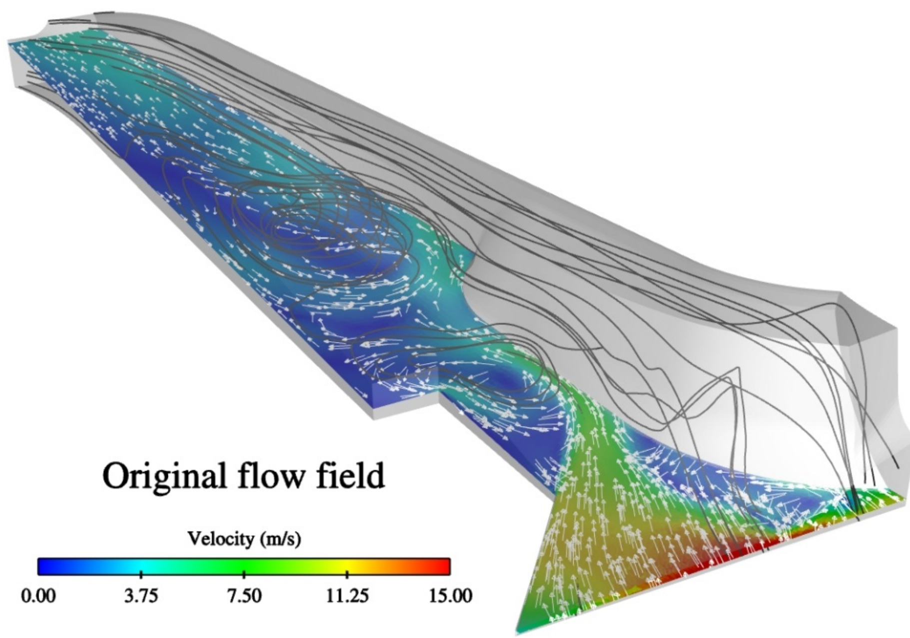

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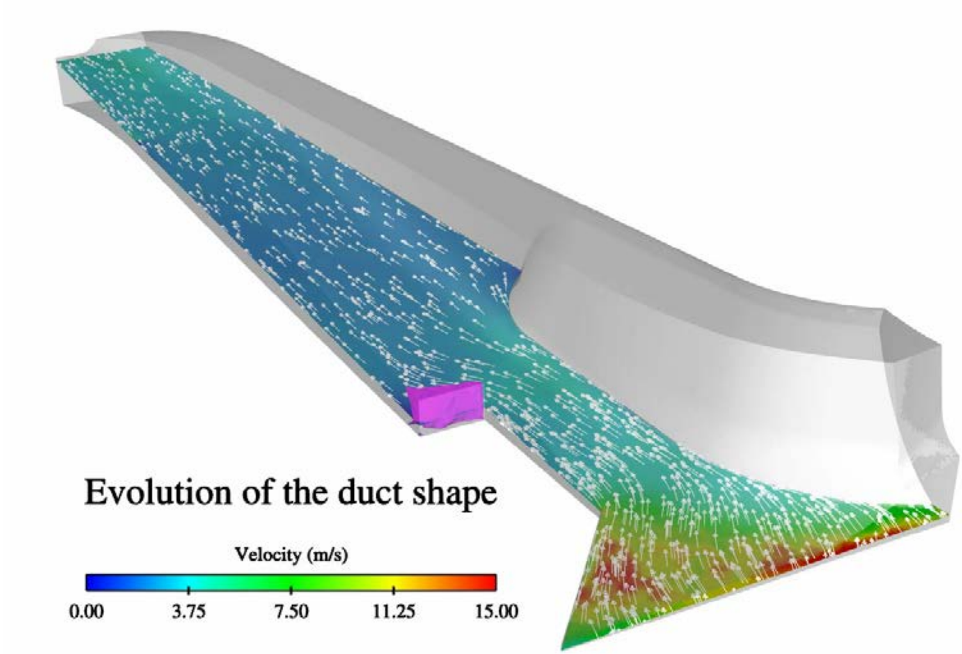

Topology Optimization for Fluid Dynamics

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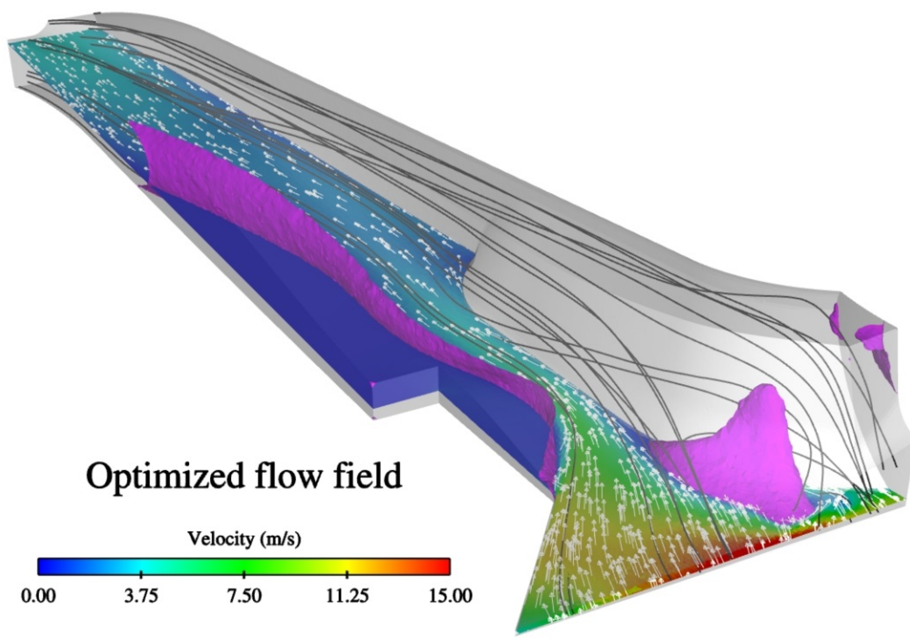
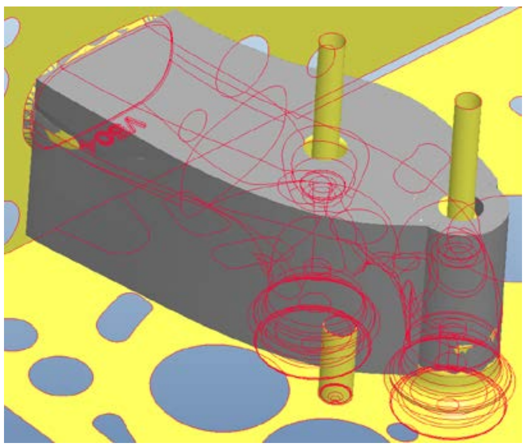


Optimized flow field

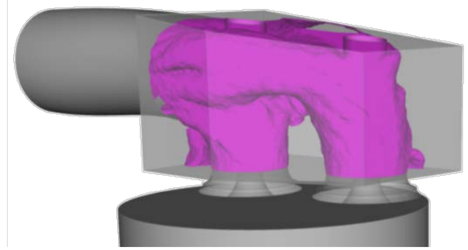
Topo Example 1: From Packaging Space to the Optimal Port

Packaging space definition

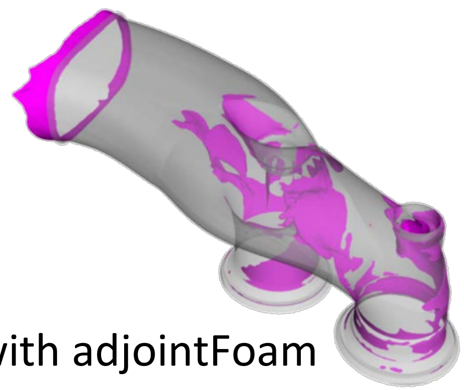


[F. Kunze and R. Niederlein]

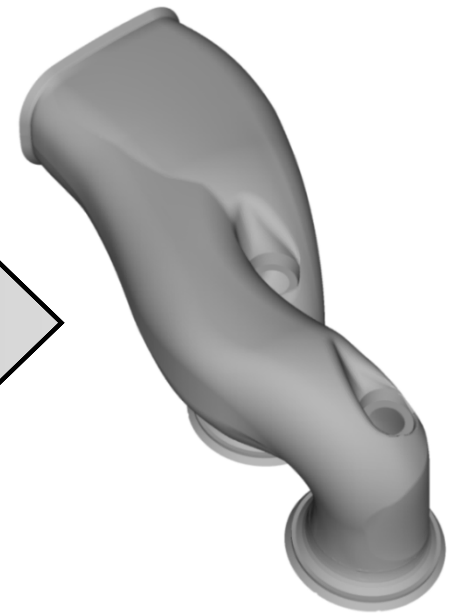
Drafting with adjointFoam



adjointFoam + manual CAD iterations

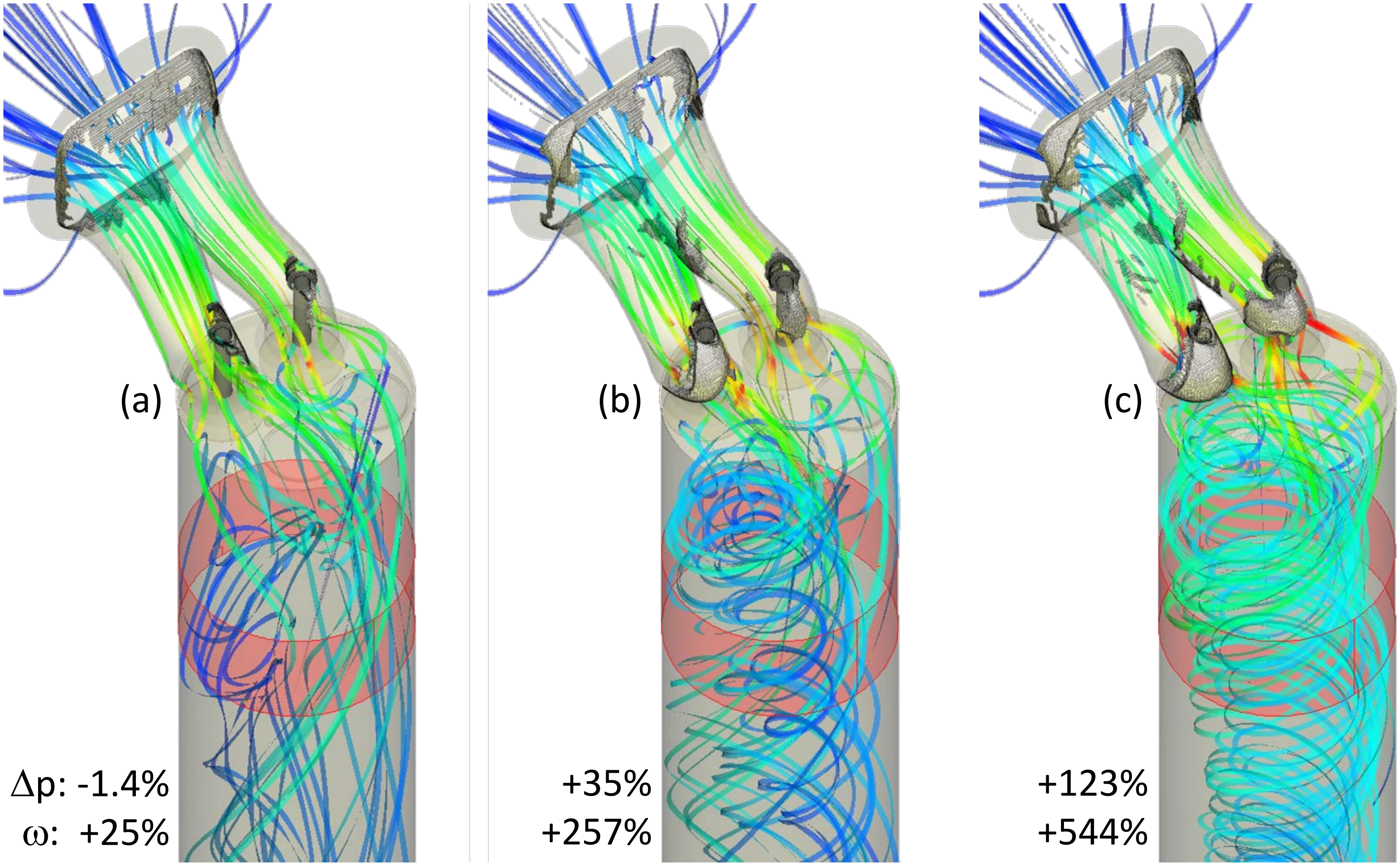


Fine-tuning with adjointFoam



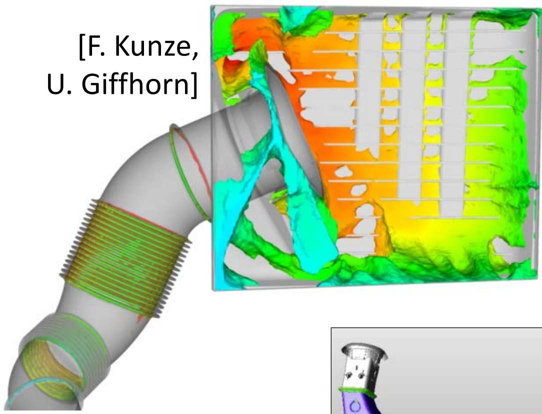
Final (hand-made) CAD geometry

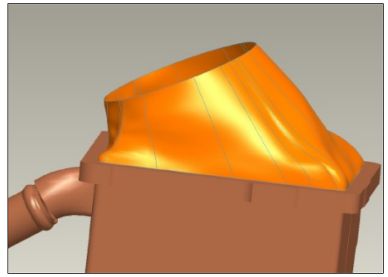
Topo Example 2: Multi-Objective Intake Port Optimization



