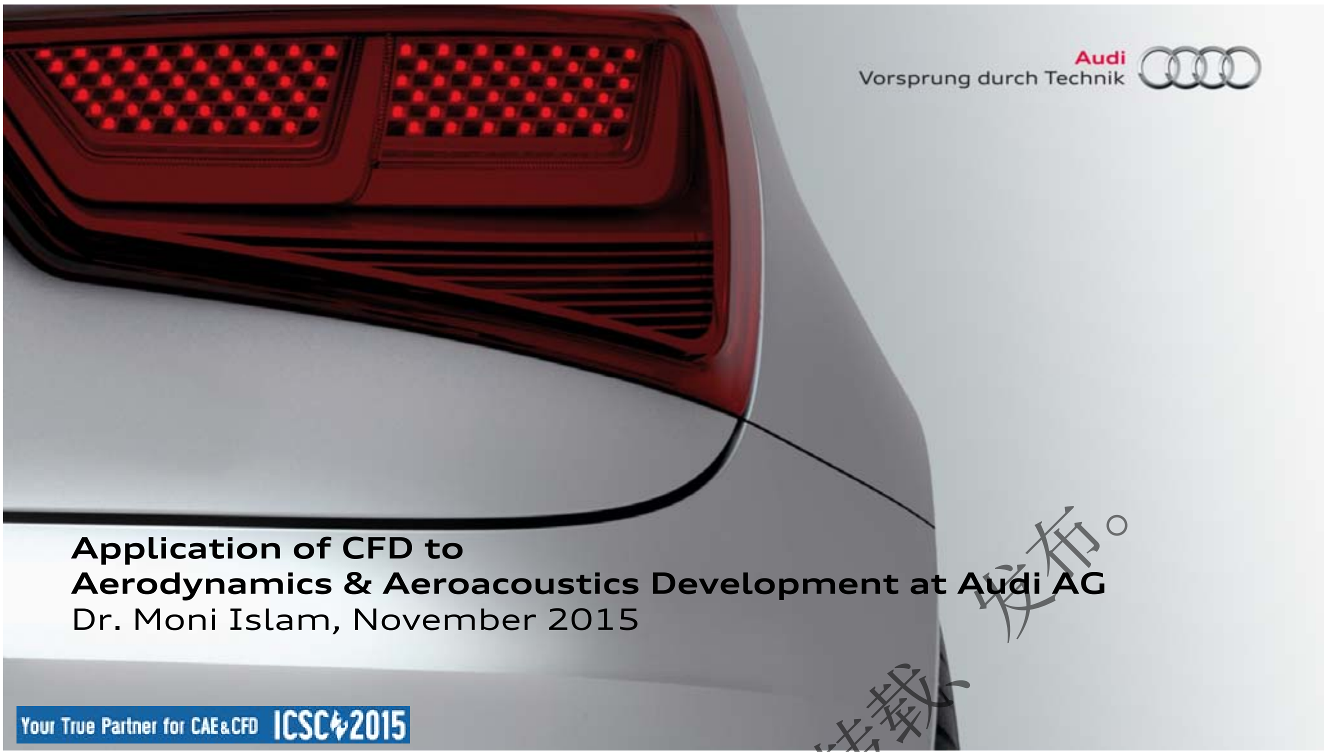

Application of CFD to Aerodynamics & Aeroacoustics Development at Audi AG

Dr. Moni Islam, November 2015

Your True Partner for CAE&CFD ICSC 2015

Aerodynamics & Aeroacoustics Development at Audi

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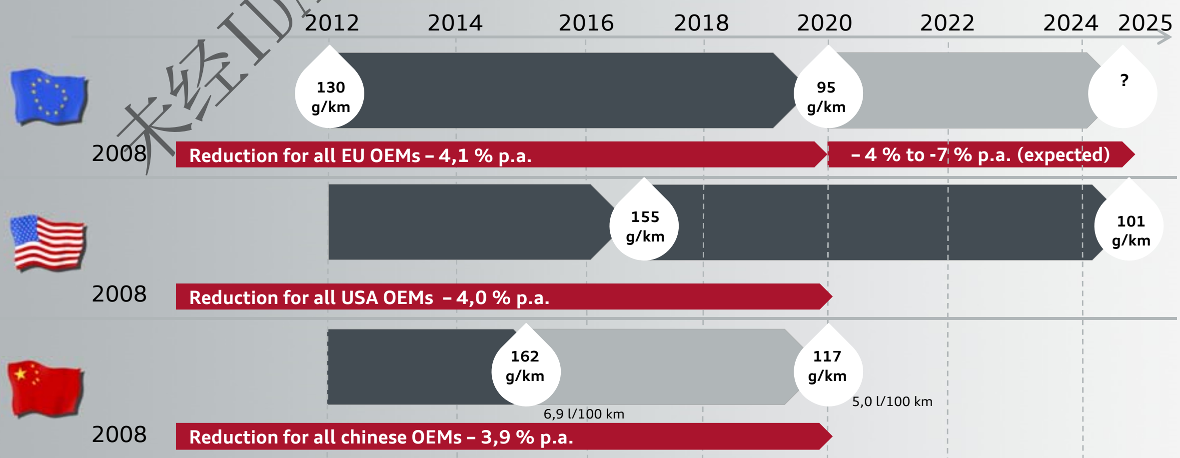
Aerodynamics & Aeroacoustics Development at Audi

