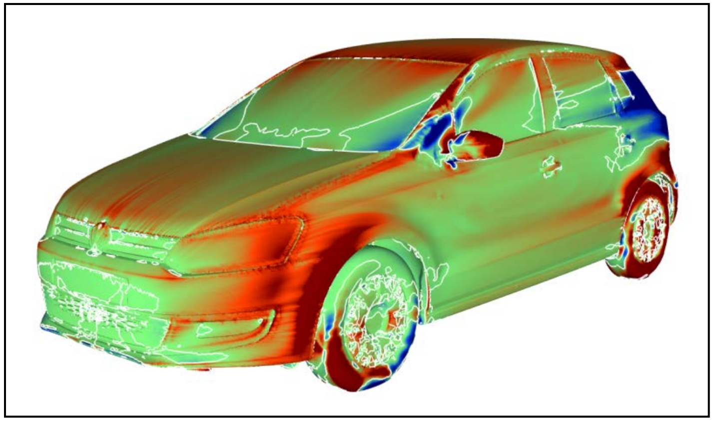
VOLKSWAGEN

AKTIENGESELLSCHAFT



AMS Seminar Series, NASA Ames Research Center
December 2, 2014

Adjoint-Based Topology and Shape Optimization for Car Development

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

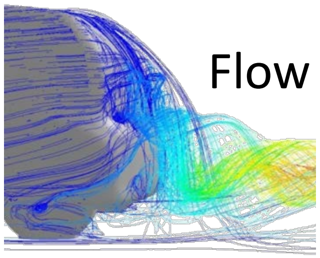
The Volkswagen Group

	Audi	SEAT
ŠKODA	BENTLEY	BUGATTI
LAMBORGHINI	PORSCHE	DUCATI
Nutzfahrzeuge	SCANIA	MAN

Volkswagen Corporate Research: ~600 people in Wolfsburg (Germany) + satellites in Tokyo, Shanghai and Belmont

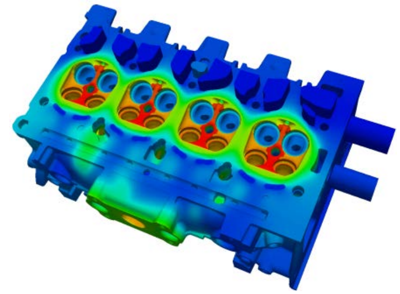
Adjoint-Based Optimization for Cars: Overview

Continuous Adjoint Method

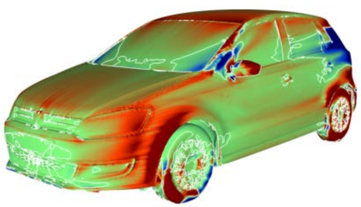


Flow Control

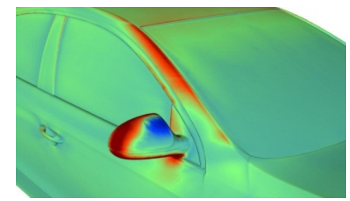
Cooling Optimization

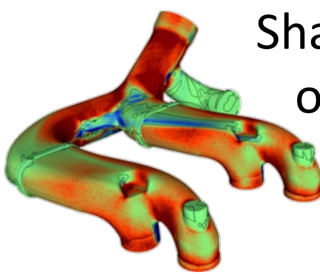


Vehicle Shape Optimization



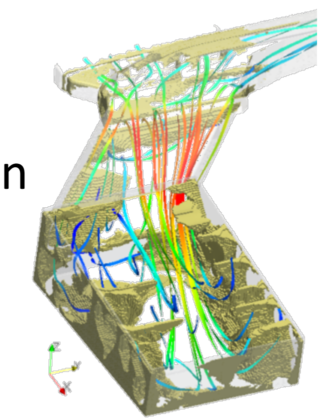
Aeroacoustic Optimization





Shape Optimization of Ducted Flows

Topology Optimization



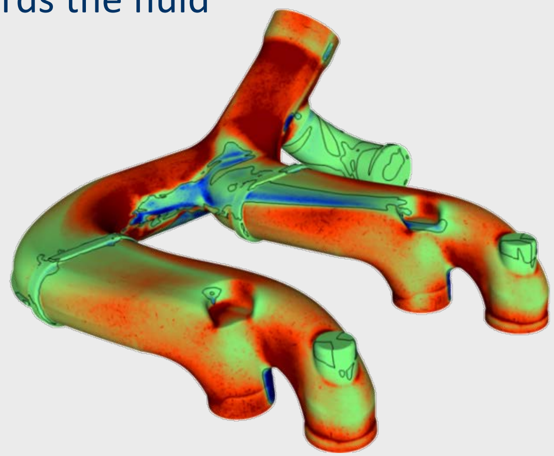
Acknowledgements

- 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

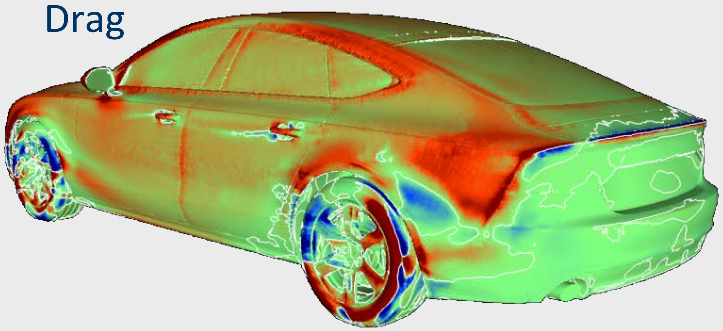
The Adjoint Method: Computation of Sensitivity Maps

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

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



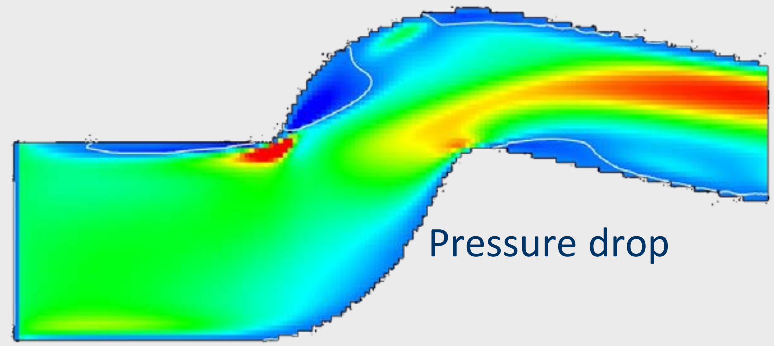
Massflow



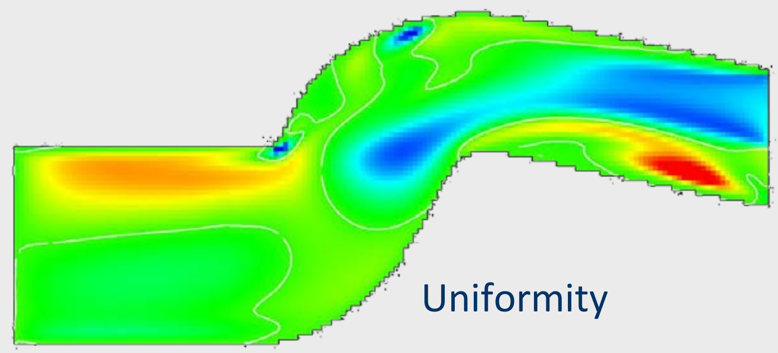
Drag

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

red: important areas
blue: counterproductive areas



Pressure drop

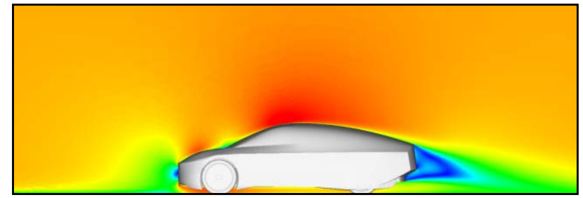


Uniformity

The Adjoint Method: Computational Process

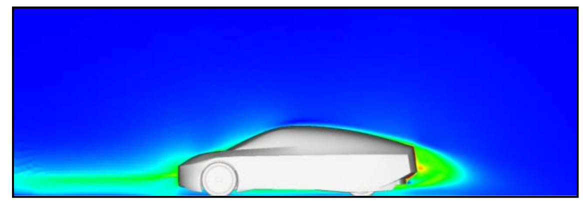
1. CFD computation: v , p ("primal field")