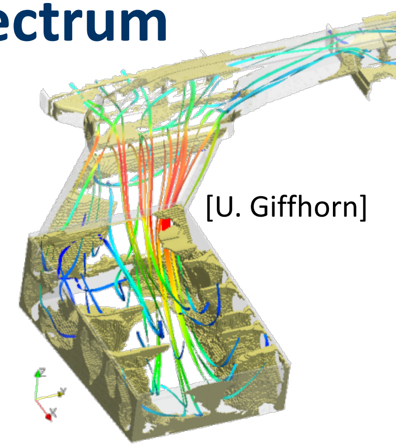
CFD Topology Optimization: Application Spectrum

[F. Kunze, U. Giffhorn]

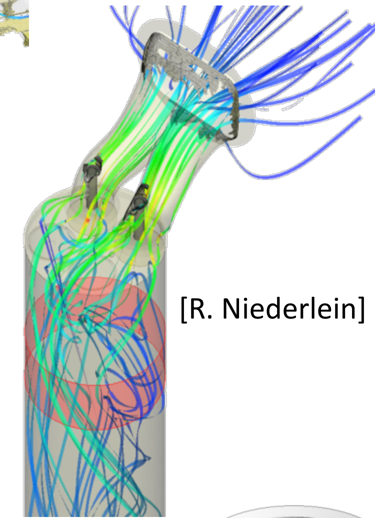




[M. Tomecki]

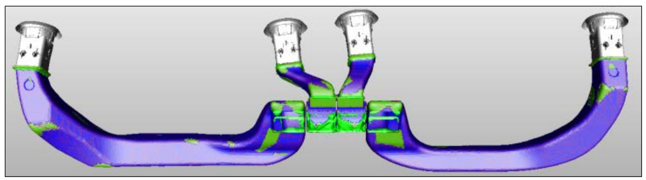


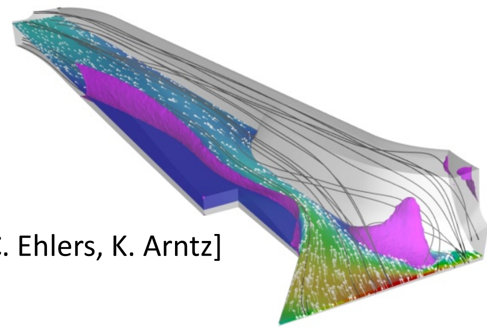
[U. Giffhorn]



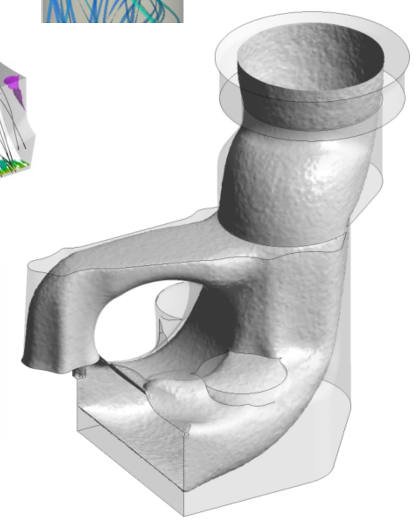
[R. Niederlein]

[N. Peller]

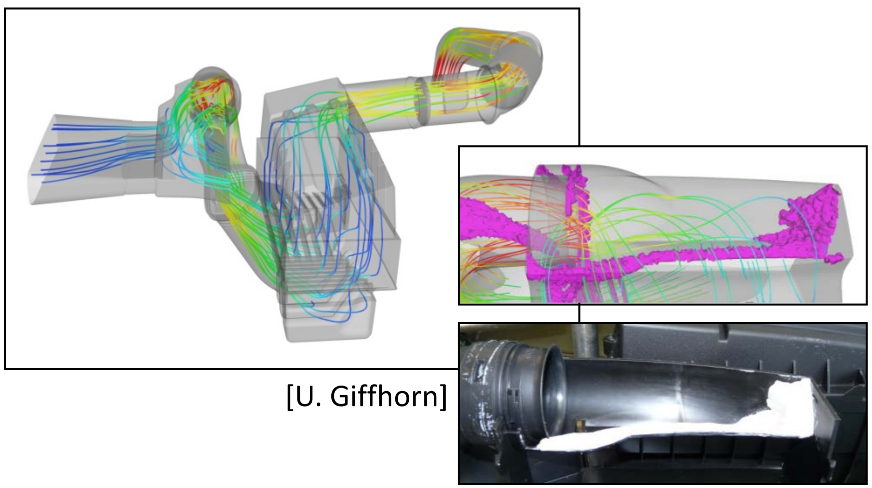




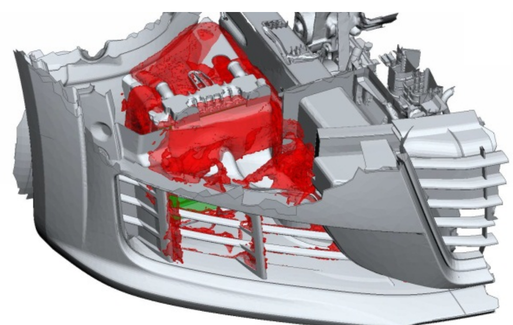
[C. Ehlers, K. Arntz]



[M. Towara]

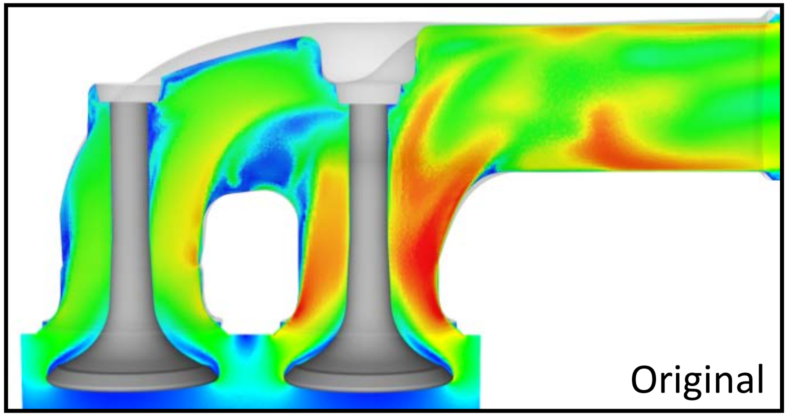


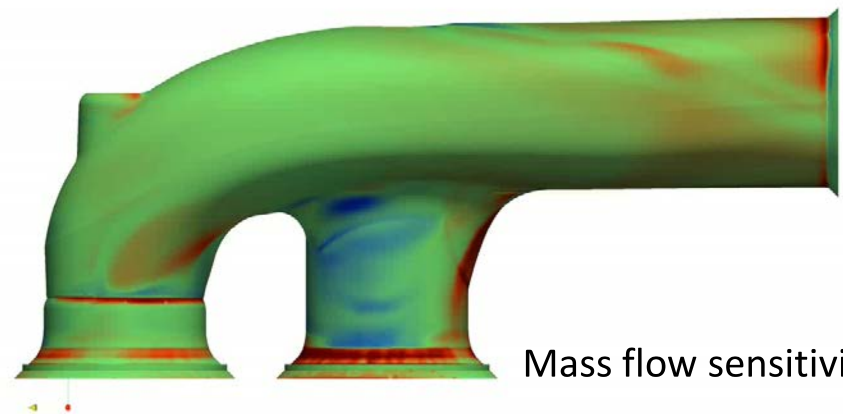
[U. Giffhorn]



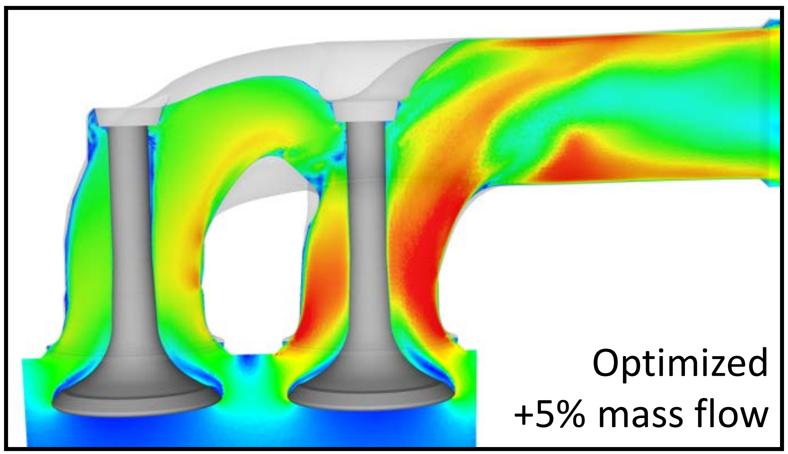
[P. Unterlechner]

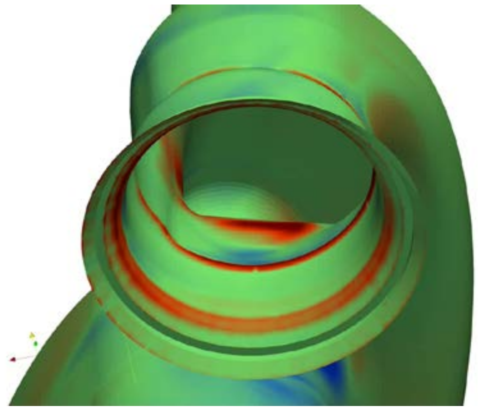
Shape Optimization for Ducted Flows: Exhaust Port Example





Mass flow sensitivities



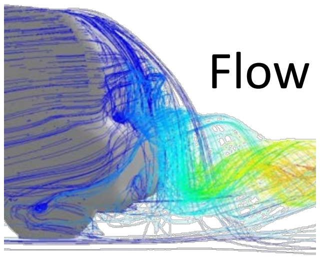


[F. Kunze and R. Niederlein]

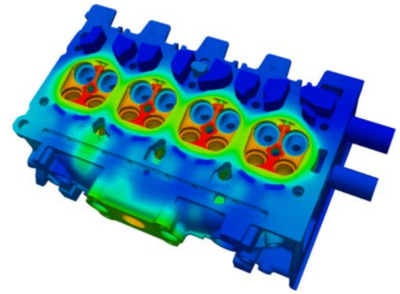
Adjoint-Based Optimization for Cars: Overview