CO_2 Targets for Audi Fleet



- Pressure on CO_2 value of entire Audi fleet due to worldwide legislation

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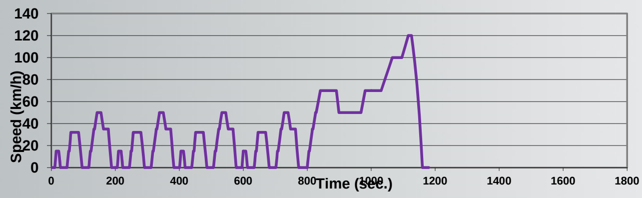
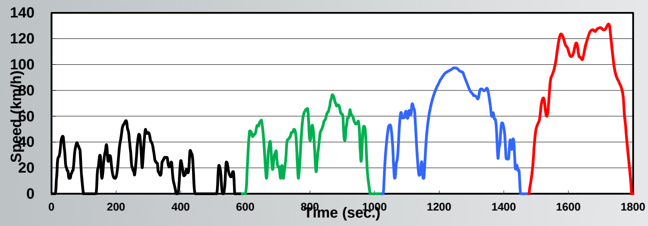
Aerodynamics & Aeroacoustics Development at Audi
WLTP Certification Cycle (1)

NEDC



33.6 km/h

WLTP



46.5 km/h

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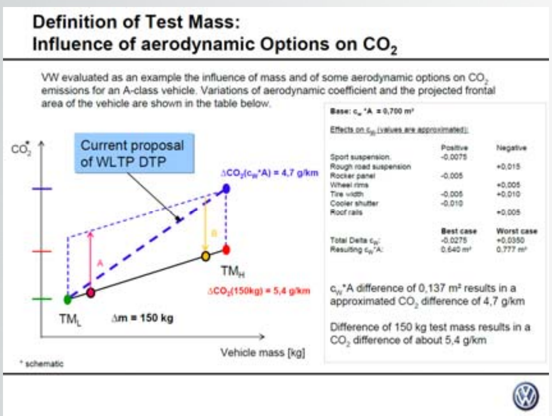
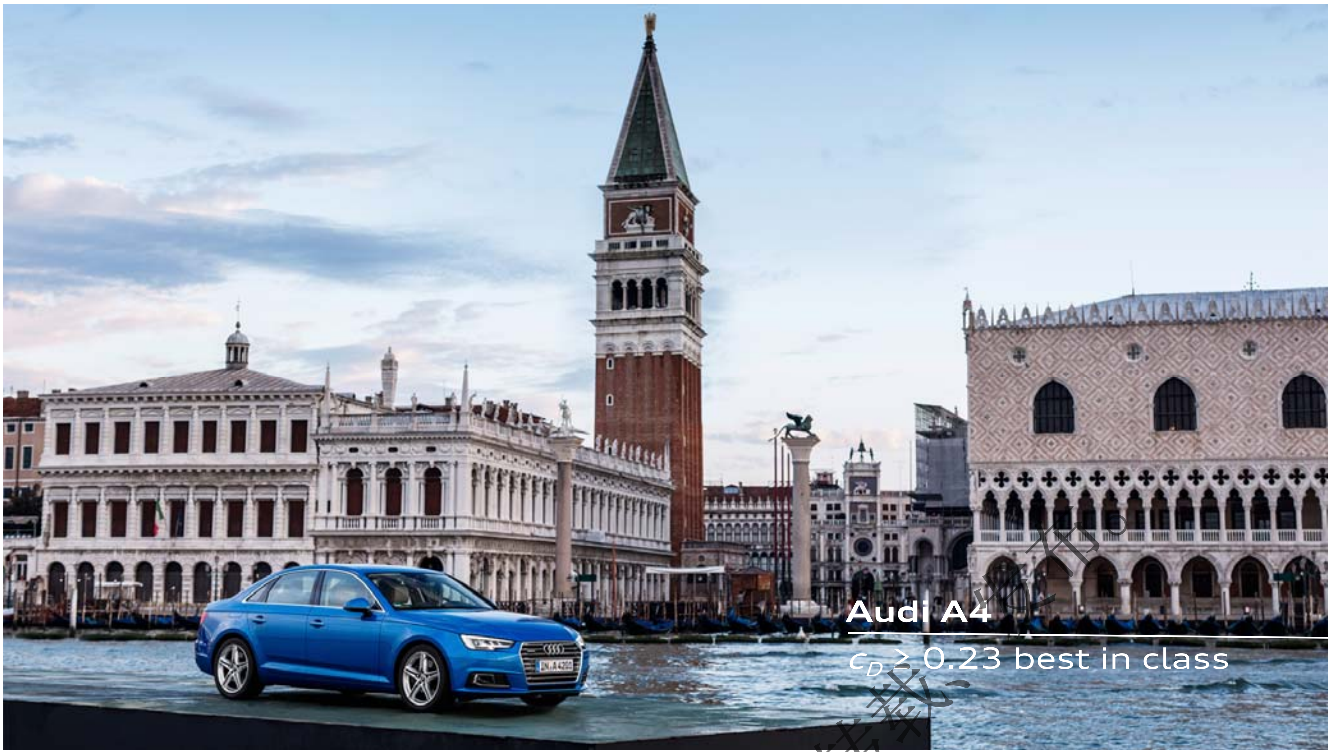
Aerodynamics & Aeroacoustics Development at Audi
WLTP Certification Cycle (2)