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



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

Implementation of an Adjoint Solver for Automotive Applications

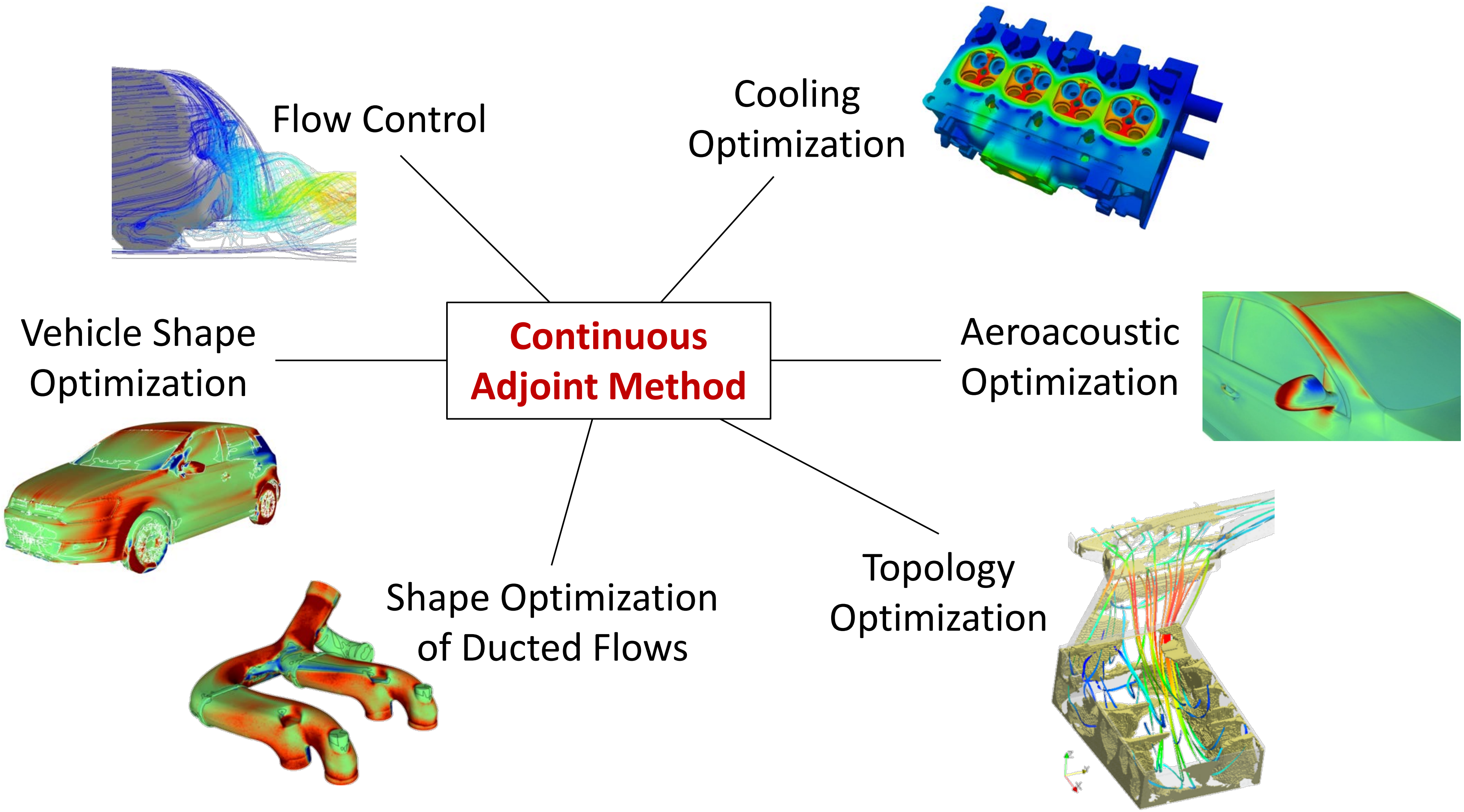
- Platform: Open source code OpenFOAM® chosen in 2006

```
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, …

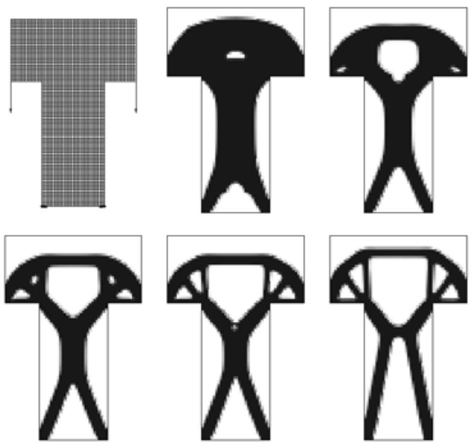
→ Versatile continuous adjoint solver “adjointFoam“ for incompressible steady-state RANS

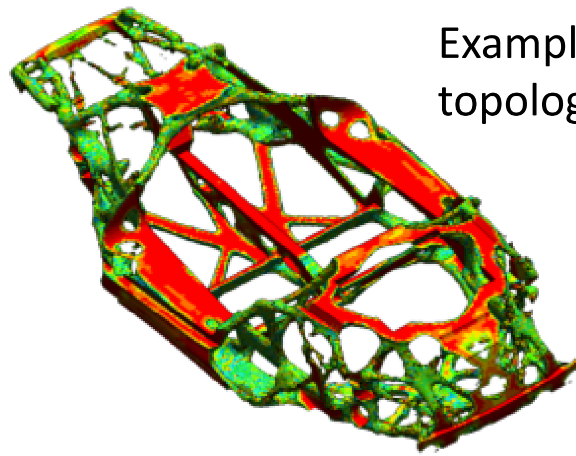
Adjoint-Based Optimization for Cars: Overview



Topology Optimization

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



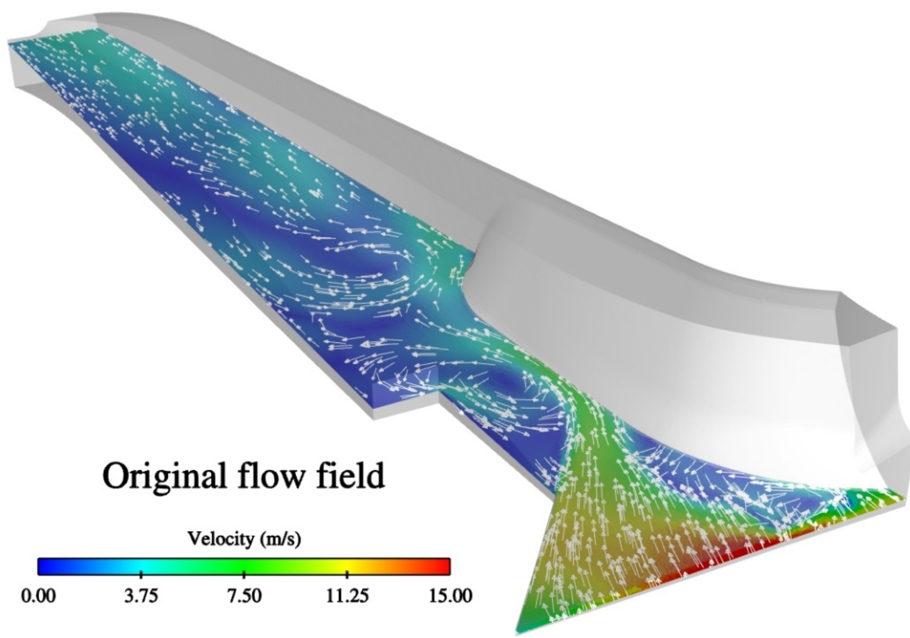


Example: Optimal car body topology [Conic, VW]

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

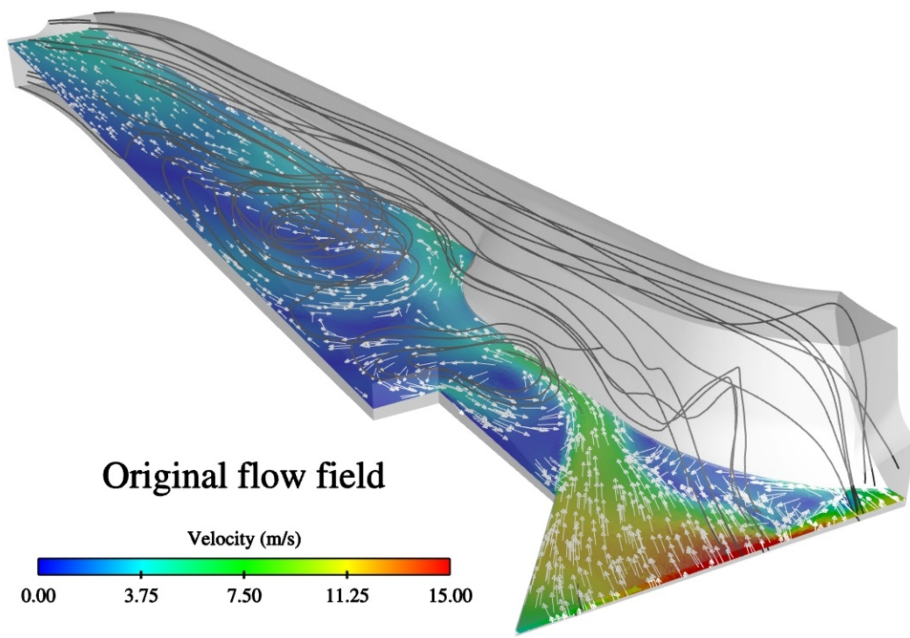
Topology Optimization for Fluid Dynamics

- 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



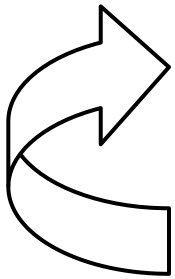
Topology Optimization for Fluid Dynamics

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

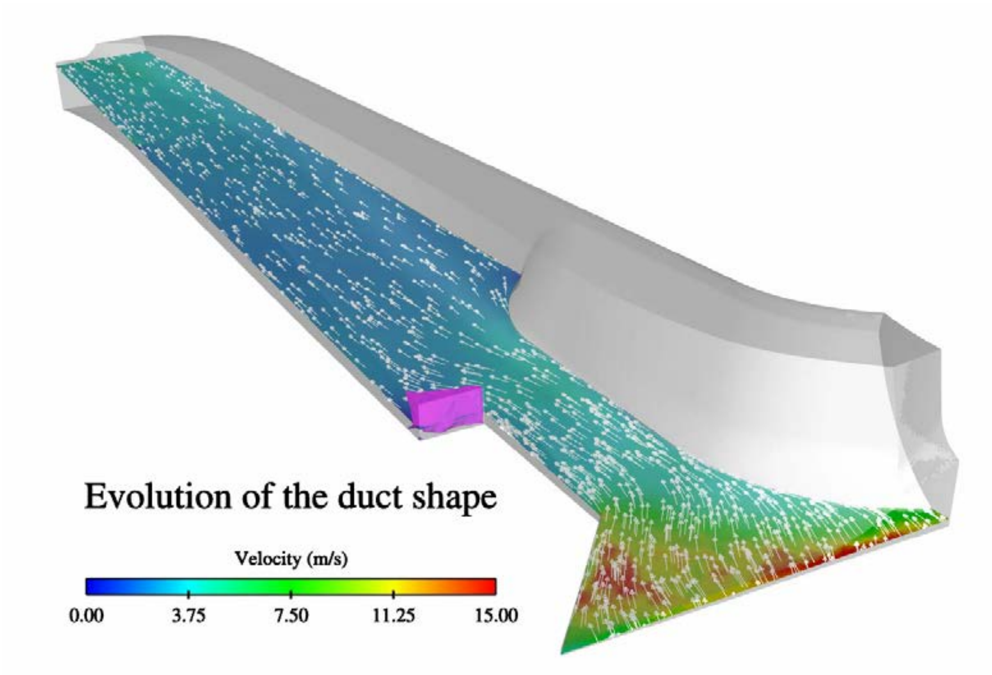


Topology Optimization for Fluid Dynamics

- Starting point: **Entire installation space**

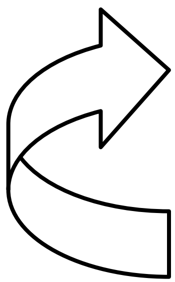


  - Flow solution
