Computational Fluid Dynamics in Automotive Applications

Hrvoje Jasak

hrvoje.jasak@fsb.hr

FSB, University of Zagreb, Croatia

Outline

Objective

- Review the adoption of Computational Fluid Dynamics (CFD) in automotive industry from mid 1980-s to today
- Outline lessons of automotive CFD relevant to other areas of numerical simulation

Topics

- Computational Fluid Dynamics (CFD): methodology and areas of application
- CFD in modern automotive industry
- CFD capabilities in 1980s
- Early adopters and validation efforts
- Years of expansion
- Lessons learned: broken process and a killer application

Computational Fluid Dynamics

- **Definition of CFD**, from Versteeg and Malalasekera: “An Introduction to Computational Fluid Dynamics”

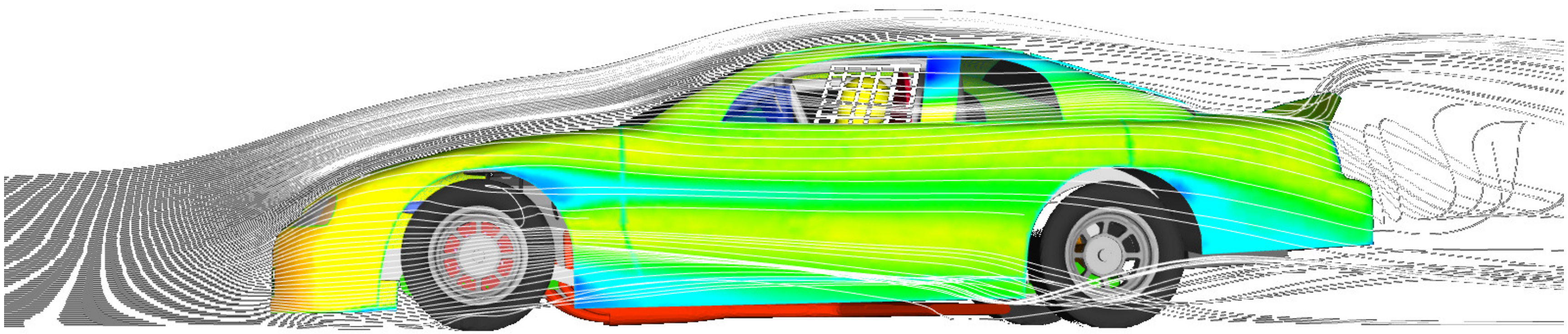
  > “Computational Fluid Dynamics or CFD is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation.”

- CFD is also a subset of Computational Continuum Mechanics: fundamentally identical numerical simulation technology is used for many sets of simular partial differential equations
  - Numerical stress analysis
  - Electromagnetics, including low- and high-frequency phenomena
  - Weather prediction and global oceanic/atmosphere circulation models
  - Large scale systems: galactic dynamics and star formation
  - Complex heat and mass transfer systems
  - Fluid-structure interaction and similar coupled systems
- In all cases, equations are very similar: capturing conservation of mass, momentum, energy and associated transport phenomena

Computational Fluid Dynamics

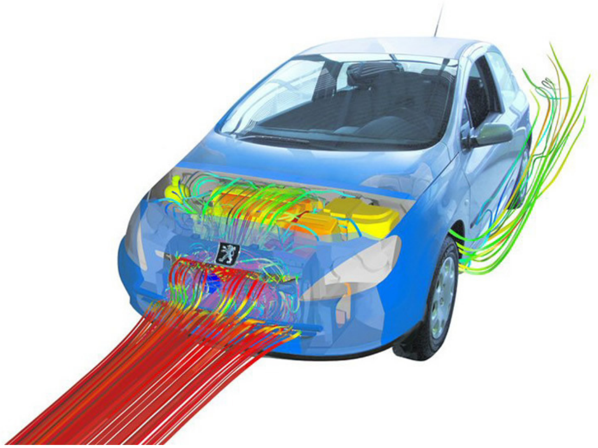
CFD Methodology

- Numerous automotive components involve fluid flow and require optimisation. This opens a wide area of potential of CFD use in automotive industry
- CFD approaches the problem of fluid flow from **fundamental equations**: no problem-specific or industry-specific simplification
- A critical step involves **complex geometry handling**: it is essential to capture real geometrical features of the engineering component under consideration
- Traditional applications involve incompressible turbulent flow of Newtonian fluids
- While most people think of automotive CFD in terms of external aerodynamics simulations, reality of industrial CFD use is significantly different

