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Vehicle Thermal Management

- a Challenge to Simulation

Kuli User Group Meeting
2007, Steyr / Austria

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Vehicle Thermal Management - a Rough Definition

„Vehicle Thermal Management“ means „supply or extract heat where needed“ while following these superior objectives:

High Thermal Reliability

Low Fuel Consumption

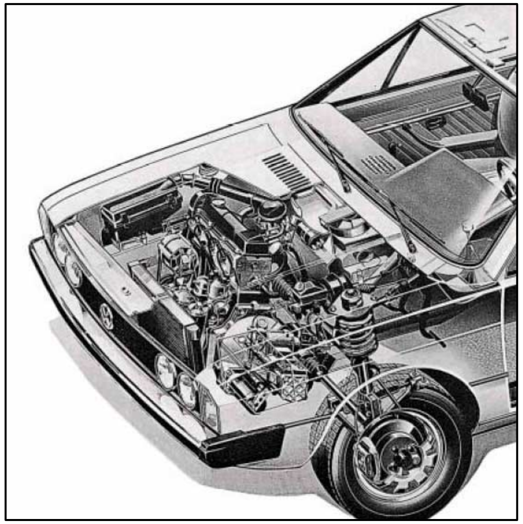
Low Emissions

High Thermal Comfort

Additionally the Automotive Industry has some basic objectives:

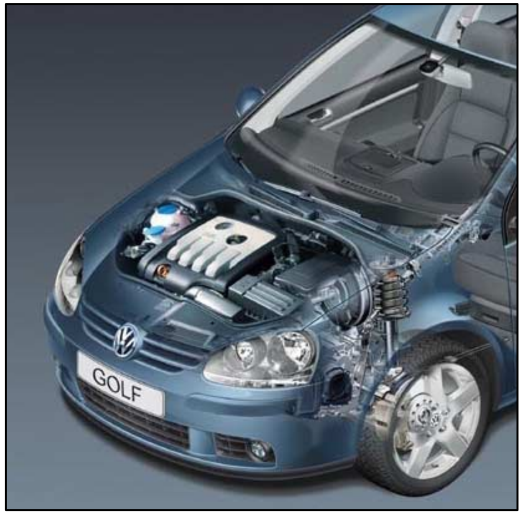
Short Development Time and Low Development Costs

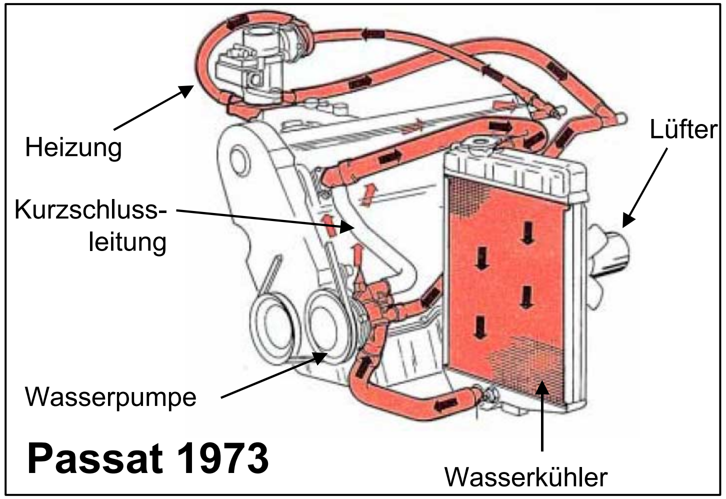
Objective: High Thermal Reliability



Golf I - 1974
1.5 l, 51 kW, 1.0 t, ca. 150km/h

Golf V - 2004
2.0 l, 103 kW, 1.8 t, ca. 200 km/h

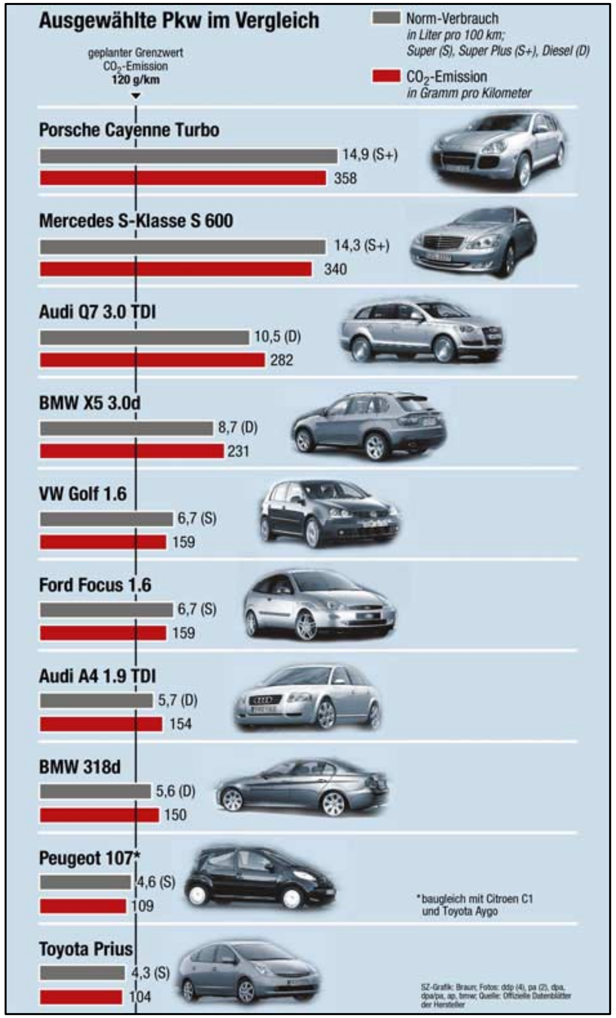




Passat 1973

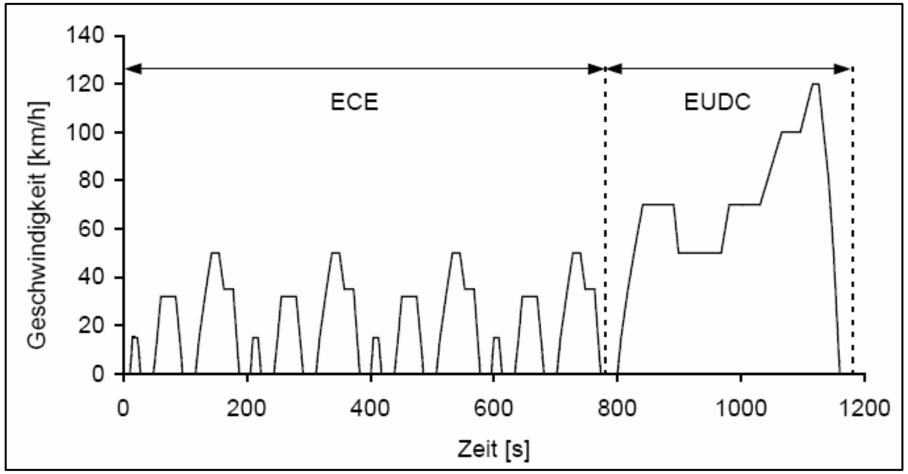
- <u>top priority</u>: safety of driver and car
- less clearance, less surrounding cooling air flow
- high heat releases (convection, radiation)
- high component temperatures
- complex systems
- complex interaction

Objective: Low Fluid Consumption, Low Emissions



from: Süddeutsche Zeitung, 02/2007

- fluid consumption measured by driving cycles
- in Europe: NEDC, 20min, 11 km, 20°C, AC „off“



- fossil resources getting shorter
- automotive industry has to comply with CO_2-limits (e.g. 120 g/km in 2012)
- fuel costs rising
- „high emissions = high taxes“ ?

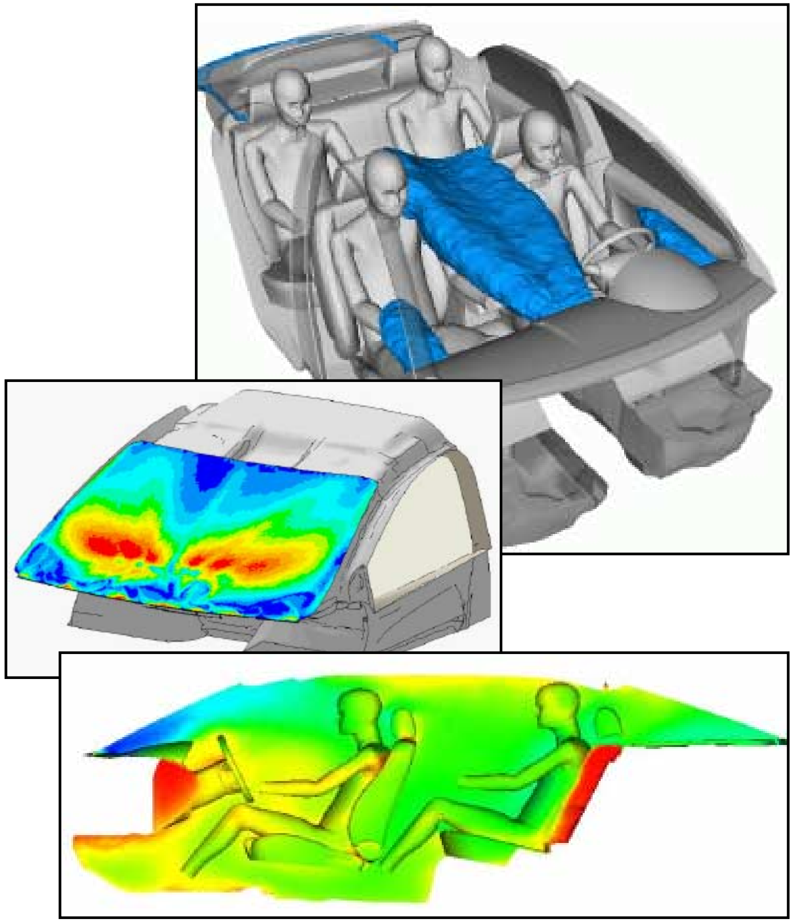
Objective: High Thermal Comfort

Temperaturen in einem Mittelklasse-PKW
bei: Fahrzeit 1 h
Außentemperatur 30 °C
Sonneneinstrahlung auf den PKW

