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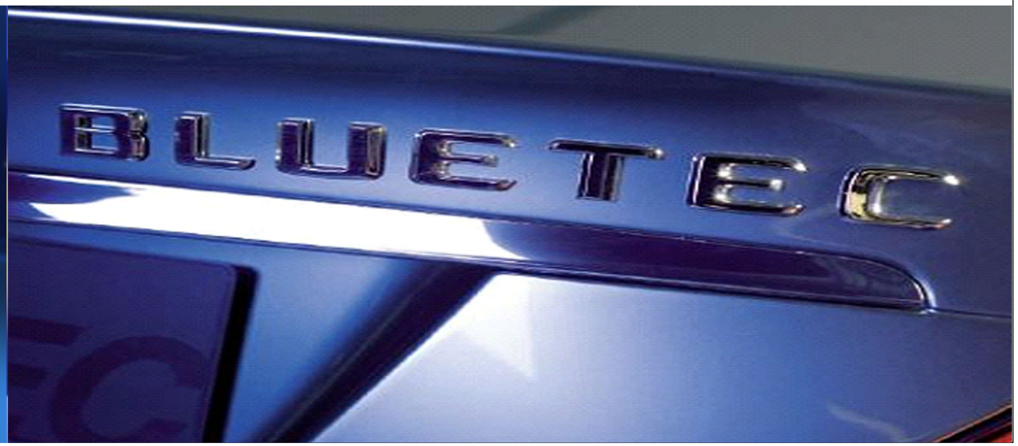
CLEERS, April 2011

System Simulation of Modern Powertrain Concepts
- From an Industrial Perspective

B. Krutzsch, M. Weibel, R. Steiner, V. Schmeißer

Daimler AG, Germany

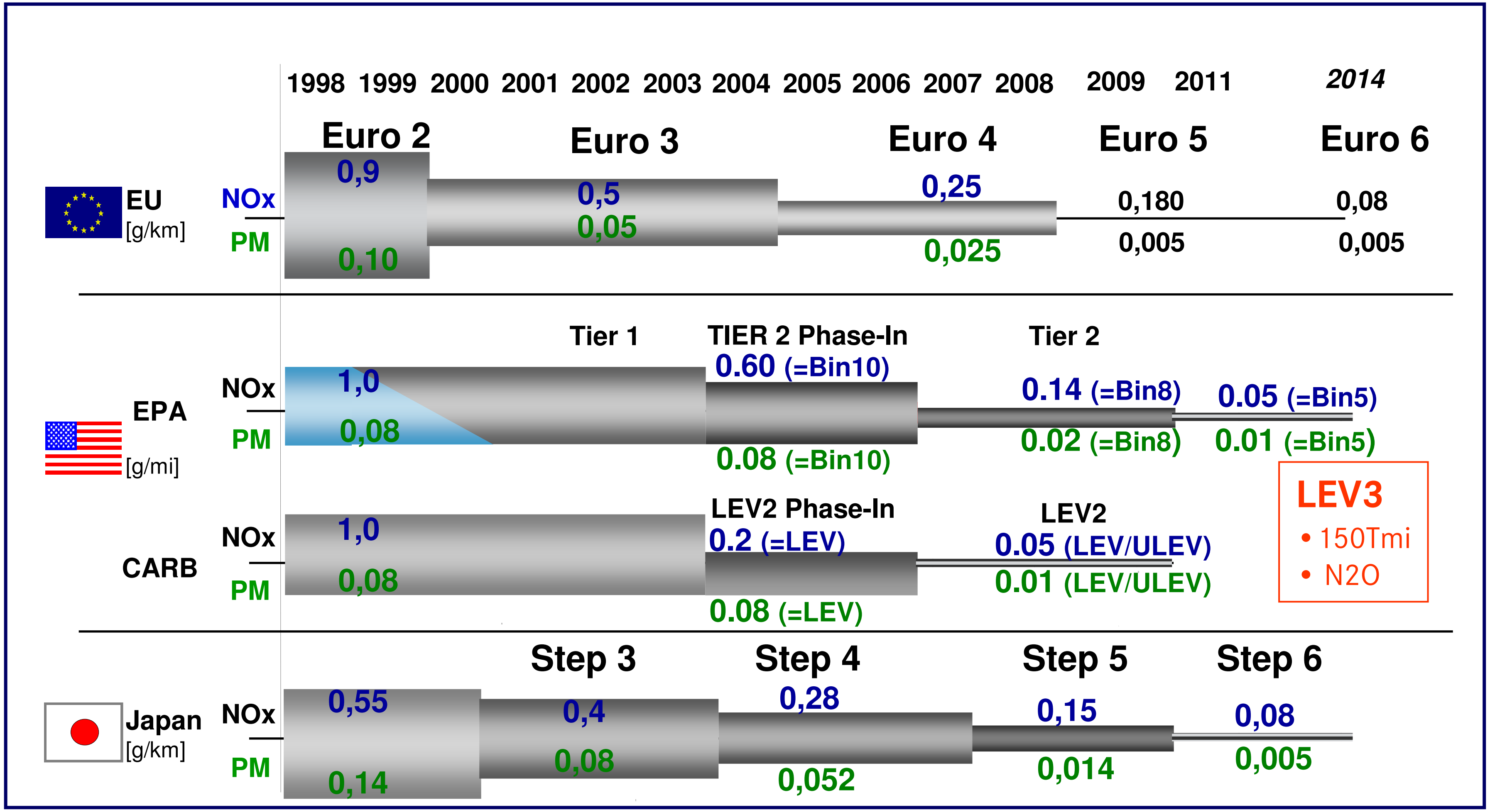


Outline

- **Introduction**
  - **- Emission Standards – Motivation - Challenges**
- **Modeling Challenges**
  - **Exhaust Gas Aftertreatment Simulation**
    - **BlueTEC Technology for Passenger Cars**
  - **Engine emission modeling**
- **Full Vehicle Simulation**
- **Summary - Conclusion**

Motivation: NOx- and PM-Emissions

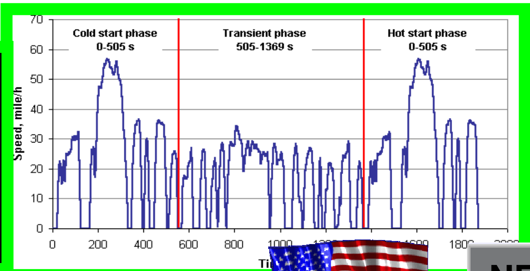
The major challenge is to fulfill the worldwide emission standards



DAIMLER Political Surroundings

Regulations in the Markets: Pollutants and CO2!

US-FTP-72/75
US-SFTP
(FTP&SC03&US06)
US-OBD
US-CAFE
...



NFZ: NOx and Particle

PKW: Fuel Consumption CAFE [1]:
→≥ 30 mpg for MY2012 !?

7,8 l/100km

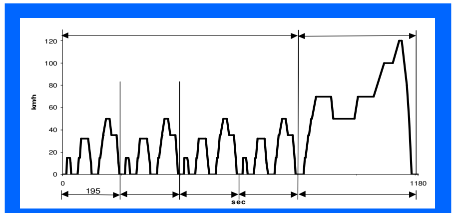
Fuel Consumption CARB [2]:
AB1493 → 205 g CO_2/mi
for MY2016 (= 127 g CO_2/km)

~ 5,3 l/100km

Emission: focus NOx reduction!
→ BIN8: 0,14 g/km NOx
→ BIN5: 0,07 g/mi NOx
→ SULEV: 0,02 g/mi NOx

ZEV & AT-PZEV Mandate !

[1] 50 states; [2] 5+ X states



EU-NEDC2000
EU-SHED2000
EU-OBD
EU-ACEA-2008
(Self obligation)
CO_2 140g/km

NFZ: NOx and Particle

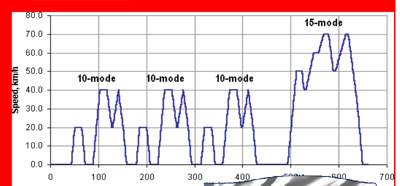
Fuel Consumption:
→ 140 g CO_2 /km in 2008 !?
→ 120 g CO_2 /km in 2012 !?