- Vehicle certification according to WLTP within the next 3 years at latest
- Greater emphasis on aerodynamics in CO_2 targets due to
  - Higher average vehicle speed
  - Influence of vehicle options (eg. rims, tyres, trim, …) must be accounted for
- Significant challenge for development methods and resources




Audi A4
$c_D \geq 0.23$ best in class


Audi A4
Aeroacoustics best in class
Vorsprung durch Technik

Aerodynamics & Aeroacoustics Development at Audi
Development Process

Concept Development

- Analysis of predecessor and competitor vehicles
- Assessment of proposed vehicle concept w.r.t.:
  - Powertrain
  - Suspension
  - Ergonomics
  - Packaging
  - Underbody
  - Doors / sealings
  - Glazing
  - Add-on parts
  - Damping measures
- Definition of targets

Development

- Continuous development and optimisation of relevant details in cooperation with styling and design departments
  - Exterior surface
  - Add-on parts, eg. mirrors, underbody panels, inlet grille, rain gutter
  - Doors / flaps
  - Roof systems incl. cabriolet soft-top
- Verification and confirmation of development progress at suitable milestones using wind-tunnel and road testing as well as CFD with models and prototypes
- Calibration of aeroacoustics with total vehicle acoustics

Pre-Production

- Optimisation of details related to final production process
- Final confirmation of all aerodynamic and aeroacoustic vehicle properties in wind tunnel and on road

Production

- Periodic monitoring of production vehicles for aeroacoustic quality control
- Analysis of potential weaknesses for improvement in successor projects

Aerodynamics & Aeroacoustics Development at Audi
Aerodynamics Goals

- Basic premise for development of production vehicle:
  - Optimum between styling, costs and aerodynamics must be achieved
- c_D target increasingly driven by CO_2 targets
- c_L targets primarily driven by vehicle-dynamics requirements

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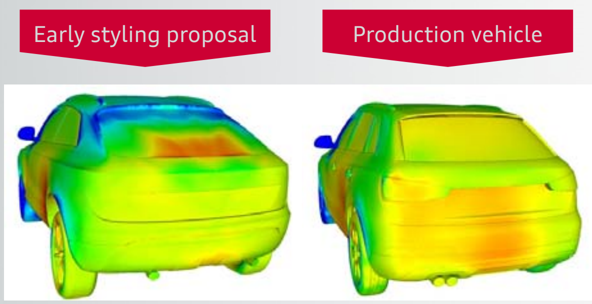
Aerodynamics & Aeroacoustics Development at Audi
Focus of Aerodynamics Development Activities (1)

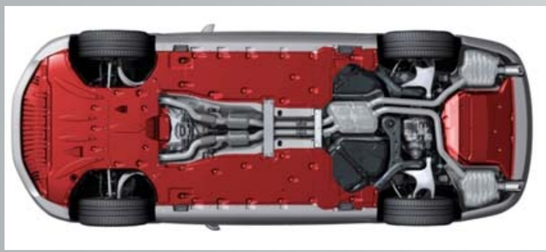
- Optimisation of add-on parts e.g. roof and rear-window spoilers

- Development of vehicle styling for optimal aerodynamics

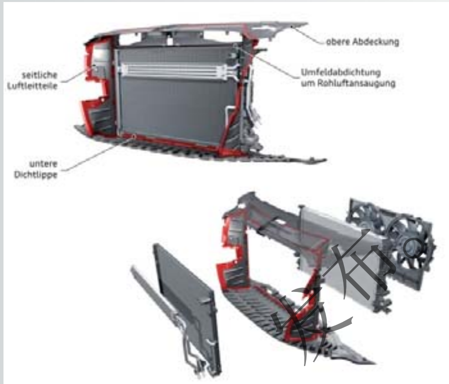


Aerodynamics & Aeroacoustics Development at Audi
Focus of Aerodynamics Development Activities (2)