Bereich	mit Klimaanlage	ohne Klimaanlage
Kopf	23 °C	42 °C
Brust	24 °C	40 °C
Fuß	28 °C	35 °C

from : SSP 208, „Klimaanlagen im Fahrzeug, Grundlagen"; Volkswagen AG

- passengers uncomfortable with heat (⇨ cooling)
- passengers uncomfortable with cold (⇨ heating)
- sensing „hot" and „cold" is relative
- „right" climate improves safety
- standards for defrost, „pull-down" test



from: „Flow inside Passenger Compartment";
Hoffmann, Fischer, Markowitz, Hupertz;
Progress in Vehicle Aerodynamics IV, Stuttgart 2006

Objective: Low Fluid Consumption + High Thermal Comfort

Bereich	Aktivität
Motor	Benzin-Direkteinspritzung
	Diesel-Hochdruckeinspritzung
	Variable Ventilsteuerung
	Brennraumgeometrie
	Reibungsreduzierung
	Luftführung und Aufladung
Getriebe	Reibungsreduzierung
	Übersetzungsverhältnis
Energiemanagement	Hybridisierung
	Thermomanagement
Rollwiderstand	Rollwiderstandsoptimierte Reifen
Aerodynamik	Design
	Strömungsmanagement
Gewichtsreduktion	Hochfeste Stähle
	Aluminium
	Kunststoffe
Fahrerinformationssysteme	Schaltpunktanzeige
	Verbrauchs- / Effizienzanzeige

Conflicting objectives

- engine cooling & aerodynamics
- high thermal comfort & low weight
- high thermal comfort & low fuel consumption
- high thermal reliability & tight package

Future Innovations of German Automotive Industry

from: „CO_2-Minderungen im Deutschen Verkehrssektor“, VDA, 2007; www.vda.com

Development Objectives: Low Costs & Short Time

- designing the heat exchangers
- designing the cooling systems
- selecting components
- rating variants
- checking / optimization
- designing control systems
- … etc.

Simulate!

… as early as possible
… supporting / backing up development
… with neutral evaluation
… close / near to experiment

Contents

2. Creative Ideas

lower fuel consumption
+
higher thermal comfort

Minimize Energy Demands
- reduce pressure losses in coolant
- reduce pressure losses in cooling air
- avoid leakage of cooling air
- switch off pumps (water, oil, …) & fans
- close cooling air path

Change Thermal Masses
- reduce fluid volume (water, oil)
- use heat storage
- use new materials (heat capacity)

Minimize Energy Removal
- use radiator shutter
- use isolation / encapsulation
- use exhaust gas enthalpy
- check fan control

Change Heat Distribution
- change volume flow rate
- use electrical water pump
- use electrical oil pump
- change oil temperature level
- use more than one in-engine coolant flow
- use separate control for separate systems

Increase Energy Supply
- change combustion
- use PTC-elements
- use heat from exhaust gas

Creative Ideas (many more available)

Idea	Potential Fuel Savings in NEDC	Comment
Electrical Water Pump	1.5% … 2-0%	New Coolant Pipes Necessary!
Engine Encapsulation	0.5% … 1.0%	Weight, Temperatures, Assembly?
Increased Gear Oil Temperature	0.5 … 1.0%	ATF-Cooler Necessary?
Radiator Shutter	< 0.5%	2% in c_W
Volume-Flow Control (Oil Pump)	1.4 … 2.4%	Control Algorithm?
Oil Volume 50% reduced	1.2%	
Adaptive Thermal Management	0.5 … 1.0%	
Total Potential = Sum ?	**? %**	**“summing-up” not realistic !**

Data from: „Wärmemanagement des Kraftfahrzeugs“, HdT Essen, 1998-2006 (various authors)

Typical Problems

- Individual Actions Affect Each Other – Complex Interactions!
- Accuracy of Measurement ≈ Potential of Individual Actions

Need Information about all systems!

Simulate!

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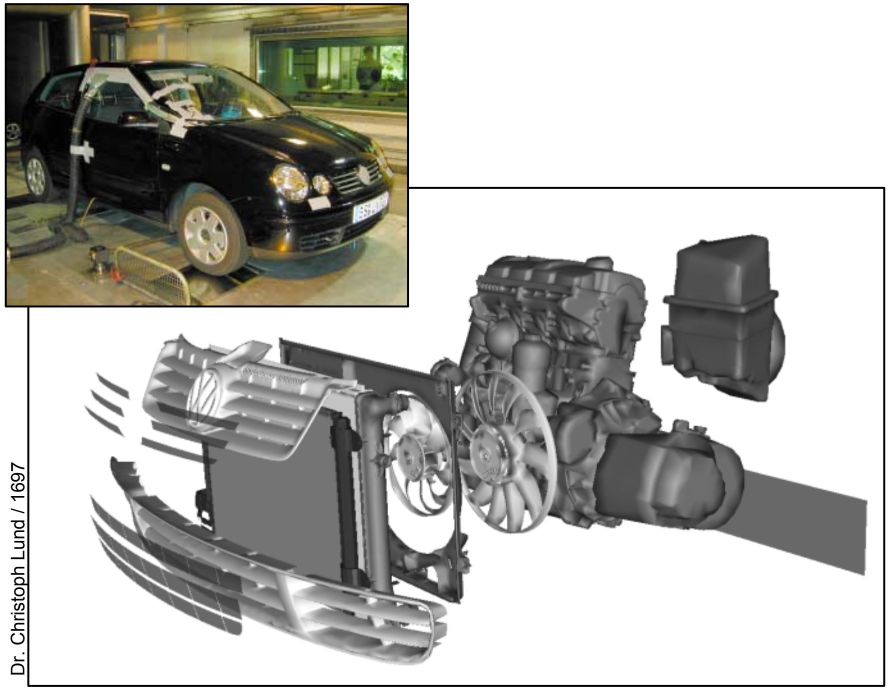
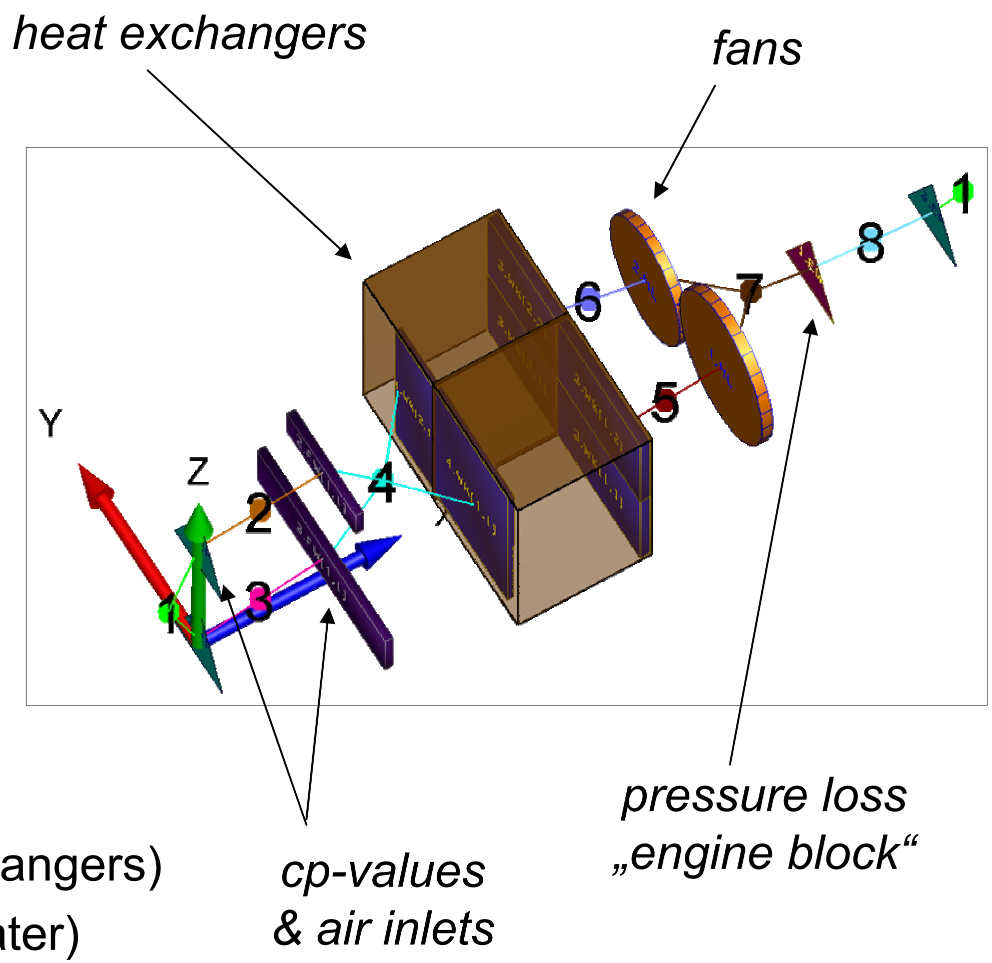
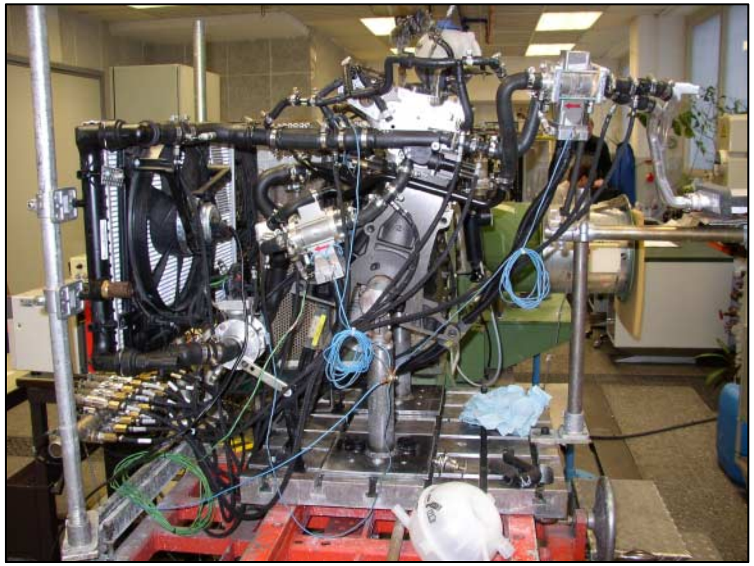
1D: Simulating Cooling Air Flow