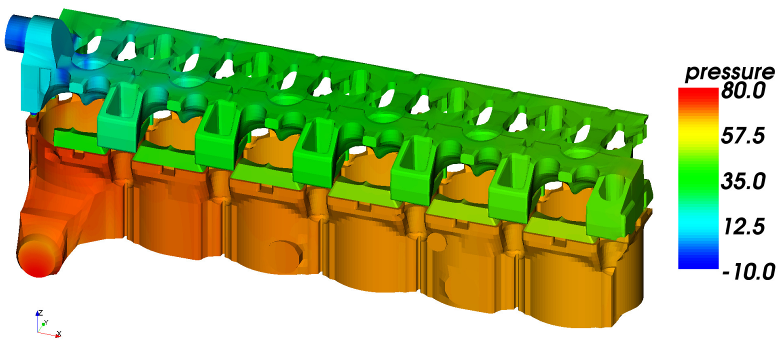


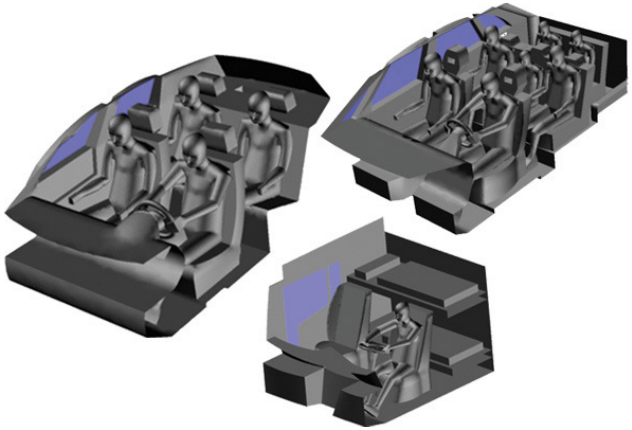
Automotive CFD Today

Use of CFD in Automotive Applications



- In numbers of users in automotive companies, CFD today is second only to CAD packages
- In some areas, CFD replaces experiments
  - Engine coolant jackets
  - Under-hood thermal management
  - Passenger compartment comfort
- In comparison with CFD, experimental studies are expensive, carry limited information and it is difficult to achieve sufficient turn-over
- The biggest obstacle is **validation**: can CFD results be trusted?