- Functional optimisation of all platform components including underbody



- Functional optimisation of cooling-air ducting



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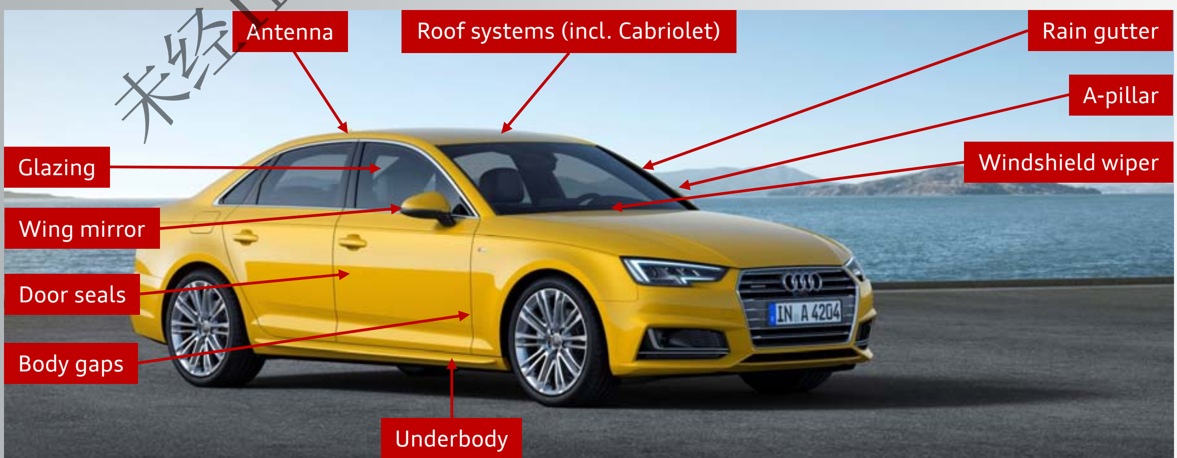
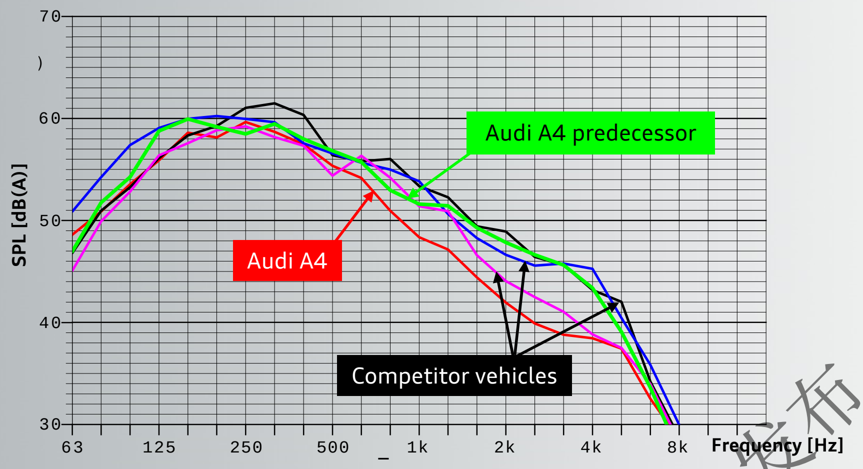
Aerodynamics & Aeroacoustics Development at Audi
Focus of Aeroacoustics Development Activities



Aerodynamics & Aeroacoustics Development at Audi
Audi A4 Aeroacoustics Benchmark



- Goal achieved: “best in class” aeroacoustics

Aerodynamics & Aeroacoustics Development at Audi
Aeroacoustic Wind-Tunnel

- Primary development tool with >2700 h / year testing time for production vehicles

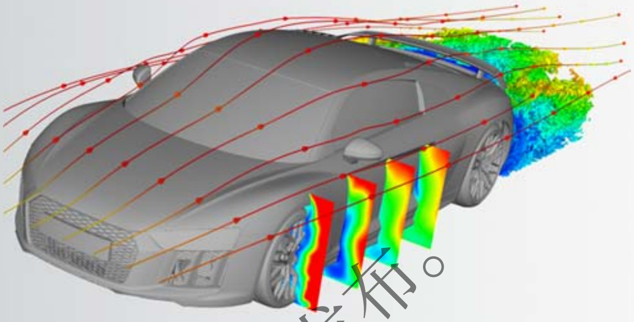
Aerodynamics & Aeroacoustics Development at Audi
Development Tools – Wind Tunnel

- Audi Aeroacoustic Wind Tunnel (1998)
  - Open test section
  - 11 m^2 nozzle
  - Full ground simulation
    - 5-belt system and BL suction
  - 6-component balance for forces and moments up to U_∞ = 300 km/h
- Demand now significantly exceeds capacity
- Used only for full-scale testing
- 1:4-scale testing performed at FKFS wind tunnel in Stuttgart

Application of CFD in the Aerodynamics / Aeroacoustics Development Process

Aerodynamics & Aeroacoustics Development at Audi
CFD – Overview

- Advanced aerodynamics development no longer possible without CFD due to complexity of problems to be solved and accuracy required
- CFD for vehicle aerodynamics standard component of development process with multiple goals
  - Evaluation of styling models in early development phase
  - Substitution of wind-tunnel experiments to compensate for insufficient testing capacity
  - Supplementary information to wind-tunnel data for analysis of phenomena of interest



Aerodynamics & Aeroacoustics Development at Audi
CFD – Requirements for Development Process

- Very short turn-around times / high process integration to keep pace with development cycle
  - <3 days from new geometry to aerodynamics result
  - High robustness of solver
  - Useable also by non-expert users
- High accuracy of results
  - Trends found in experiments must be captured
  - Accuracy must be reliable, especially where no experiments are available
- Acceptable costs
  - Must be competitive with wind tunnel experiments

Aerodynamics & Aeroacoustics Development at Audi
CFD – Motivation for Considering Open-Source Software

- Commercial environment for CFD codes
  - Very small number of commercial codes truly viable for productive use
  - Proprietary technology offering limited insight or black-box approach
  - License fees increase with increasing use
  - Code development driven primarily by vendor's interest
  - Very high overhead associated with switching to alternative product
- Limitations to meeting requirements for aerodynamics development process
- Audi's conclusion: Alternative approach needed!