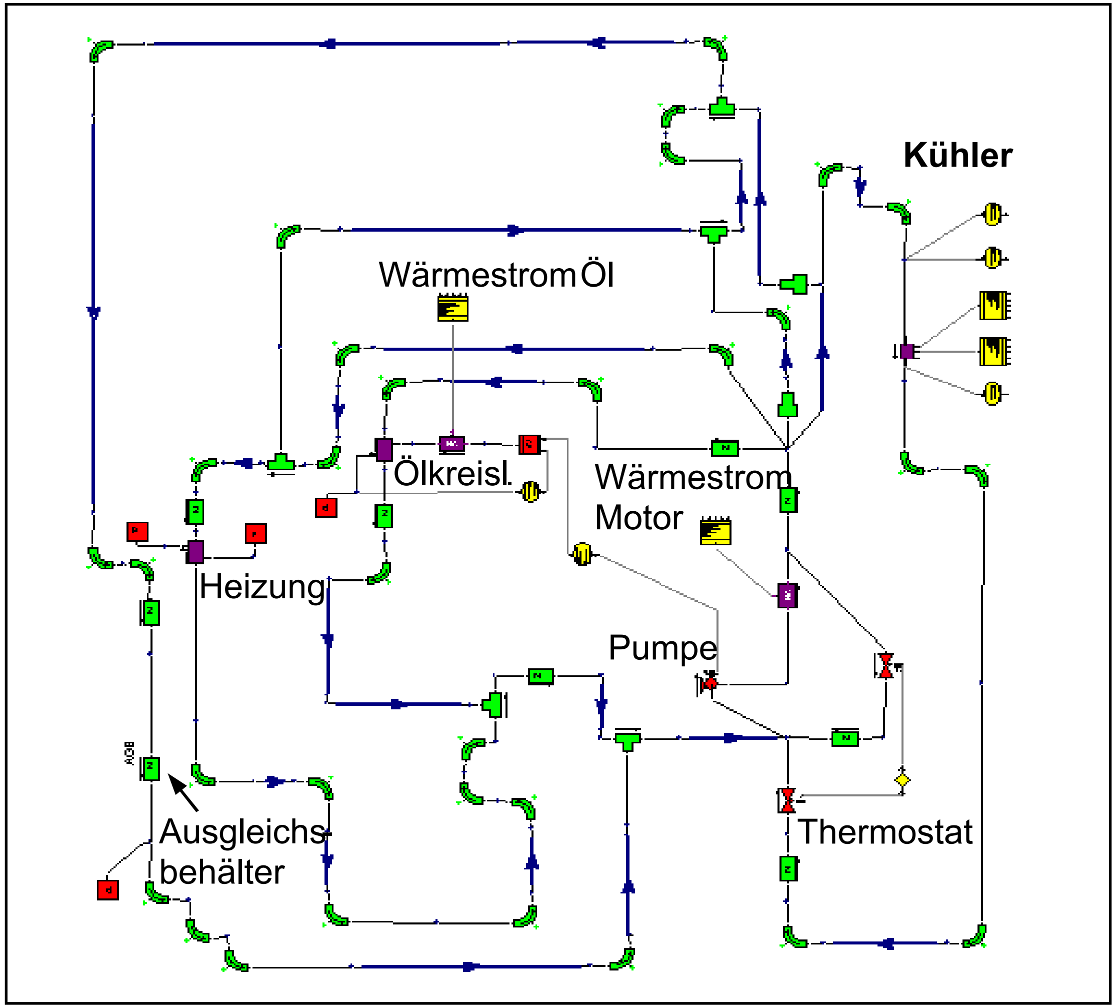




- cooling air mass flow
- component selection (grill, fans, heat exchangers)
- coupling to engine cooling system (e.g. water)

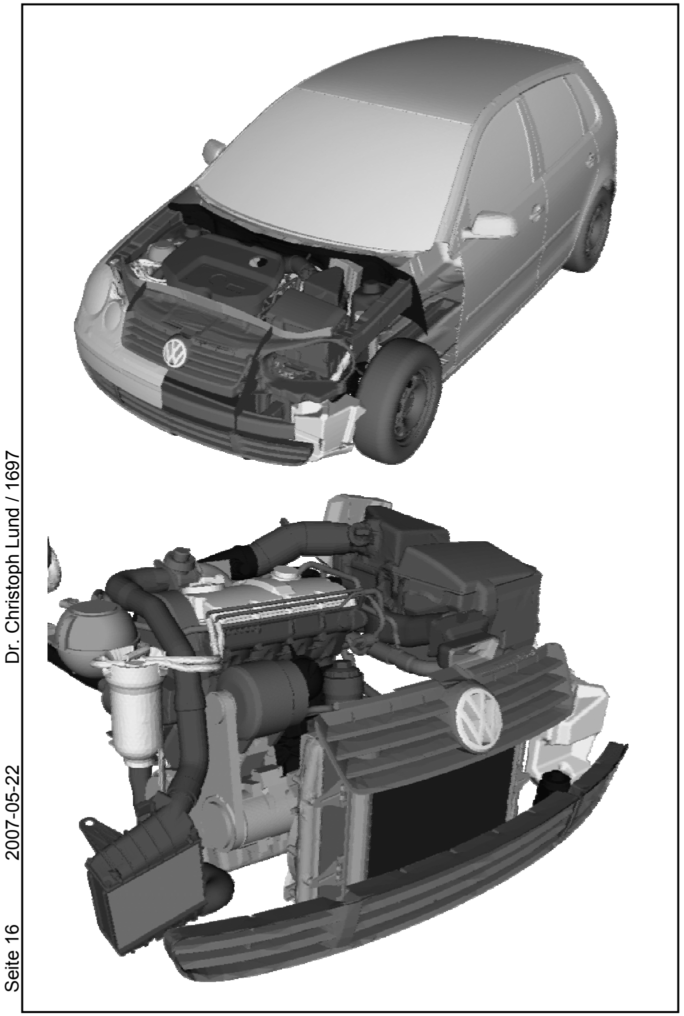
1D: Simulating Cooling Systems (Water, Oil, …)

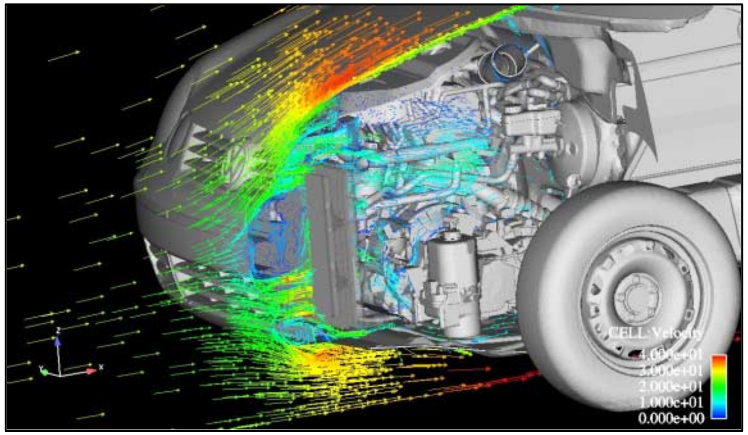


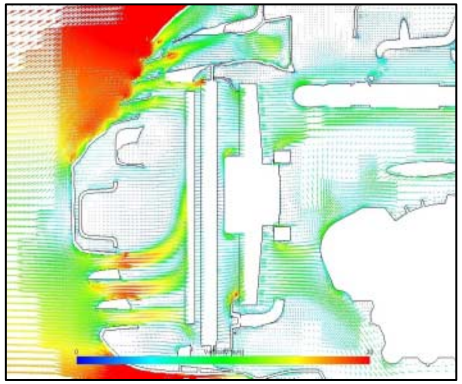


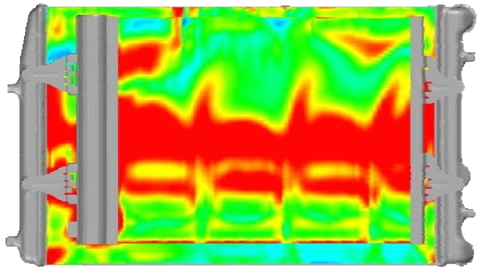
- coolant mass flow
- pressure loss
- component selection (heat exchangers, pump, pipes)
- system behaviour