Continuous Adjoint Method

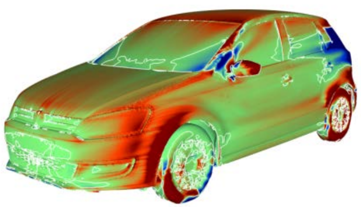
Flow Control



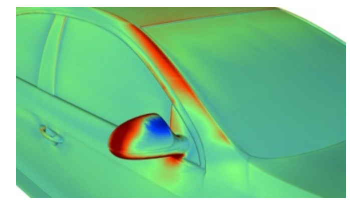
Cooling Optimization



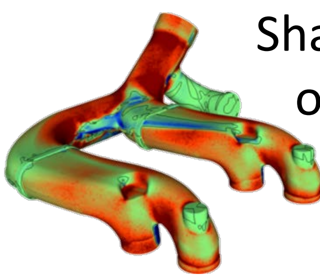
Vehicle Shape Optimization



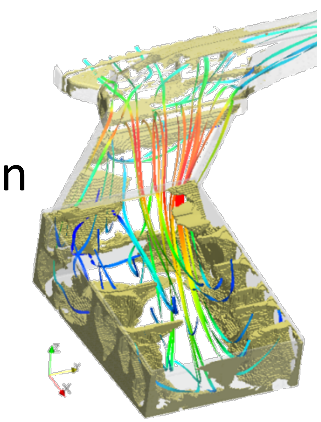
Aeroacoustic Optimization



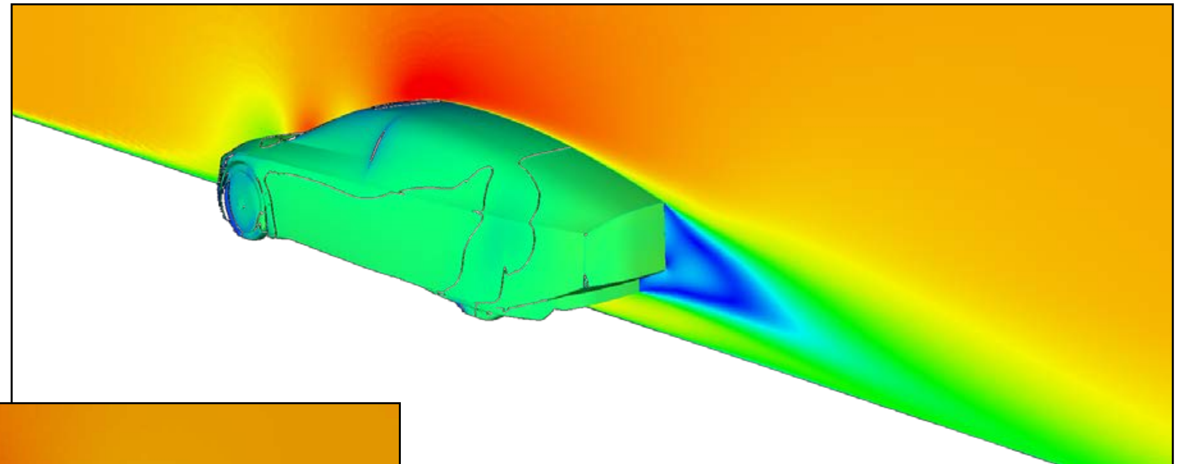
Shape Optimization of Ducted Flows

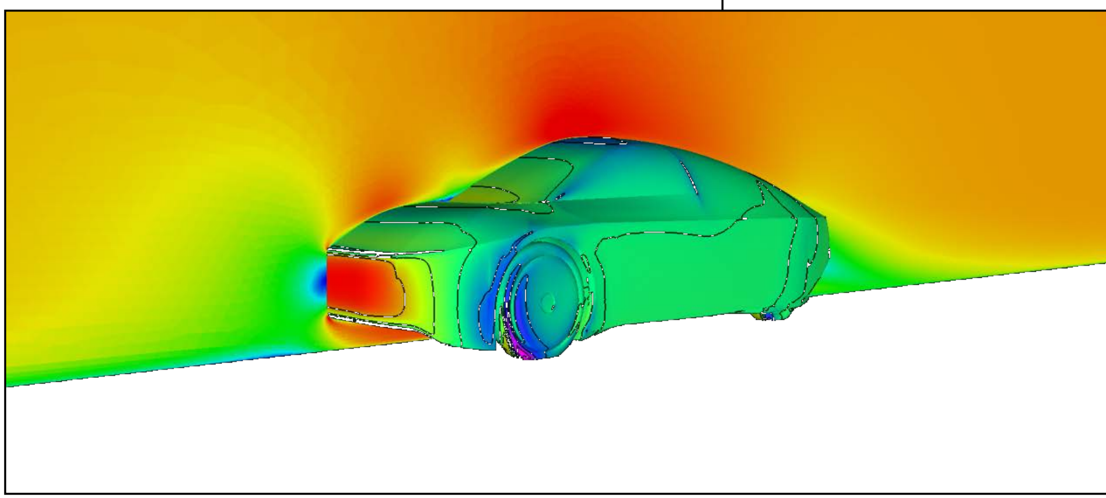


Topology Optimization



Shape Optimization in External Aerodynamics: Example 1

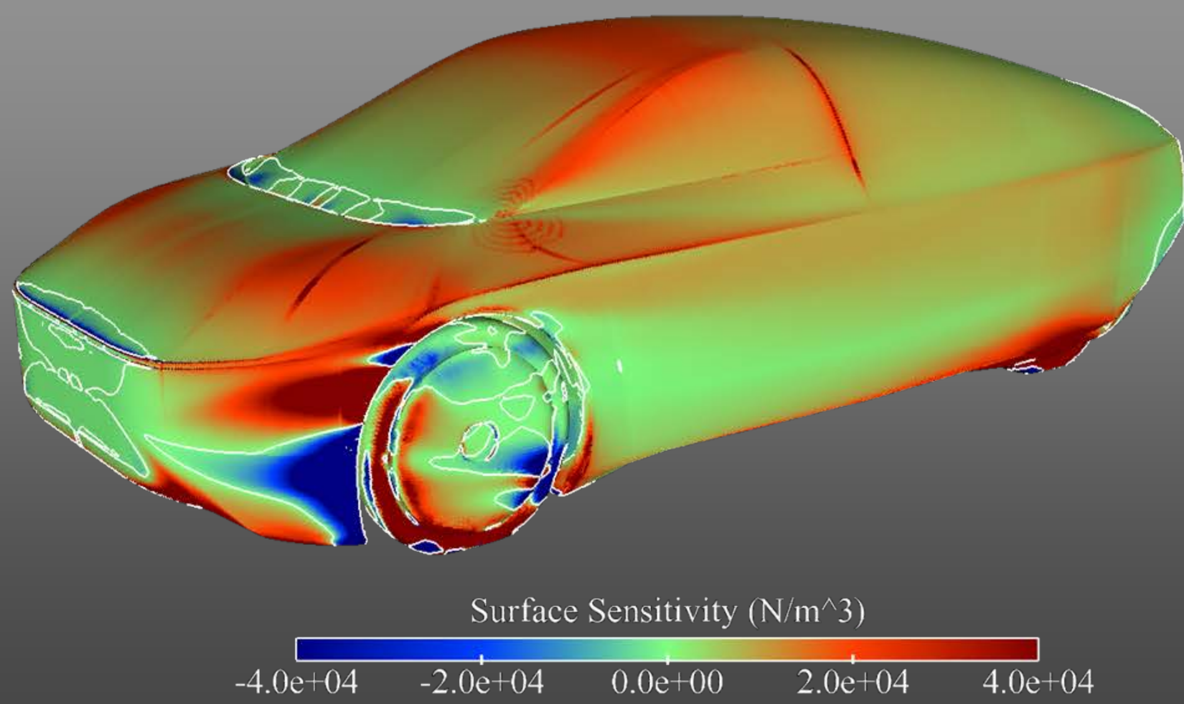




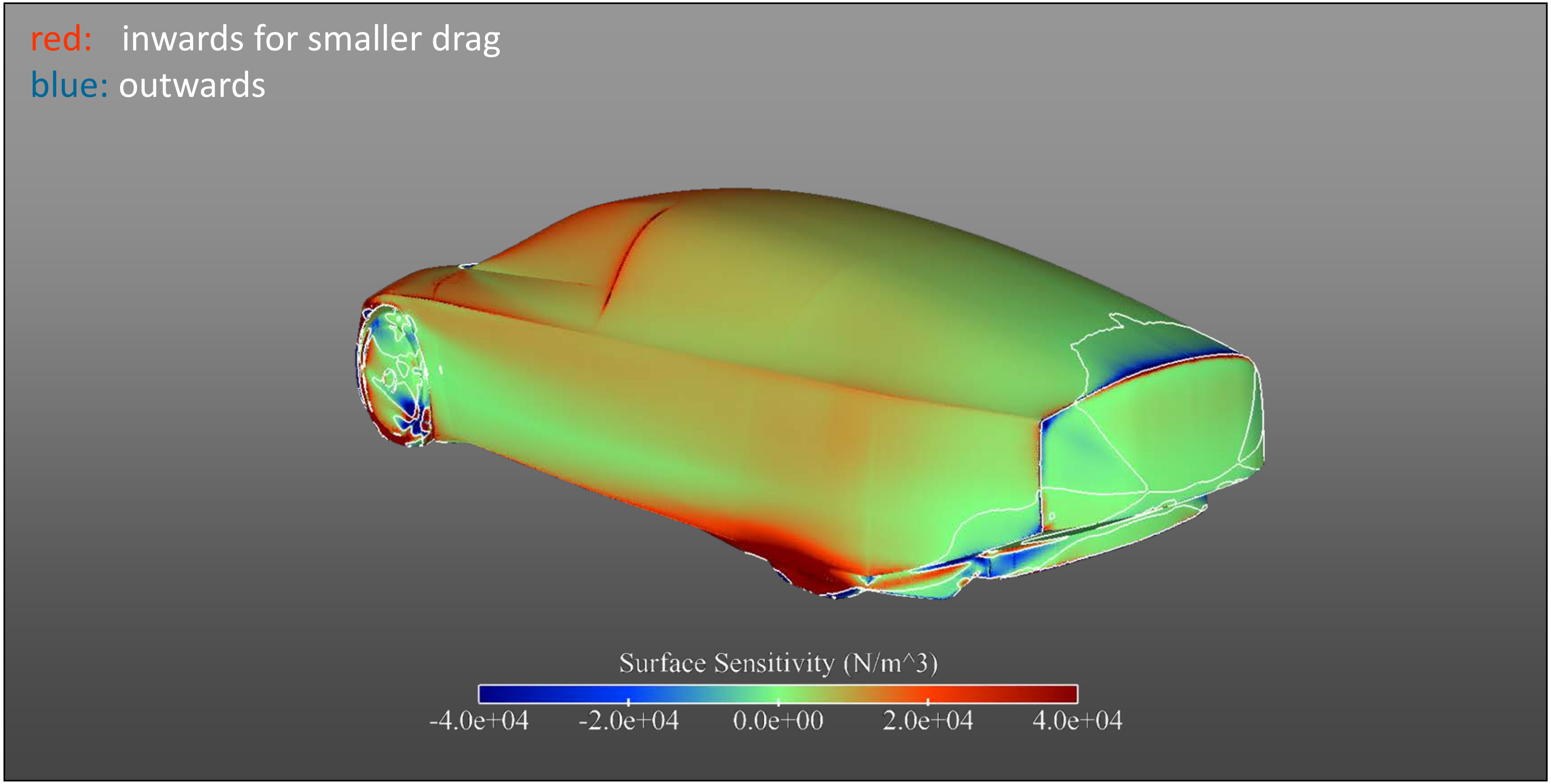
- Volkswagen XL1
- v=33m/s
- RANS with Spalart-Allmaras
- low-Reynolds mesh ($y^+ \sim 1$)
- half-model

Volkswagen XL1: Sensitivities (1)

red: inwards for smaller drag
blue: outwards

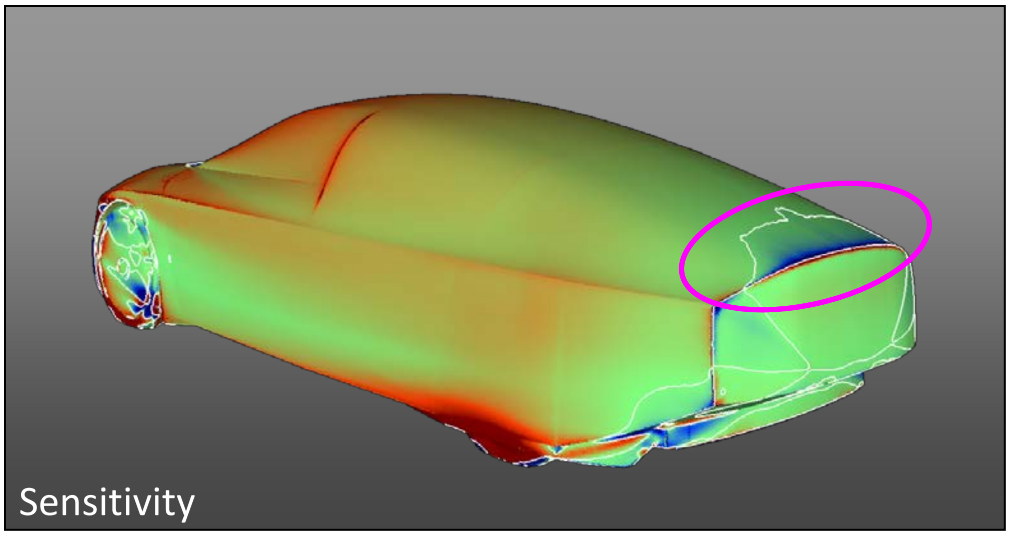


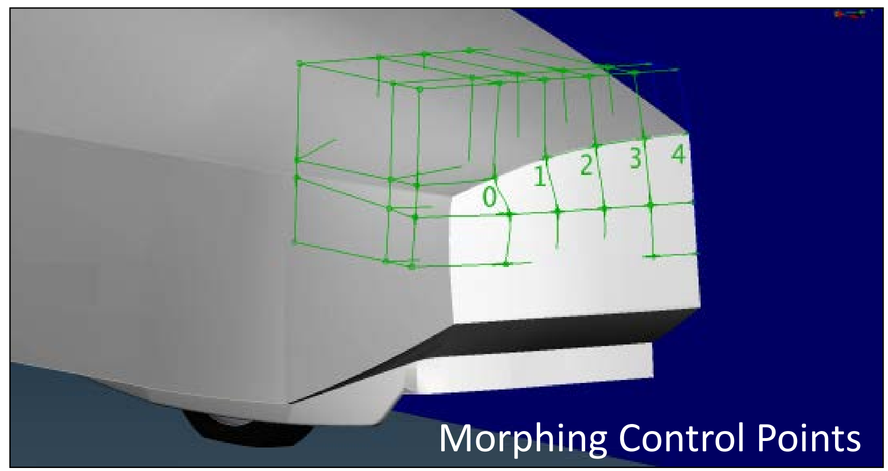
Volkswagen XL1: Sensitivities (2)



One-Shot Optimization of the Rear Spoiler

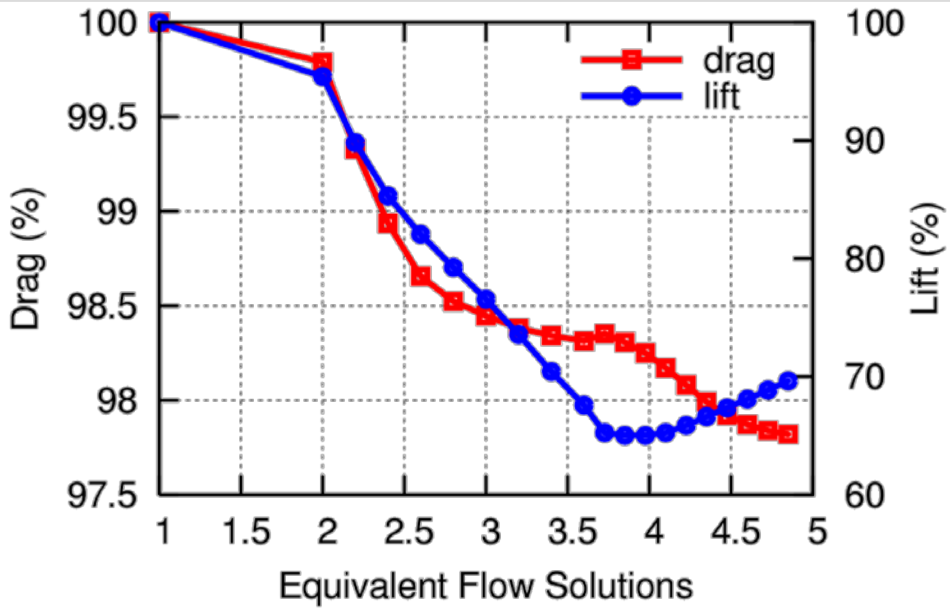
- 5 free-form-deformation control points defined to control rear edge
- Variation in the z-direction only → 5 design variables
- Objective function: Drag