Emission: EU5 in 2009
→ 0,18* g/km NOx

~ 5,0 l/100km

* Final decision pending

J-10-15 /11 mode
J-CD3
J-OBD
J-Green Tax...



NFZ: NOx and Particle

Fuel Consumption:
→ weight classes in 2010

Emission: Urban NOx Control
→ 0,14 g/km NOx in 2007
→ J-LEV Programm

Fuel Consumption:
→ Oriented on CARB

Emission:
→ Oriented on EPA

§

Fuel Consumption:
→ 16 weight classes in 2008:
from 43 mpg to 21 mpg

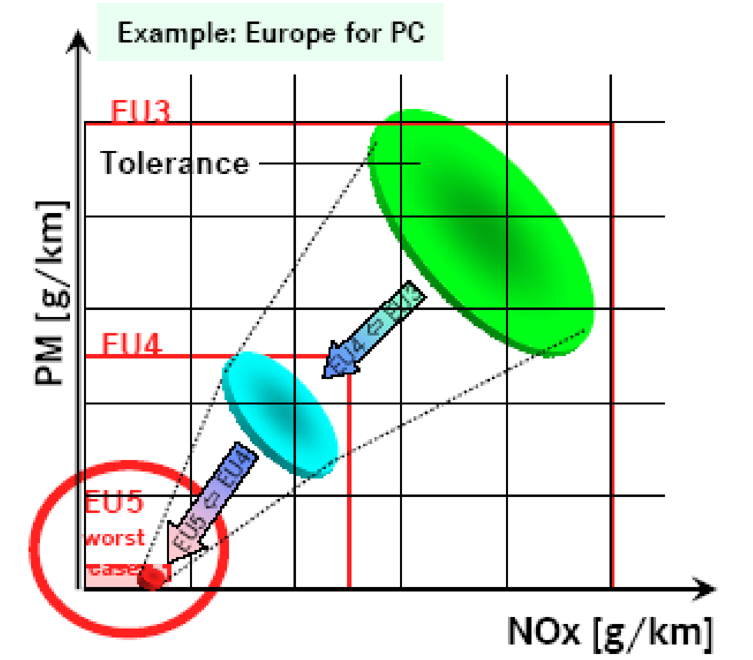
Emission: EU orientated
→ EU4 in 2006

5,5-13,9 l/100km

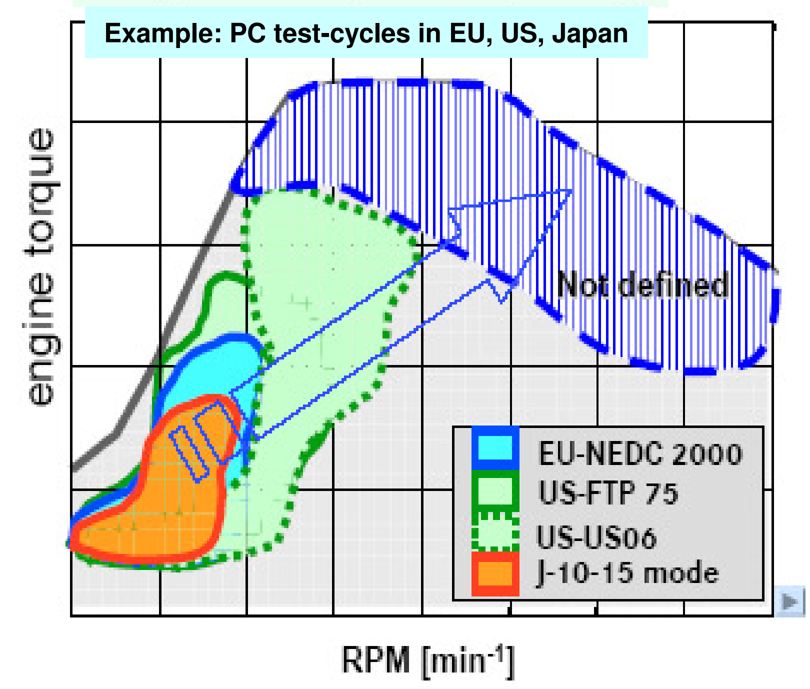
It is expected that fuel consumption and emission targets will tighten even further in the future!

Challenges Related To Emission Legislation

Emission Legislation is becoming more and more stringent (robustness)

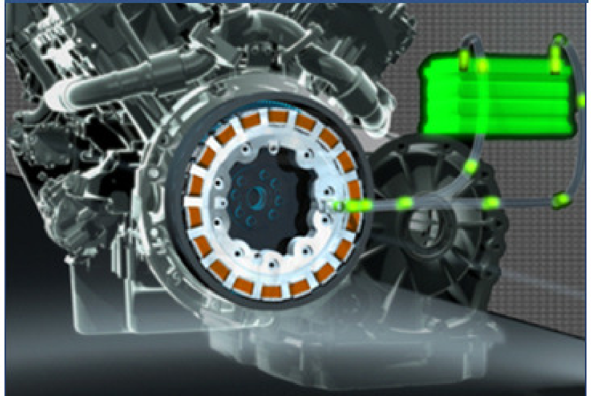


Test procedure will be probably extended to whole engine map (off-cycle)



To meet future standards, fuels with closely restricted specifications and extensive improvements in combustion and exhaust gas after treatment systems are obligatory

Innovative powertrain systems towards sustainable mobility for the future

Further optimization of combustion engine	Increase efficiency with hybridization	Locally emission-free driving
		
BlueEFFICIENCY CGI, BlueDIRECT, BlueTEC, DIESOTTO	Hybrid Range Extender Plug-In	Electric drive E-CELL/E-CELL PLUS F-CELL