  - Identification of “counter-productive“ cells via a **local criterion** (v•u)
  - Punishment of counter-productive cells with porosity
- Result: Optimal topology



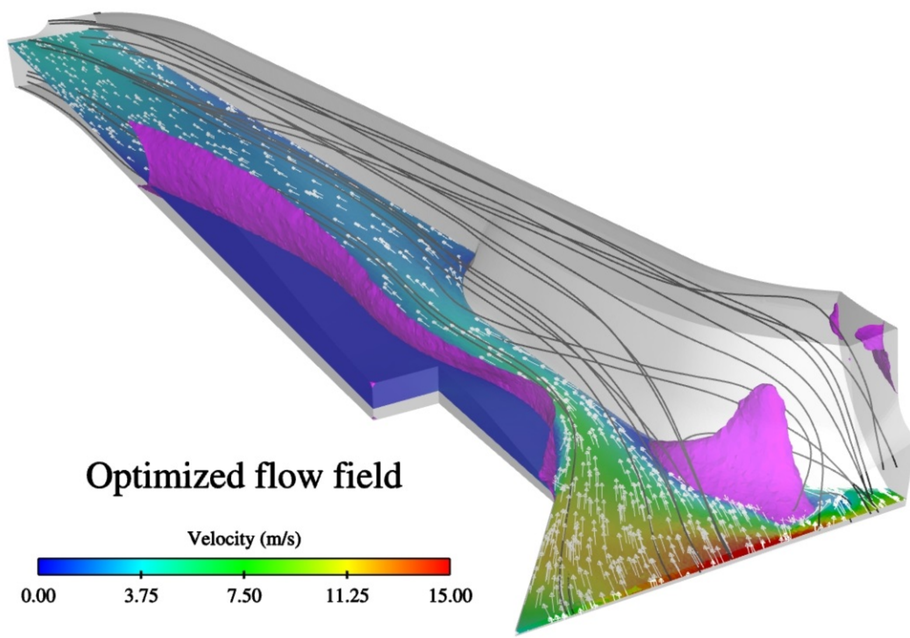
Topology Optimization for Fluid Dynamics

- 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

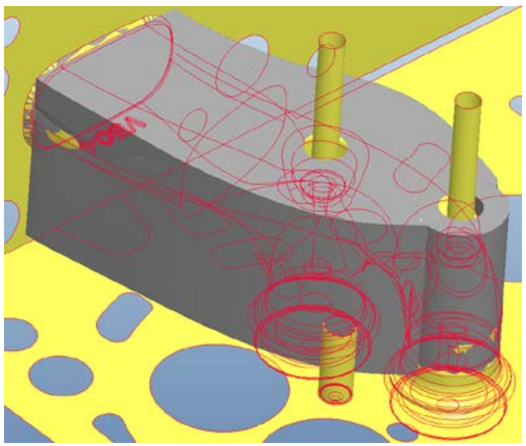
- Result: Optimal topology



Optimized flow field

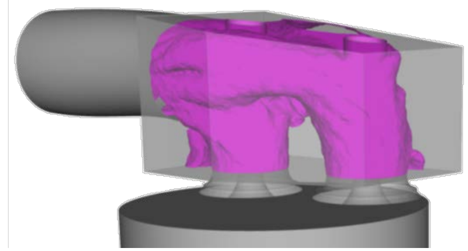
Topo Example 1: From Packaging Space to the Optimal Port

Packaging space definition

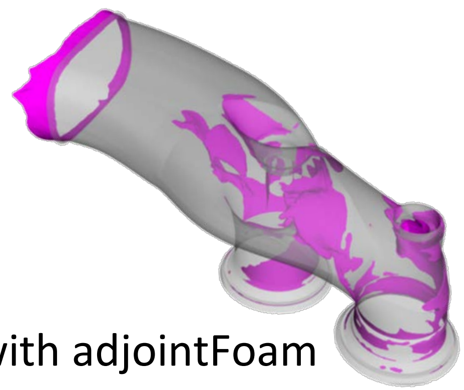


[F. Kunze and R. Niederlein]

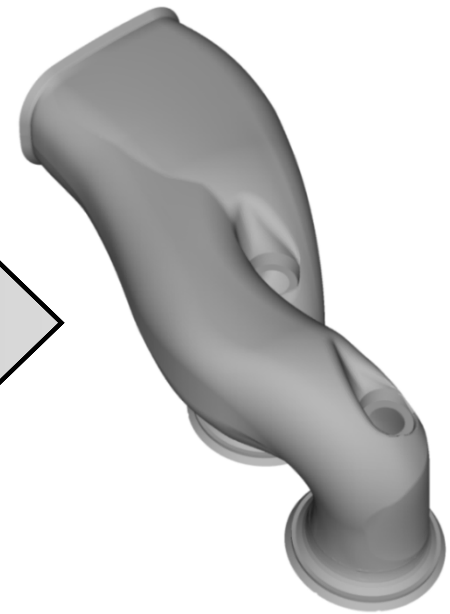
Drafting with adjointFoam



adjointFoam + manual CAD iterations

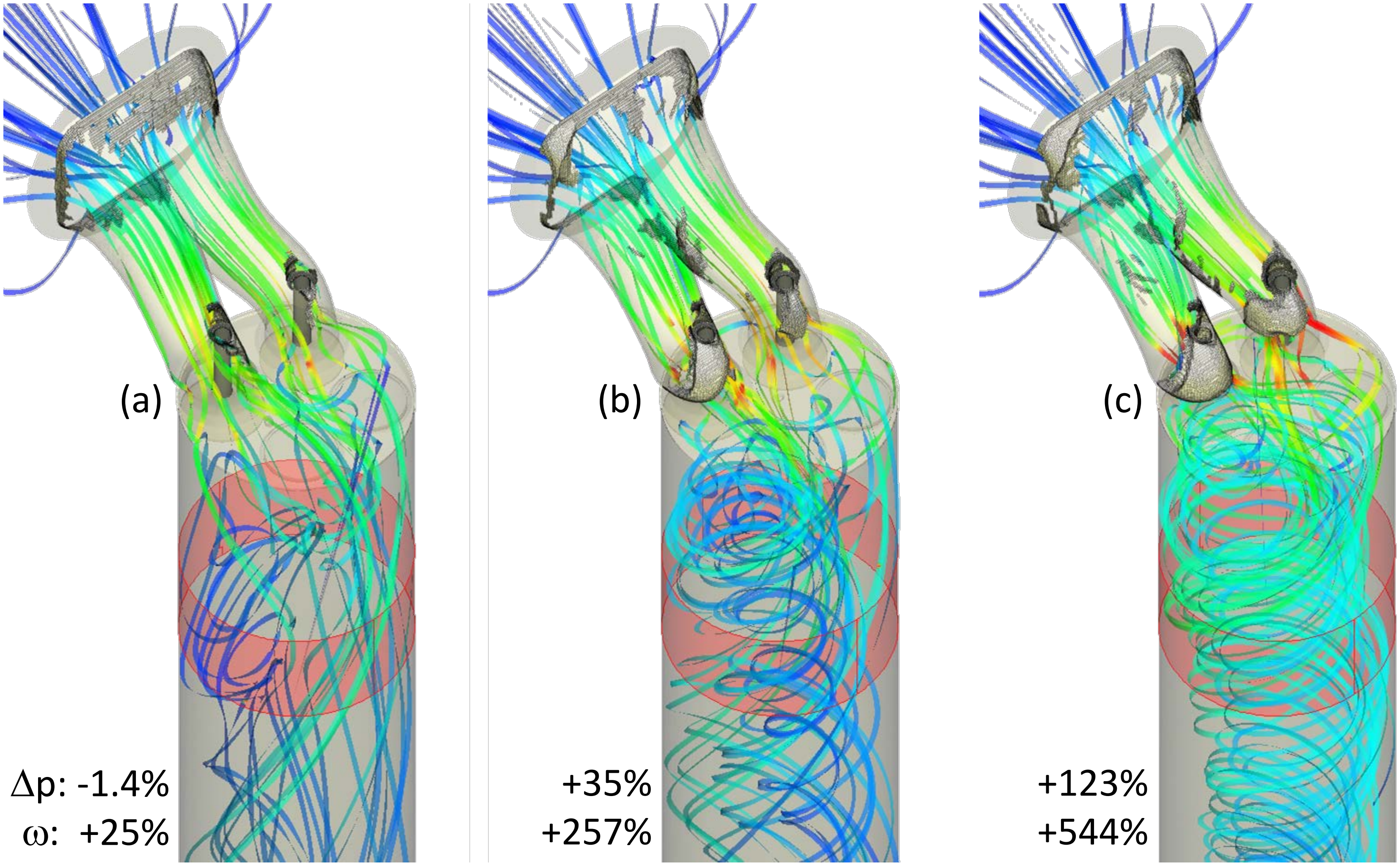


Fine-tuning with adjointFoam



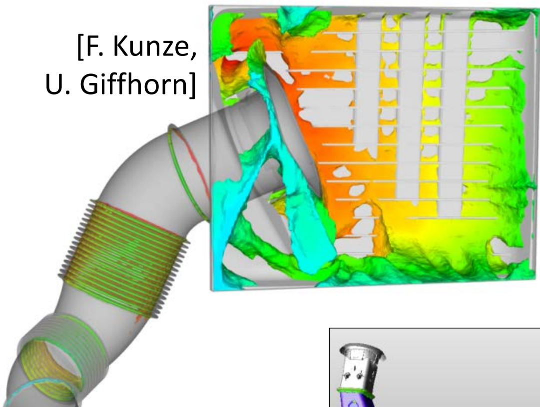
Final (hand-made) CAD geometry

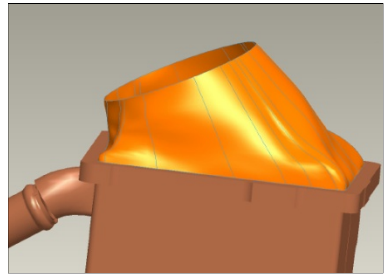
Topo Example 2: Multi-Objective Intake Port Optimization



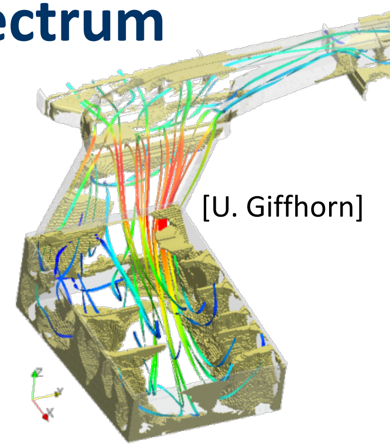
CFD Topology Optimization: Application Spectrum

[F. Kunze, U. Giffhorn]

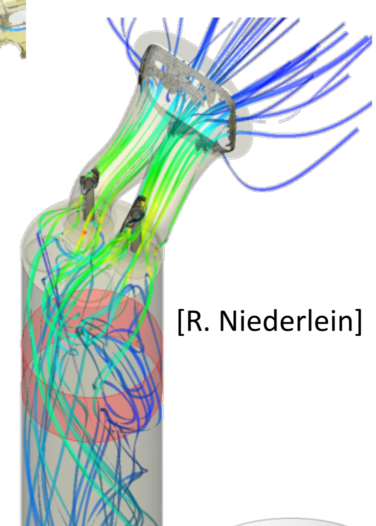




[M. Tomecki]

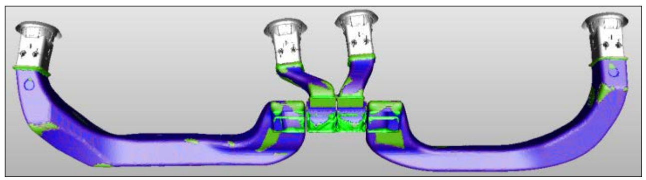


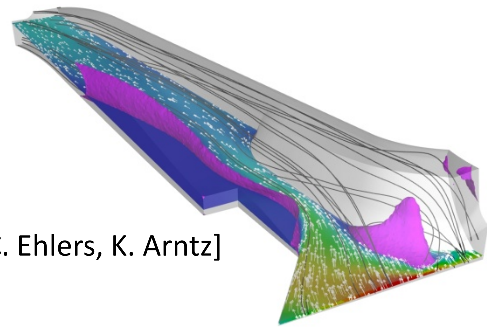
[U. Giffhorn]



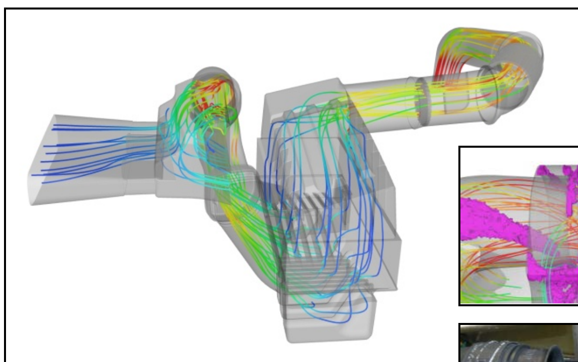