Sensitivity

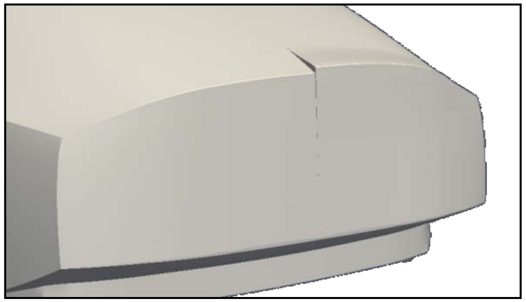


Morphing Control Points

Optimization Results



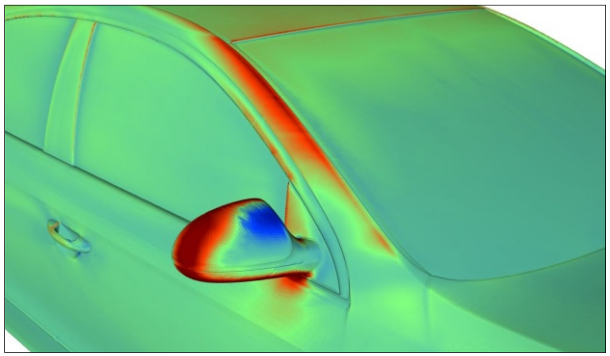
- >2% drag reduction, 30% lift improvement
- Deformation in z-direction < 20mm
- Overall cost: <5 EFS

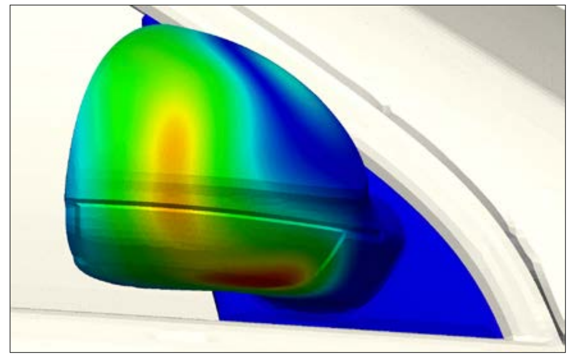


Shape Optimization in External Aerodynamics: Example 2

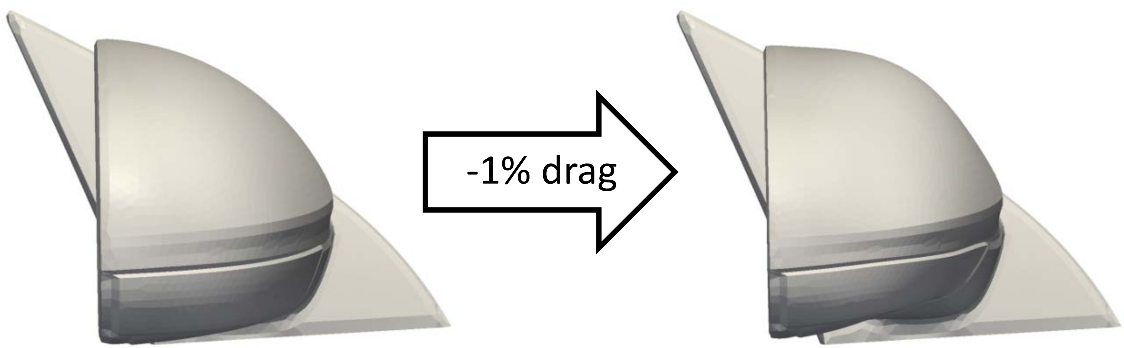
- External mirror shape optimization w.r.t. total vehicle drag
- Sensitivities by adjointFoam, morphing with Carat (TU Munich)

Sensitivity



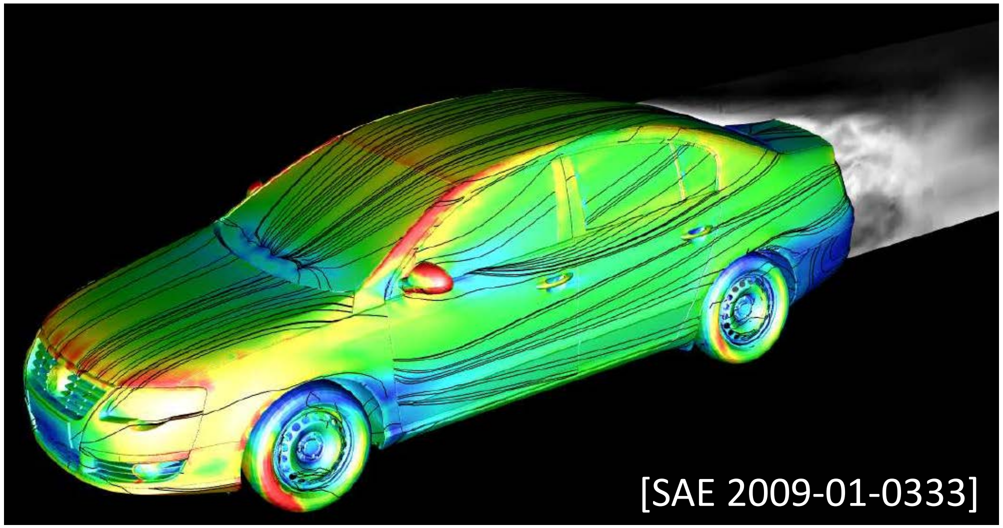


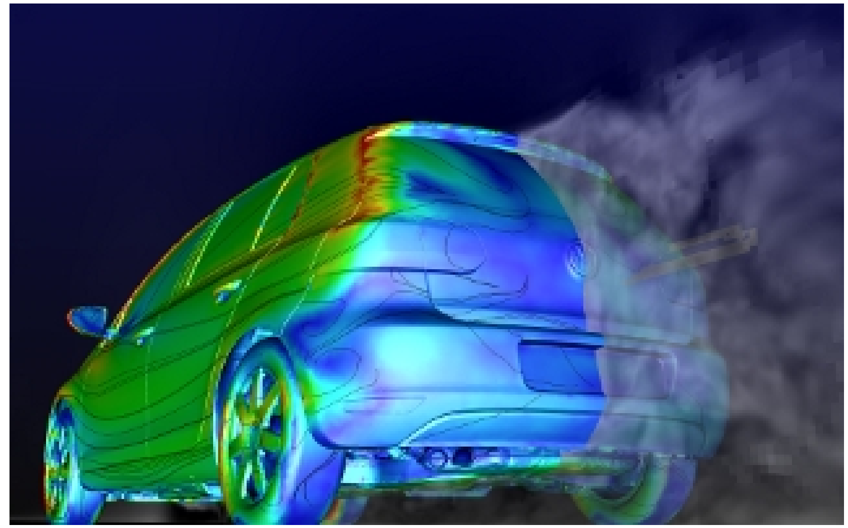
Displacement

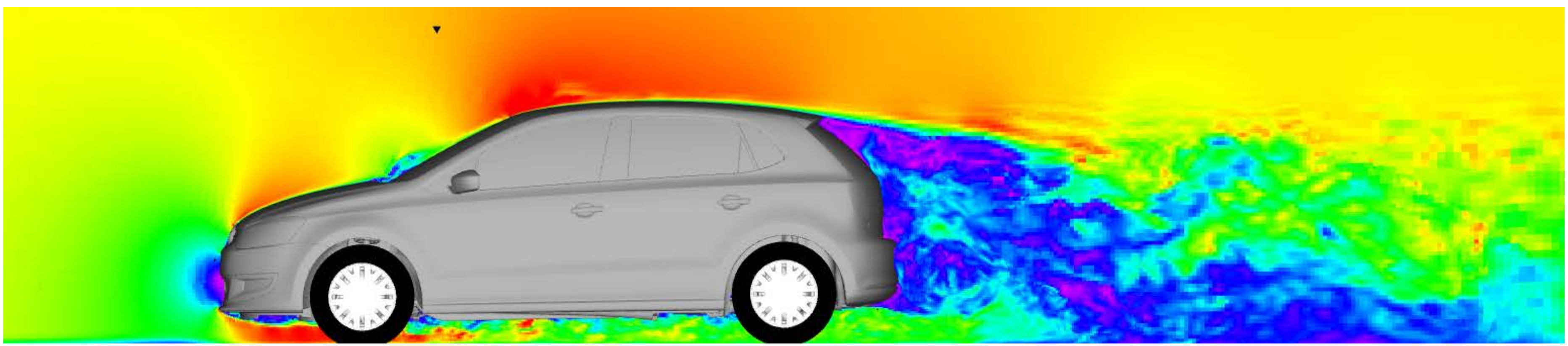


- Conservation of feature lines is an essential ingredient for external aero optimization

Productive Aerodynamics Computations: DES instead of RANS







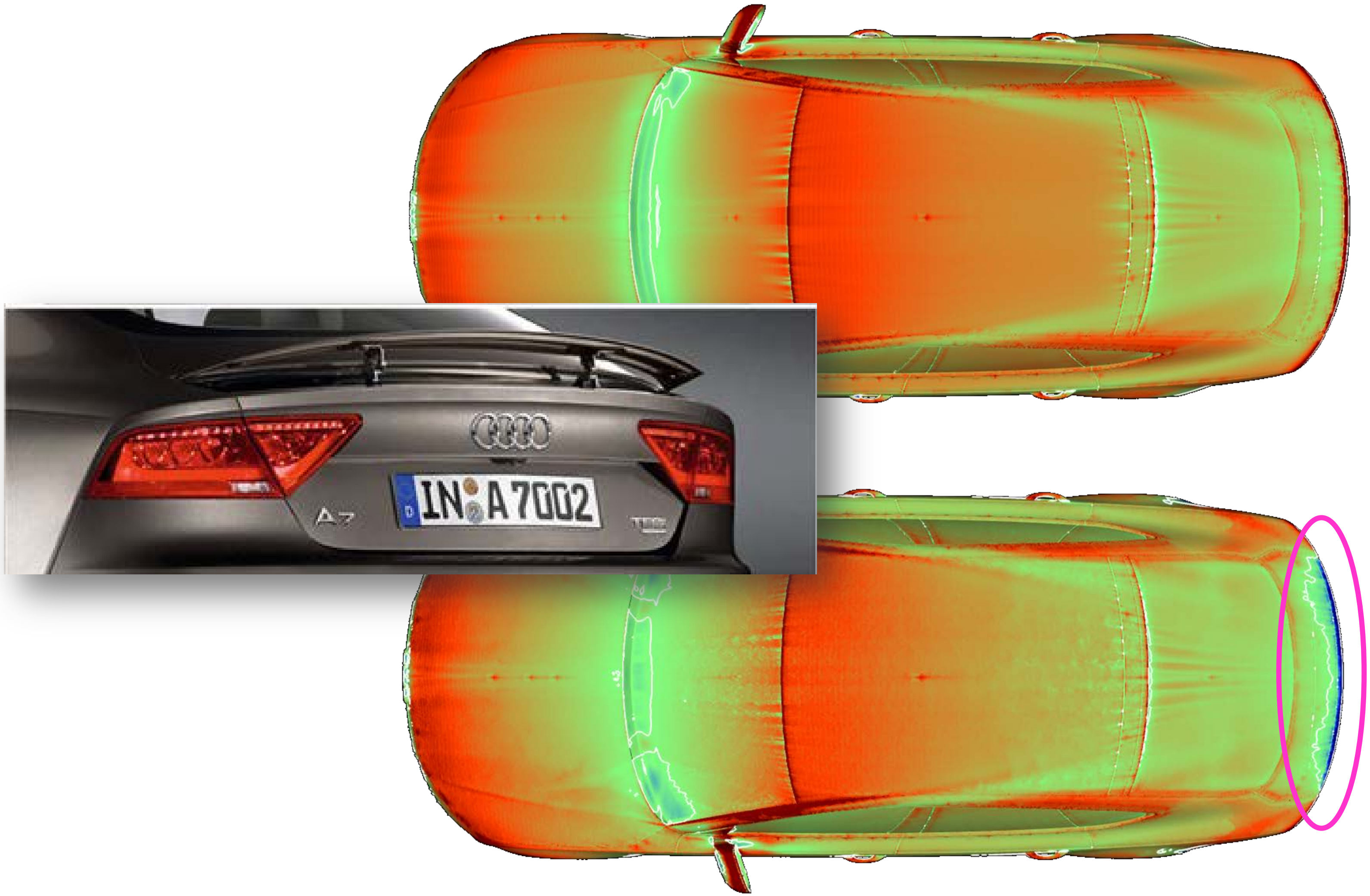
Approximate DES-Based Sensitivities

1. Basis: Time-averaged primal DES, compute drag and lift coefficients
2. Take time-averaged primal velocity and solve for a RANS-nu_t
3. Run adjoint RANS with averaged primal velocity and nu_t