Clean fuels

Energy sources for future mobility

Battery/Fuel cell

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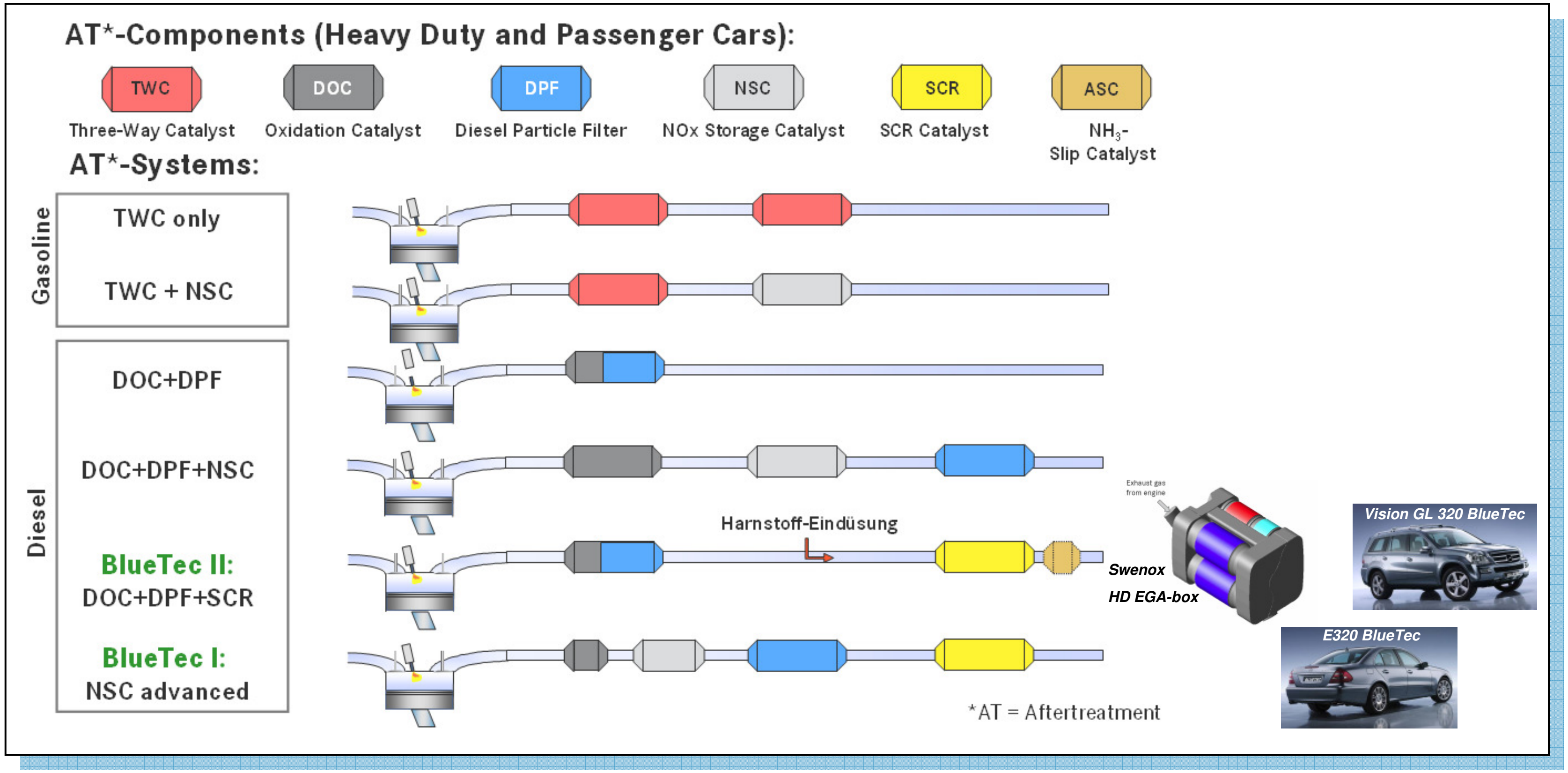
- Modeling Challenges
  - Exhaust Gas Aftertreatment Simulation
    - BlueTEC Technology for Passenger Cars
  - Engine emission modeling
- Full Vehicle Simulation
- Summary - Conclusion

Motivation

AGN-Simulation as sub-component of systemsimulation for the development of low-emission vehicles with combustion engines including alternative propulsion (e-Drive)



→ **high complexity of aftert-treatment and propulsion systems and fundamental role of simulation**

→ **Without simulation it`s impossible to adapt a system to all the different vehicle and engine variants offered on the markets around the world**

Modeling and Simulation at Daimler

combustion + emission sim (combining engine + EGA)
- CO2- and emission optimization
- operating strategies (e.g. hybrid)

6

simplified control oriented EGA models
- engine control
- EGA control
- OBD purposes

1D EGA simulation for
- configuration
- design and layout
- catalyst size, position
- sensitivity analysis
- potential estimation

2

1

„virtual testbench“ method incl. ECU algorithms (SiL)
- development of control algorithms
- operating strategies
- pre-calibration of ECU

3

coupling

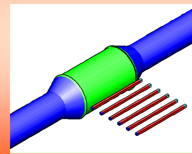
Engine Models

kinetic parameter calibration 4

EGA 1D-modeling

Tool ExACT 1

3D-CFD including 1D-reaction simulation



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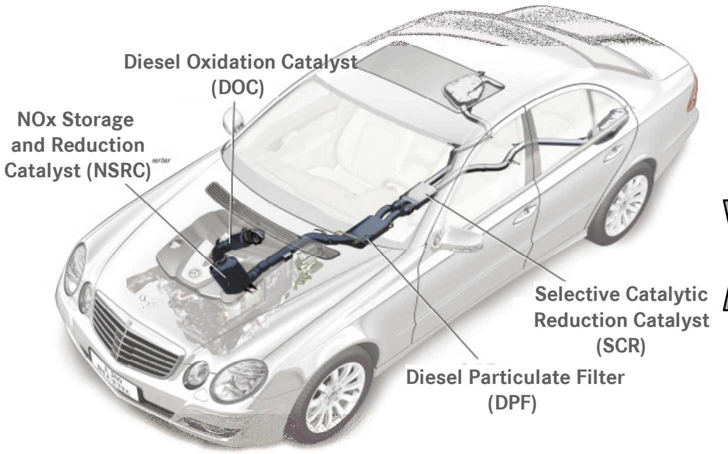
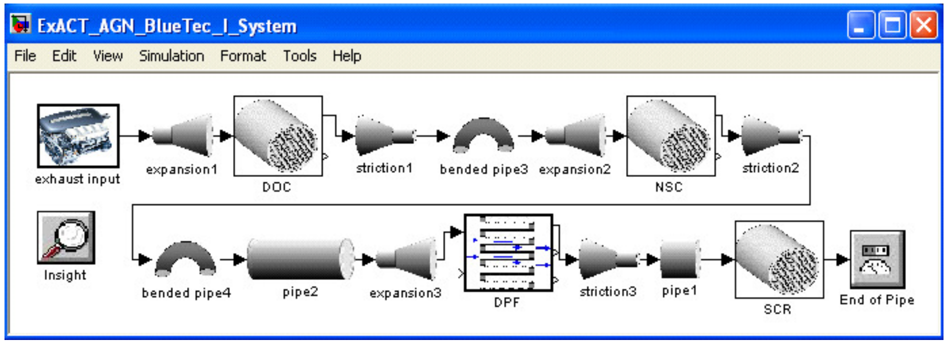
Exhaust Aftertreatment Component Toolbox (ExACT)

History

- 1996: Technology-Monitoring: Tools EGA-Sim commercially not available
- 1997: Start FVV-Project, Lead Daimler (PhD: Daniel Chatterjee)
- 2000: Start Modeling in R&D Projects: TWC, DOC, NO-Oxidation
  Cooperation with Universities Prague , Milano, Thessaloniki
  (Models or SCR, TWC, NSC, DOC, DPF)

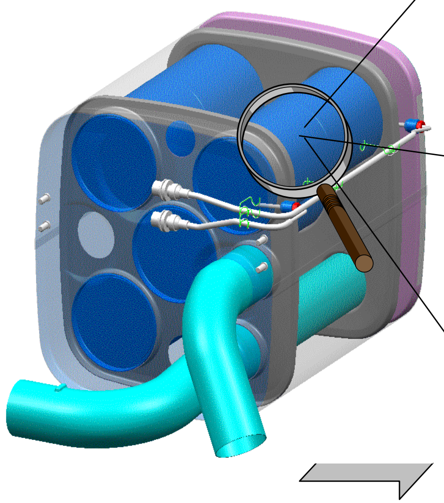
→ **Tool *ExACT***



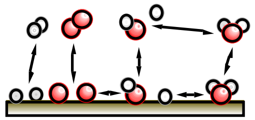


ExACT toolbox consists of 1D models for SCR, DOC, DPF, LNT, TWC and ASC. Simulation of combined aftertreatment systems. Model generation by drag & drop.
Focus: Testcycle simulation, system design, operating strategies, DCU development

1 D-Modeling of Catalytic Converters/DPF

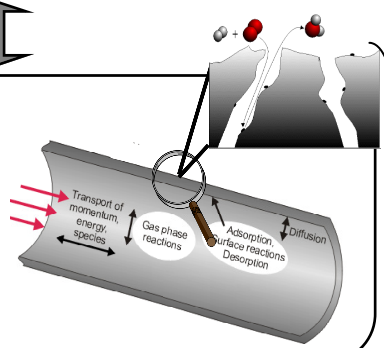


surface reactions:
(chemistry)

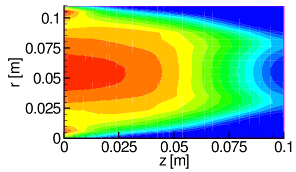


Variation of coating requires recalibration

single channel:
(heat and mass transfer)



monolith:
(solid temperature)

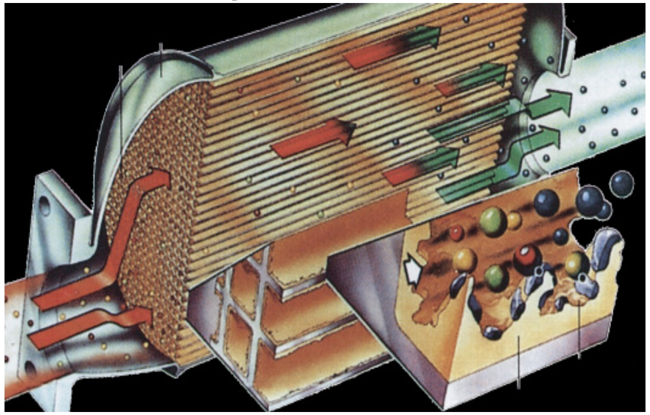


Variation of geom. parameters (e.g. cell density, length, structure,...) possible.