[R. Niederlein]

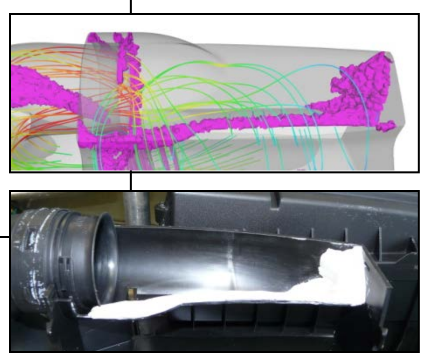
[N. Peller]



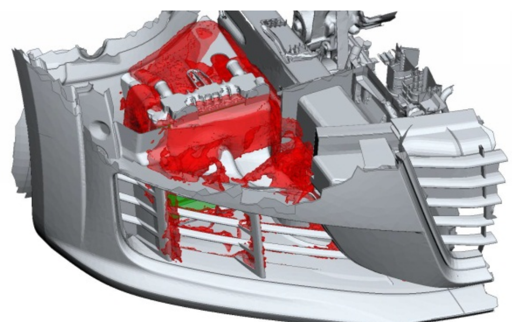


[C. Ehlers, K. Arntz]

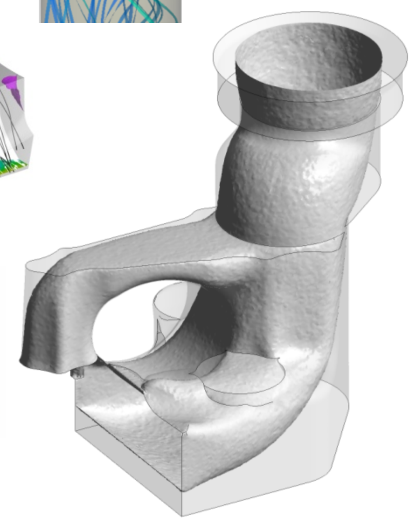




[U. Giffhorn]

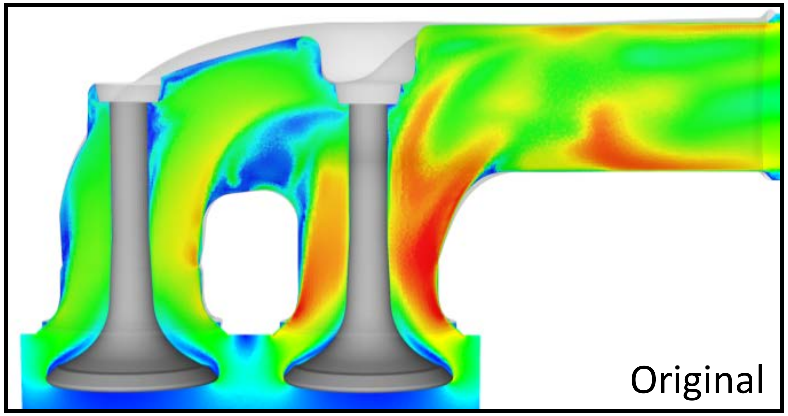


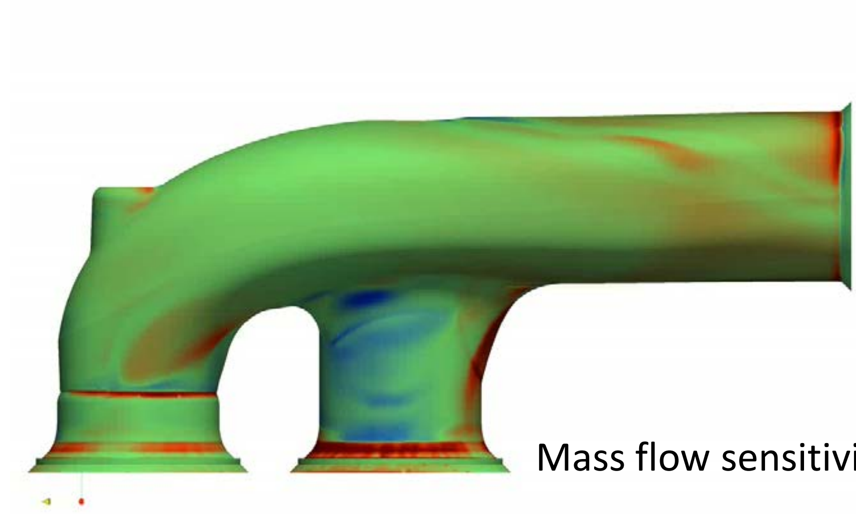
[P. Unterlechner]



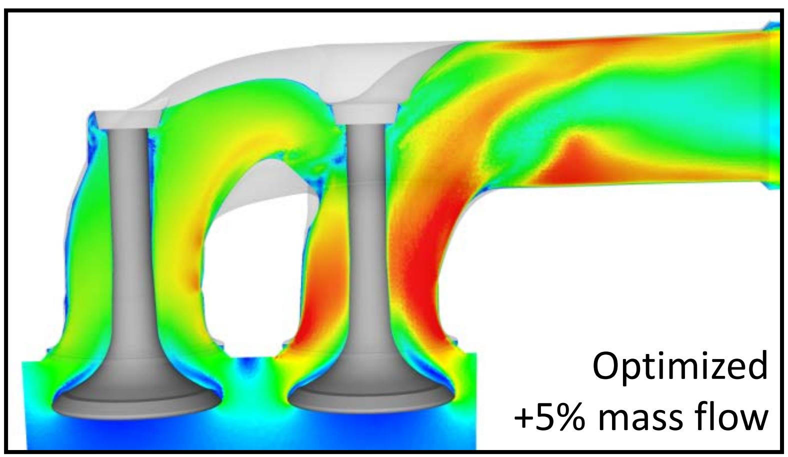
[M. Towara]

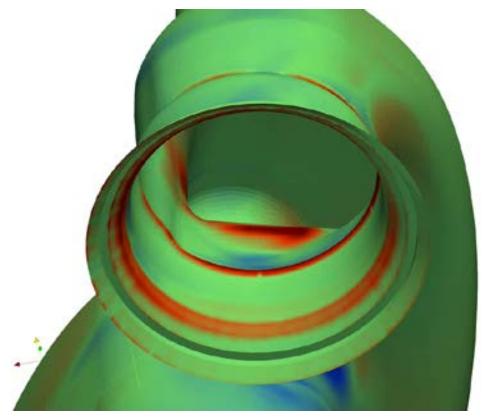
Shape Optimization for Ducted Flows: Exhaust Port Example





Mass flow sensitivities

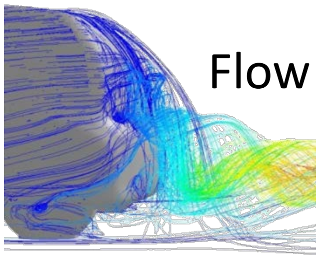




[F. Kunze and R. Niederlein]

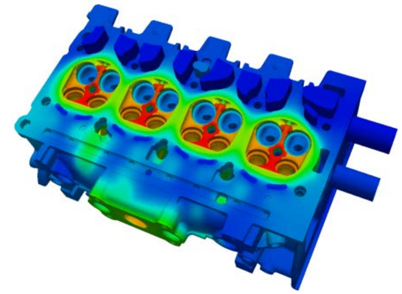
Adjoint-Based Optimization for Cars: Overview

Continuous Adjoint Method

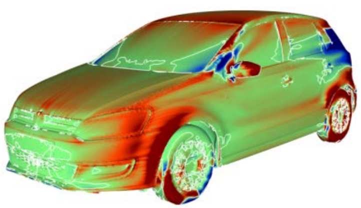


Flow Control

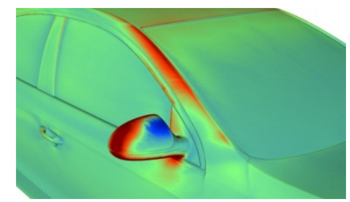
Cooling Optimization



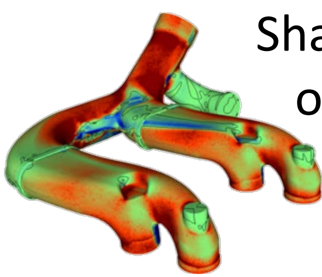
Vehicle Shape Optimization



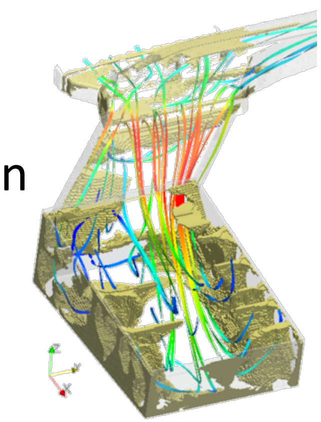
Aeroacoustic Optimization



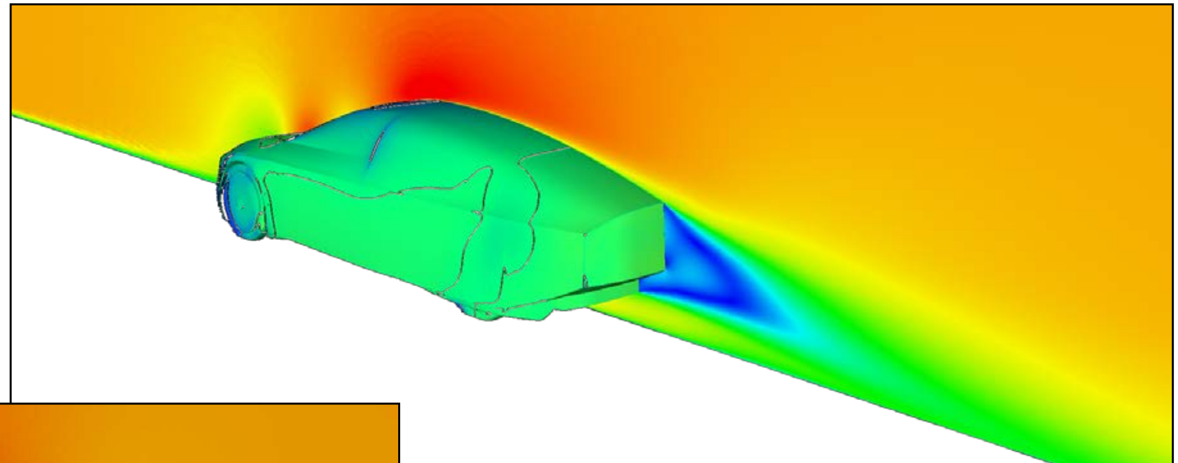
Shape Optimization of Ducted Flows

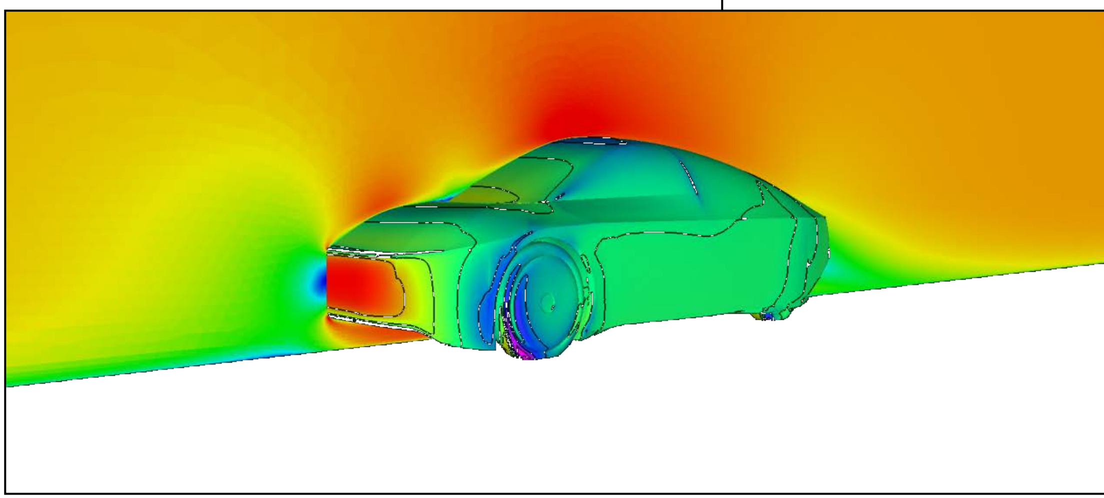


Topology Optimization



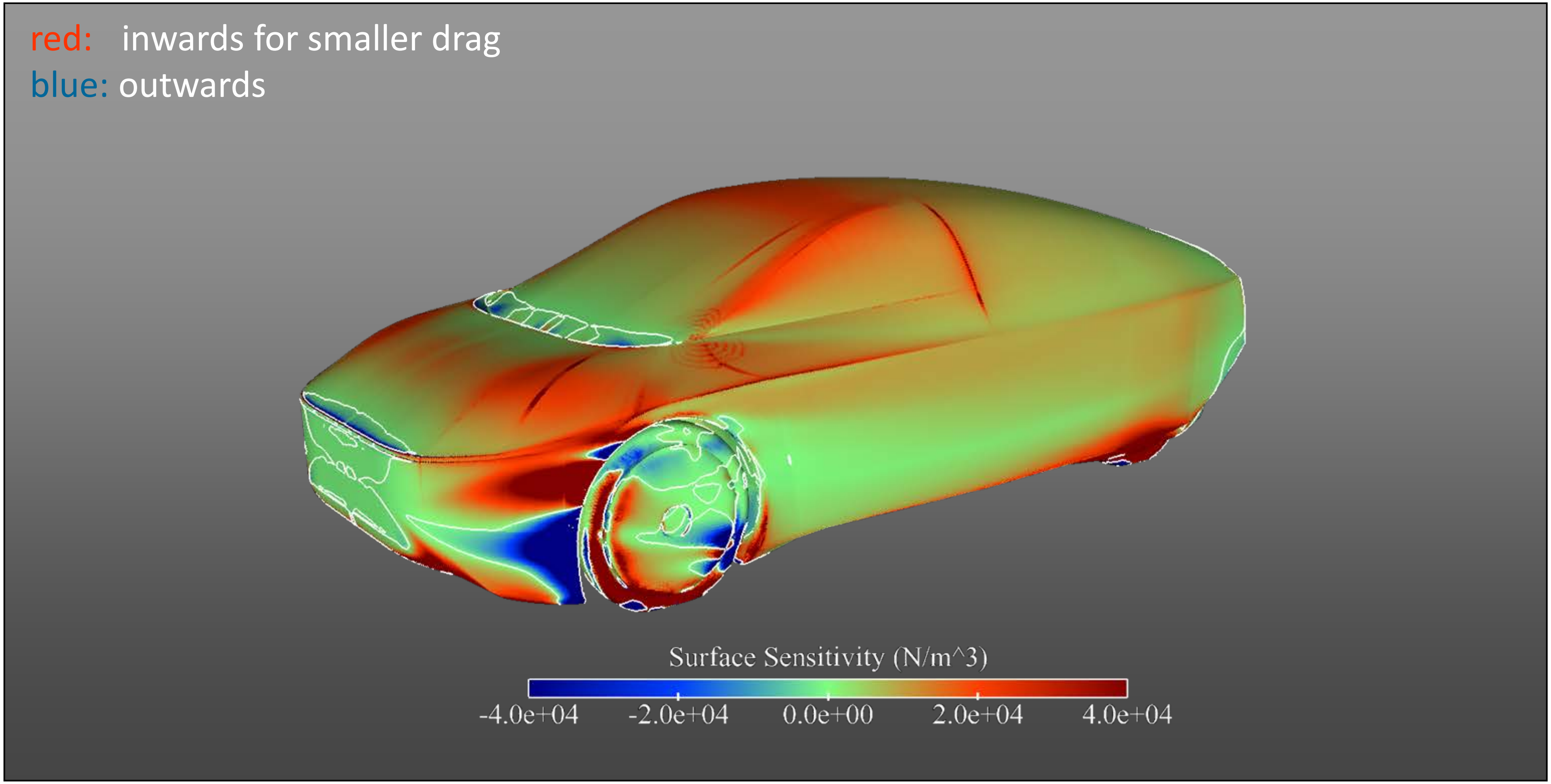
Shape Optimization in External Aerodynamics: Example 1



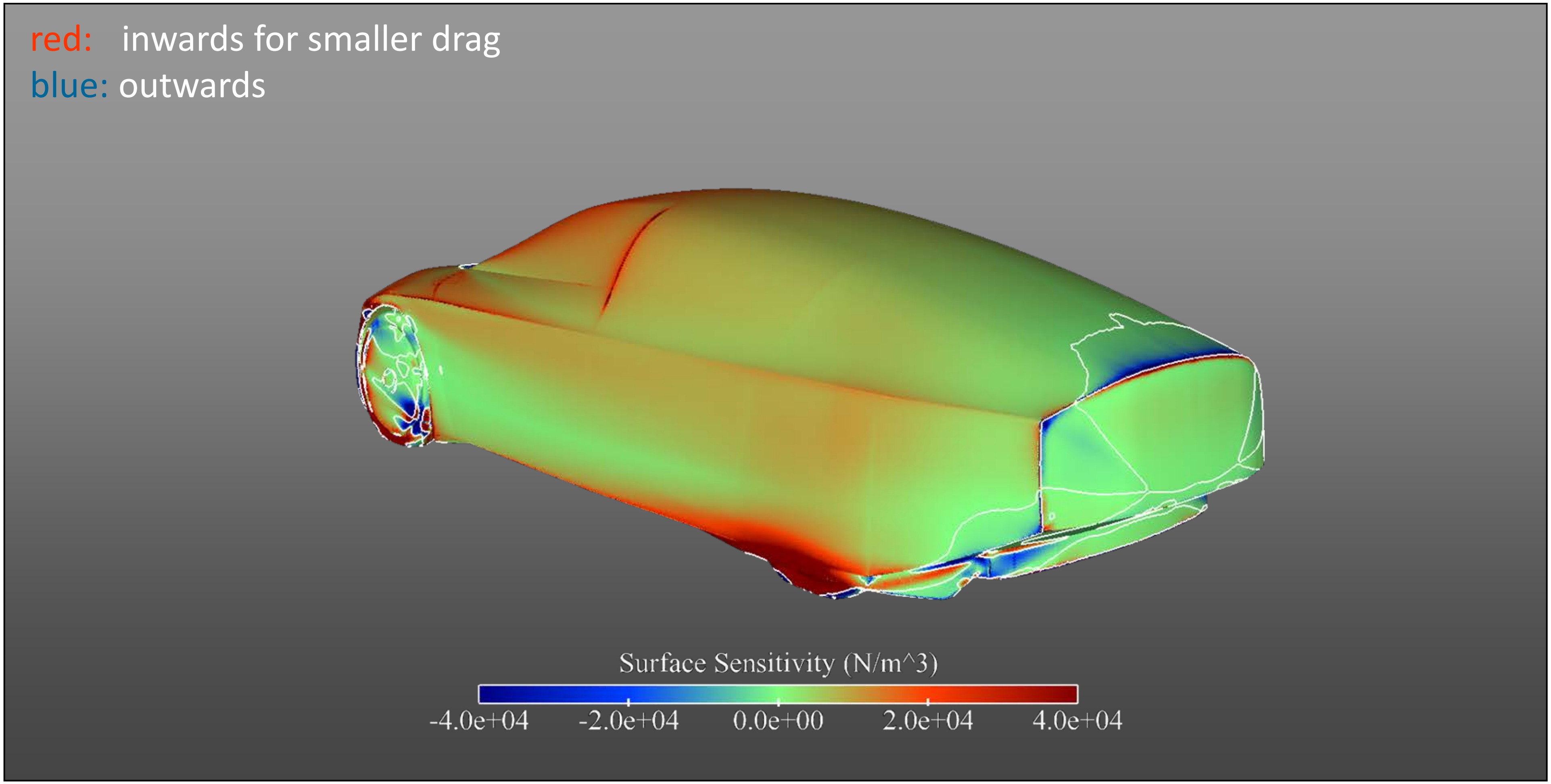


- Volkswagen XL1
- v=33m/s