- Finite differences: far off, *qualitative* agreement only

RANS vs. DES: Case Study Audi A7

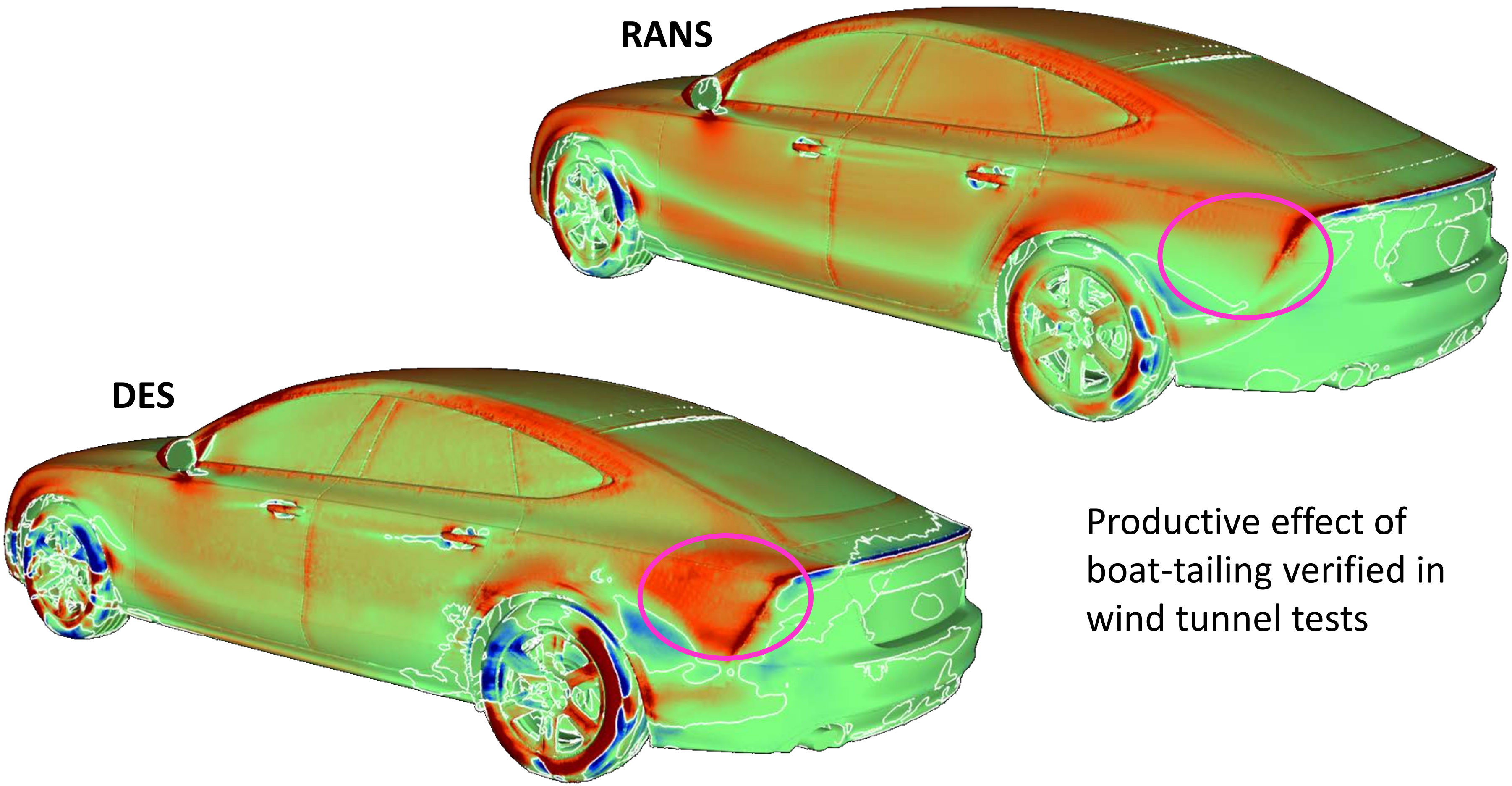
RANS vs. DES: Drag Sensitivities Audi A7