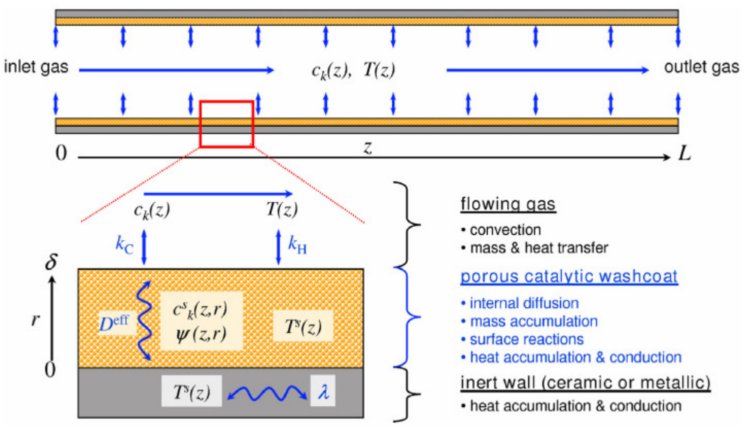
Modeling of most relevant physical and chemical processes required for predictive simulations. Variation of geom. parameters (cell density etc.) in the simulation makes separation of transport effects and chemistry kinetics necessary.

General Remarks

Catalyst-Monolith:

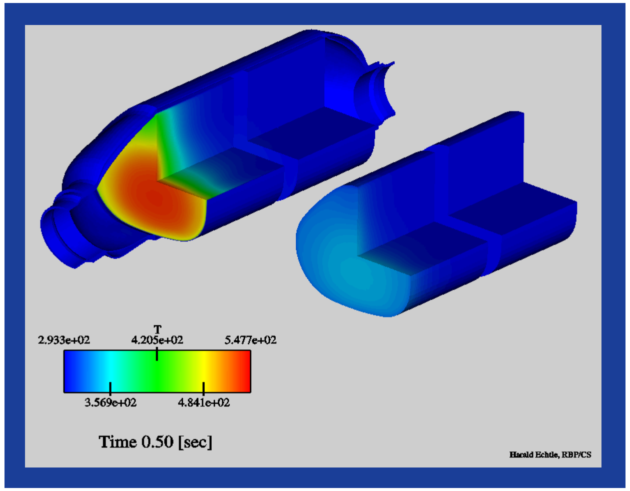


1D-Modeling:



- 1 chanel, representative für overall catalyst
- Assumption: radial ideal dristribution
- Real axiale distribution

3D-Modeling:



- Real axiale and radiale extension
- Inlet-flow
- Temperature distribution

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ExACT-Development at Daimler

ExACT-User:

Business Units

- *Passenger Cars*
- *Medium Duty*
- *Heavy Duty*

→ *thermal behavior*
→ *emissions*
→ *ECU calibration*

ExACT

ExACT-Development:

GR/APE

ExACT

Application in Research Projects:

ExACT

Tool Development

Strategic Partners:

Prof. Marek
INSTITUTE OF CHEMICAL TECHNOLOGY PRAGUE
DOC
TWC
NSC

Prof. Tronconi
POLITECNICO MILANO
SCR
ASC

Prof. Koltsakis
LAT LABORATORY OF APPLIED THERMODYNAMICS
DPF
Axitrap

MBtech
MBtech Mercedes-Benz technology
Development and Testing

TWT GmbH
TWT
Tool-Environment

model calibration

IAV GmbH
IAV
cDPF Kalibrierung

Prof. Bock
iwr
Optimierung Kalibrier-methodik

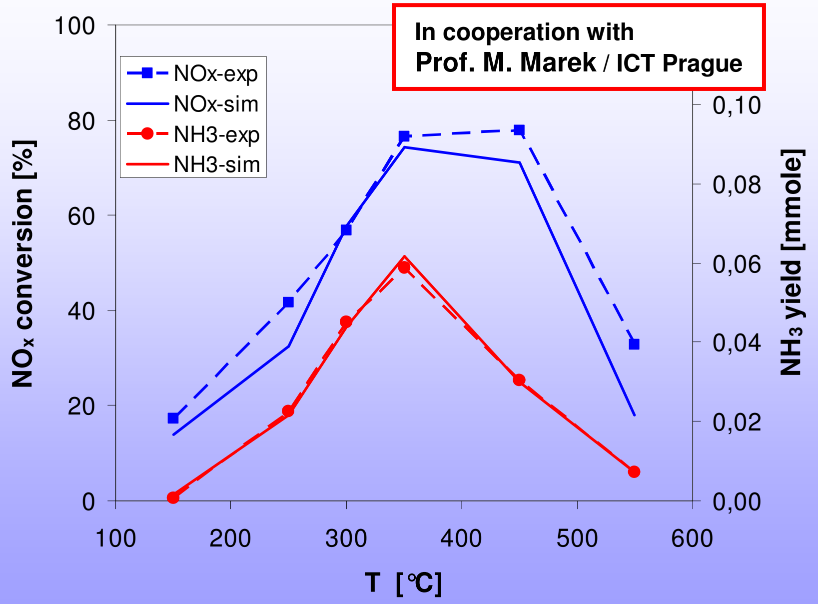
Prof. Deutschmann
Universität Karlsruhe (TH) Research University • founded 1825
KIT Karlsruher Institut für Technologie
Kalibrier-Messungen

MBRDI Bangalore
ExACT-Calibration & Development

Modeling of NSC and SCR: NOx Conversion and NH3 Yield (Simulation versus Experiment)

Steady state NO_x conversion, NH_3 Yield

NO_x Storage Catalyst

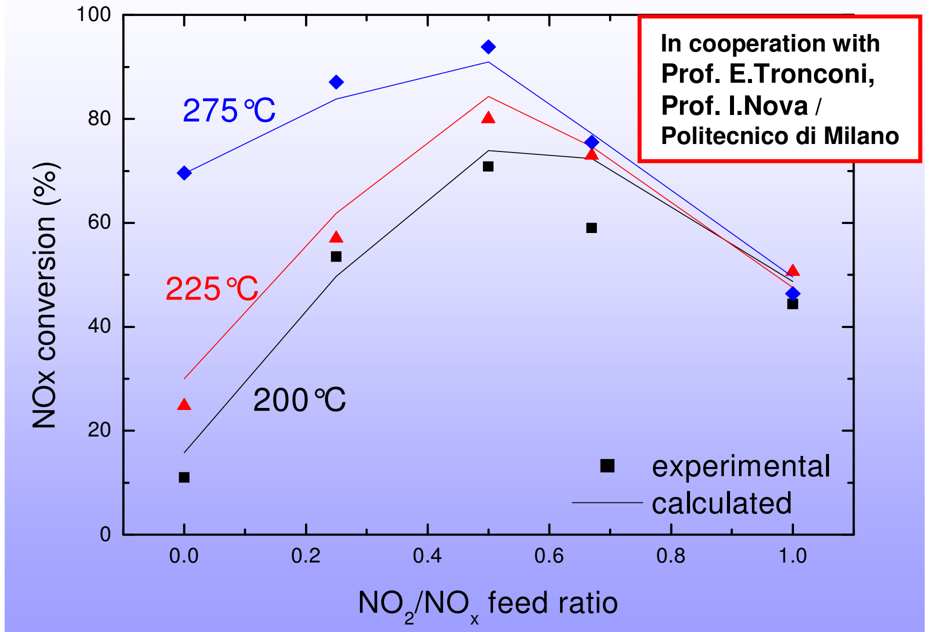


Monolith reactor sim./exp.:

Feed 200 ppm NOx, λ_{rich}=0,93, lean/rich: 180s/7s GHSV = 50k h^{-1}

Steady state NO_x conversion

SCR Catalyst



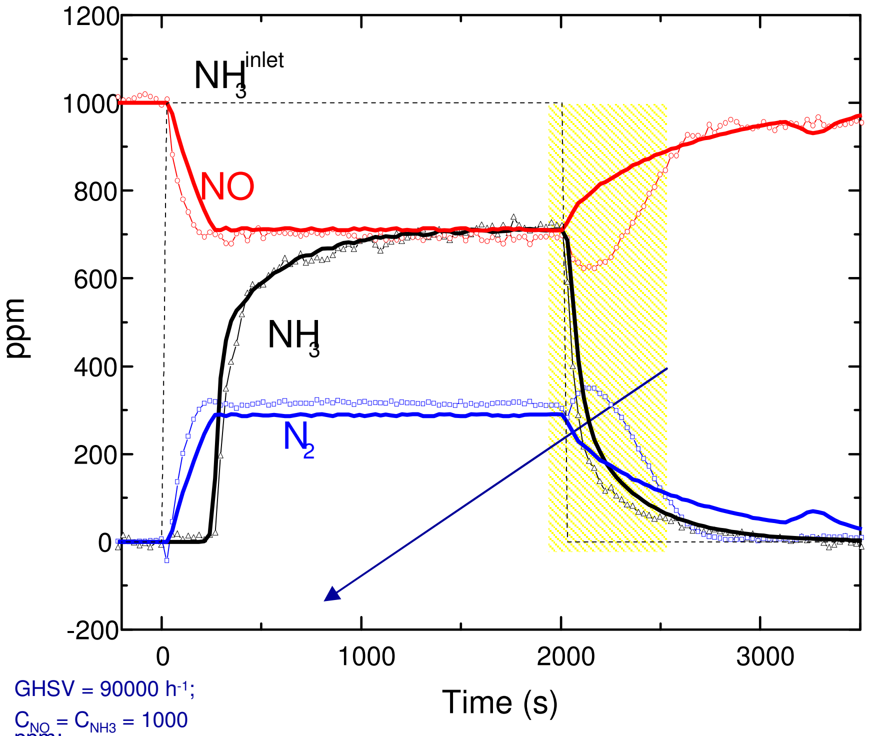
Microreactor sim./exp.:

Feed 1000ppm NH3, 1000ppm NOx, GHSV = 210000 h^{-1}

NSC: NH3 selectivity during regeneration favoured around 350 °C.
SCR: Conversion efficiency is influenced by the NO2/NOx feed ratio.
Model correlates well with measured product selectivity and NOx conversion.

Reaction Mechanism: How important is the detailed chemistry?

1. Eley-Rideal Kinetics (ER)

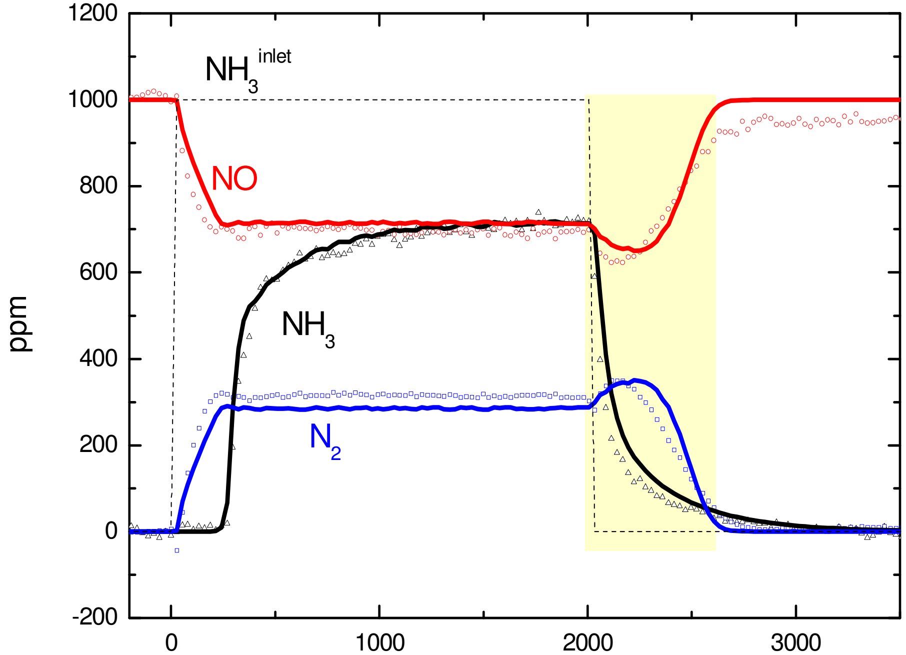


GHSV = 90000 h-1;
$C_{NO} = C_{NH3} = 1000$ ppm;
$C_{H2O} = 1\%$;
$C_{O2} = 2\%$;
T = 200°C

- **Source:** C. Ciardelli, I. Nova, **E. Tronconi,** B. Konrad, D. Chatterjee, K. Ecke, M. Weibel, Chem. Eng. Sci. 59 (2004) 5301.
- **Nova et al.,** *AIChE J,* 52 (2006) 3222

Eley-Rideal unable to explain the inhibition of N2-formation by NH3.

2. Modified Redox kinetics (MR)



(a) $S_1{=}O + NO \Leftrightarrow S_1{=}O(NO)$
(b) $S_2 + NH_3 \Leftrightarrow S_2(NH_3)$
(c) $S_1{=}O(NO) + S_2(NH_3)$
$\rightarrow N_2 + H_2O + S_1\text{-}OH + S_2$
(d) $S_1\text{-}OH + ¼\ O_2 \rightarrow S_1{=}O + ½H2O$
(e) $S_1 + S_2(NH_3) \Leftrightarrow S_1\ (NH_3) + S_2$

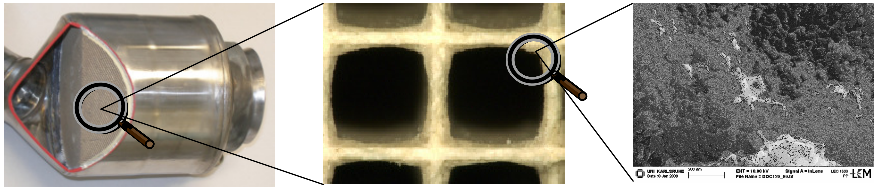
S_1 = redox sites (associated with V, Fe, Cu)
S_2 = acidic sites (possibly associated with W/Ti)

With a modified mechanism MR excellent compliance between Sim and Experiment

Kinetic Parameter Calibration

Dr. V. Schmeißer, Dr. B. Ganz

Model calibration



global kinetics

- change of washcoat or ageing condition requires calibration
- only kinetic parameters calibration – geometry not affected

reactions and rates - example:

$$CO + \frac{1}{2}O_2 \longrightarrow CO_2 \qquad R_{NSRC1} = k_{NSRC1} y_{CO} y_{O_2} \frac{1}{G_{1b}}$$

$$C_3H_6 + \frac{9}{2}O_2 \longrightarrow 3CO_2 + 3H_2O \qquad R_{NSRC3} = k_{NSRC3} y_{C_3H_6} y_{O_2} \frac{1}{G_1}$$