- RANS with Spalart-Allmaras
- low-Reynolds mesh ($y^+ \sim 1$)
- half-model

Volkswagen XL1: Sensitivities (1)

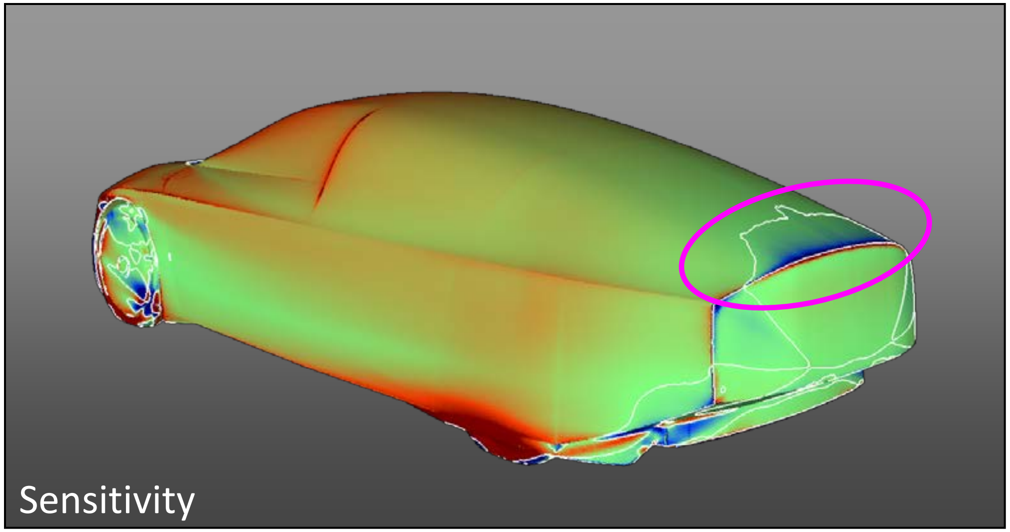


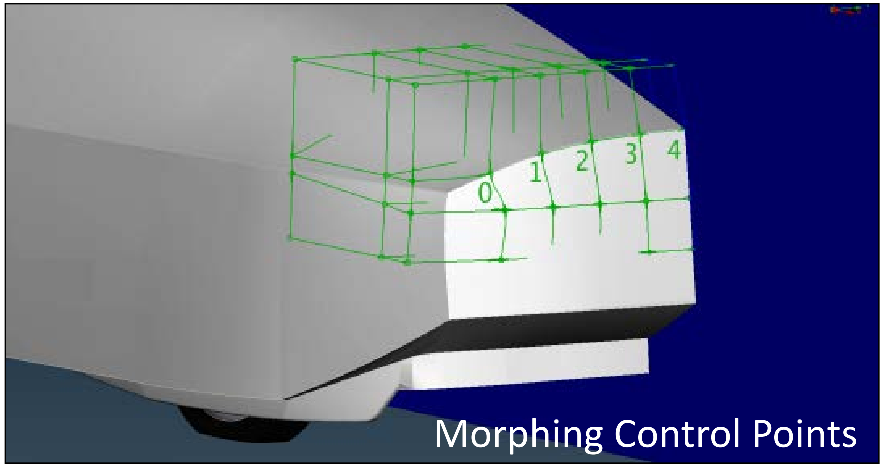
Volkswagen XL1: Sensitivities (2)



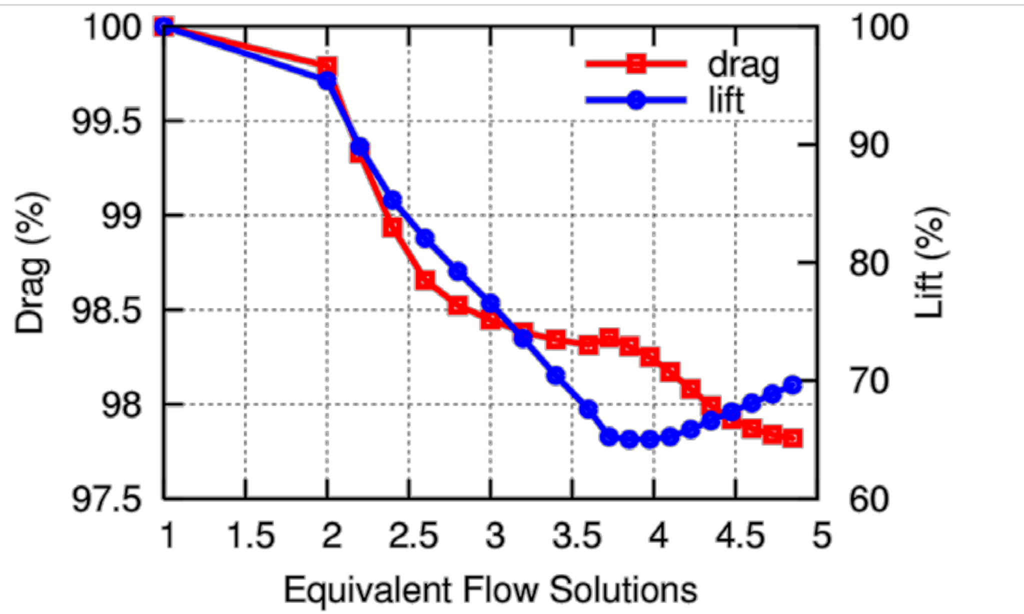
One-Shot Optimization of the Rear Spoiler

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

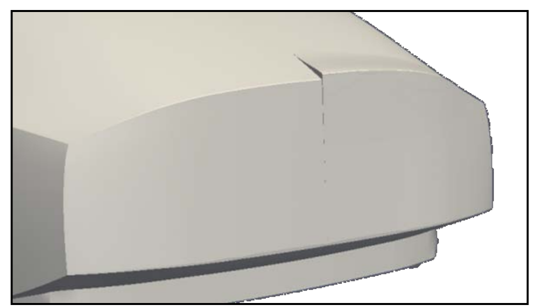




Optimization Results



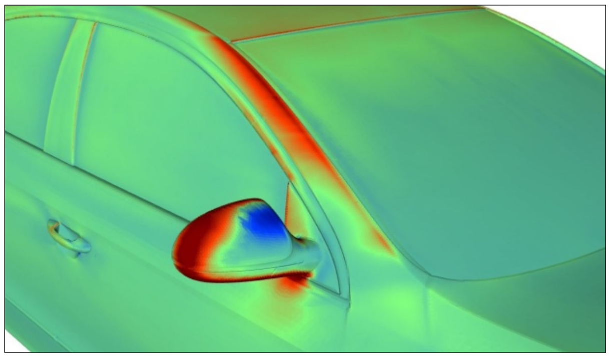
- >2% drag reduction, 30% lift improvement
- Deformation in z-direction < 20mm
- Overall cost: <5 EFS

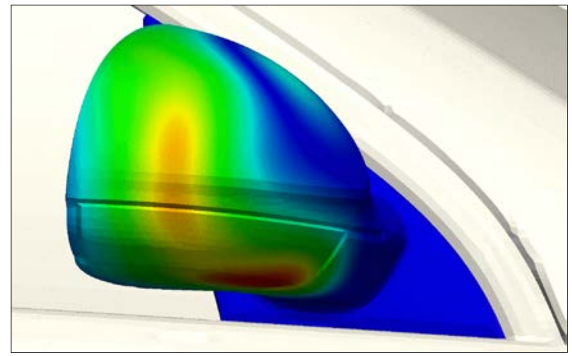


Shape Optimization in External Aerodynamics: Example 2

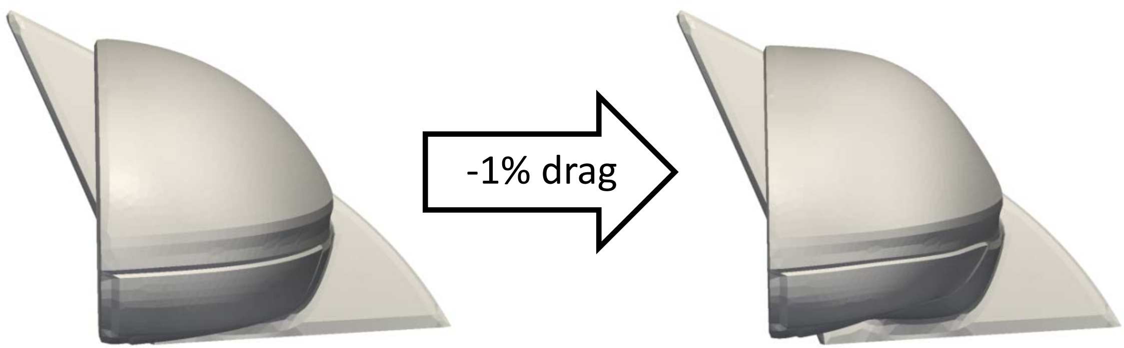
- External mirror shape optimization w.r.t. total vehicle drag
- Sensitivities by adjointFoam, morphing with Carat (TU Munich)

Sensitivity



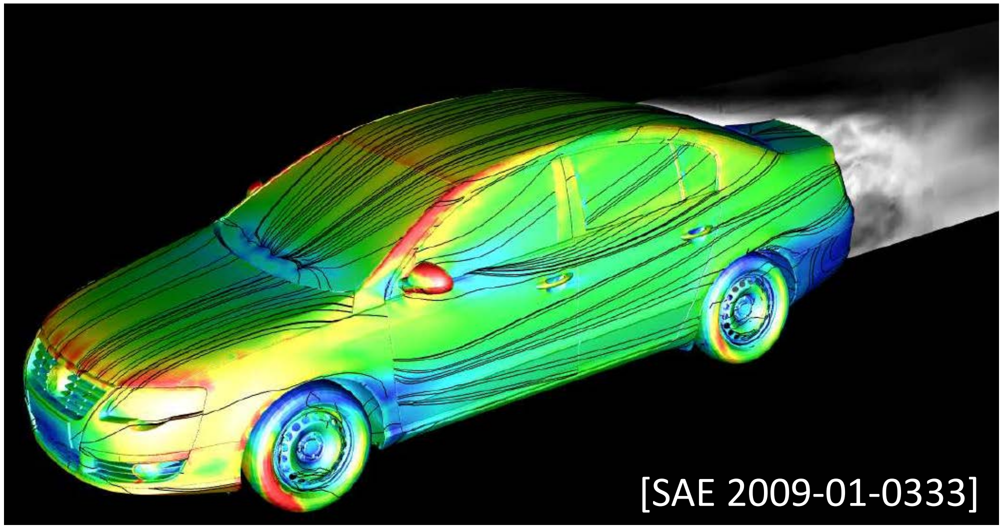


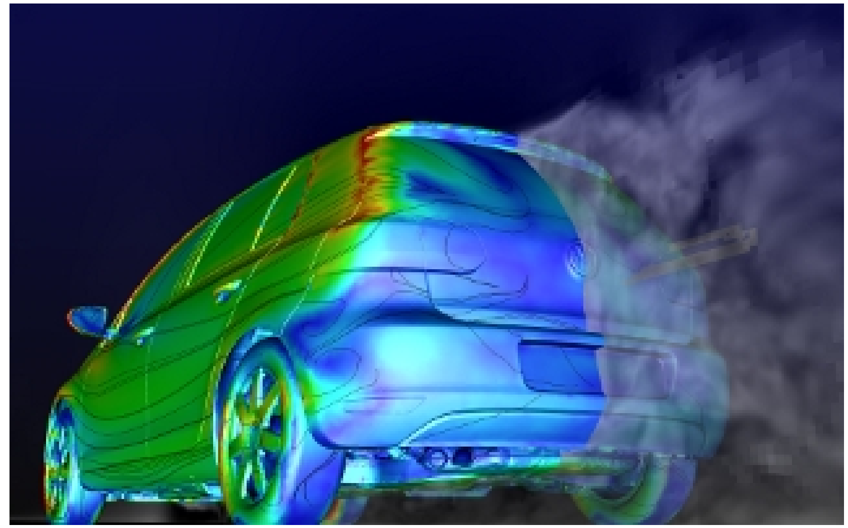
Displacement

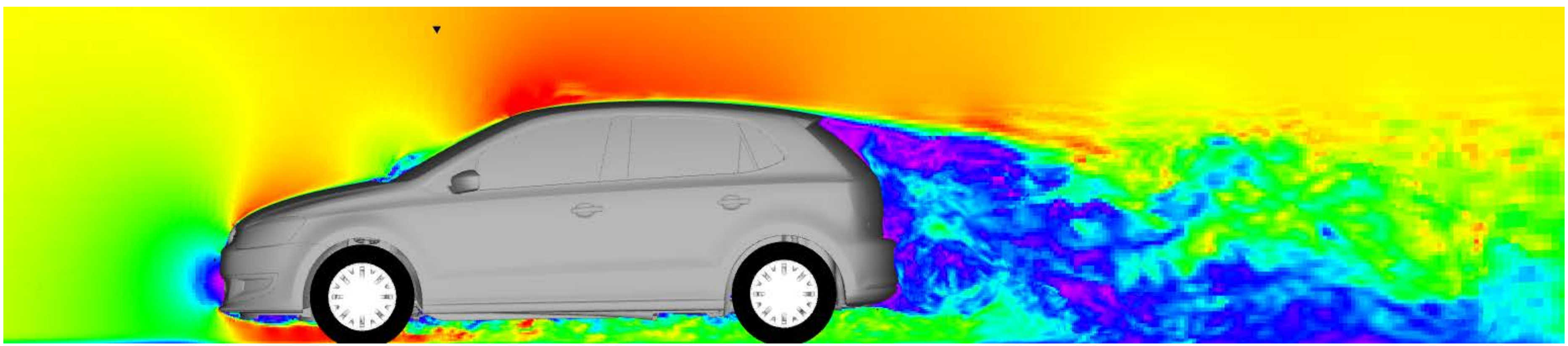


- Conservation of feature lines is an essential ingredient for external aero optimization

Productive Aerodynamics Computations: DES instead of RANS







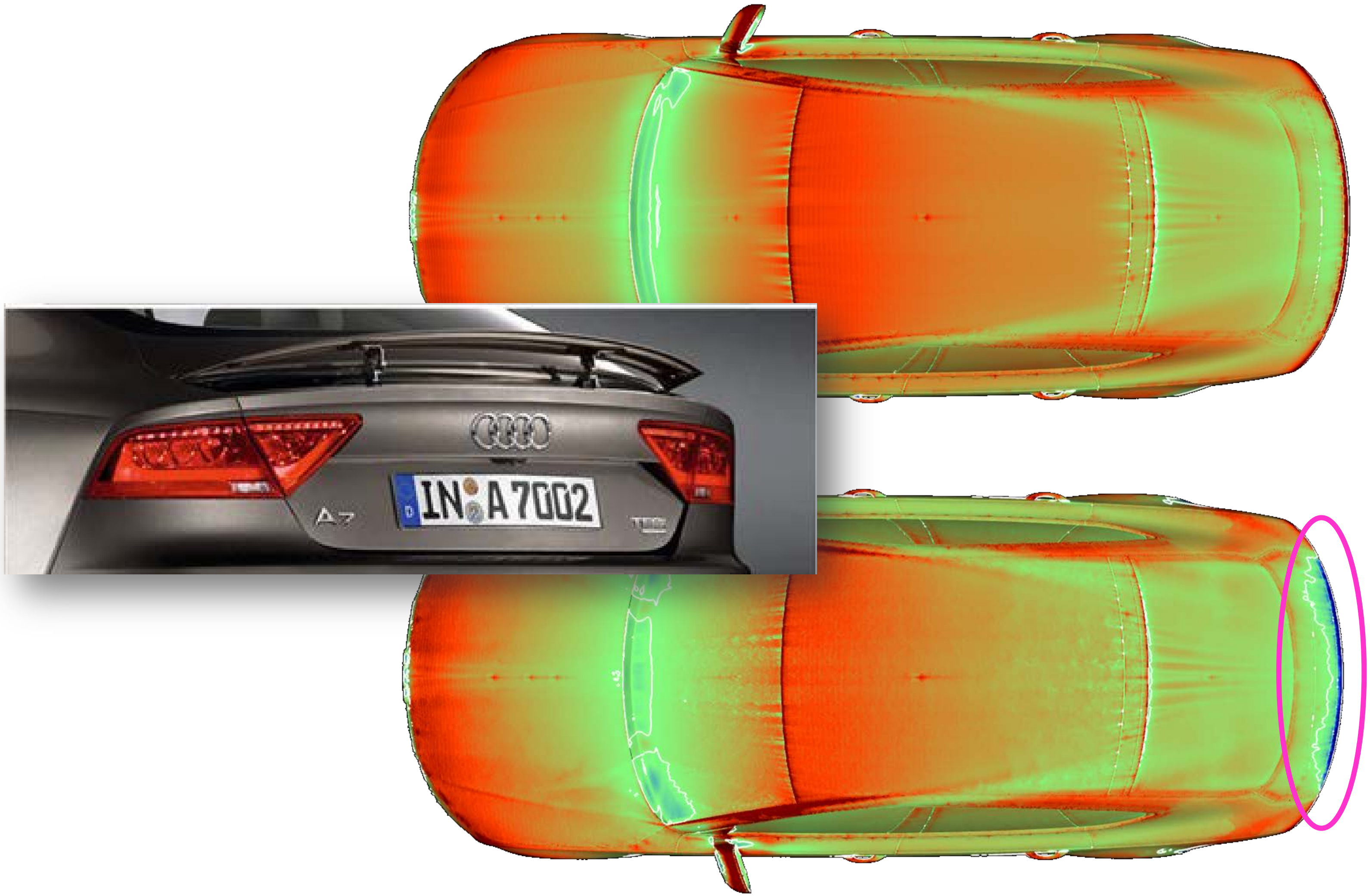
Approximate DES-Based Sensitivities