RANS

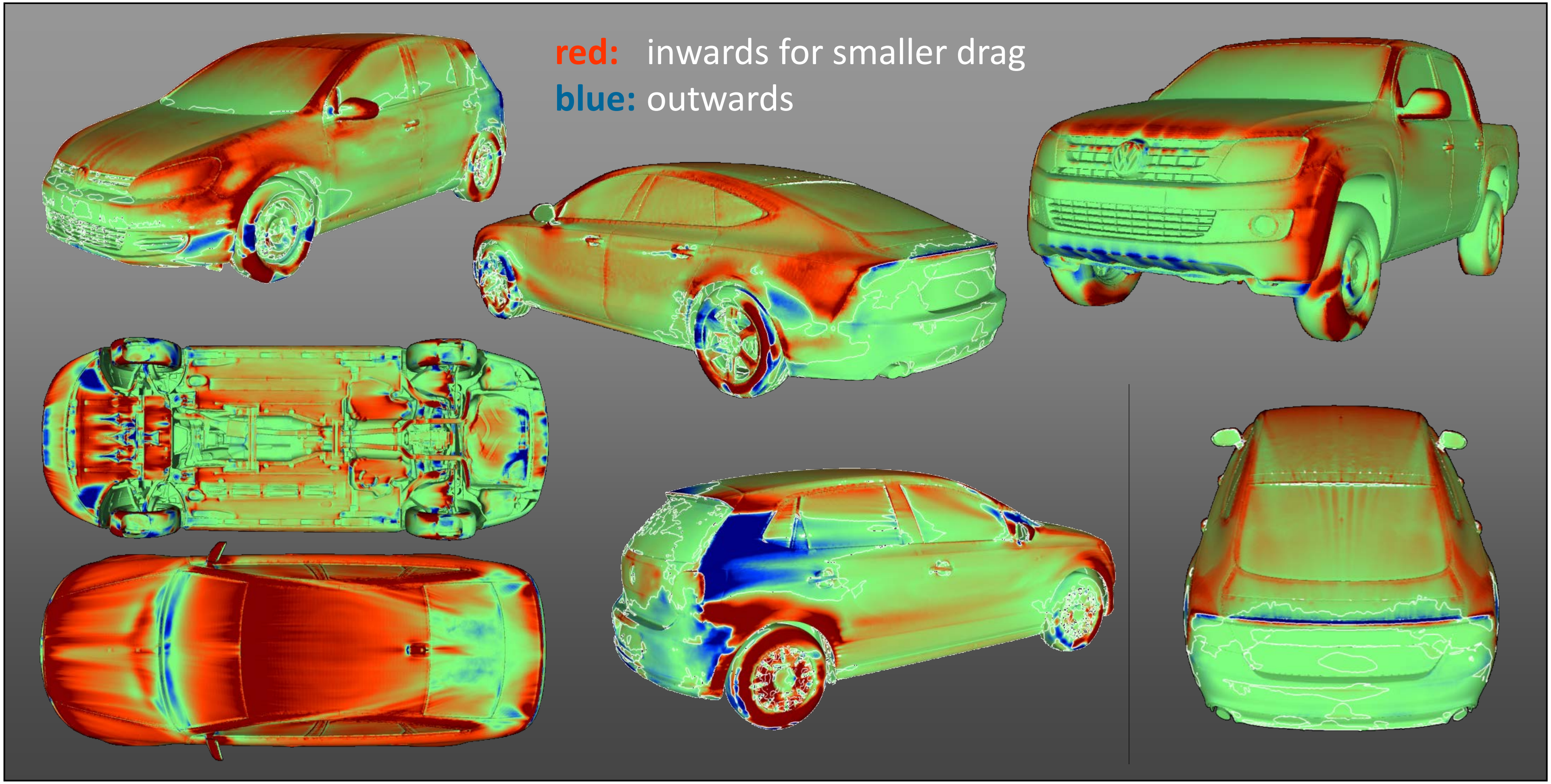
DES

RANS vs. DES: Drag Sensitivities Audi A7

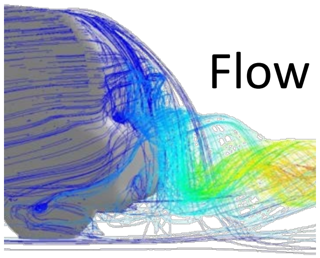


Productive effect of boat-tailing verified in wind tunnel tests

Drag Sensitivity Maps Based on DES: Further Examples

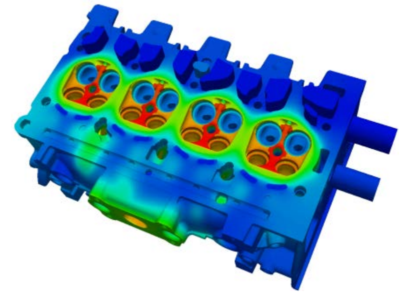


Adjoint-Based Optimization for Cars: Overview



Flow Control

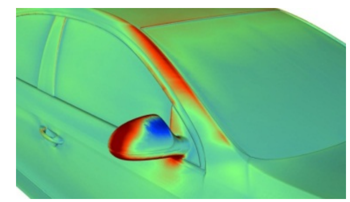
Cooling Optimization

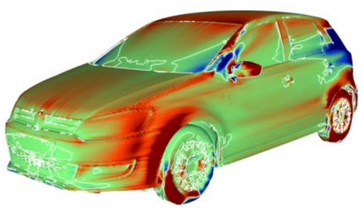


Vehicle Shape Optimization

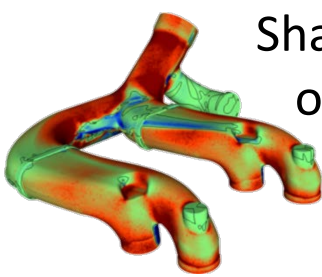
Continuous Adjoint Method

Aeroacoustic Optimization

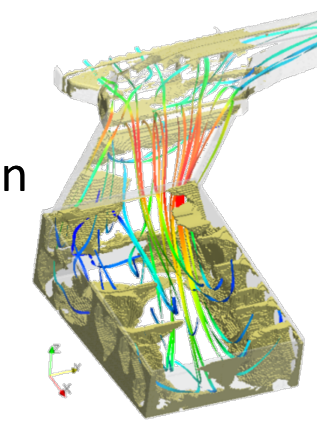




Shape Optimization of Ducted Flows



Topology Optimization

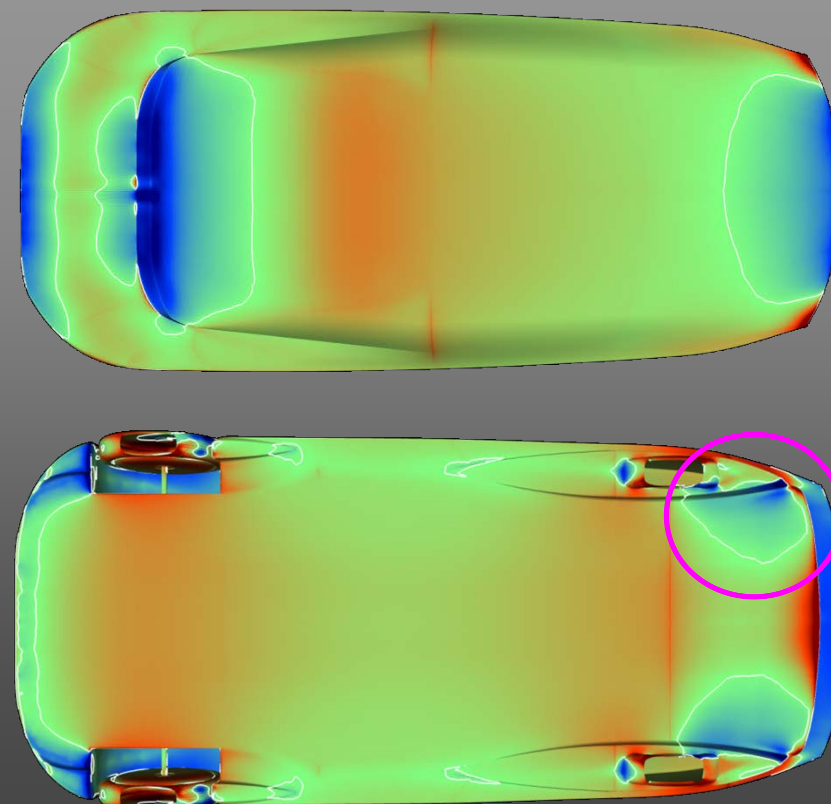


Case Study Volkswagen XL1: Drag Sensitivities

Sensitivity Map of dF_x/dv_n , with v_n : blowing/suction velocity

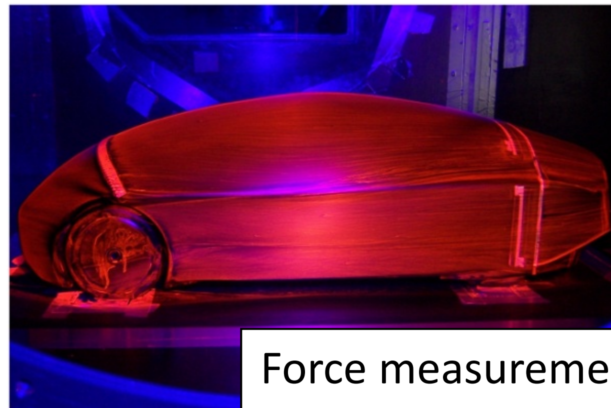
blue: blowing favourable

red: suction favourable

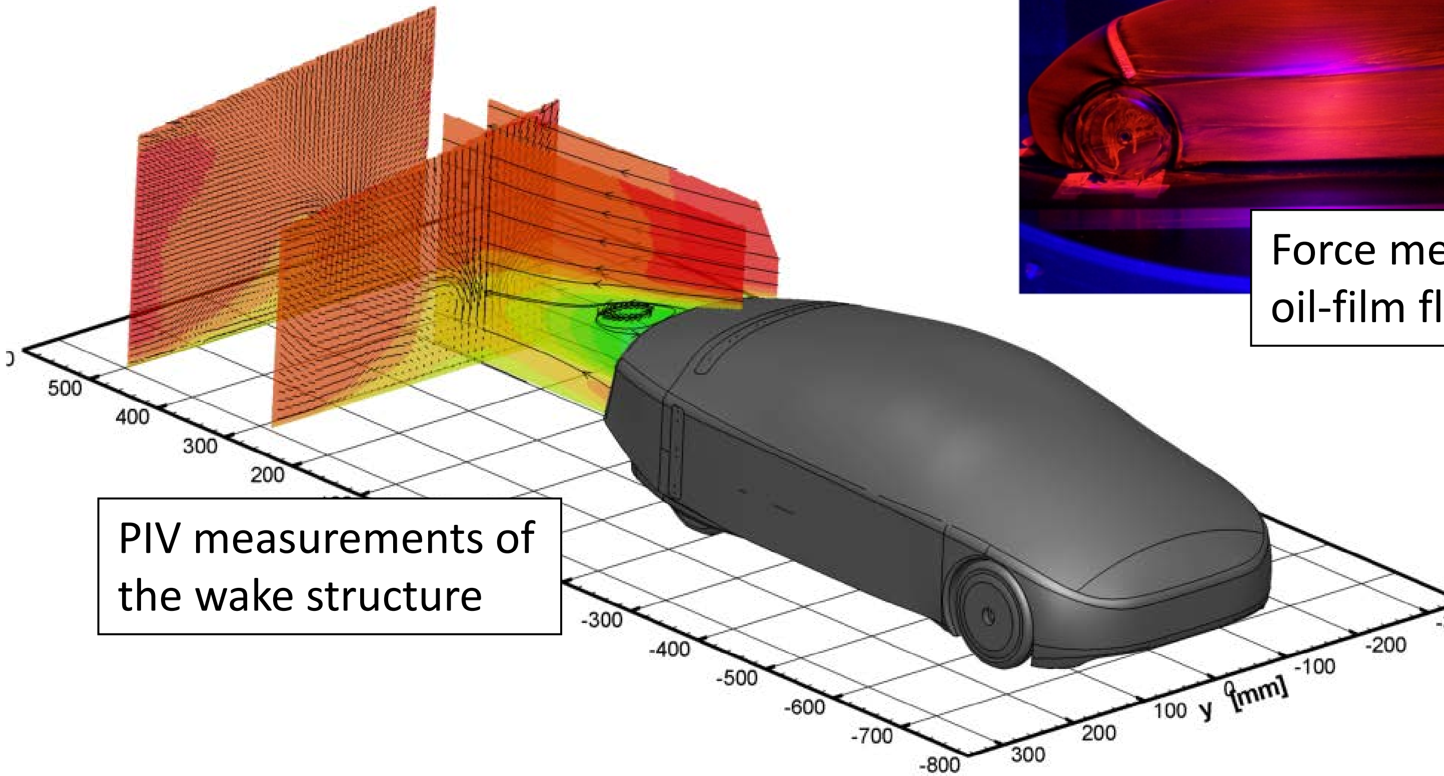


Wind Tunnel Measurements on a 1:4 Model

- Placement of blowing jets on the rear underbody
- Cooperation with TU Braunschweig

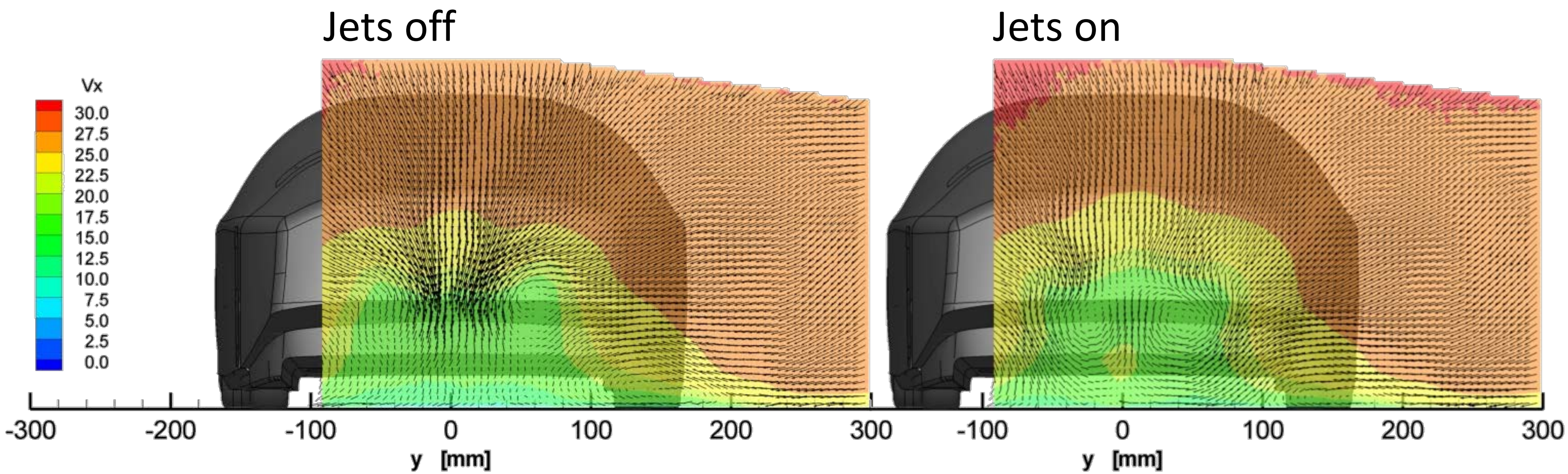


Force measurements and oil-film flow visualization



PIV measurements of the wake structure

PIV Measurements behind the Car



- Much weaker longitudinal vortices

- Significant reduction on rear lift: 0.10 → 0.08
- Measurable effect on drag (<1%), but still too small to be economic

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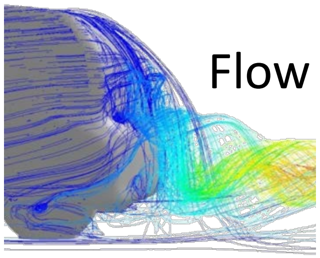

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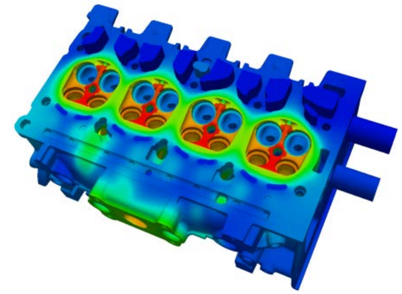

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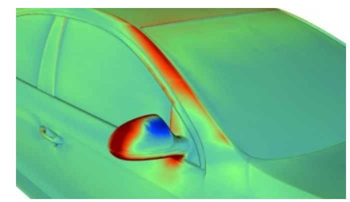

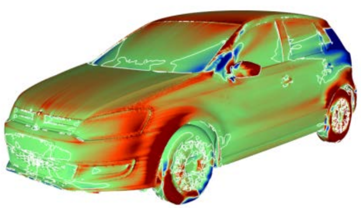

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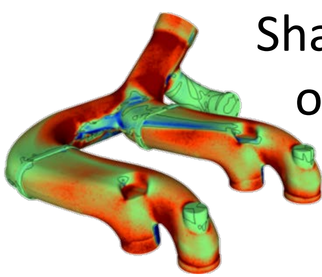
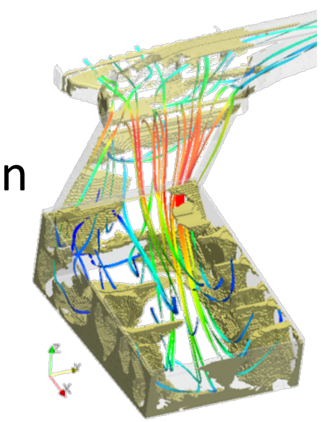
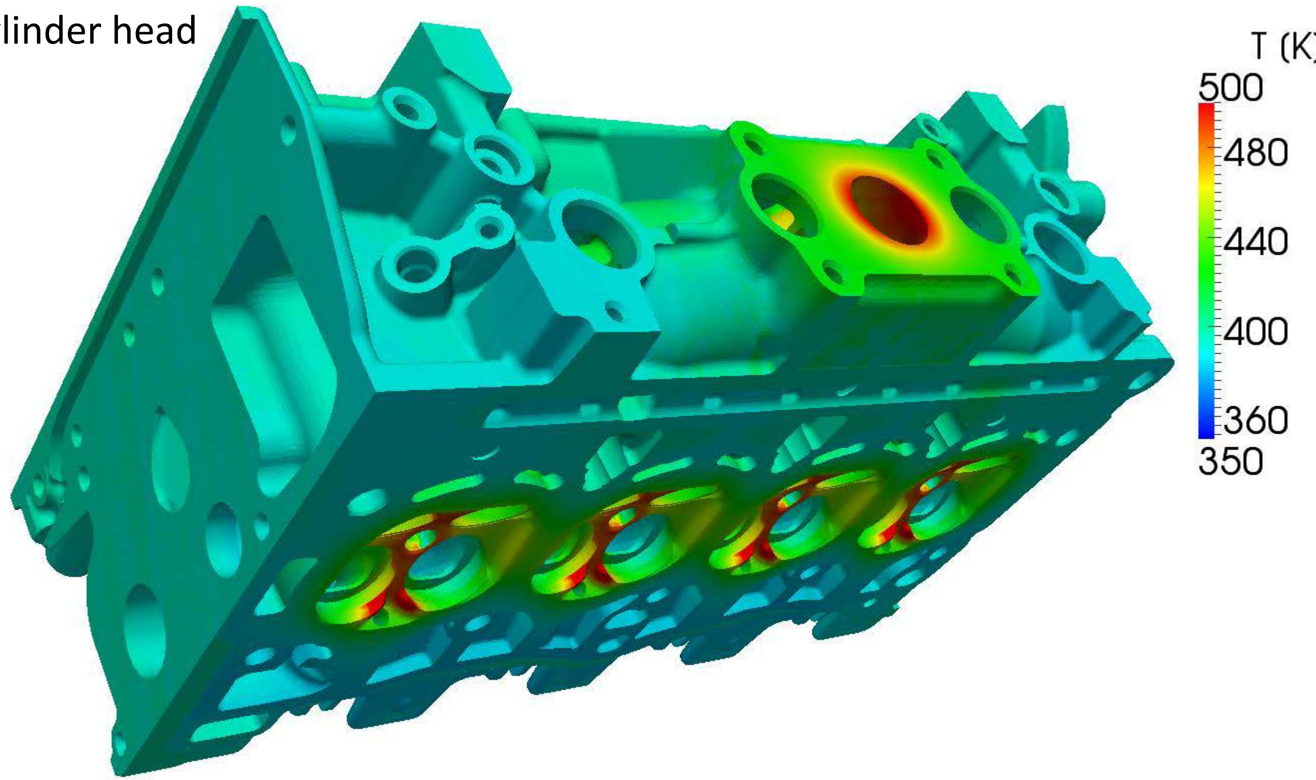