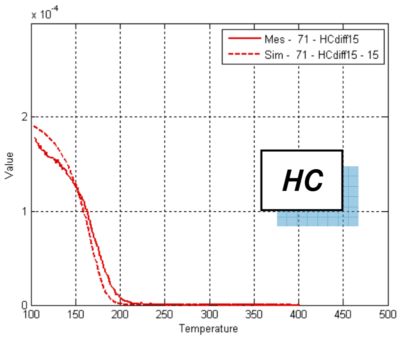
$$k_i = k_{0,i} \cdot \exp\left(\frac{-E_{a,i}}{\mathbf{R}T^s}\right)$$

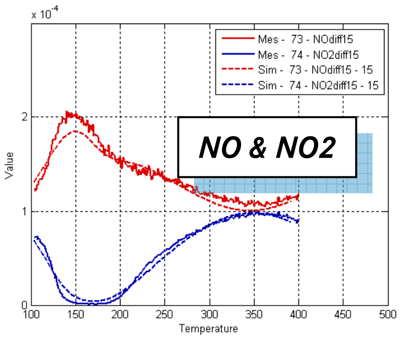
$$K_{inh,l} = K_{inh0,l} \cdot \exp\left(\frac{E_l}{T^s}\right)$$

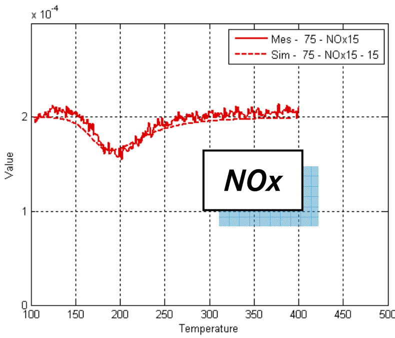
$$G_1 = \left(1 + K_{inh,1} y_{CO} + K_{inh,2} y_{C_3H_6}\right)^2 \cdot \left(1 + K_{inh,3} y_{CO}^2\, y_{C_3H_6}^2\right) \cdot \left(1 + K_{inh,4}\, y_{NO_x}^{0.7}\right) \cdot T$$

kinetic parameters:

- *numerous*
- *to be determined according to measurements*







- new catalysts/PGM-loadings/aging require kinetic calibration
- effective techniques necessary:
  - using conventional parameter estimation tools (e.g. simplex)
  - using automated calibration

Advanced calibration methods

Demand:

availability of kinetic parameters for new technologies/conditions within a short time!

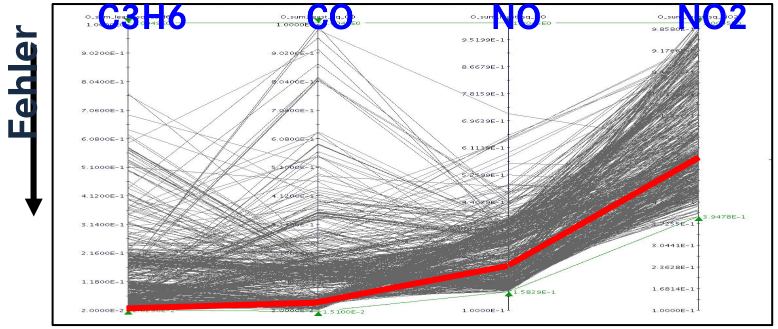
example calibration of DOC:

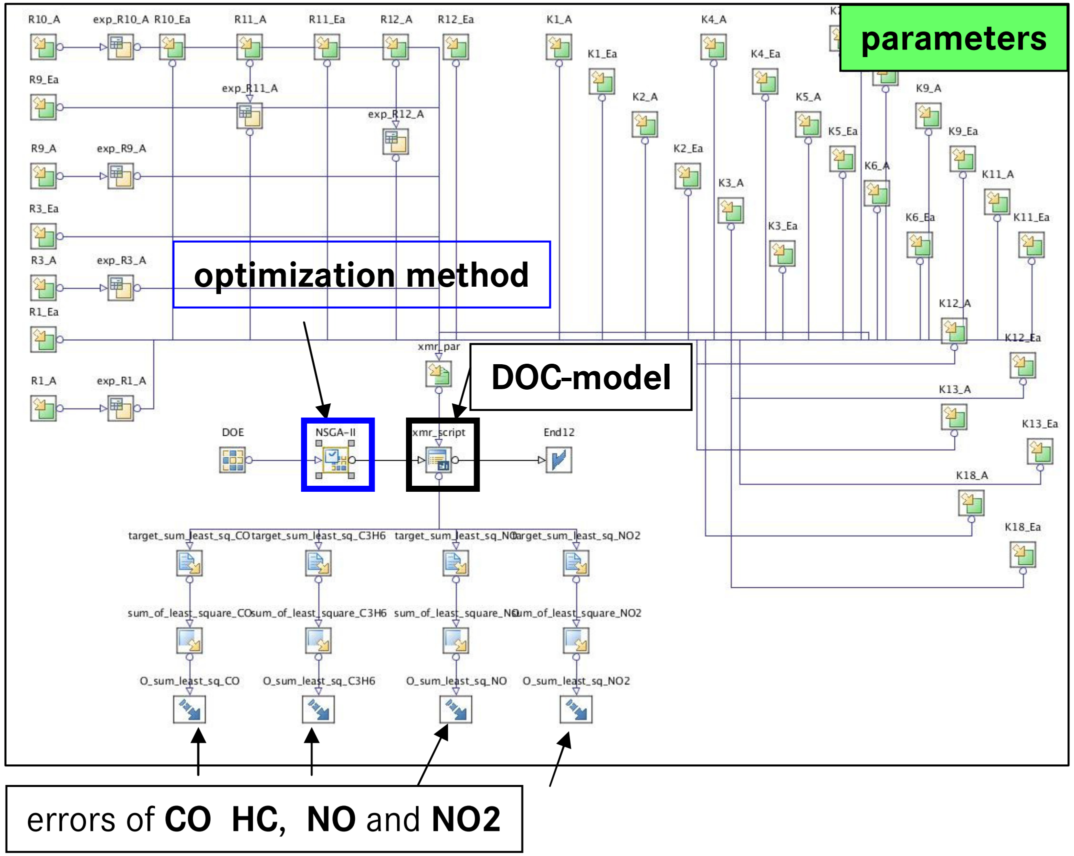
36 parameters (pre-exponential factors and energies for reactions and inhibitions)

4 species of interest (CO, HC, NO, NO2)

Time: **2 days** on 100 Processors compared to 2 months conventional before

combination of
1. DOE in a wide parameter range
→ solution as starting point for optimization
2. optimization (SIMPLEX, NSGA, BFGS)*





New Calibration Methodology could be used for all tested cases
fast calibration process due to parallelization on computer cluster

* SIMPLEX (gradientenbasiert), NSGA (Non-sorting-genetic algorithm), BFGS (Broyden–Fletcher–Goldfarb–Shanno)

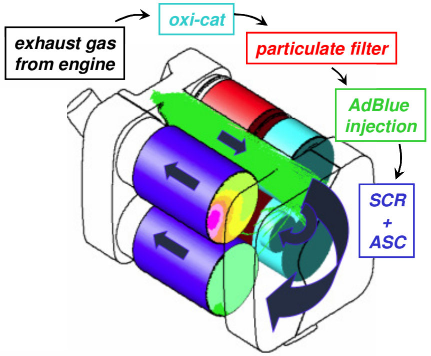
1D EGA simulation:
Heavy Duty EGA-System

Dr. F. Hofmann, Dr. J. Koop

Heavy Duty EGA-System

Motivation

- *high complexity of EAT systems and increased requirements*
- *support by simulation required*