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

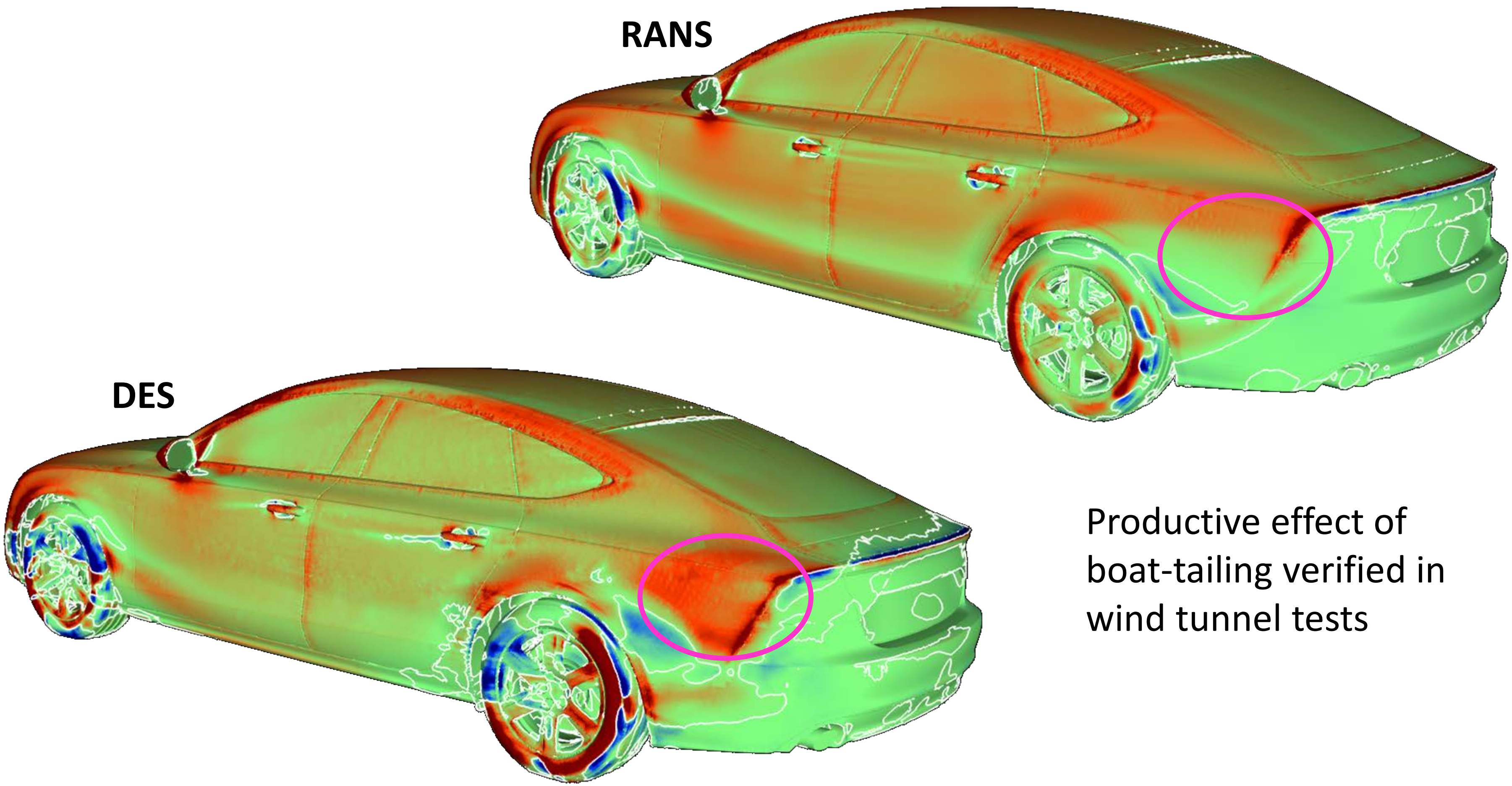
RANS vs. DES: Drag Sensitivities Audi A7



RANS

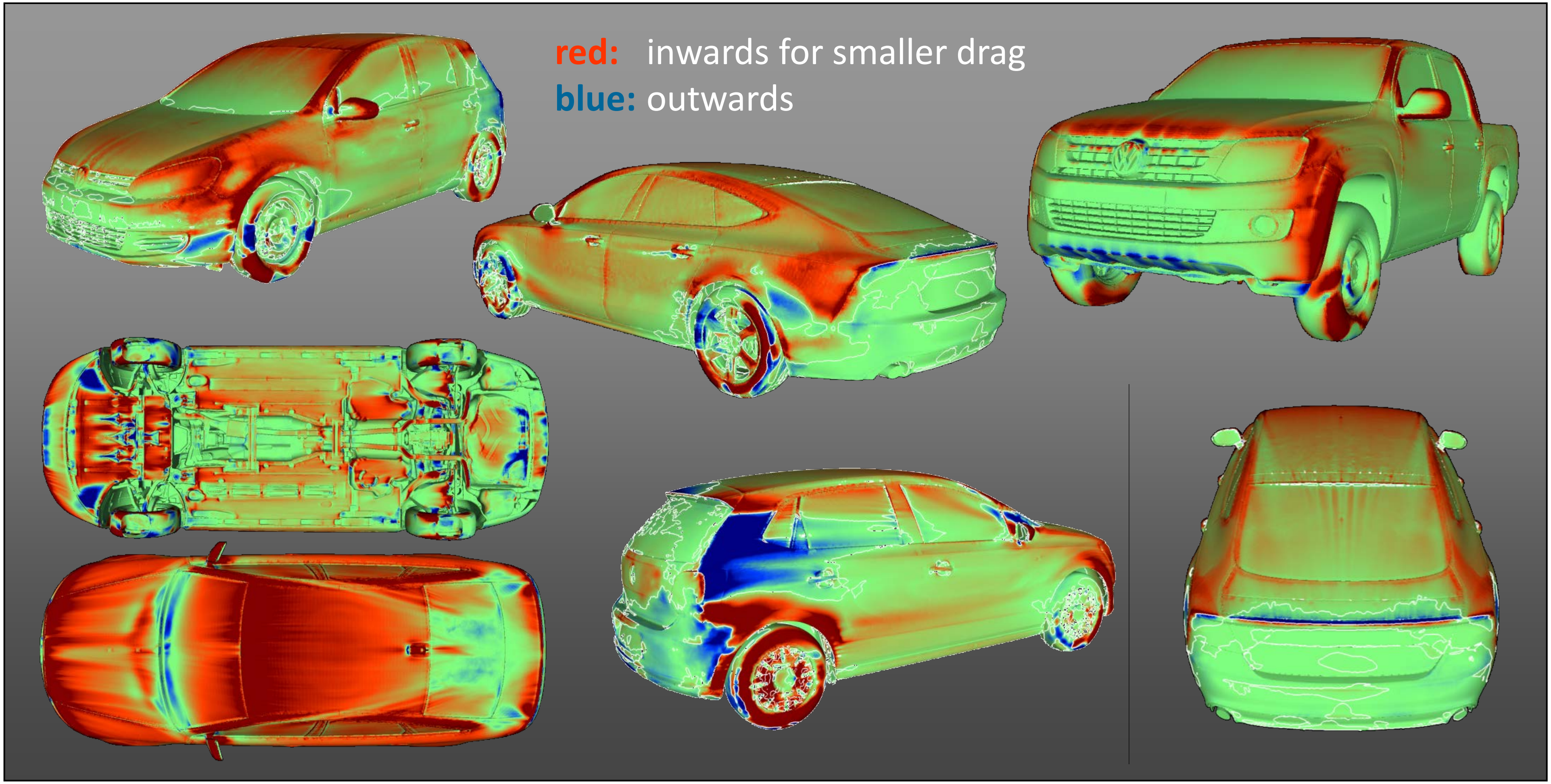
DES

RANS vs. DES: Drag Sensitivities Audi A7

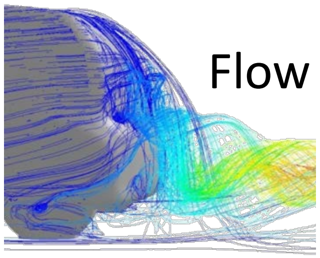


Productive effect of boat-tailing verified in wind tunnel tests

Drag Sensitivity Maps Based on DES: Further Examples

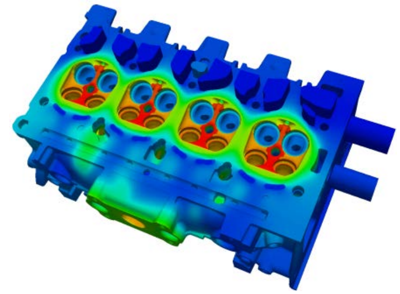


Adjoint-Based Optimization for Cars: Overview



Flow Control

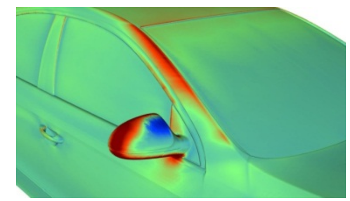
Cooling Optimization

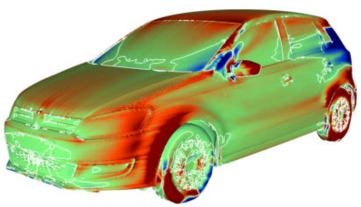


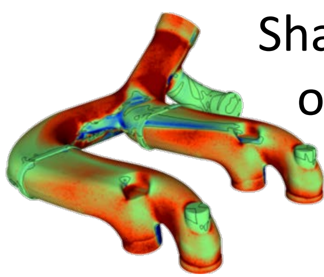
Vehicle Shape Optimization

Continuous Adjoint Method

Aeroacoustic Optimization

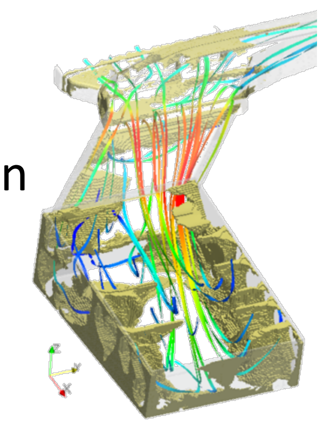






Shape Optimization of Ducted Flows

Topology Optimization

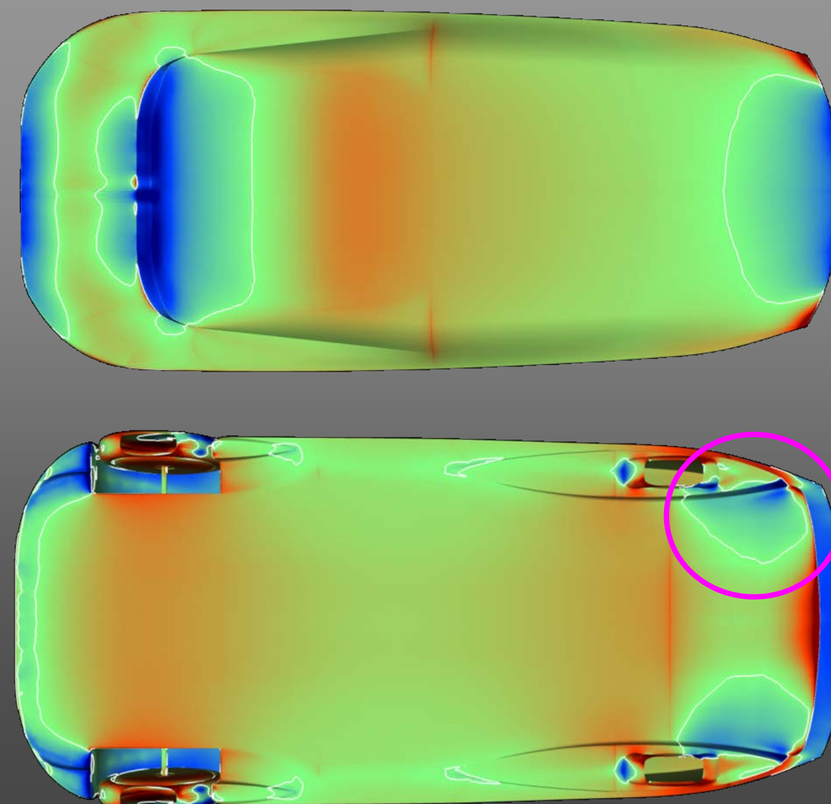


Case Study Volkswagen XL1: Drag Sensitivities

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

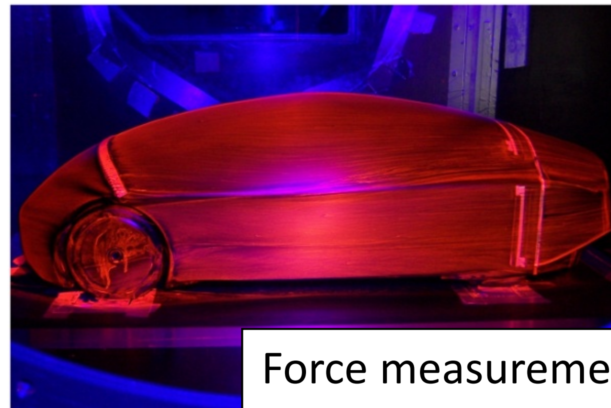
blue: blowing favourable

red: suction favourable

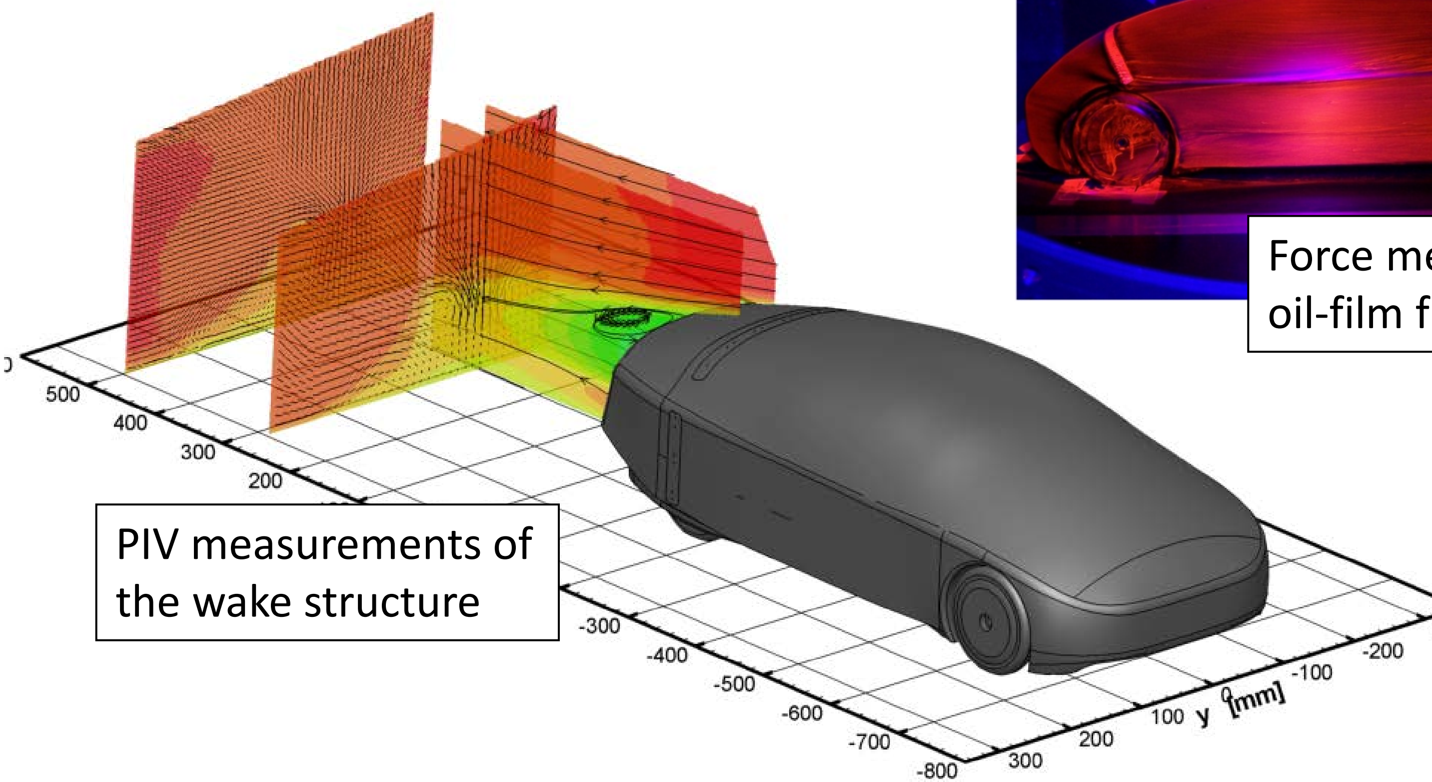


Wind Tunnel Measurements on a 1:4 Model

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

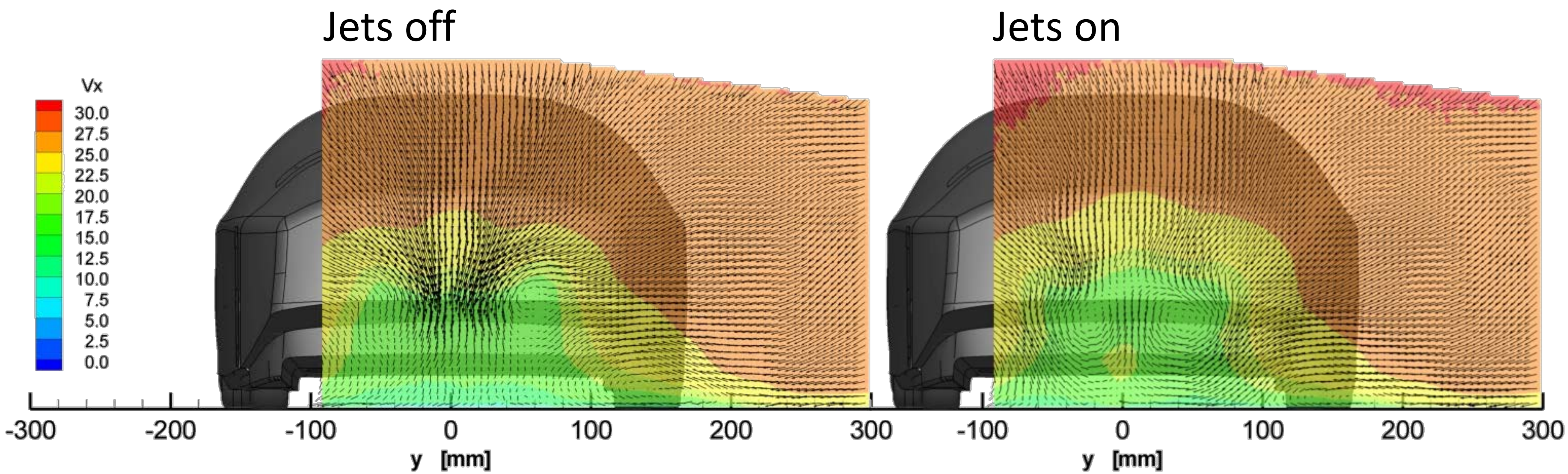