Aerodynamics & Aeroacoustics Development at Audi
CFD – Features of Open-Source Software (1)

- Solution to many observed problems provided by open-source model for CFD code
- High process integration
  - Robustness, ease of use and application speed achieved by application-specific customisation
- High accuracy in principle
  - Full transparency of technology (vs. black-box approach) permits complete analysis and solution of problems
  - New / alternative technology can be implemented rapidly on demand

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Aerodynamics & Aeroacoustics Development at Audi
CFD – Features of Open-Source Software (2)

- Costs under GPL licensing
  - Remain fixed with increasing use: No license fees coupled to solver use
  - Limited and predictable: User pays for only what he needs
- General advantages
  - Excellent long-term potential for technological development and process integration due to high customisability
  - No inherent disincentives to use of technology
    - Closer coupling to vehicle development process through increased use
    - More rapid technological development
  - User has free choice of technology provider

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Aerodynamics & Aeroacoustics Development at Audi
Application of Open-Source CFD Technology

- OpenFOAM®-based open-source CFD toolbox chosen by Audi
  - Customised applications development, support and consulting by ICON Ltd.
  - Initially based on public-domain OpenFOAM toolbox
- Multi-year project to fully integrate open-source applications into Audi aerodynamics development process
  - Development and support by ICON and other engineering service providers
  - Validation and integration in collaboration with Volkswagen and SEAT
  - Details first published in SAE 2009-01-0333
- **Full, exclusive productive use for vehicle development since January 2009**

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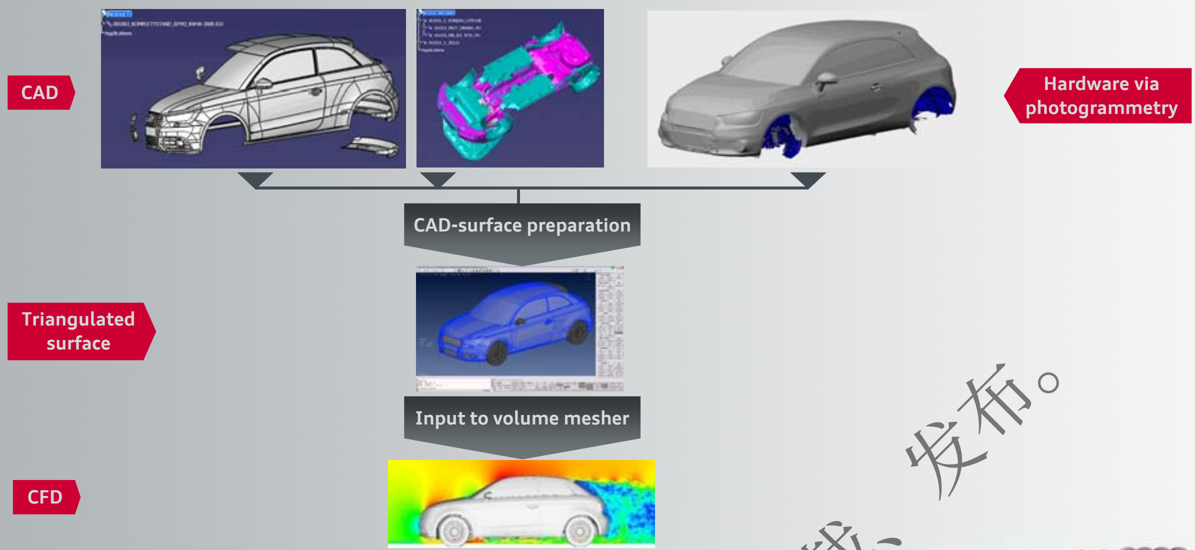
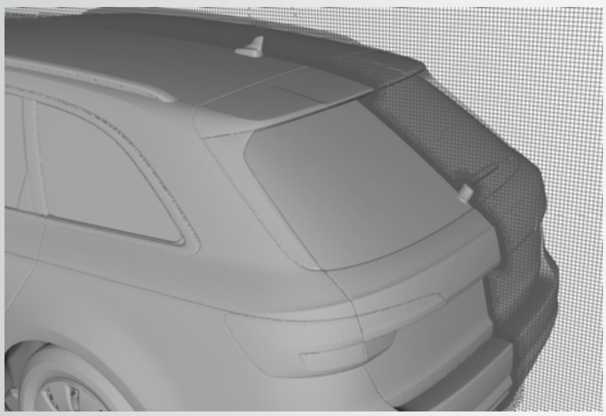
Aerodynamics & Aeroacoustics Development at Audi
Aerodynamics CFD Process



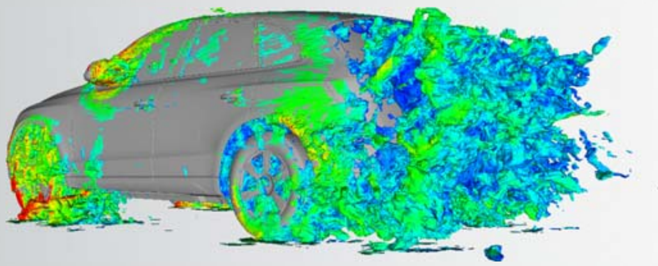
Aerodynamics & Aeroacoustics Development at Audi
Aerodynamics CFD Applications – Mesh Generator