3D: Simulating the Underhood Flow



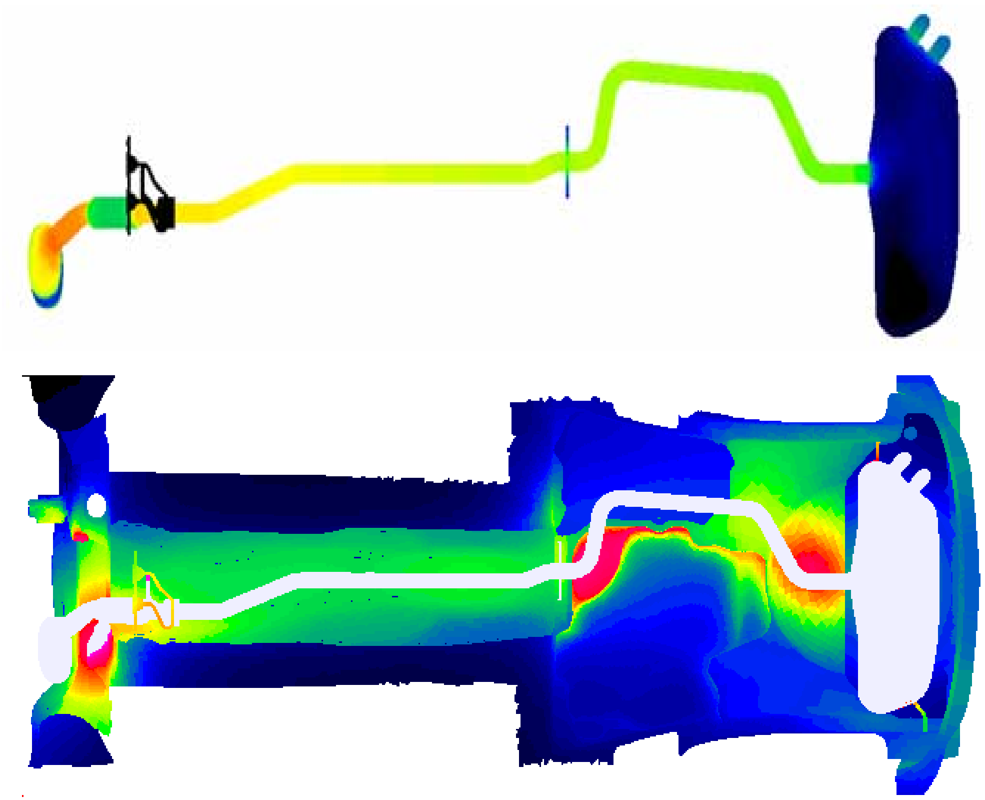




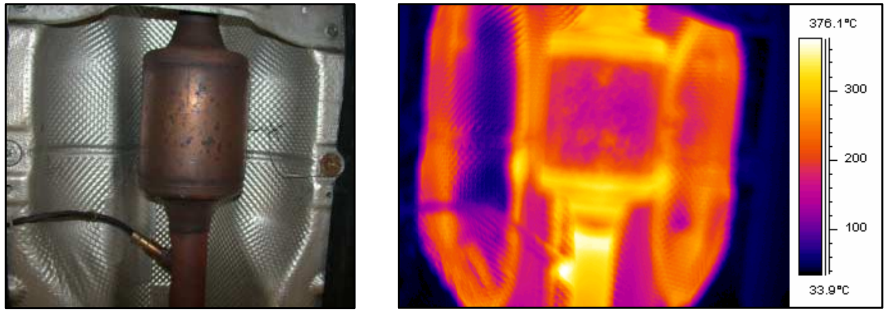


- detailed cooling air flow
- circulations, back flow, flow topology
- cooling air mass flows, flow onto the heat exchangers
- coupling to engine cooling system (e.g. water)
- heat transfer coefficients (component temperatures)

3D: Simulating Radiation / Component Temperatures



Temperatures along Exhaust System and Underbody



Catalyst – Normal and Thermographic Photo

- component surface temperatures
- component selection (e.g. heat shields)
- material selection
- underbody (exhaust heat)
- cabin (solar radiation)

Simulation Tools

Typical Applications
- cooling air flow
- cooling water flow
- coolant water jacket
- charge air system
- heat conduction
- aerodynamic forces
- component temperatures
- cabin air flow, solar radiation
- engine gas exchange
- driving performance
- aerodynamics
- … and more

Current Situation
- a lot of experience available
- many different targets
- many applications established
- many departments involved
- many similar sw tools available
- still many vehicle tests needed!

Simulations mostly aimed at components or single systems

Note: „Ultimate Rating“ Requires A <u>Complete</u> Vehicle

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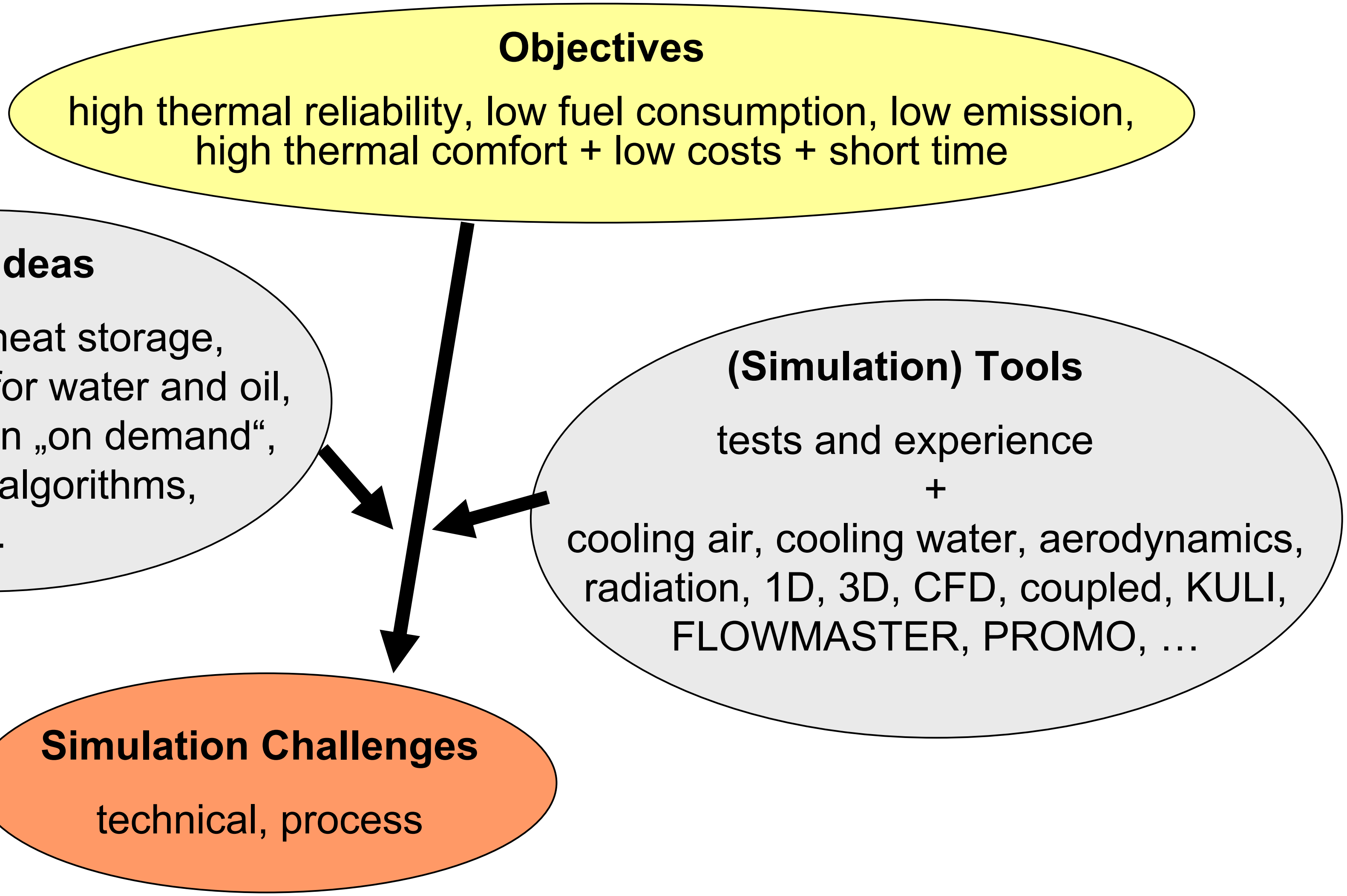
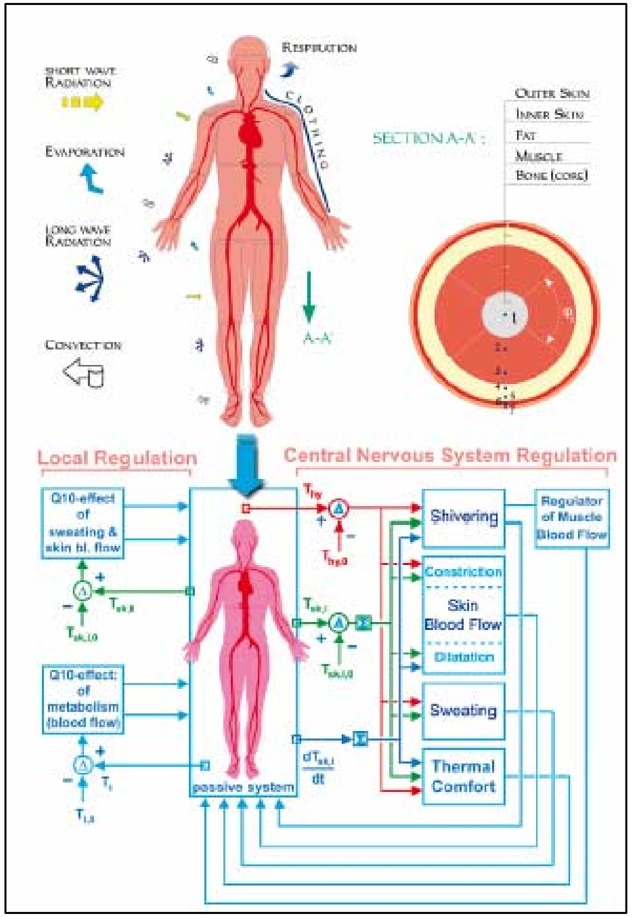
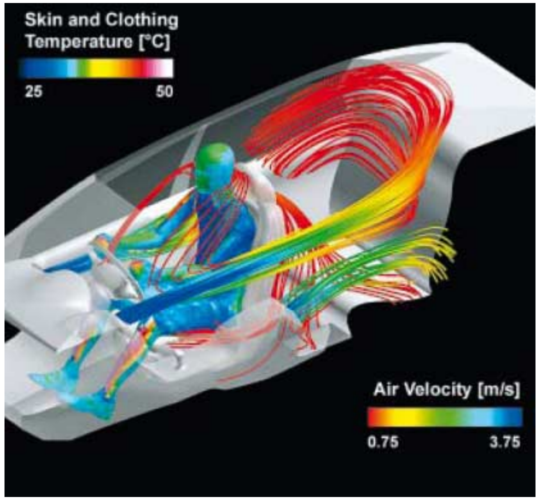
Challenges