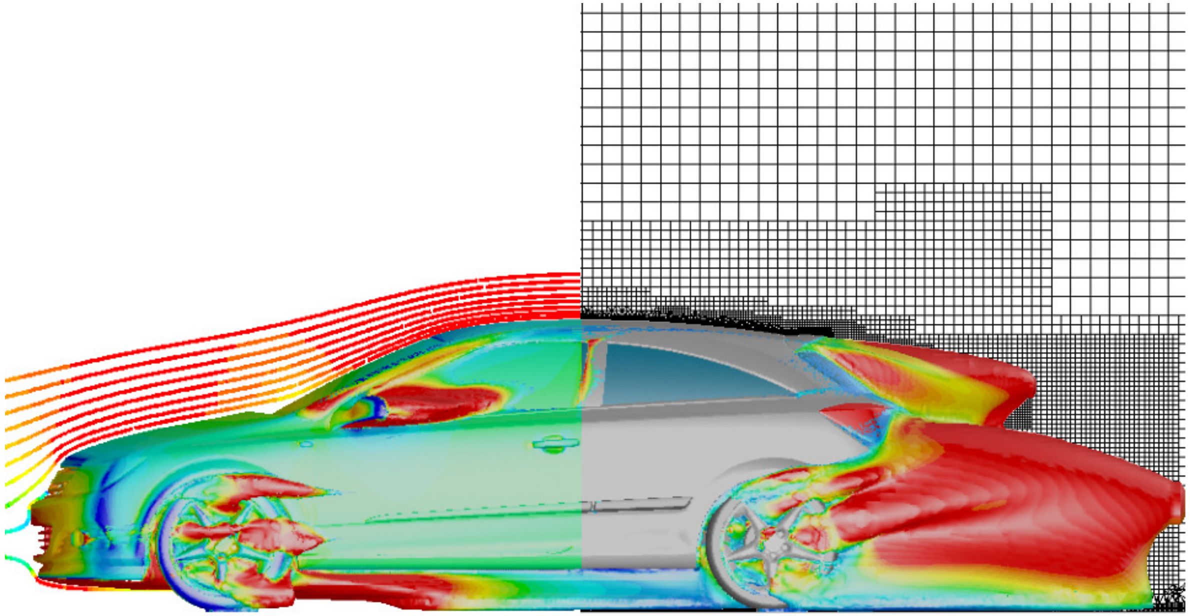


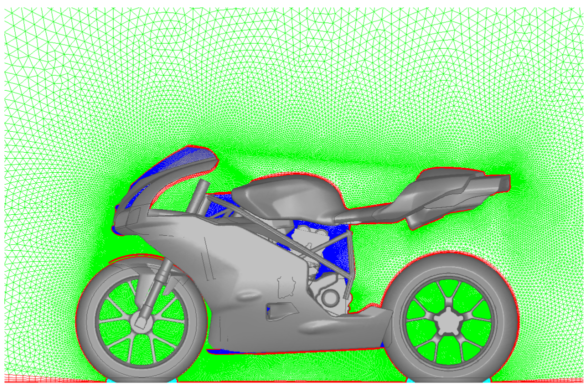
Automotive CFD Today

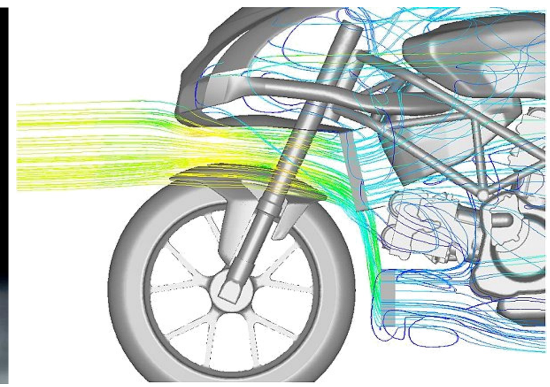
Use of CFD in Automotive Applications (cont'd)

- In other areas, CFD is insufficiently accurate for complete design studies
  - Required accuracy is beyond the current state of physical modelling (especially turbulence modelling)
  - Simulation cost is prohibitive or turn-around is too slow
  - Flow physics is too complex: incomplete modelling or insufficient understanding of detailed physical processes
  - In some cases, combined 1-D/3-D studies capture the physics without resorting to complete 3-D study
- Examples:
  - Prediction of the lift and drag coefficient on a car body
  - In-cylinder simulations in an internal combustion engine
  - Complete internal combustion engine system: air intake, turbo-charger, engine ports and valves, in-cylinder flow, exhaust and gas after-treatment
- CFD can still contribute: parametric study (trends), reduced experimental work etc.
- Numerical modelling is particularly useful in understanding the flow or looking for qualitative improvements: e.g. optimisation of vehicle soiling pattern on windows