Topology Optimization



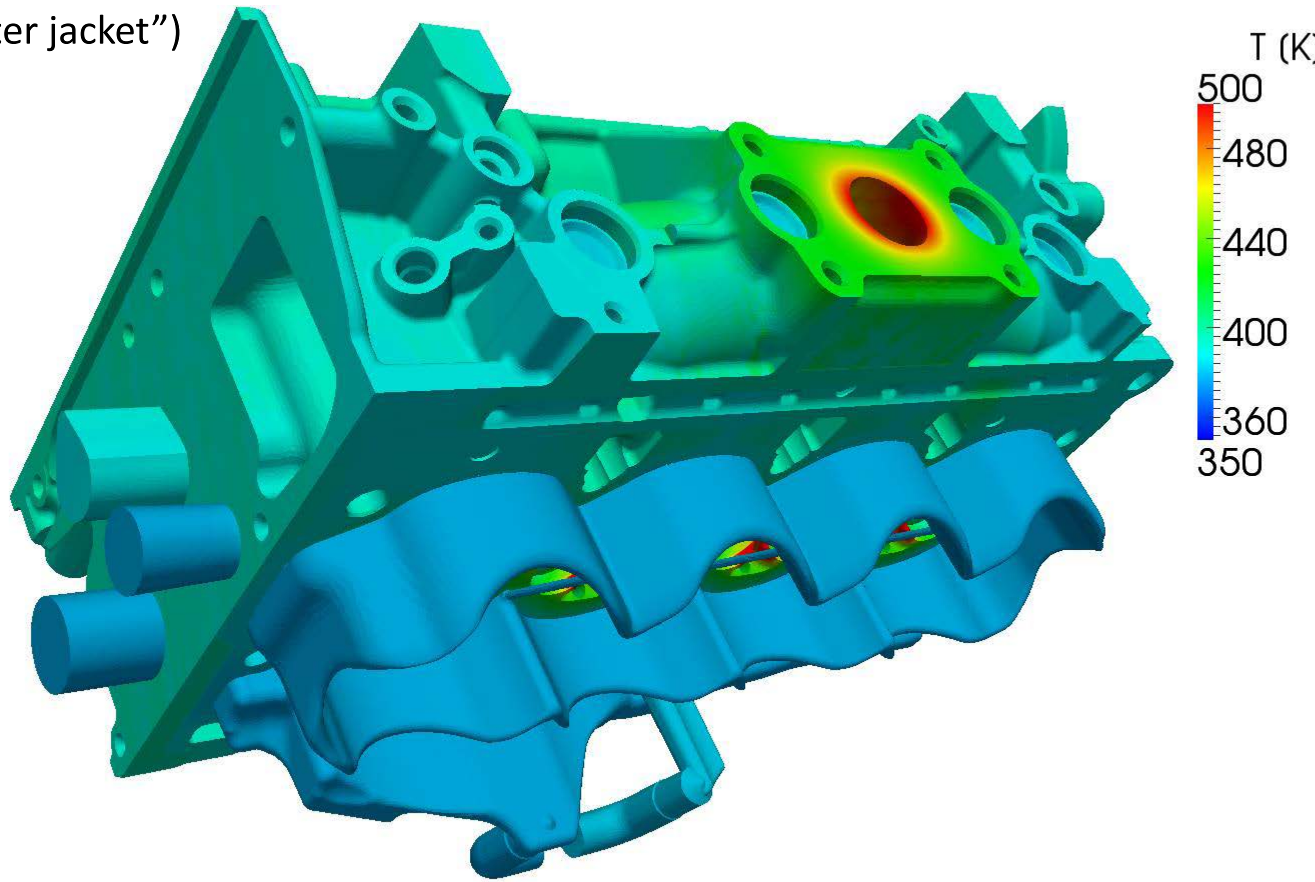
Main Motivation: Cylinder Head Cooling

Solid part of the cylinder head



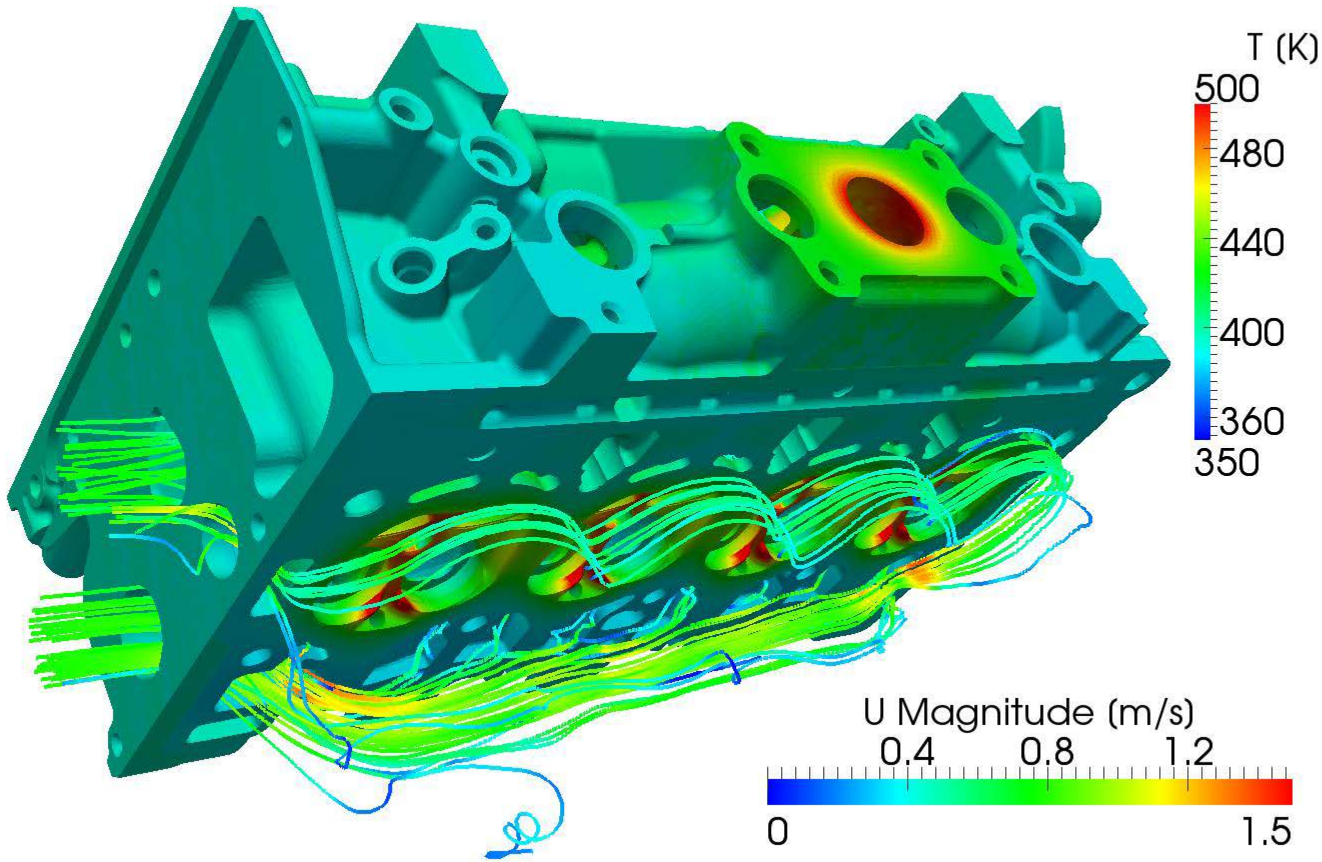
Main Motivation: Cylinder Head Cooling

Fluid volume (“water jacket”)



Main Motivation: Cylinder Head Cooling

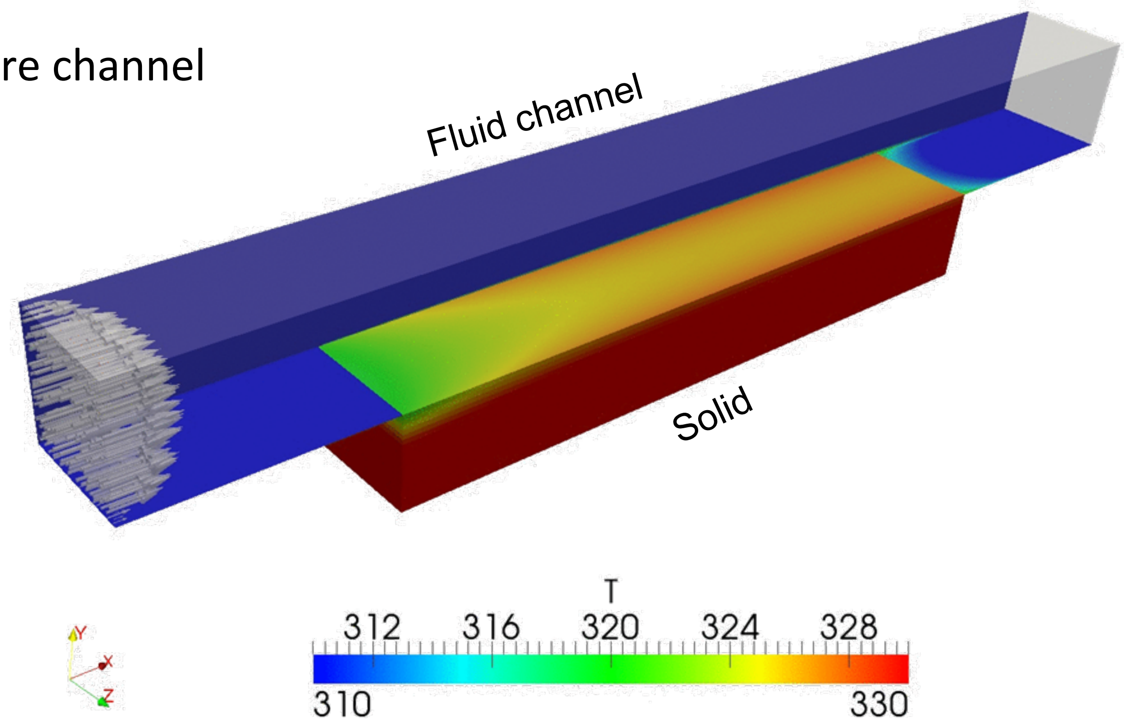
Streamlines



Extension of the Adjoint Solver towards Conjugate Heat Transfer

- Development and validation of an adjoint conjugate heat transfer code (NTU Athens in cooperation with Volkswagen Research)
- Objective function: average T^n in the solid domain
- Design variables: node displacements along the fluid/solid interface

- Test case: square channel



[from H. Narten, VW EA]

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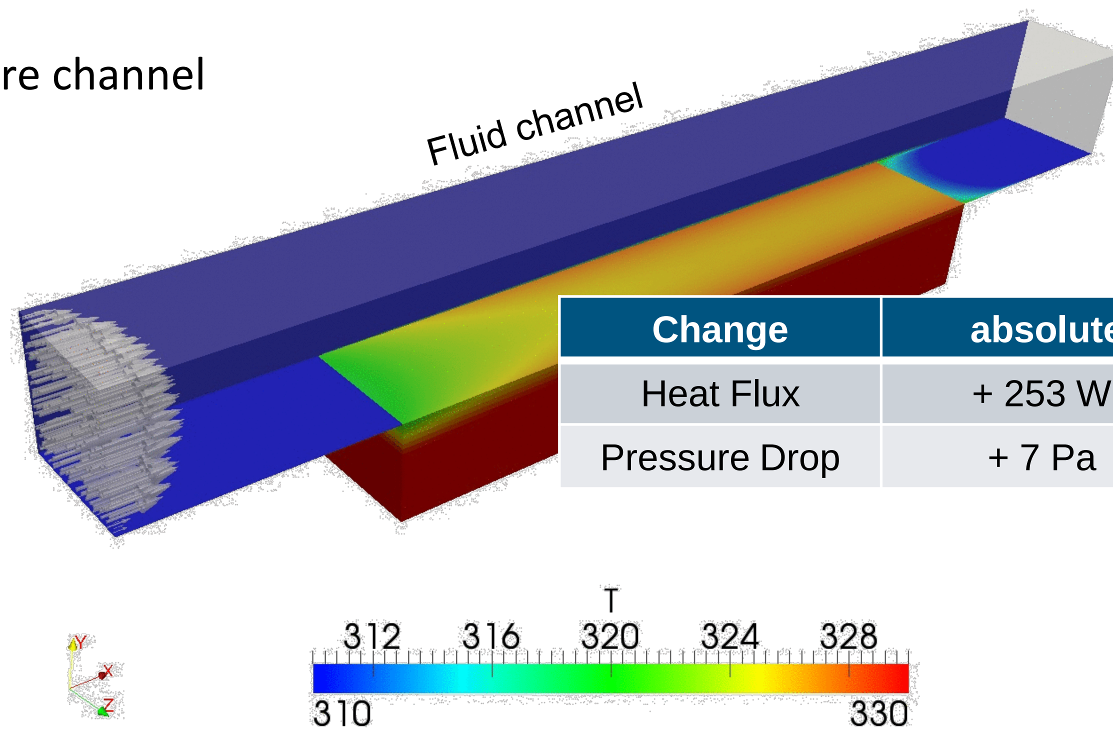
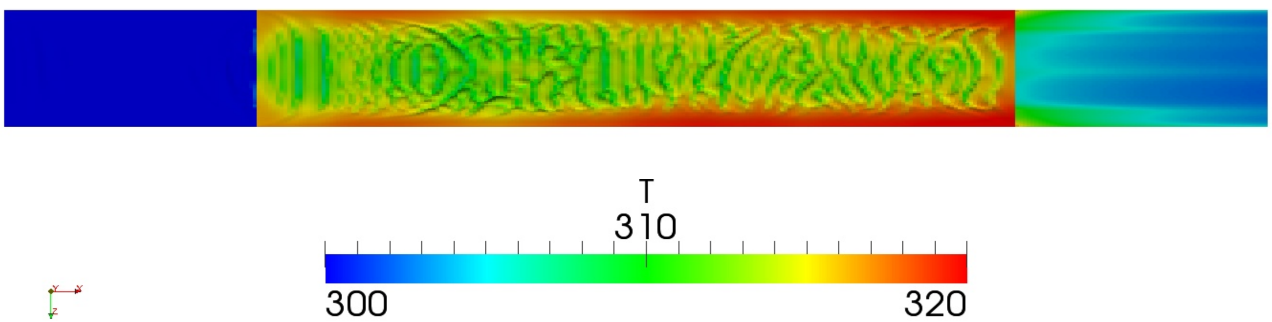


[from H. Narten, VW EA]

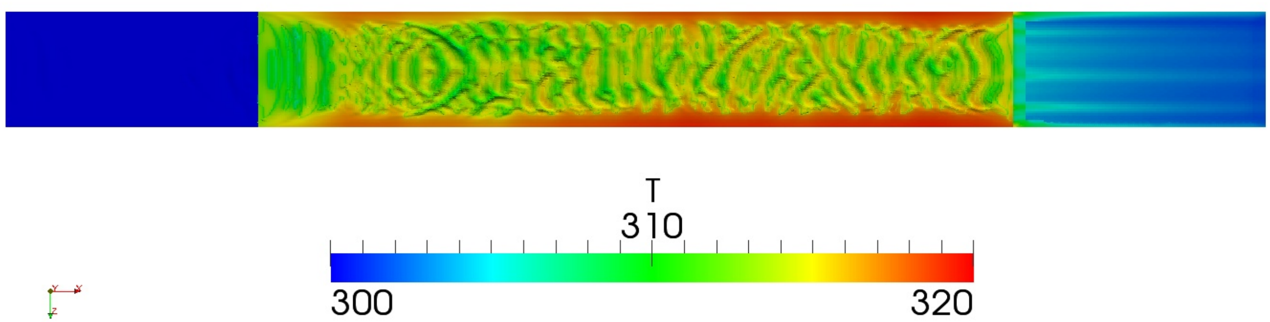
Change	absolute	relative
Heat Flux	+ 253 W	+ 47 %
Pressure Drop	+ 7 Pa	+ 13 %

Check 1: Physics or Numerical Noise?