Force measurements and oil-film flow visualization



PIV measurements of the wake structure

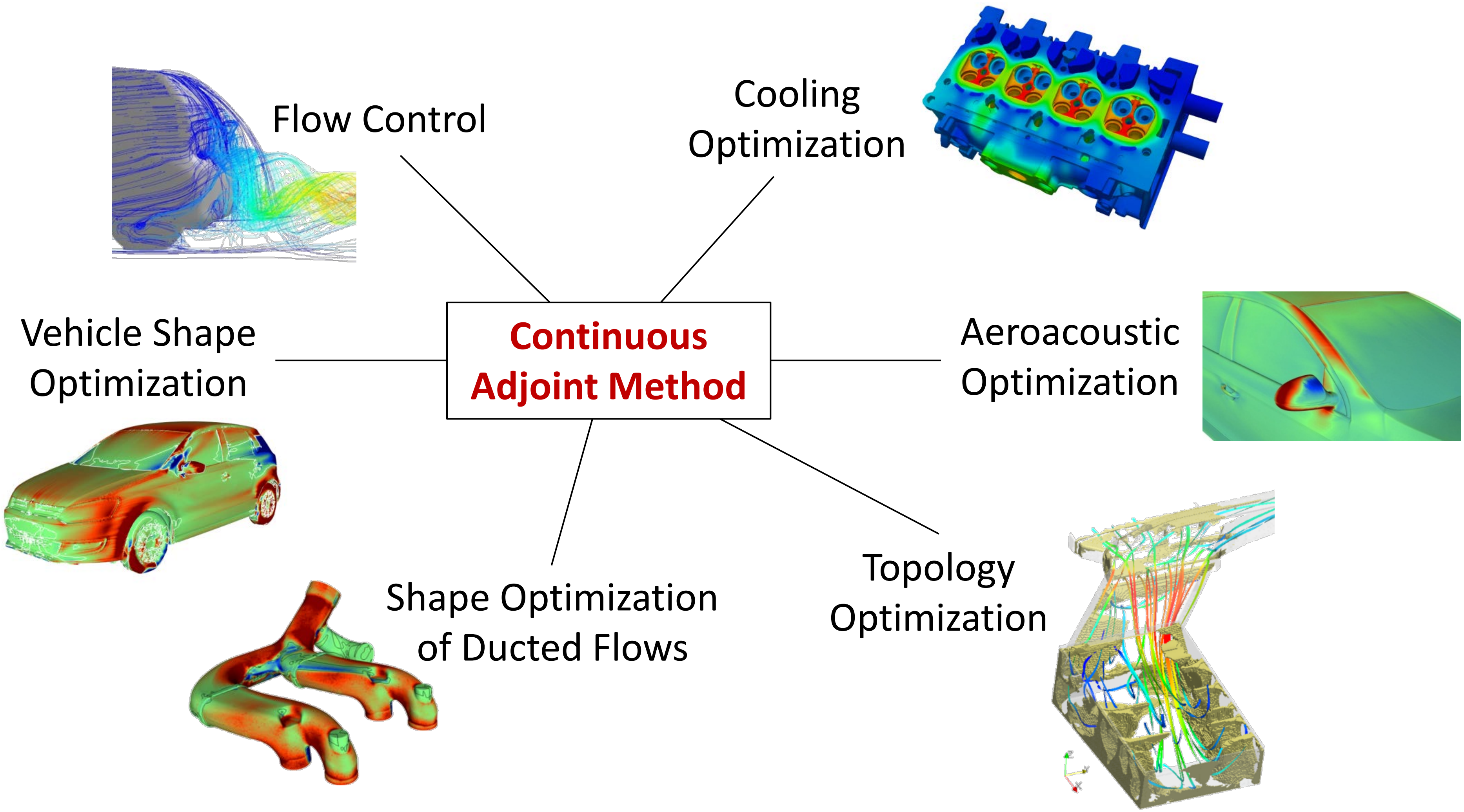
PIV Measurements behind the Car



- Much weaker longitudinal vortices

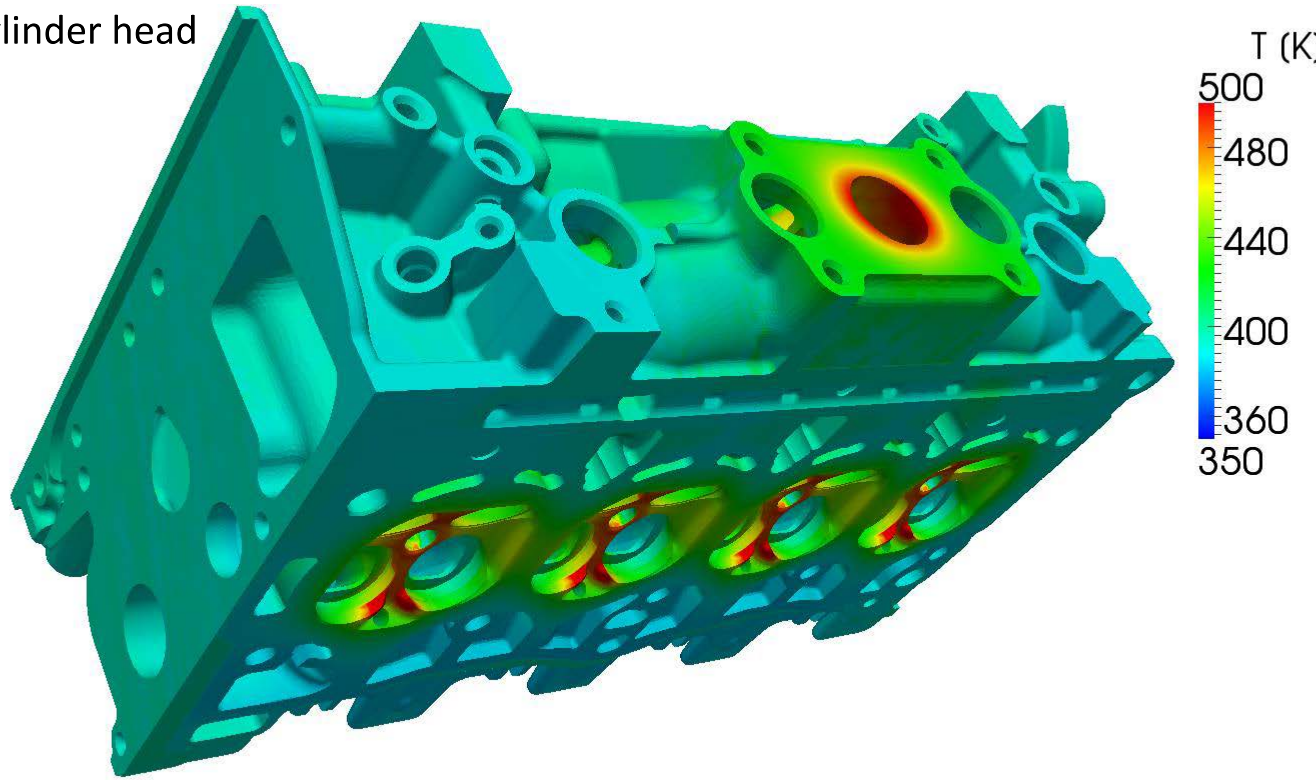
- Significant reduction on rear lift: 0.10 → 0.08
- Measurable effect on drag (<1%), but still too small to be economic

Adjoint-Based Optimization for Cars: Overview



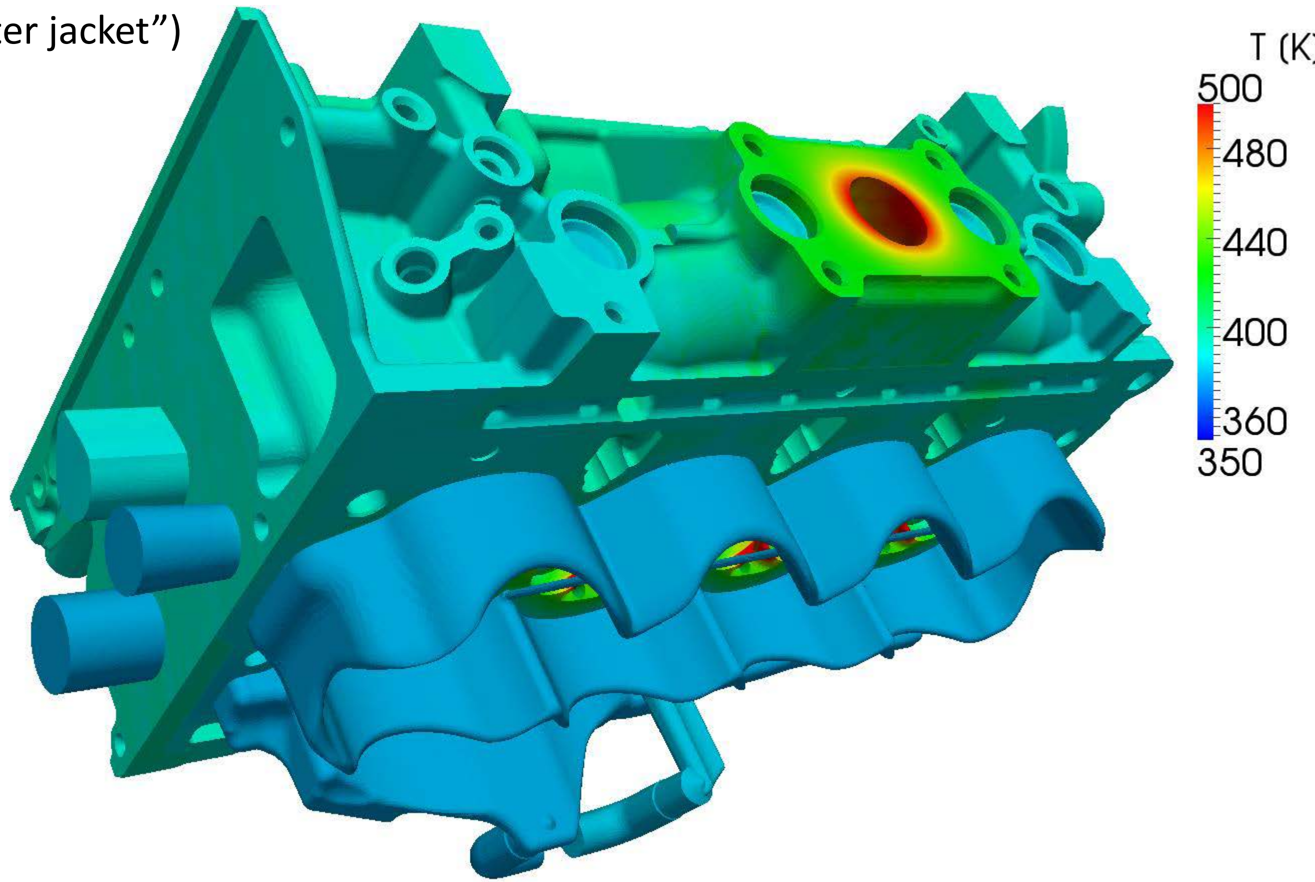
Main Motivation: Cylinder Head Cooling

Solid part of the cylinder head



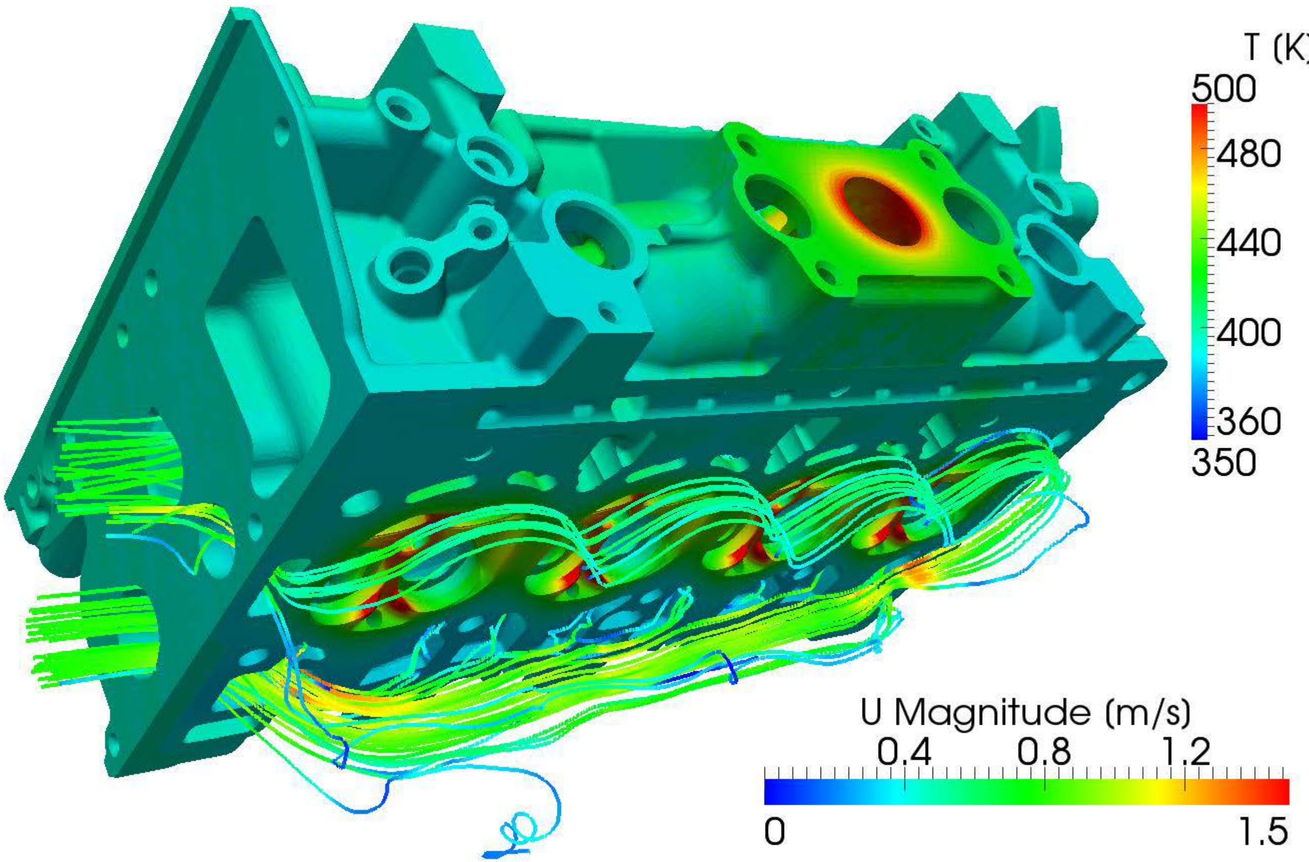
Main Motivation: Cylinder Head Cooling

Fluid volume ("water jacket")



Main Motivation: Cylinder Head Cooling

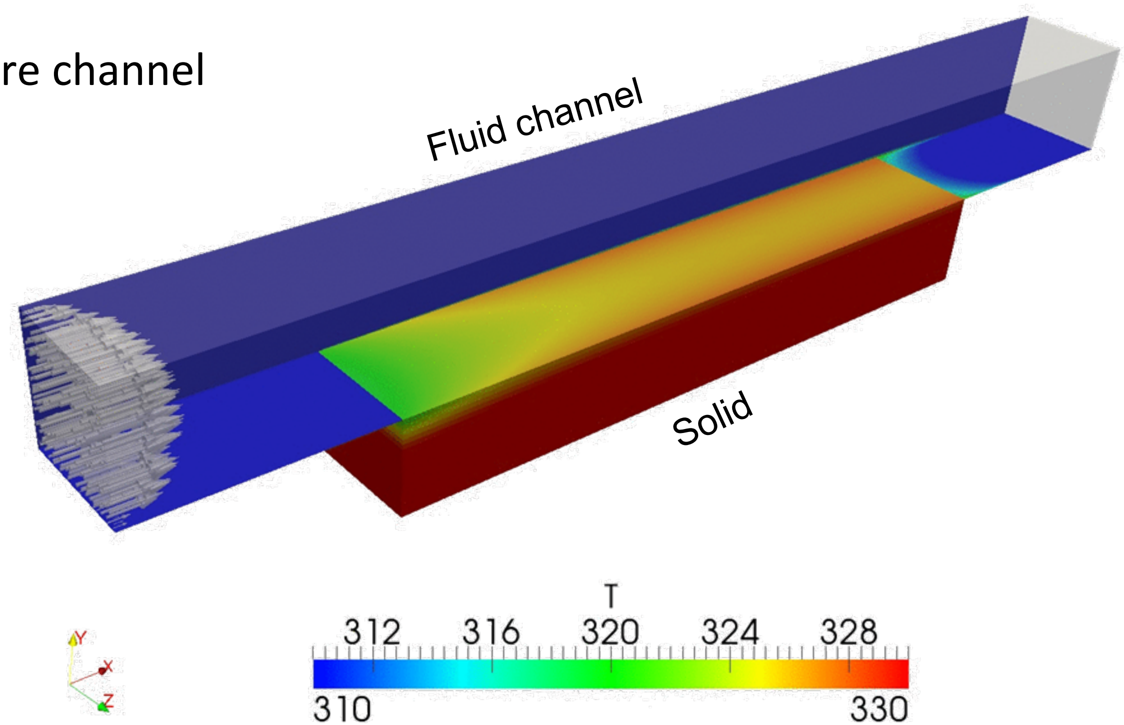
Streamlines



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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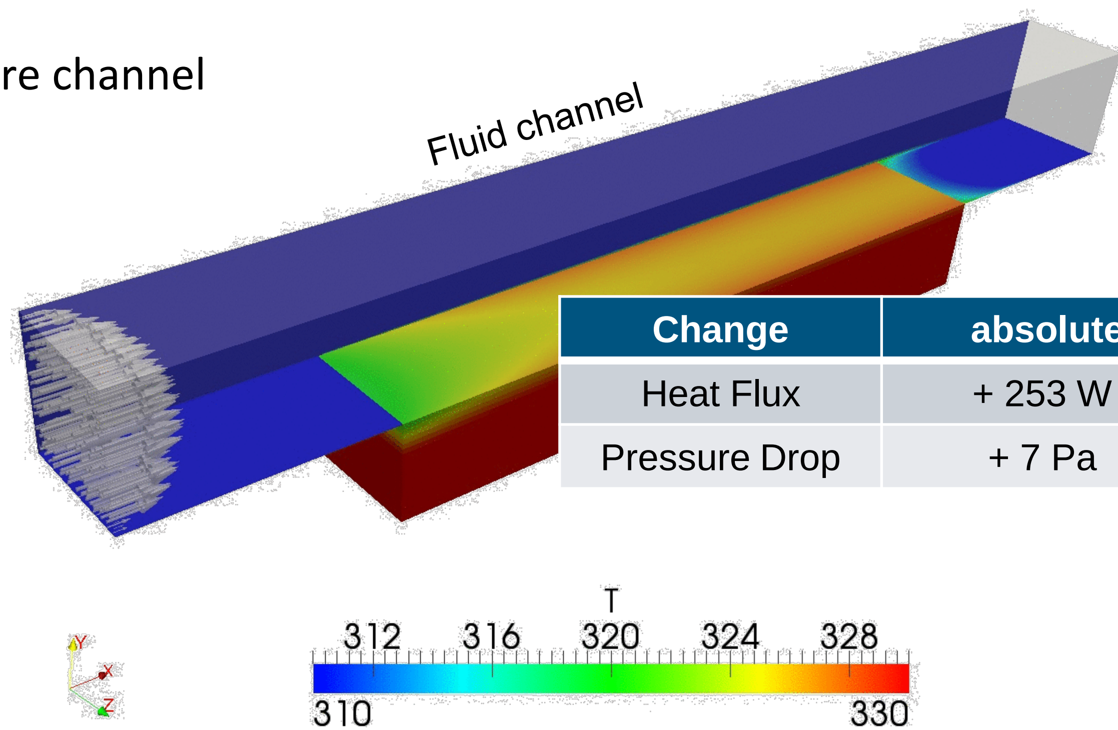
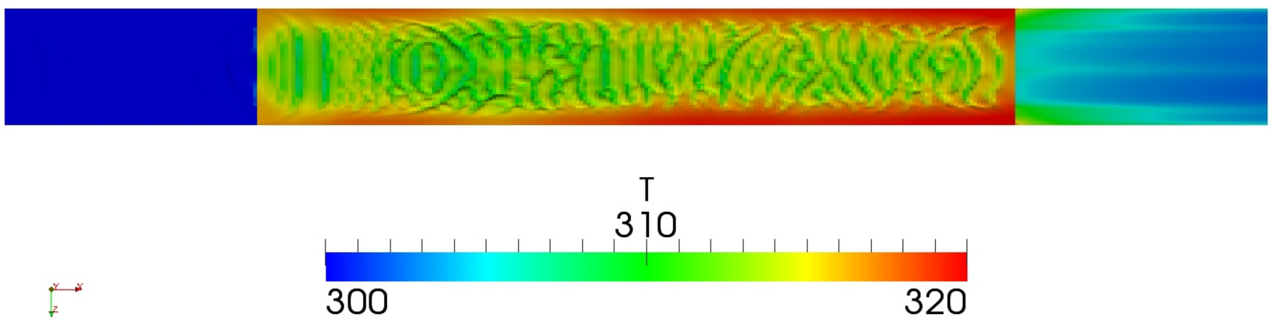


[from H. Narten, VW EA]

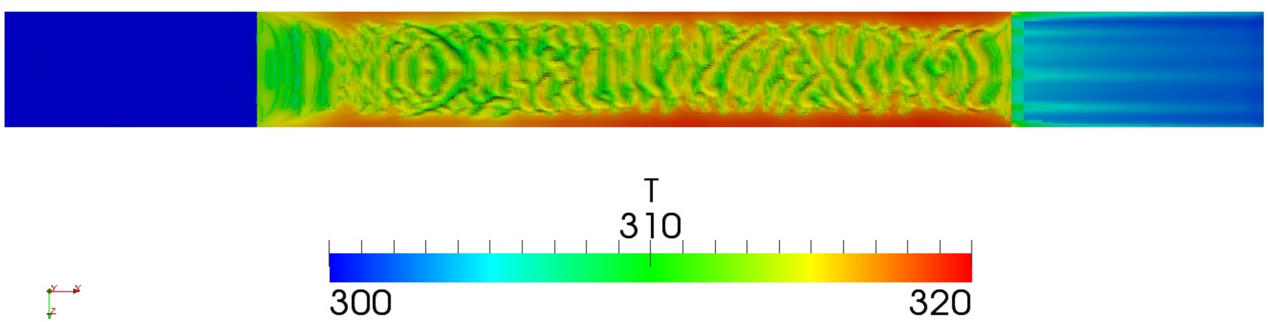
Change	absolute	relative
Heat Flux	+ 253 W	**+ 47 %**
Pressure Drop	+ 7 Pa	+ 13 %

Check 1: Physics or Numerical Noise?

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



Original

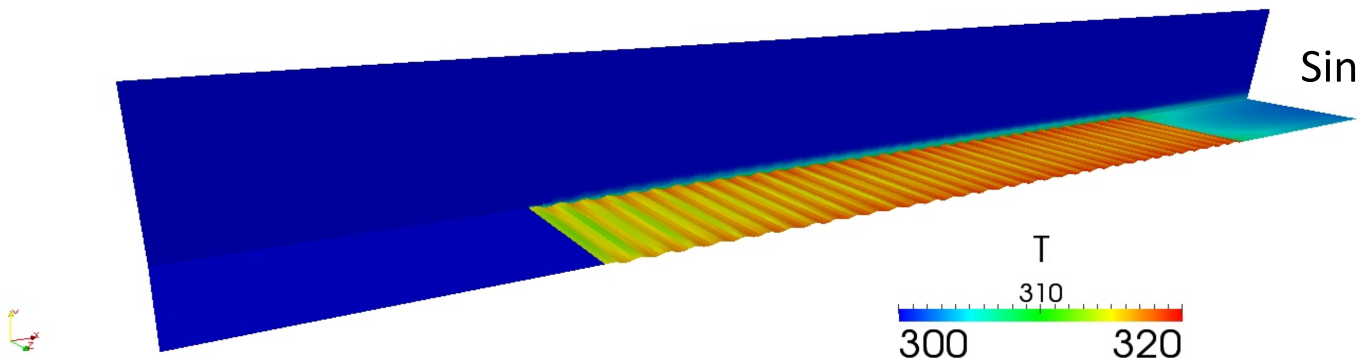


Fine Mesh

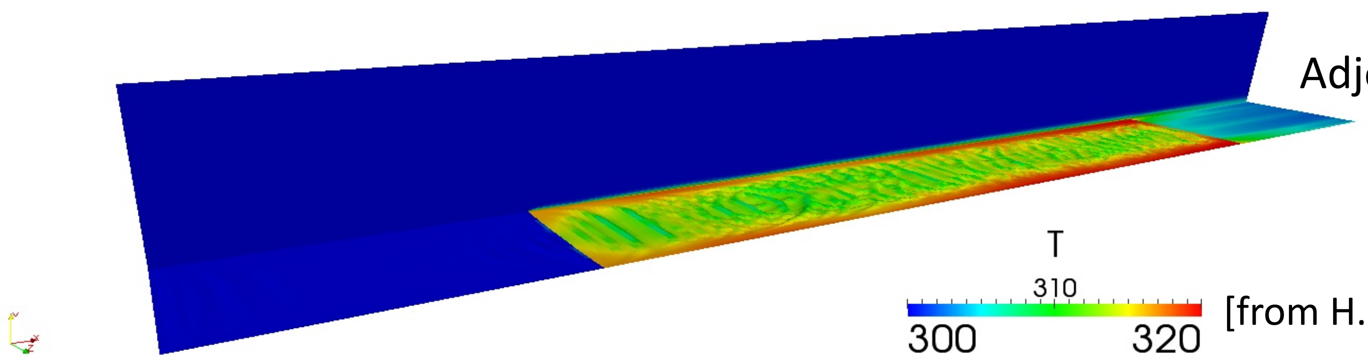