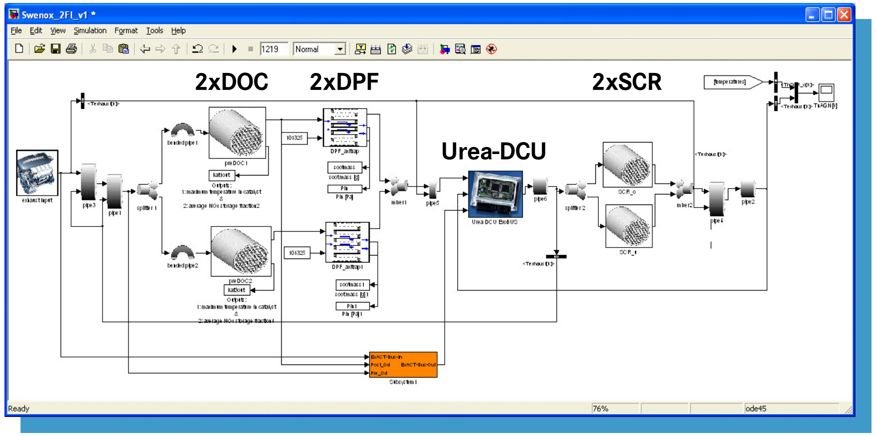
example:
Euro6 Swenox ATS-Box

Technical and Functional Approach

- ➢ *EAT model development using Matlab/Simulink (ExACT) and StarCD*
- ➢ *pipes, DOC, (c)DPF, SCR, ASC, TWC, NSC, AdBlue® dosing and processing*

Current Status

- ➢ *status of in-house developed models: high quality*
- ➢ *model application in various projects (Euro6, Tier4, Helo)*
- ➢ *further development according to future technologies (e.g. hybrids)*



example:
EAT model in ExACT

EAT modeling and simulation for:

- ➢ **development of operation strategies**
- ➢ **prediction of conversion behaviour**

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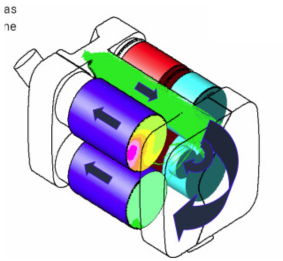
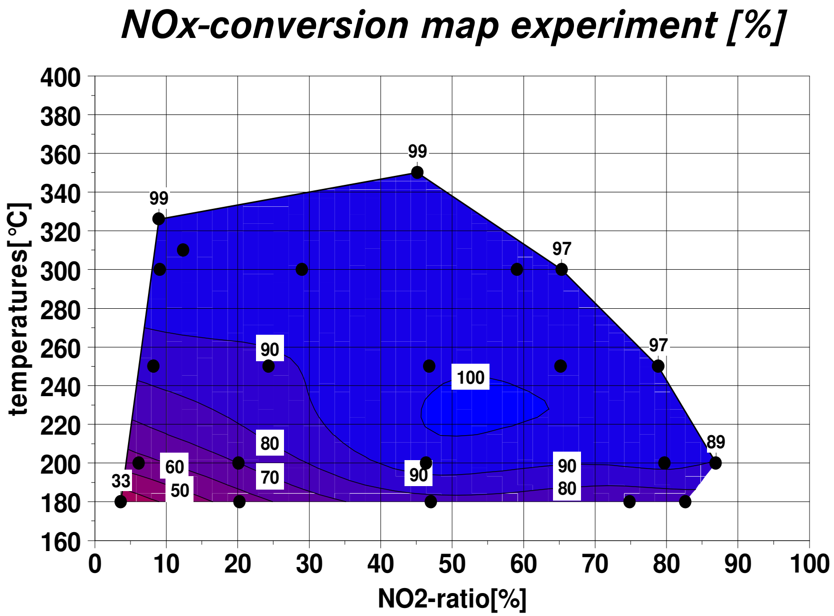
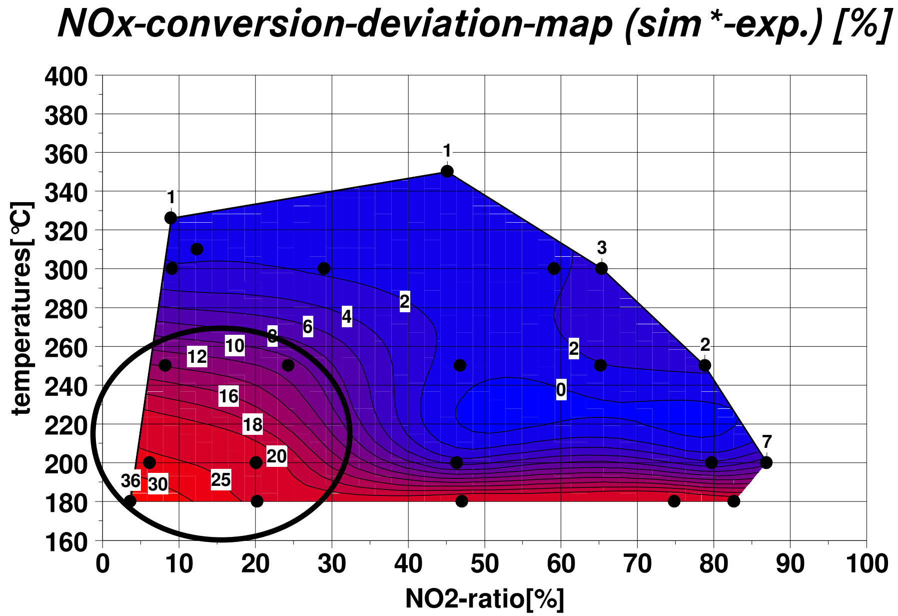
Heavy Duty EGA-System:
Analyis of Urea Processing on SCR-Performance







* 1D *ExACT* Simulation

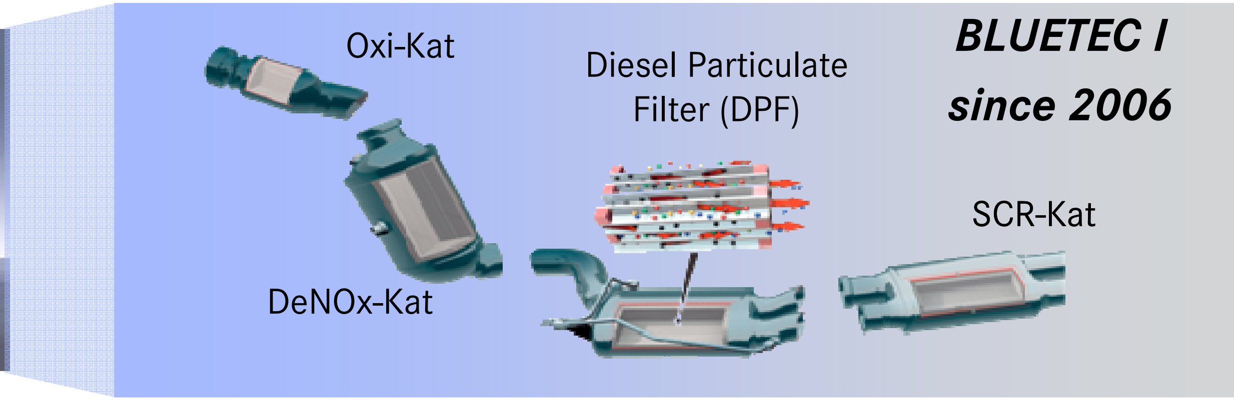
OM460 with ATS-Katbox EURO6 (17L DOC; 27L cDPF; 39,7L SCR), m_{exh} 300 kg/h

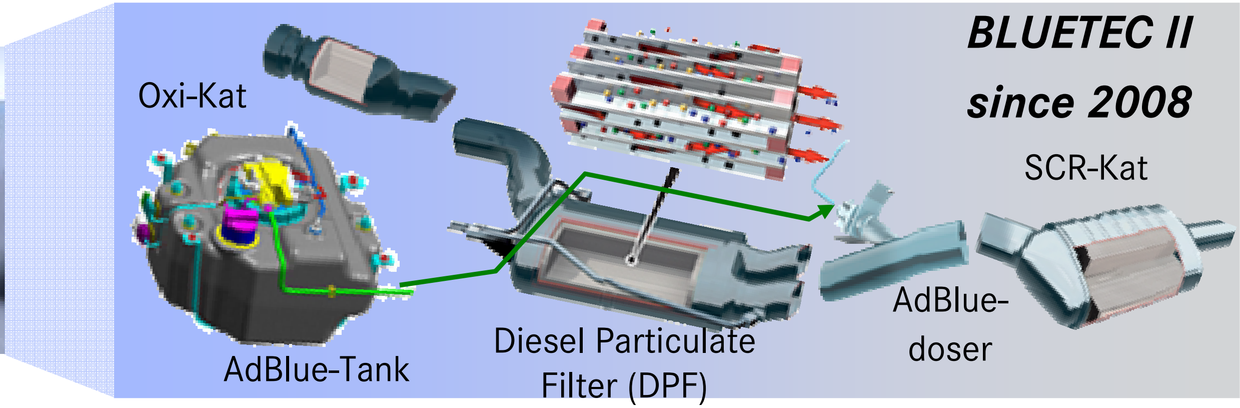
Simulation reveals a potential of improvement of the low temperature SCR efficiency around 10-20% by improving the NH_3-uniformity.