- 10 times higher resolution along the interface
- Result: Deviation of heat flux < 0.5%



Original

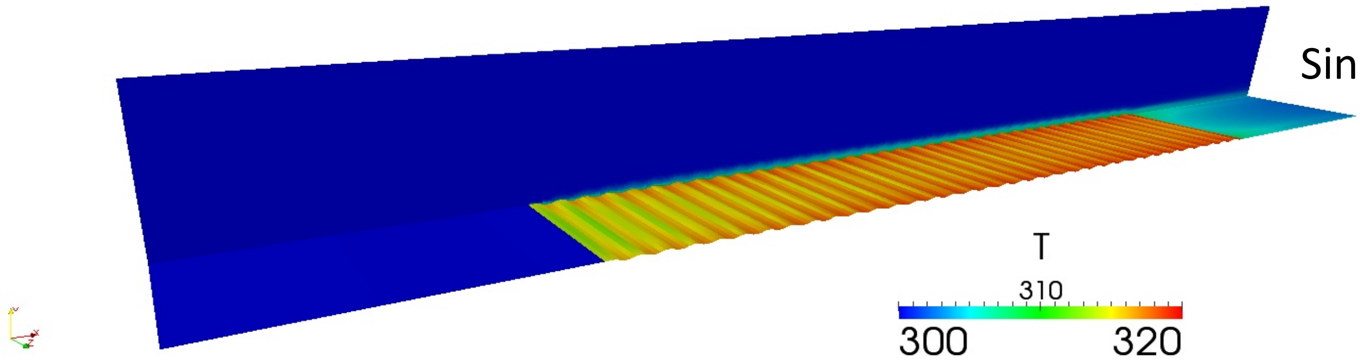


Fine Mesh

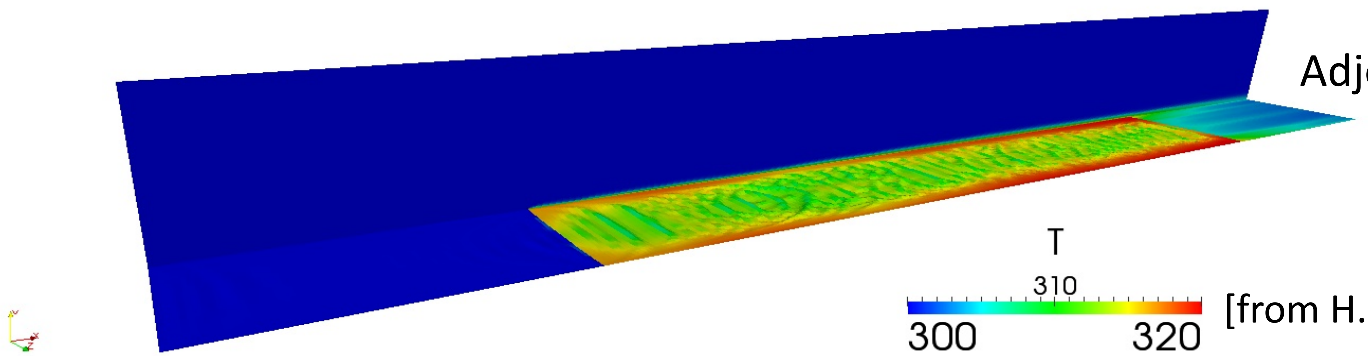
[from H. Narten, VW EA]

Check 2: Comparison with Sinusoidal Wave Pattern

- Wavelength taken from FFT of optimized interface
- Heat flux significantly lower for sinusoidal waves (-20%)



Sinusoidal waves



Adjoint-based waves

[from H. Narten, VW EA]

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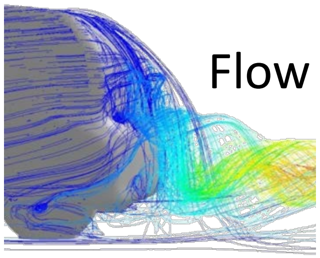

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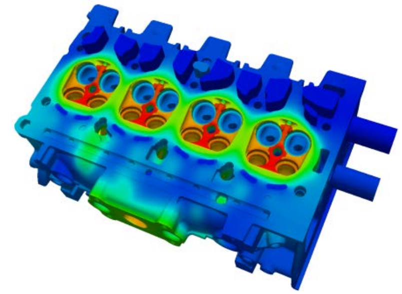

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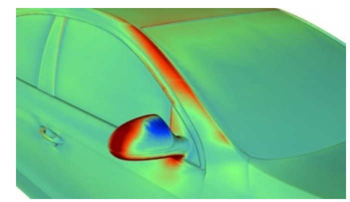

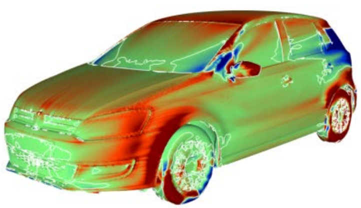

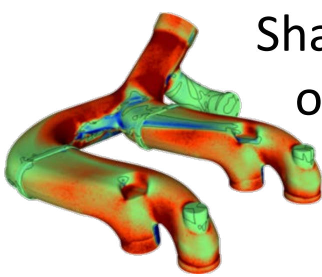

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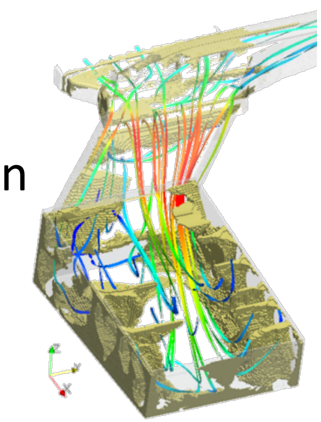
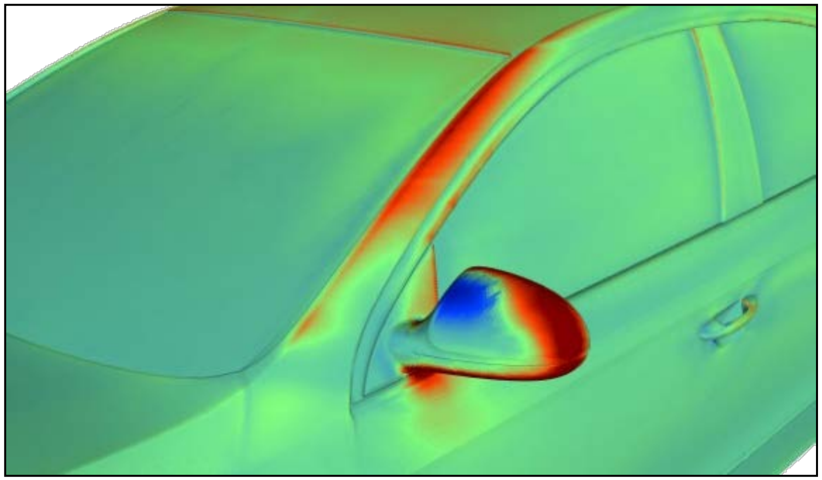


Aeroacoustics: Mirror Noise

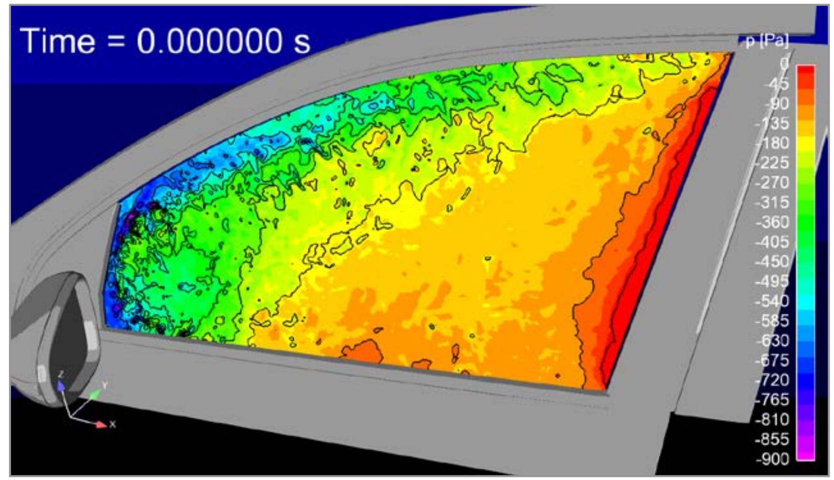
RANS



Surrogate cost functions:

- nu_t inside a volume adjacent to the side window
- (wall shear stress)^2 integrated over the side window

DES [from M. Hartmann, VW Research]



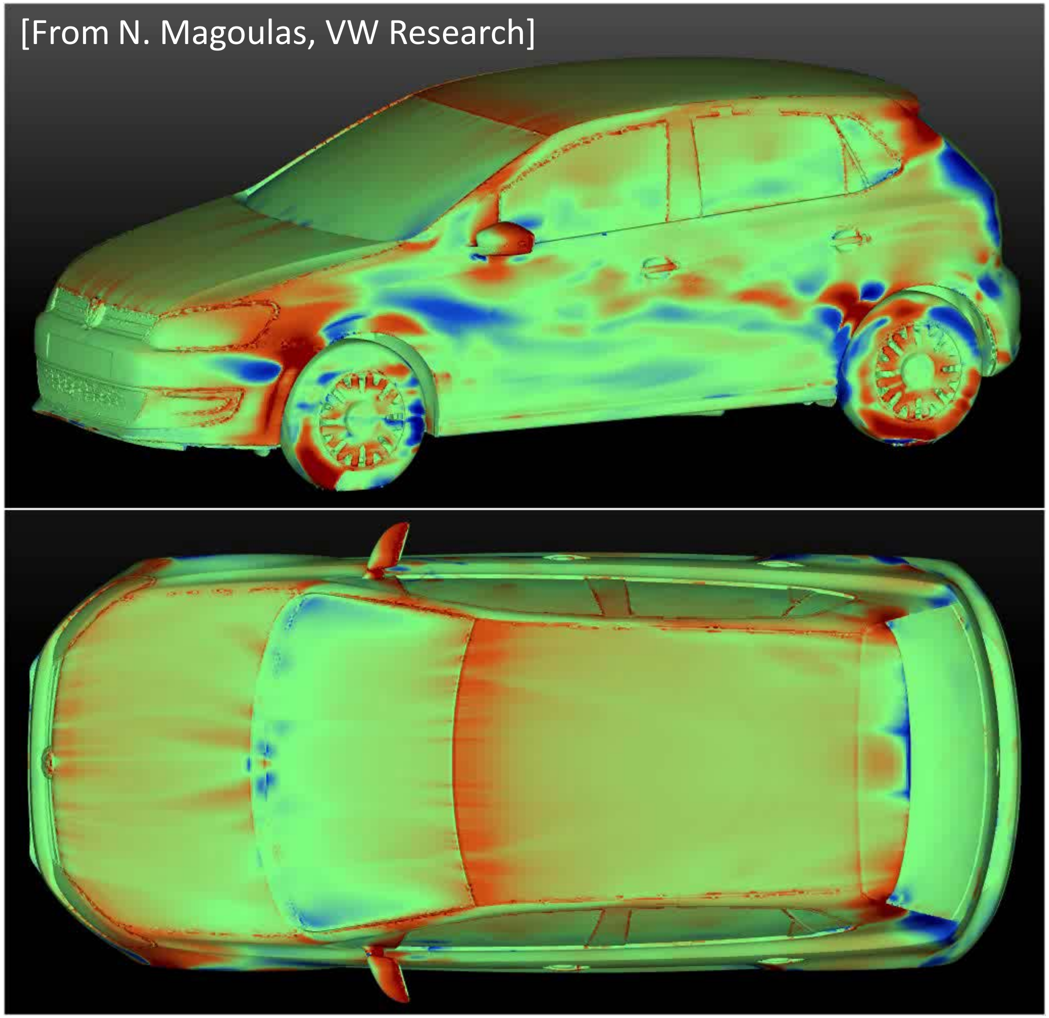
More adequate cost function:

- $J = (p(t) - p_{avg})^2$

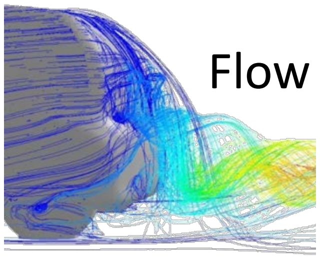
Time-varying adjoint source term:

- $\mathrm{div}\, u = p(t) - p_{avg}$

Towards Unsteady Adjoints: DES Drag Sensitivities



Summary



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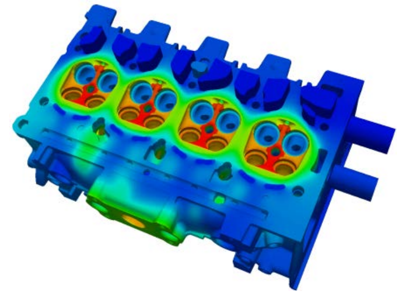

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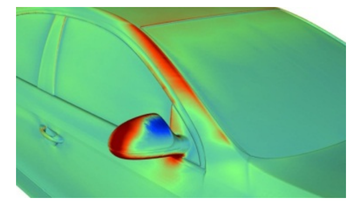

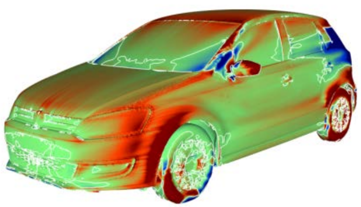

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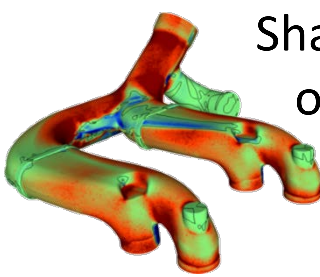

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