Objectives
high thermal reliability, low fuel consumption, low emission,
high thermal comfort + low costs + short time
Creative Ideas
radiator shutter, heat storage,
electrical pumps for water and oil,
heat redistribution „on demand“,
new control algorithms,
…
(Simulation) Tools
tests and experience
+
cooling air, cooling water, aerodynamics,
radiation, 1D, 3D, CFD, coupled, KULI,
FLOWMASTER, PROMO, …
Simulation Challenges
technical, process

Challenge: Thermal Comfort Evaluation





pictures from: „Modernes Thermomanagement am Beispiel der Innenraumklimatisierung“; Schneider, Ellinger, Paulke, Wagner, Pastohr; ATZ 02 / 2007

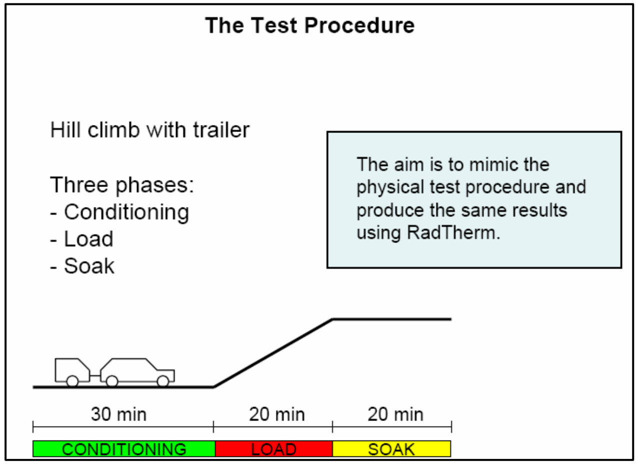
Technical Difficulties

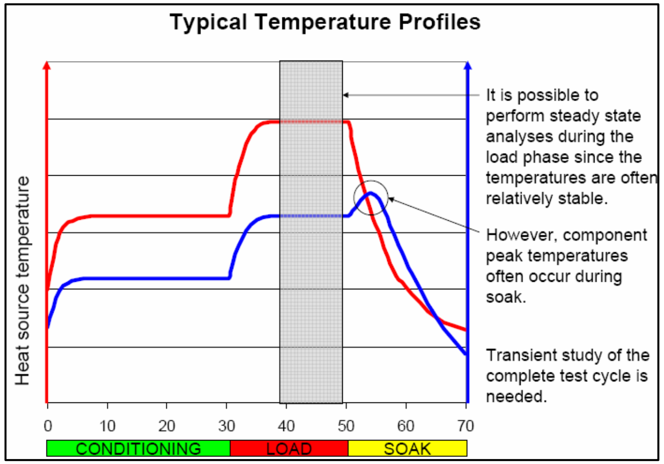
- „thermal comfort“ is relative
- absolute comfort rating difficult to test
- different test procedures

Simulation Difficulties

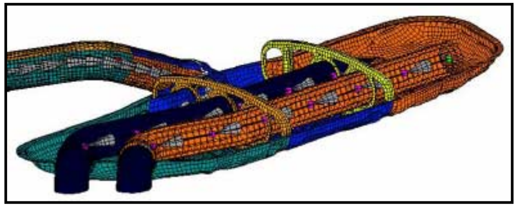
- thermo-physiological model of human body
- comfort model giving both global and local „simple“ ratings
- coupling to AC and cabin heater
- CFD results of cabin model sensitive to turbulence model

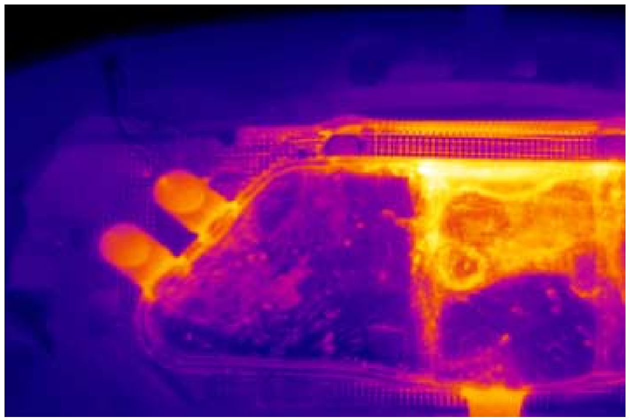
Challenge: Prediction of Transient Component Temperatures





from: „Virtual Thermal Testing at Volvo Cars“; Maria Krantz; 2nd European RadTherm UGM, Stuttgart 2006





from: „Underbody Temperature Simulations – are there Pitfalls?“; Herrera, Lund; 3rd RadTherm UGM, Stuttgart 2007

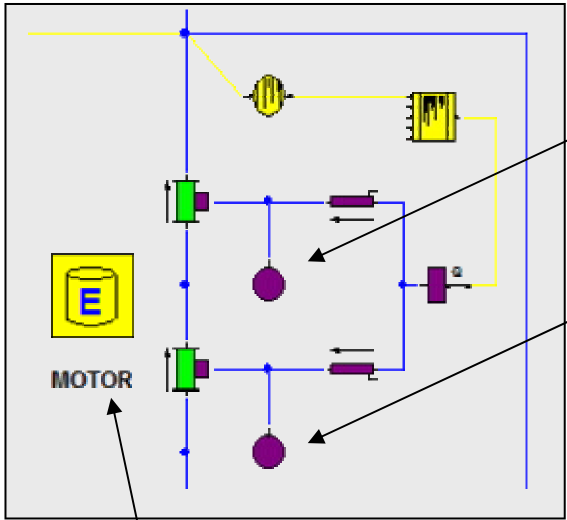
Simulation Difficulties

- problem is transient
- engine shut-off leads to very complex heat redistribution
- very complex interaction of conduction, convection and radiation
- time-dependent forced and later free convection
- difficult boundary and initial conditions
- not much experience with component models (DPF, catalyst, muffler)

Challenge: Thermal Engine Model

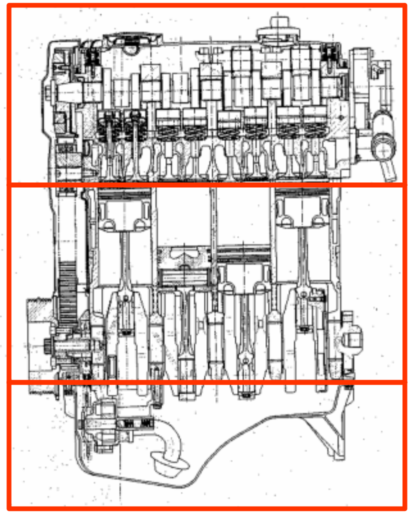
Objectives

- fuel consumption
- heat flux to water, oil, ambient
- heat flux to exhaust
- friction
- warming up