External Aerodynamics Simulations





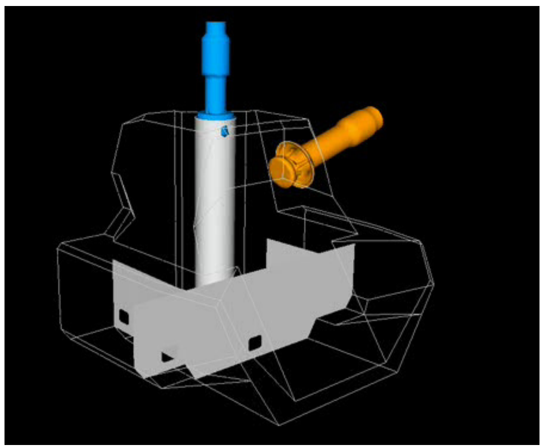


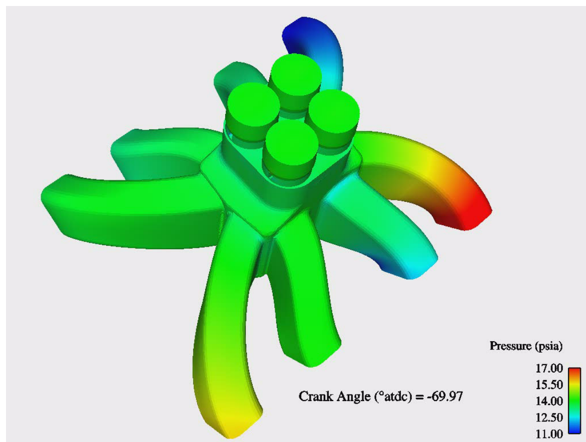
External Aerodynamics Simulations

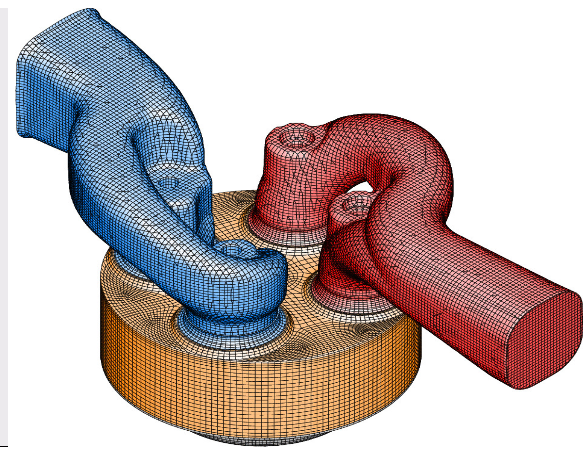
Automotive CFD Today

Use of CFD in Automotive Applications (cont'd)

- CFD is used across the industry, at various levels of sophistication
- Impact of simulations and reliance on numerical methods is greatest in areas that were not studied in detail beforehand
- Considerable use in cases where it is difficult to quantify the results in simple terms like the lift and drag coefficient
  - Flow organisation, stability and optimisation
  - Detailed look at the flow field, especially in complex geometry
  - Optimisation of secondary effects: fuel-air mixture preparation



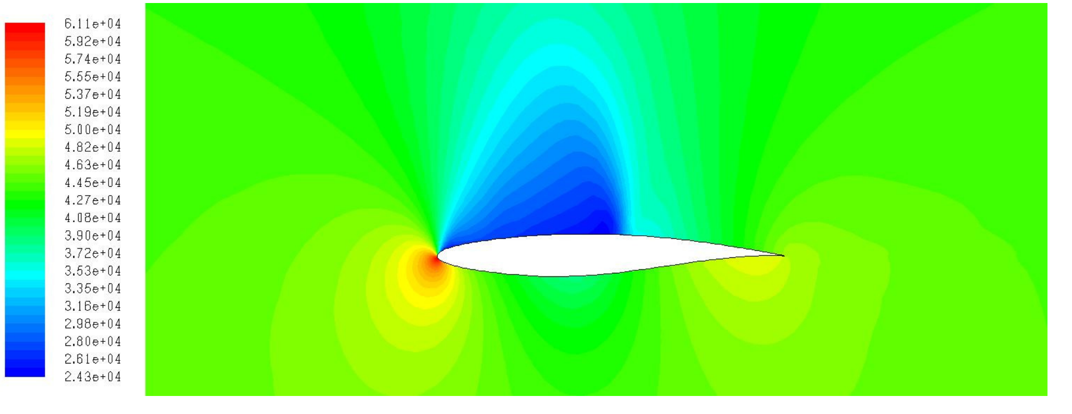




CFD Capabilities in 1980s

Early Adoption of CFD: Aerospace Industry

- Historically, early efforts in CFD involve simplified equations and simulations relevant for **aerospace industry**
- Experience in achieving best results with limited computational resources: attention given to solution acceleration techniques
- Application-specific physical models
  - Linearised potential equations, Hess and Smith, Douglas Aircraft 1966
  - 3-D panel codes developed by Boeing, Lockheed, Douglas and others in 1968
  - Specific turbulence models for aerospace flows, e.g. Baldwin-Lomax
  - Coupled boundary layer-potential flow solver, Euler flow solver
- Capabilities beyond steady-state compressible flow were very limited