- Volume mesher developed and maintained by ICON
  - Originally based on **autoHexMesh** from public OpenFOAM release
  - Unstructured hexahedral meshes
  - Local refinement
  - Feature-line handling
  - Cell-quality optimisation
  - Fully parallel operation



Aerodynamics & Aeroacoustics Development at Audi
Aerodynamics CFD Applications – Flow Solver

- Multi-step solution procedure developed and maintained by ICON
  - Incompressible LES
  - DES formulation using Spalart-Allmaras model
  - Based on **oodles** solver from public OpenFOAM release
  - Case set-up application to set initial and boundary conditions
  - Local blending for differencing schemes to increase solver stability
  - Function objects for on-the-fly analysis



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Aerodynamics & Aeroacoustics Development at Audi
Aerodynamics CFD Productivity

- Sample computing resources
  - NEC LX2200 cluster with 8064 cores (Intel Xeon E5-2660)
  - QDR Infiniband interconnect
  - Jobs run on 128 to 256 cores
  - Queueing system configured to run up to 10 jobs simultaneously
  - Total of >800 jobs run per year

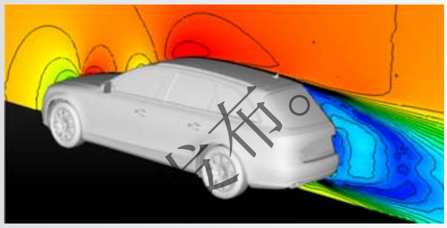
- Bottleneck no longer computing capacity, but human resources!

Aerodynamics & Aeroacoustics Development at Audi
Sample Aerodynamics CFD Result

- Example from standard CFD setup
  - Audi A4 Avant (predecessor vehicle)
  - Includes ground simulation & underbonnet flow
  - Model size: ca. 100 M cells
  - Number of cores: 256
  - Simulation run time: ca. 87 h for 2 s physical time

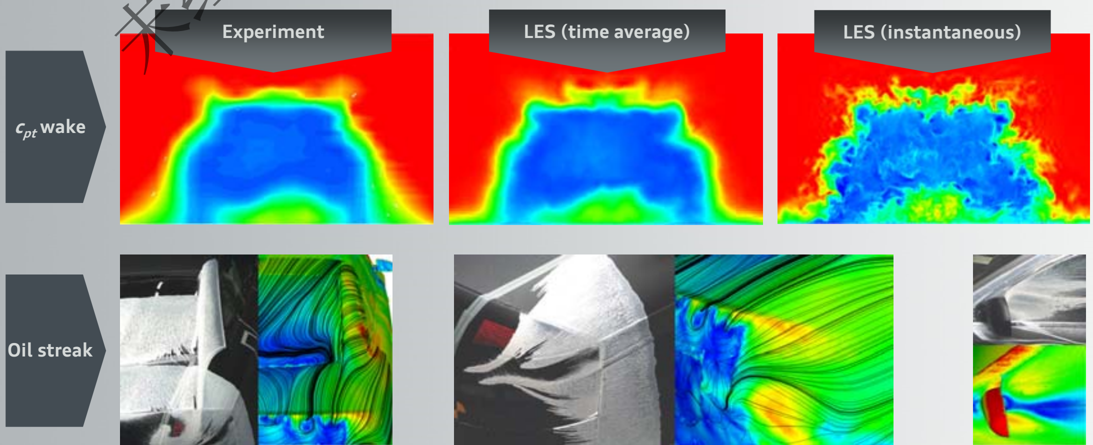
	c_D [-]	c_{Lf} [-]	c_{Lr} [-]
Experiment	0.316	0.086	0.047
Simulation	0.313	0.084	0.071

  - Rear lift typically problematic for estate vehicle



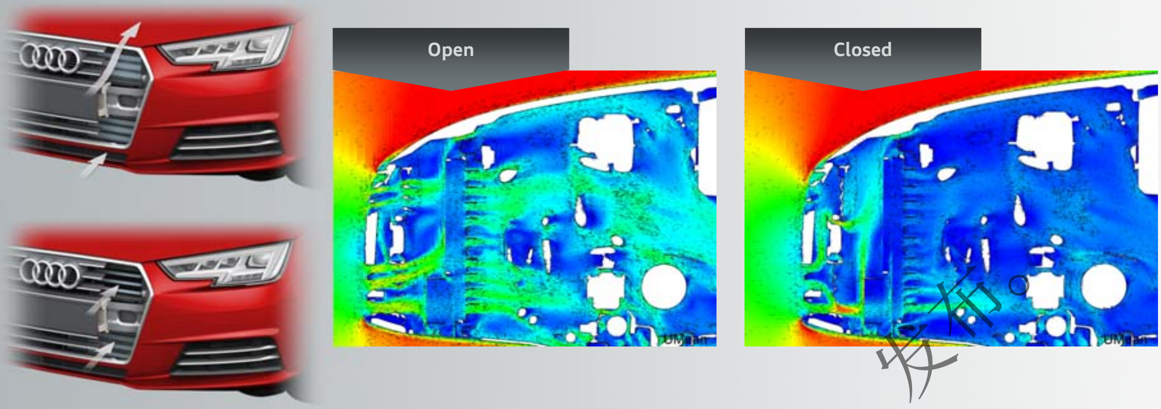
Aerodynamics & Aeroacoustics Development at Audi
CFD Validation Example from 2009 SAE Paper