Heat Input

FLOWMASTER 2004

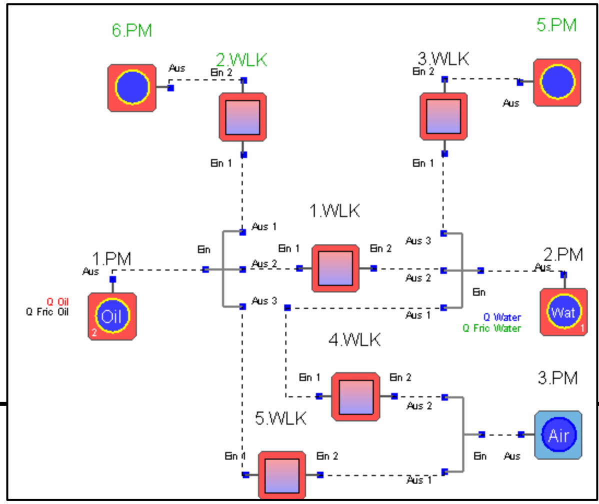


„Deckel“

„Gehäuse“

„Öl“

nicht dargestellt: „Wasser“



KULI 2007

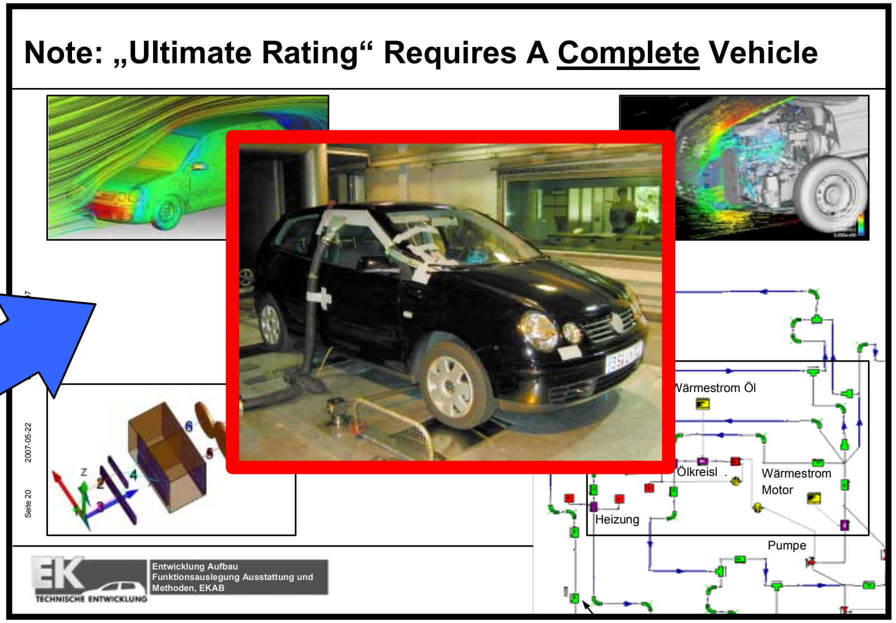
4 point masses mixing water / metal and oil / metal; automatic calibration

Challenge: Thermal Engine Model

Simulation Difficulties

- conflicting objectives: good prediction & easy calibration
- high number of point masses → better approximation
- high number of point masses → complicated calibration
- friction models complicated for oil temperatures < 40°C
- combustion models (e.g. Vibe) complicated for temperatures < 40°C
- engine on test rig ≠ engine within car
- new engine control unit ⇒ new thermal engine model ?
- thermal engine model required by „car engineers“ – not by „motor engineers“
- „single point mass model“ much too simple – „engine gas exchange model“ much too complicated
- more than one engine model for a single engine necessary – details increasing with development time
- scaling of engine models needed to predict behaviour for e.g. higher cylinder capacity

Challenge: Complete Thermal Vehicle Model



Vehicle Thermal Management - a Rough Definition

„Vehicle Thermal Management“ means „supply or extract heat where needed“ while following these superior objectives:

High Thermal Reliability

Low Fuel Consumption

Low Emissions

High Thermal Comfort

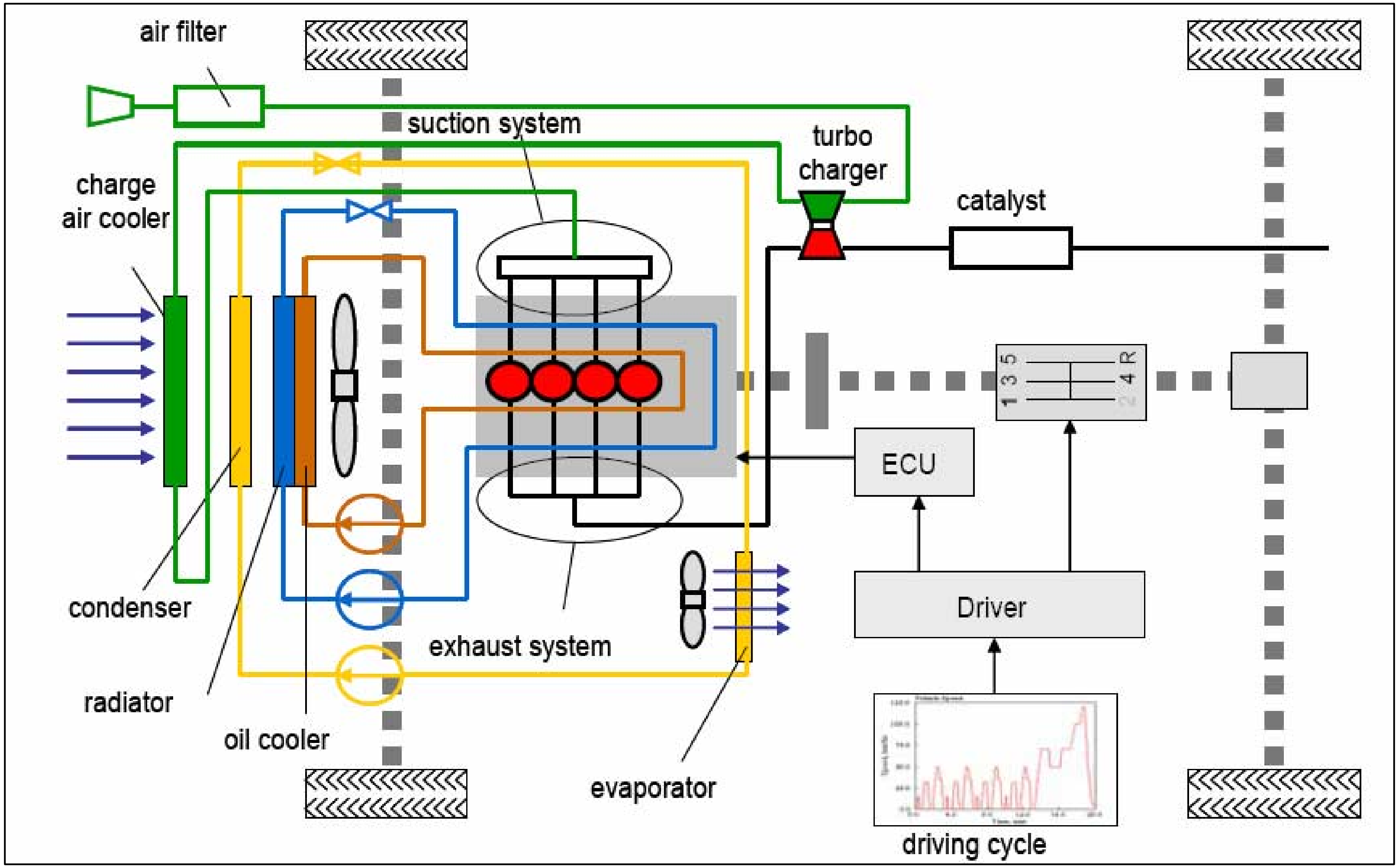
Additionally the Automotive Industry has some basic objectives:

Short Development Time and Low Development Costs

Entwicklung Aufbau Funktionsauslegung Ausstattung und Methoden, EKAB
TECHNISCHE ENTWICKLUNG

Need to Simulate Thermal Behaviour of Complete Car!

A Thermal Model of a Car – the Basic Technique



from: Puntigam, Lang, Petutschnig, Almbauer, VDI-Bericht Nr. 1967, 2006

Looks complete – but so many different systems …?

A Thermal Model of a Car – the Situation in Industry

Typical Sub-Systems	Typical Departments
• cooling air	• engine #1
• cooling water	• engine #2
• engine oil	• cooling #1
• gear oil	• cooling #1
• charge air	• climate #1
• exhaust	• design #1
• air conditioning	• car #1
• engine	• car #2
• gear box	• electronics #1
• cabin	• electronics #2
• driving	• testing #1
• engine control	• testing #2

Typical Software

KULI

MAGNA
MAGNA POWERTRAIN

RICARDO

WAVE

AVL

cruise

boost

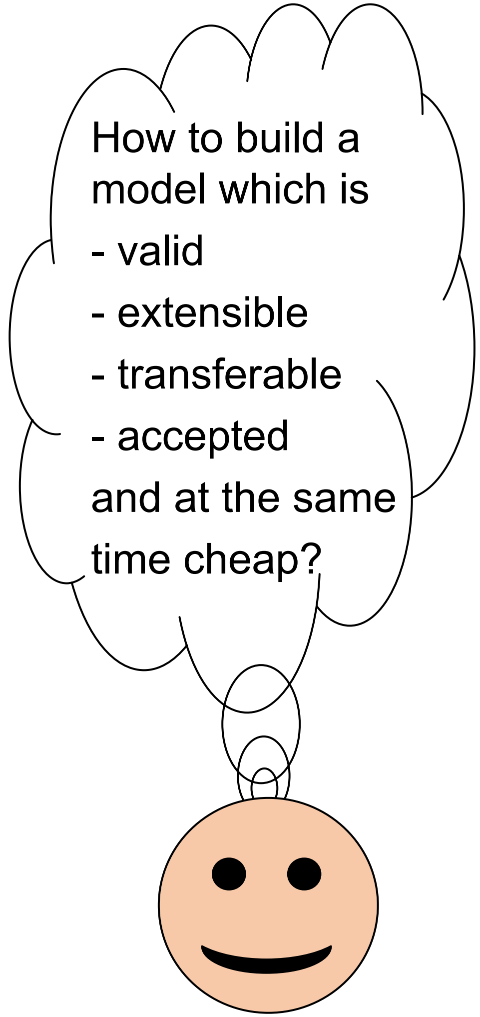
The MathWorks
Accelerating the pace of engineering and science