[from H. Narten, VW EA]

Check 2: Comparison with Sinusoidal Wave Pattern

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



Sinusoidal waves

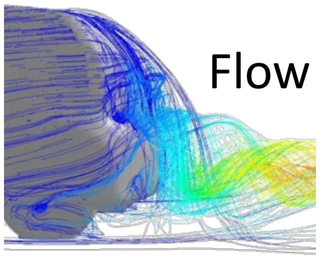


Adjoint-based waves

[from H. Narten, VW EA]

Adjoint-Based Optimization for Cars: Overview

Continuous Adjoint Method



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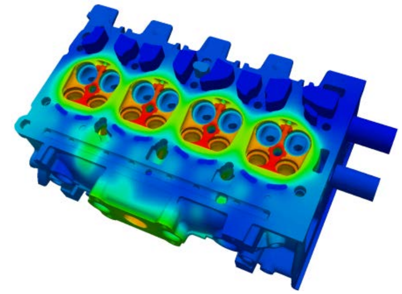
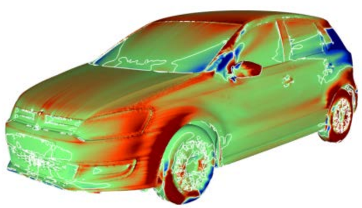
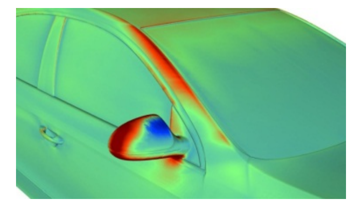
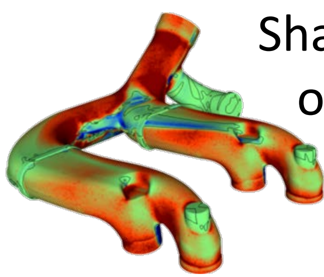


Vehicle Shape Optimization



Aeroacoustic Optimization





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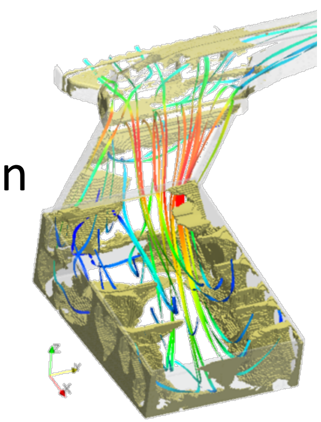
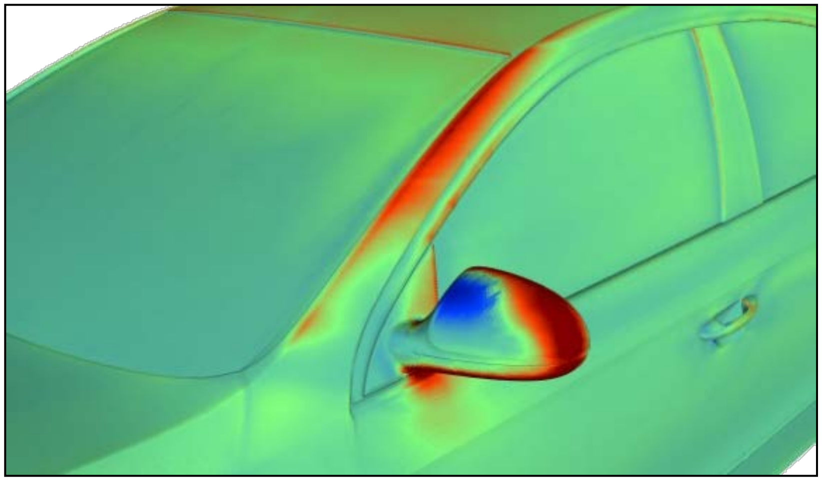
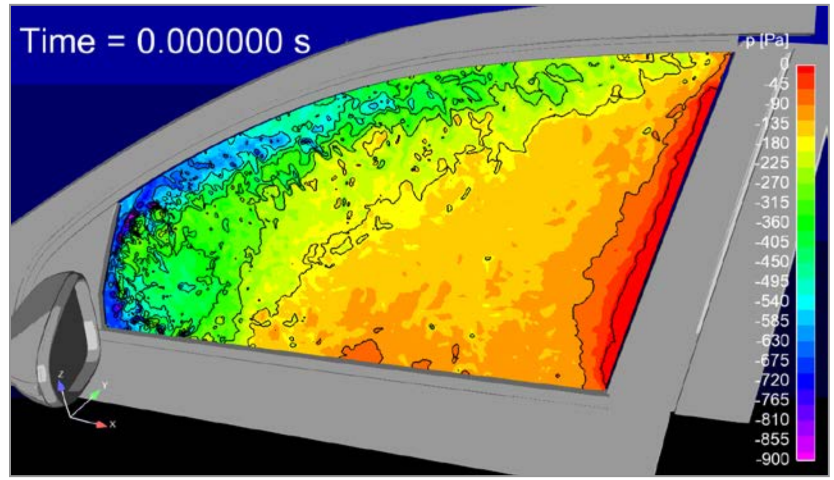


Aeroacoustics: Mirror Noise

RANS



DES [from M. Hartmann, VW Research]



Surrogate cost functions:

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

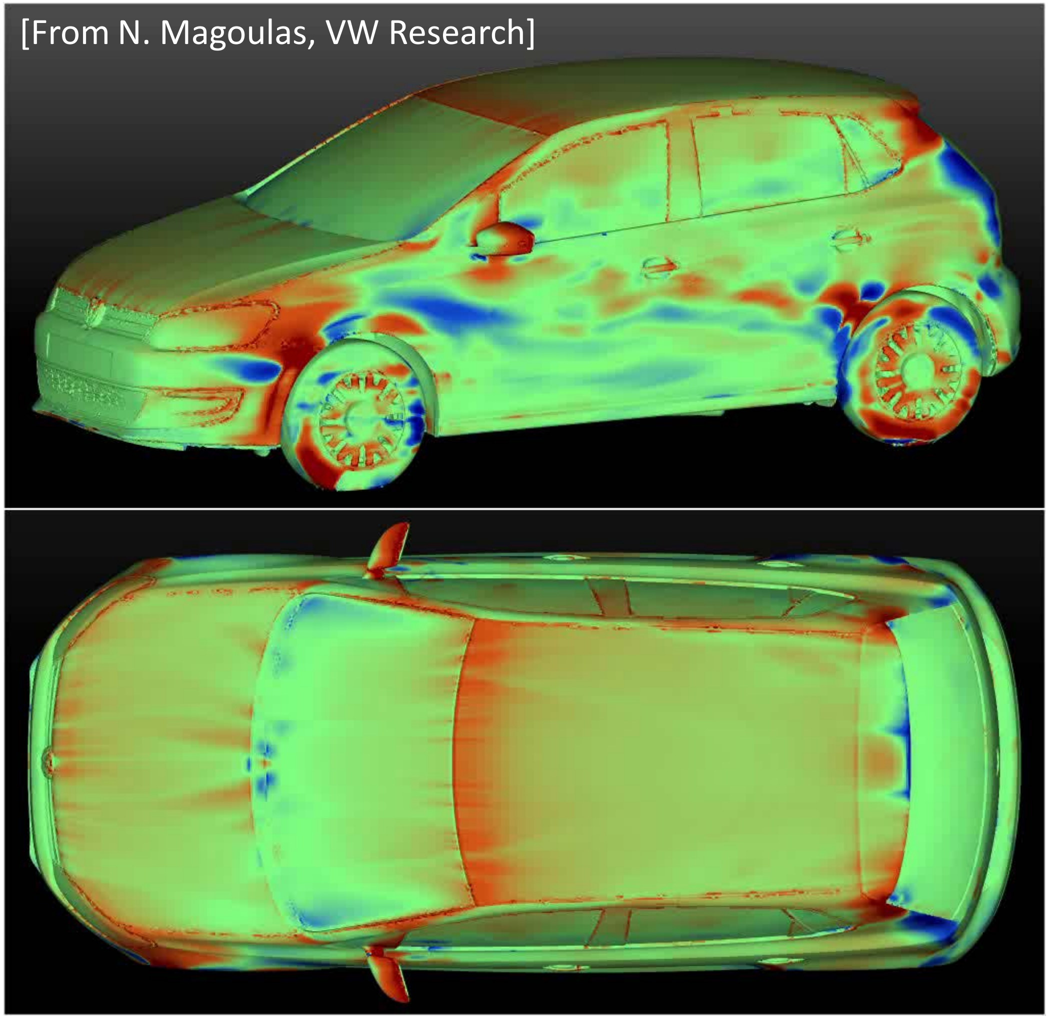
More adequate cost function:

- $J = (p(t)–p_{avg})^2$

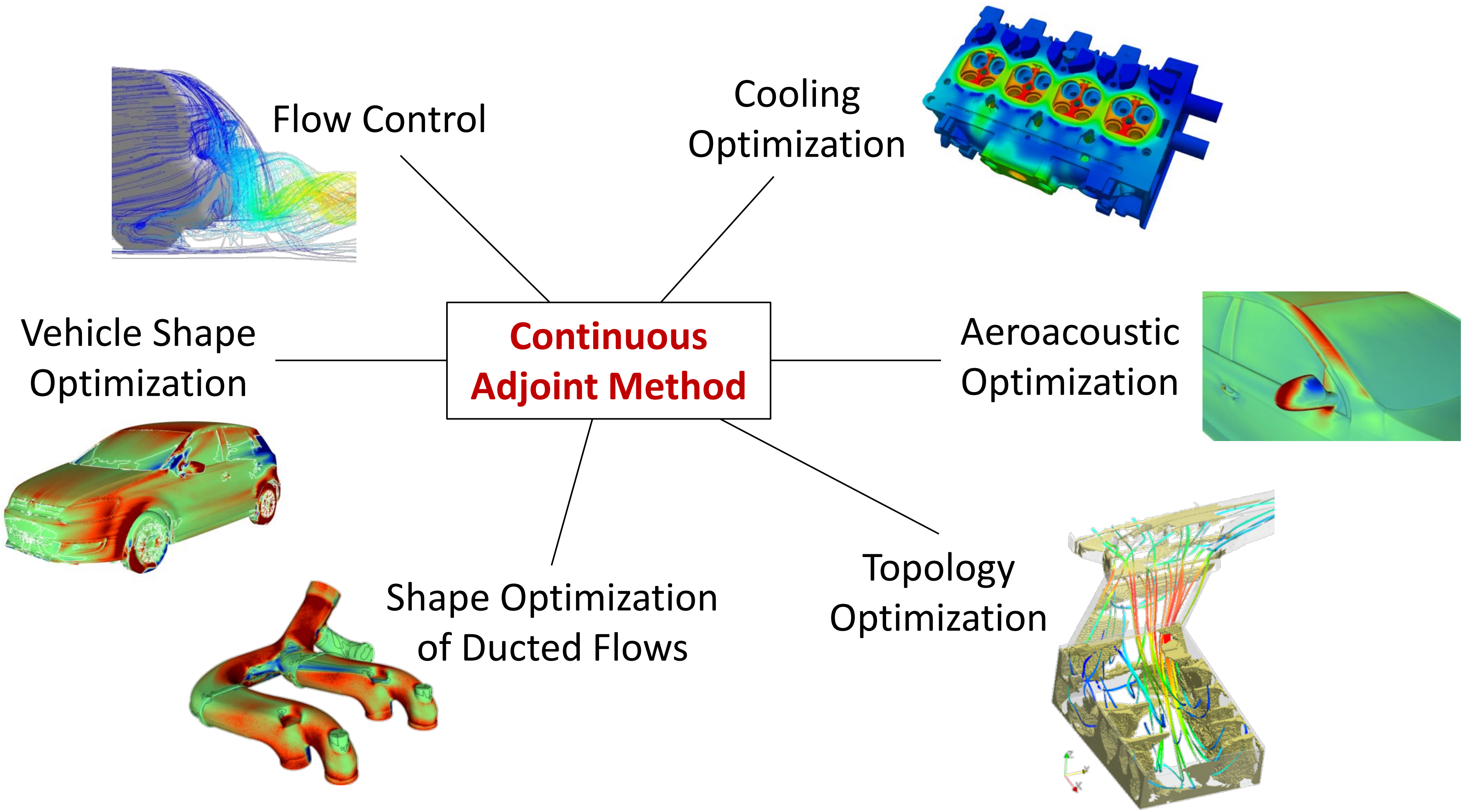
Time-varying adjoint source term:

- $\text{div } u = p(t)–p_{avg}$

Towards Unsteady Adjoints: DES Drag Sensitivities



Summary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