- Example: Audi A6 predecessor production vehicle (mock-up, no ground simulation)



Aerodynamics & Aeroacoustics Development at Audi
CFD for Audi A4 – Active Inlet Louvres

- Active inlet louvres restrict cooling-air flow, thereby reducing c_D by 0.008



Aerodynamics & Aeroacoustics Development at Audi
Optimised Underbody of Audi A4

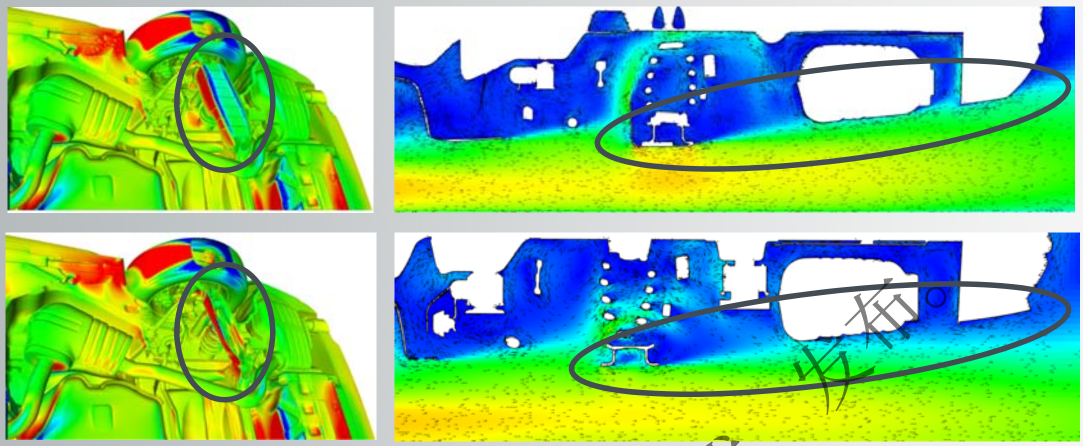
- Optimised underbody reduces c_D by 0.010 compared to predecessor vehicle

Aerodynamics & Aeroacoustics Development at Audi
CFD for Audi A4 – Rear-Axle Flow Deflectors

- Rear-axle flow deflectors reduce c_D by 0.004

With deflectors

Without deflectors



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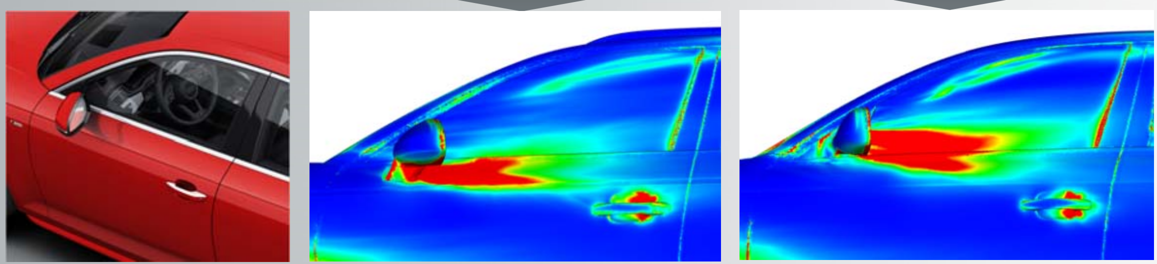
Aerodynamics & Aeroacoustics Development at Audi
CFD for Audi A4 – Wing Mirror

- Mean square pressure fluctuations on side window significantly reduced by optimised mirror concept on new Audi A4 ⇒ major contribution to “best in class” aeroacoustics

Audi A4

Audi A4 predecessor



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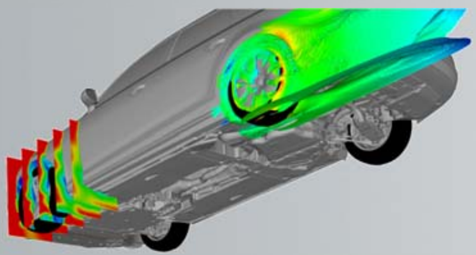
Aerodynamics & Aeroacoustics Development at Audi
CFD Methods Development - Aerodynamics

- Refinement of existing methodology ongoing, as need for improved accuracy always exists
- Methods development always done together with vehicle development
- Deep understanding of all aspects of wind-tunnel testing essential for assessing accuracy of experimental data and pointing to weaknesses of current methodology