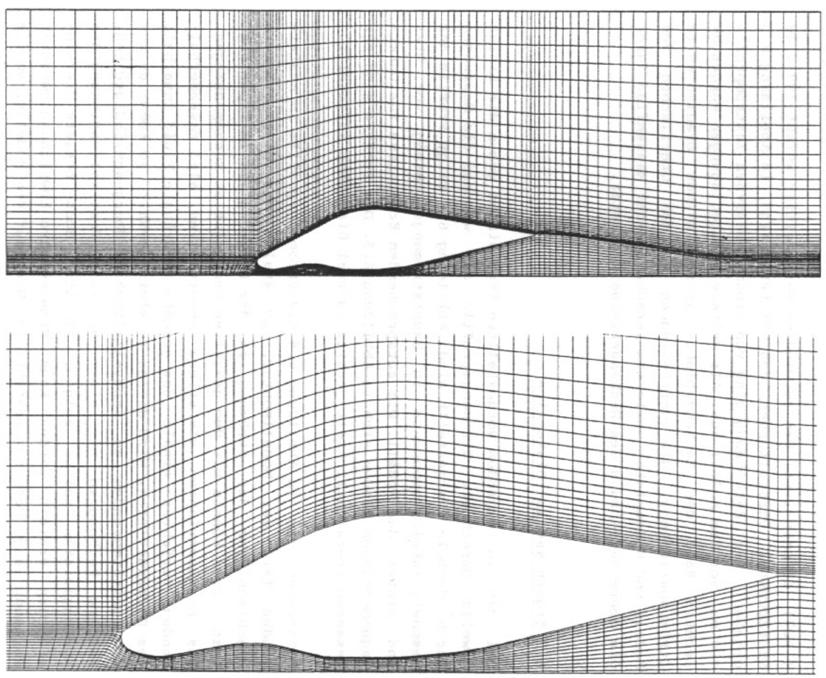


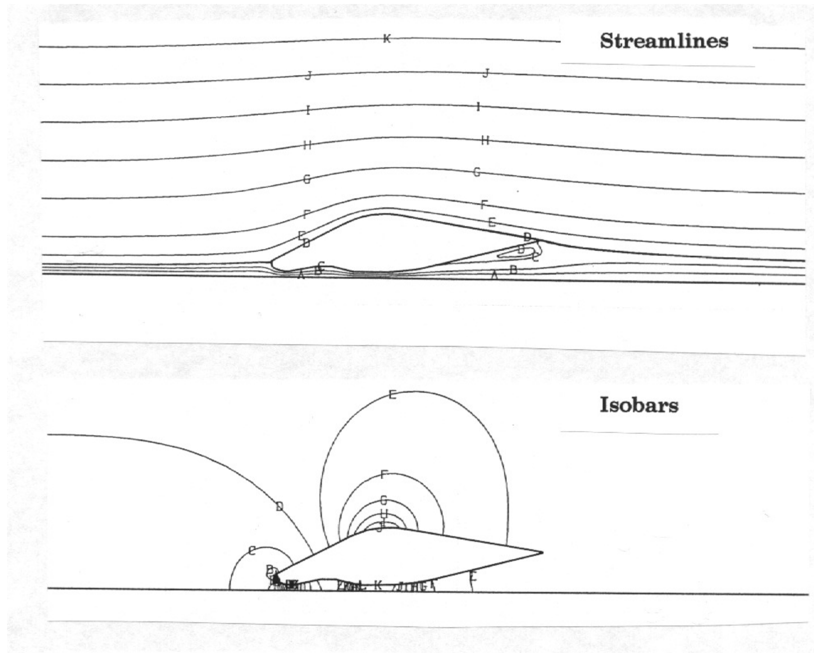
Early Adopters and Validation Efforts

Early Automotive CFD Simulations

- First efforts aimed at simplified external aerodynamics (1985-1988)
- . . . but airfoil assumptions are not necessarily applicable
- Joint numerical and experimental studies: validation of numerical techniques and simulation tools, qualitative results, analysis of flow patterns and similar