Flowmaster

MODELICA

Dymola
Multi-Engineering
Modeling and Simulation

AMESim



Managing Complex Sub-Systems by Simulation

Typical Physical Difficulties

- different time scales
- different signs (e.g. heat flow)
- many interactions
- complex initial conditions
- not everything is 1D
- complex control

Typical Complex Simulations

- power plant simulator
- submarine simulator

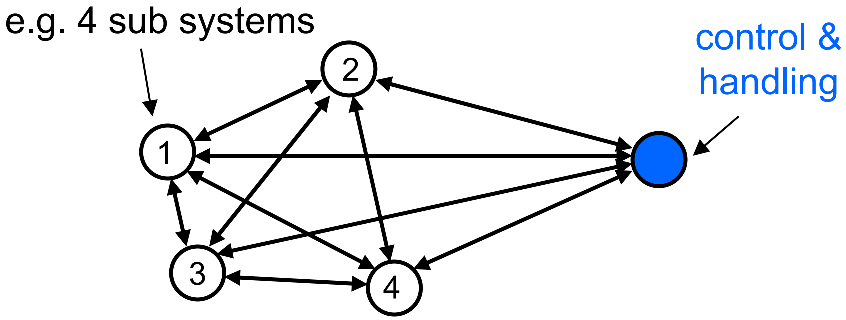
Main Difference to Automotive Sector:

- simulation companies use a single software (e.g. C++, FORTRAN + libraries)
- only a single department involved
- often the product already exists – the simulation is just a „simpler“ copy

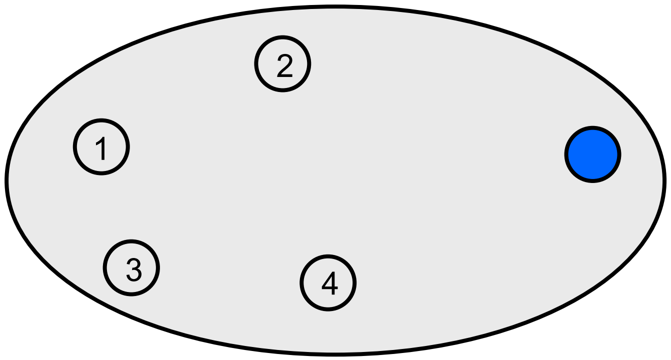
Automotive Sector

- the simulation is needed to design the product
- many different departments involved
- each department is responsible for 1 component / system

Coupling of Software-Systems – 3 Basic Options



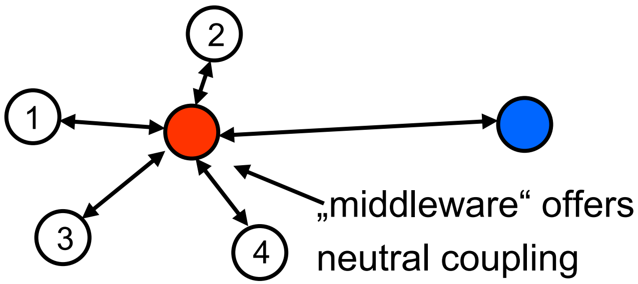
Different tools for partial systems / sub-systems
- many interfaces, complex support
- complex handling & postprocessing



Only a single tool for all systems
- simple interface, simple support
- easy to use, easy post-processing

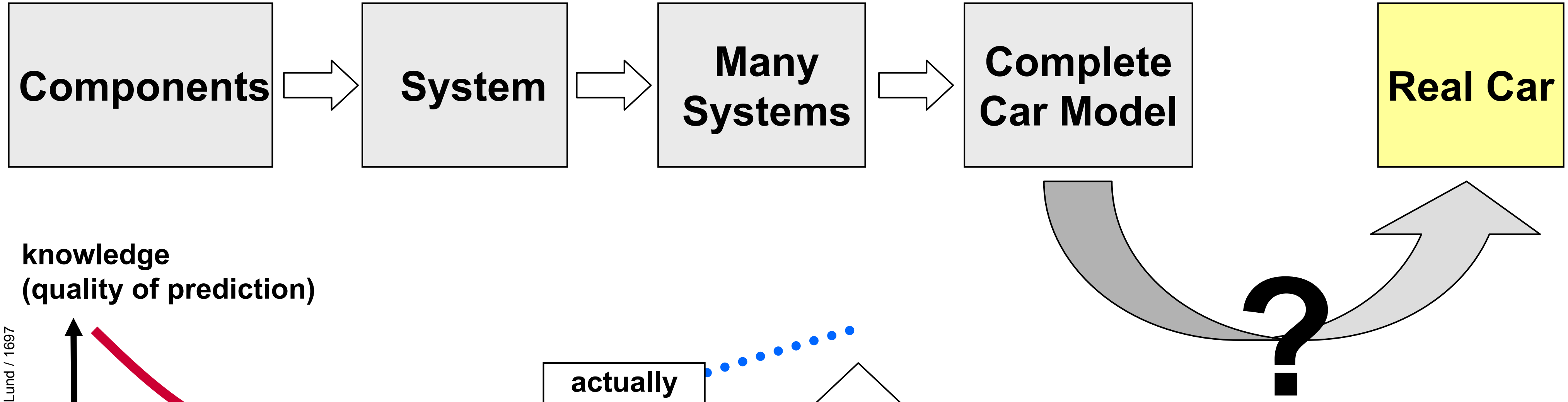
<u>option A</u>: all departments accept and use a single tool

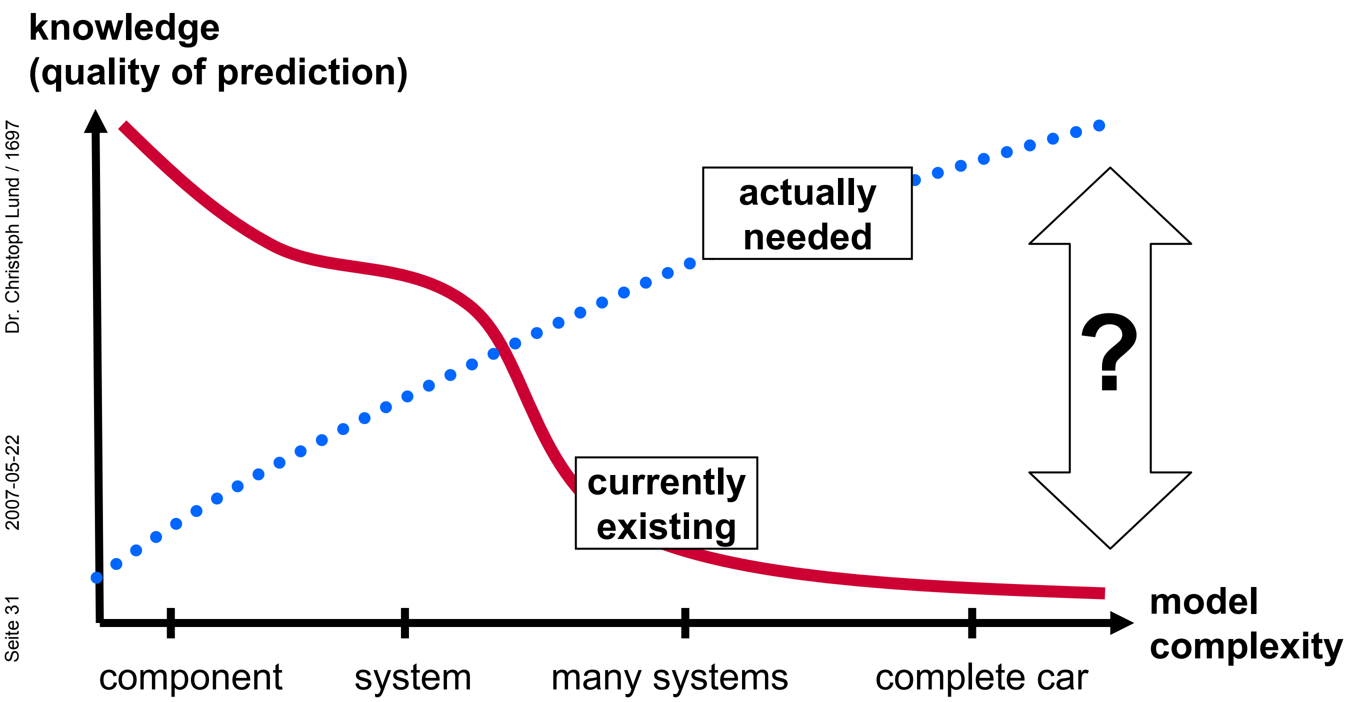
<u>option B</u>: a special team rebuilds all department models using a single software – while the other departments use many different software tools



Different tools for partial systems, coupled by special / neutral coupling tool
- easy to use, easy support
- examples: EXCITE, MpCCI, vif, TISC, …
- high potential - but no experience in industry!