Ground simulation

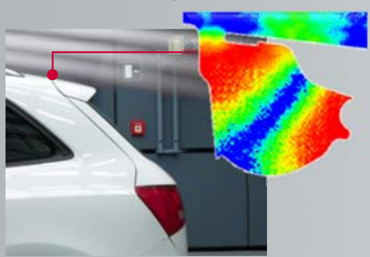


Cooling drag / lift

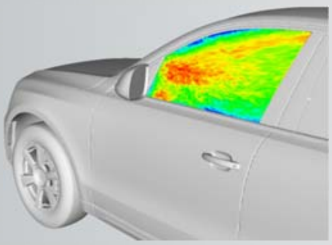
Aerodynamics & Aeroacoustics Development at Audi
CFD Methods Development – Aeroacoustics

- Aeroacoustics CFD currently not standard part of vehicle-development process
- Methods development for various applications ongoing
- Productive use only expected in the long term due to very high complexity of physics

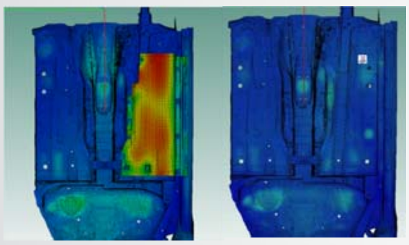
Cavity flow

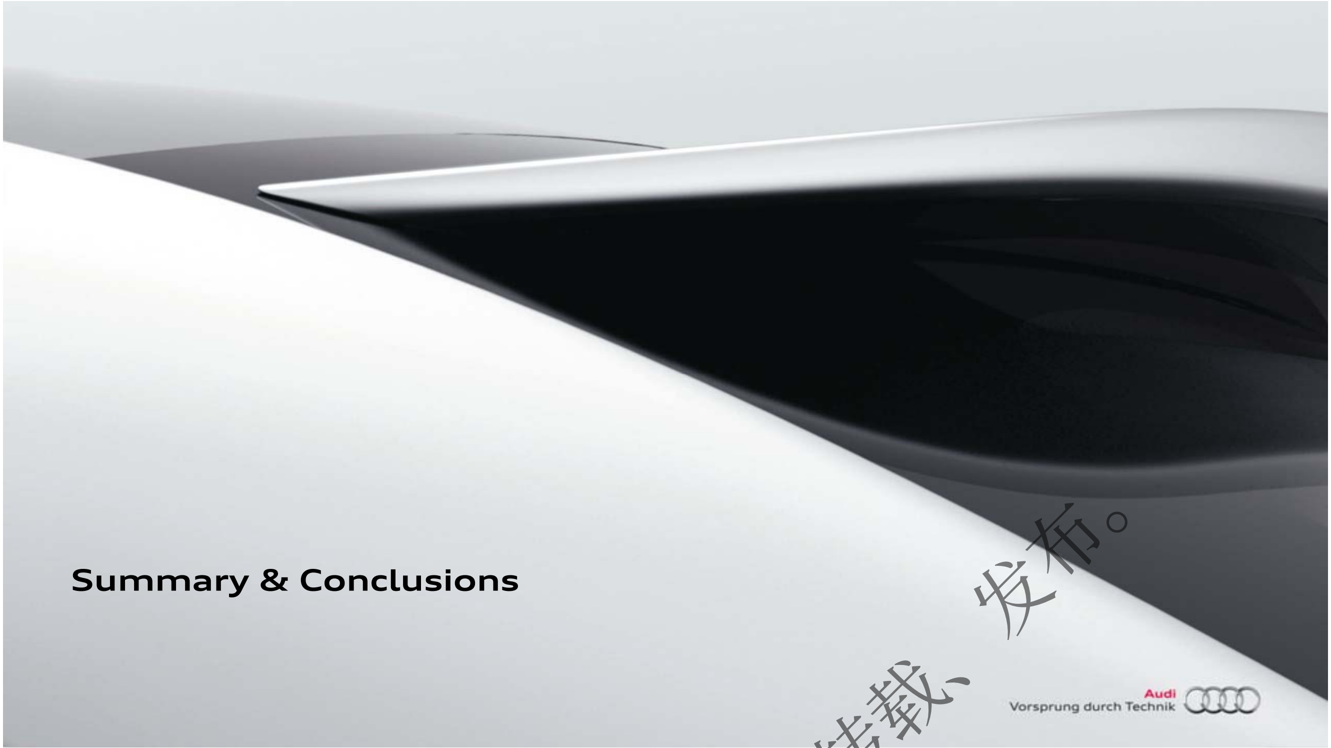


Mirror flow



Flow-induced vibration





Aerodynamics & Aeroacoustics Development at Audi
Open-Source Software in an Industrial Environment

- Integrating open-source software in industrial environment demonstrably viable
- Debunking of common myths required first
  - Open source / GPL licensing does not mean CFD costs nothing
  - Costs exist and must be borne by the user
- Level of complexity no longer higher than closed-source codes thanks to tailored user interface
  - Partnership approach with technology provider important in order to customise applications and improve simulation methods

Aerodynamics & Aeroacoustics Development at Audi
Summary and Conclusions

- Increasing importance of vehicle aerodynamics and aeroacoustics requires modern development tools
- Integrated application of wind-tunnel testing and CFD in Audi's development process
- Open-source CFD most promising technology available for productive process integration
- Both wind-tunnel and CFD technology continue to be developed at Audi to meet challenge of continuously increasing design targets