Abb. 6.3: Geometrie und Rechengitter der numerischen Untersuchung der Strömung (links vollständig, rechts Ausschnitt)





Predicted streamlines and isobars for the Porsche model body

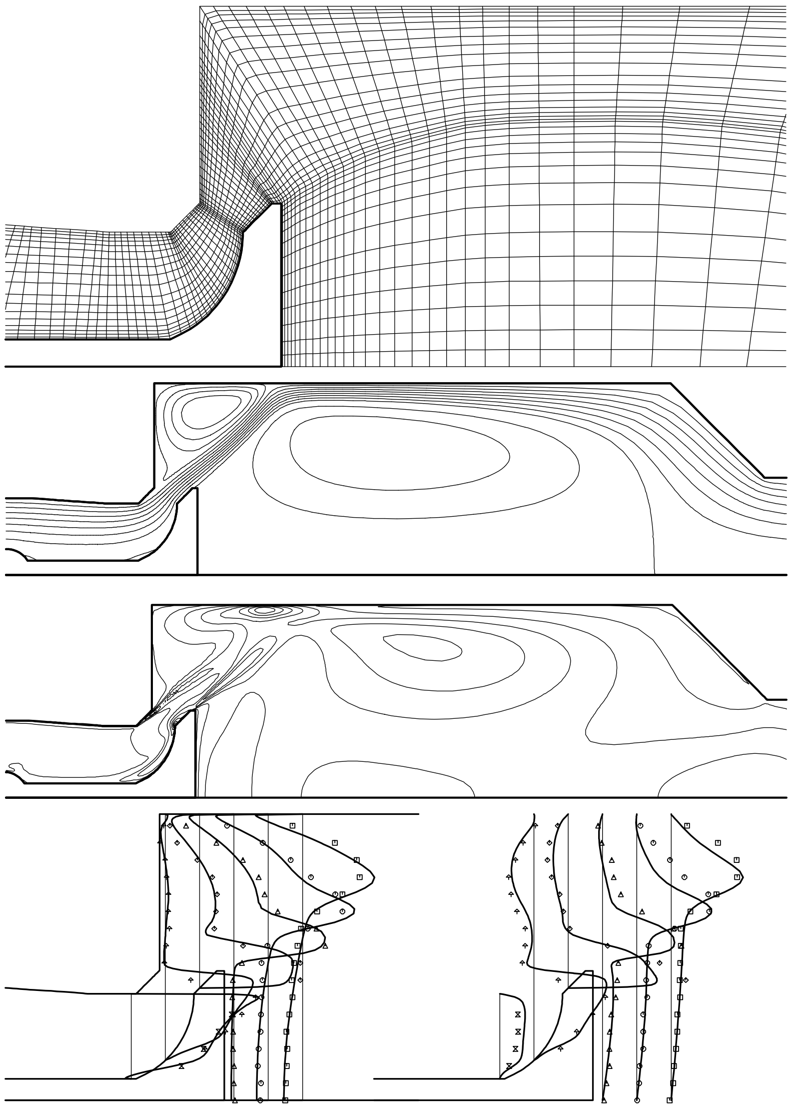
Early Adopters and Validation Efforts

Early Automotive CFD Simulations

- It is quickly recognised that the needs of automotive industry and (potential) capabilities of CFD solvers are well beyond contemporary experimental work
- Focus of early numerical work is on performance-critical components: internal combustion engines and external aerodynamics
- Geometry and flow conditions are simplified to help with simulation set-up

Example: Intake Valve and Manifold

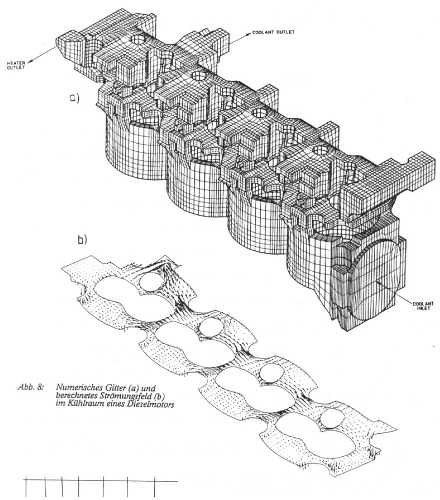
- 2-D steady-state incompressible turbulent fluid flow
- Axi-symmetric geometry with a straight intake manifold and fixed valve lift
- Simulation by Peric, Imperial College London 1985