Building a Complete Thermal Model of a Car





Typical problems
- coupling method
  (e.g. temperature, heat flux)
- system calibration
- initialisation
  (e.g. -20°C … +40°C)

Challenges to Simulation

- simple, robust and reliable models; details increasing with development time
- thermal engine models with combustion and friction - even for cold start
- thermal gear box models – even for cold start
- thermal comfort models – reliable and robust

- evaluation of thermal operational behaviour of complete vehicles
  - using different software tools and including different departments
  - models depending on load, ambient data and time
  - models compute fuel consumption, „thermal comfort“ and energy balance
  - easy and direct link to experimental data
- automatic calibration of sub-systems and complete models
- easy data handling for complex models and their variants

- real time capability (or faster) for complete vehicle thermal model
- design of control systems, interface to engine control unit

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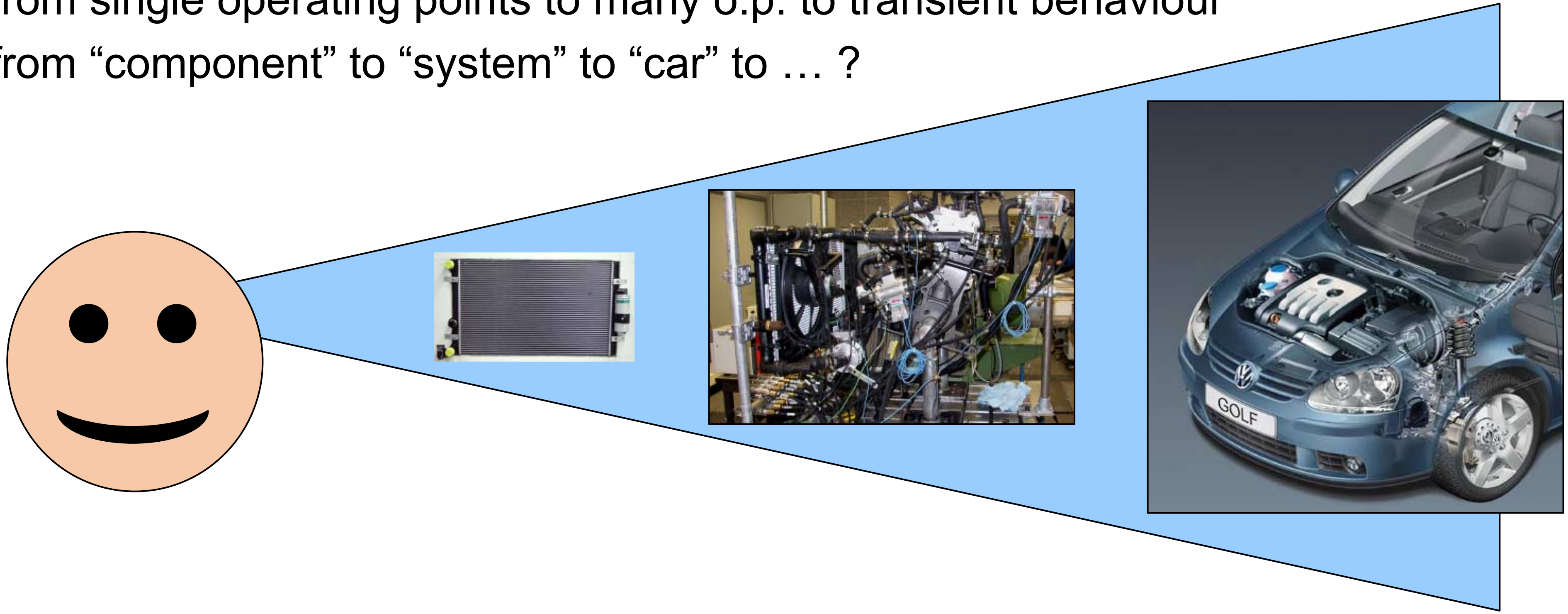
Summary and Outlook

- The Thermal Management simulation focus widens …

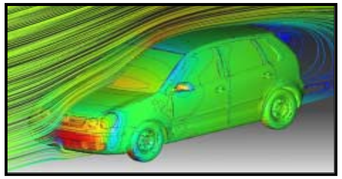
… from single operating points to many o.p. to transient behaviour

… from “component” to “system” to “car” to … ?



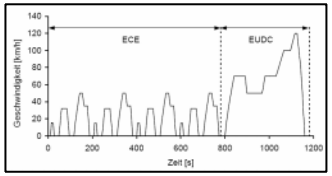
- Simulation is the <u>only</u> way to really „manage“ Vehicle Thermal Management
- A “Complete Vehicle Thermal Model” is necessary and technically possible !

Simulation within the Development Process - a "Traditional" Way



car & cabin

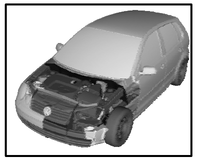
- exterior design
- interior design
- climate
- „package"

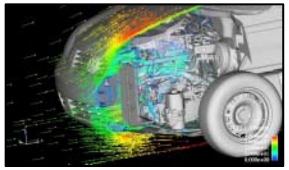


„complete" CAD car → test car(s) → final test car

- engine
- gear box
- cooling

engine & assembly

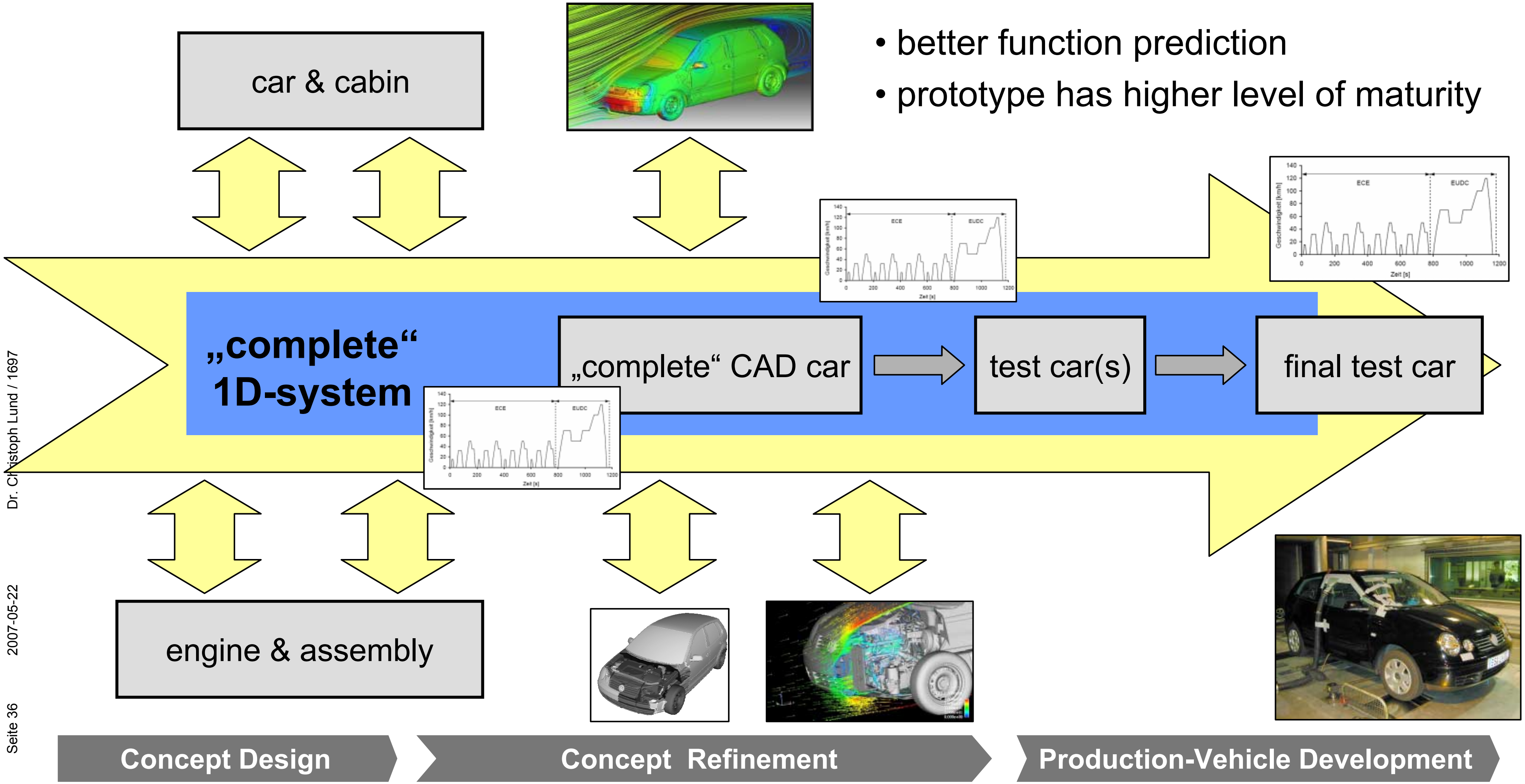




Concept Design → Concept Refinement → Production-Vehicle Development

System-Simulation within the Development Process - the Future Challenge

- better function prediction
- prototype has higher level of maturity



Outlook – Vehicle Thermal Simulation in 5 Years ?

Simulation Models

- simple, robust and flexible coupling
- supplier industry provides sub-models
- unique interface descriptions
- simple data handling
- "complete car models" are standard
- interface to engine / climate control
- simple interface between 1D and 3D

Simulation Results

- transient energy „distribution“
- thermal comfort; transient ?
- emissions ?

Simulation Engineers

- experts for single systems
- experts for complete cars
- very, very friendly ☺

Calibration Test for Simulation Models

- special standardized component tests
- special standardized engine tests
- special standardized car tests

Let's try it!

Thank You

for Your Attention!

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