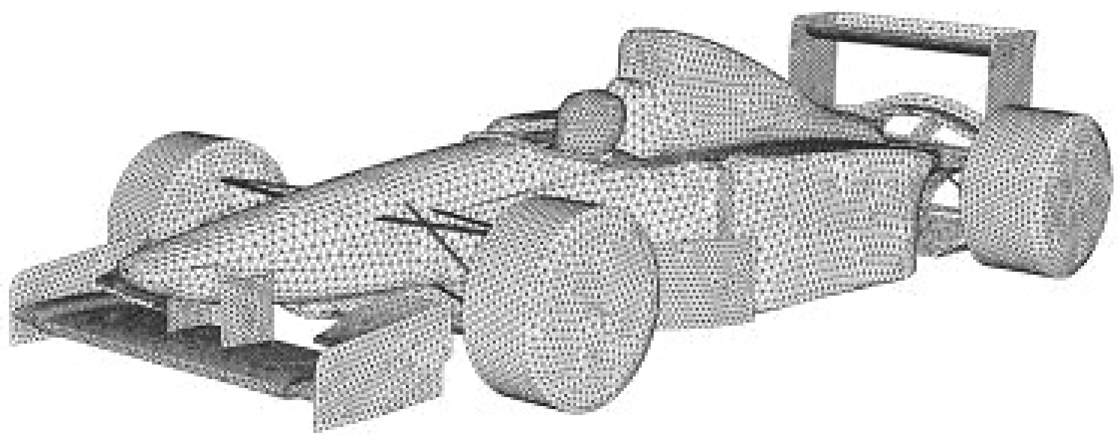


Automotive of CFD in 1990s

Expanding Computer Power and Validated Models

- Numerical modelling is moving towards product design
  - Improvements in computer performance: reduced hardware cost, Moore's law
  - Improved physical modelling and numerics: fundamental problems are with flow, turbulence and discretisation are resolved
  - Sufficient validation and experience accumulated over 10 years
- Notable improvement in geometrical handling: realistic 3-D geometry
- Graphical post-processing tools and animations: easier solution analysis
- Mesh generation for complex geometry is a bottle-neck: need better tools





Expansion of Automotive CFD

Computational Resources

- Increase in computer performance drives the expansion of CFD into new areas by reducing simulation turn-over time
- Massively parallel computers provide the equivalent largest supercomputers at prices affordable in industrial environment (1000s of CPUs)

Physical Modelling

- New physical models quickly find their use, e.g. free surface flows
- Looking at more complex systems in transient mode and in 3-D: simulation of a multi-cylinder engine, with dynamic effects in the intake and exhaust system
- Computing power brings in new areas of simulation and physical modelling paradigms. Example: Large Eddy Simulation (LES) of turbulent flows

Integration into a CAE Environment

- Computer-Aided Design software is the basis of automotive industry
- Historically, mesh generation and CFD software are developed separately and outside of CAD environment, but the work flow is CAD based!
- Current trend looks to seamlessly include CFD capabilities in CAD

Summary

Summary: Automotive CFD Today

- CFD is successfully used across automotive product development
- Initial “landing target” of external aerodynamics and in-cylinder engine simulation still not reached (!) – sufficient accuracy difficult to achieve

Lessons Learned

- The success of CFD in automotive simulation is based on providing industry needs rather than choosing problems we may simulate: find a critical **broken process** and offer a solution
- Numerical simulation tools will be adopted only when they fit the product development process: robust, accurate and validated solver, rapid turn-over
- Experimental and numerical work complement each other even if sufficient accuracy for predictive simulations cannot be achieved
  - Validation of simulation results $\leftrightarrow$ understanding experimental set-up
  - Parametric studies: speeding up experimental turn-over
- True impact of simulation tools is beyond the obvious uses: industry will drive the research effort to answer its needs