1D EGA simulation:
NSC + SCR-combination (BlueTEC I)

Dr. Weibel et. al.

Exhaust gas after treatment with Bluetec I / Bluetec II

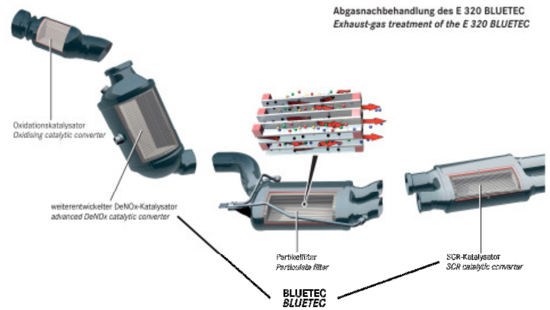


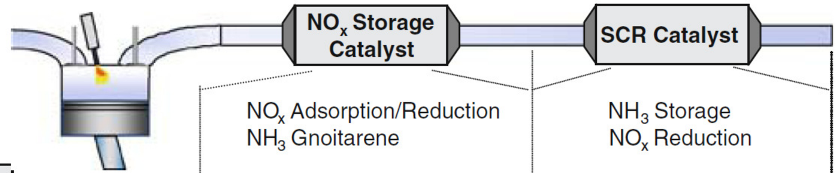


Target: Diesel engines as clean as gasoline engines thanks to BLUETEC
- on the way to the most stringent emission standards EU5 and EU6

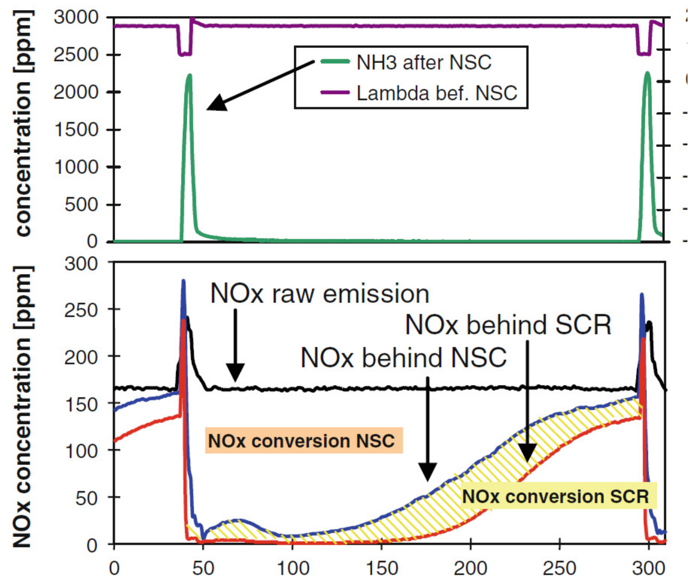
ExACT-simulation: NSC + SCR-combination

BlueTEC I: on-board generation of NH_3





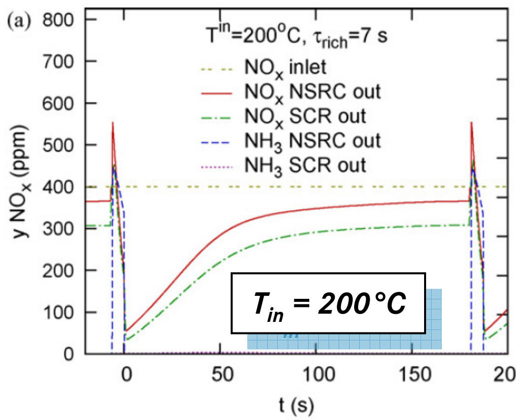
Engine Control Management	NO_x Storage Catalyst: NO_x Adsorption/Reduction, NH_3 Gnoitaerene	SCR Catalyst: NH_3 Storage, NO_x Reduction
Lean λ > 1 : (min scale)	**NO_x-Adsorption $Ba(NO_3)_2$** NOx-Breakthrough	**NO_x-Reduction** with stored NH_3
Rich λ < 1 : (sec. scale)	**NO_x-Reduction** (Reduction of $Ba(NO_3)_2$ to N_2 and NH_3)	**Storage of NH_3**
NSC Desulfation (min scale)	*Reduction of $BaSO_4$*	

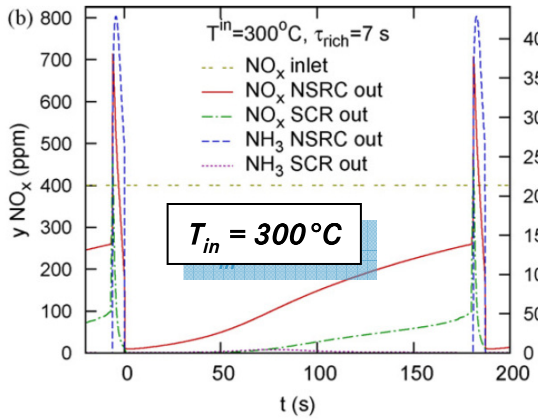


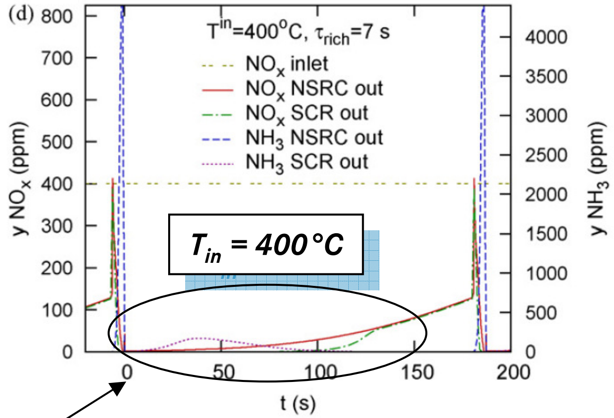
BlueTEC 1 as complex aftertreatment system with influence and interaction between catalyst modules including a lean / rich strategy by the engine

ExACT-simulation: NSC + SCR-combination

lean/rich-cycles (steady state), SV = 35.000 1/h, lean: 180s, rich: 7s

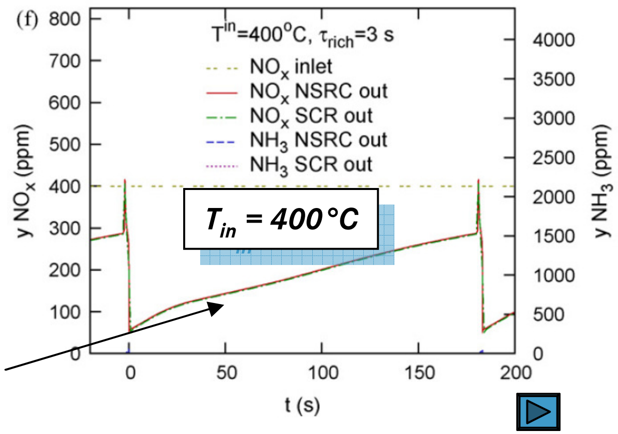






SCR-benefit limited, NH_3-slip!

rich: 3s



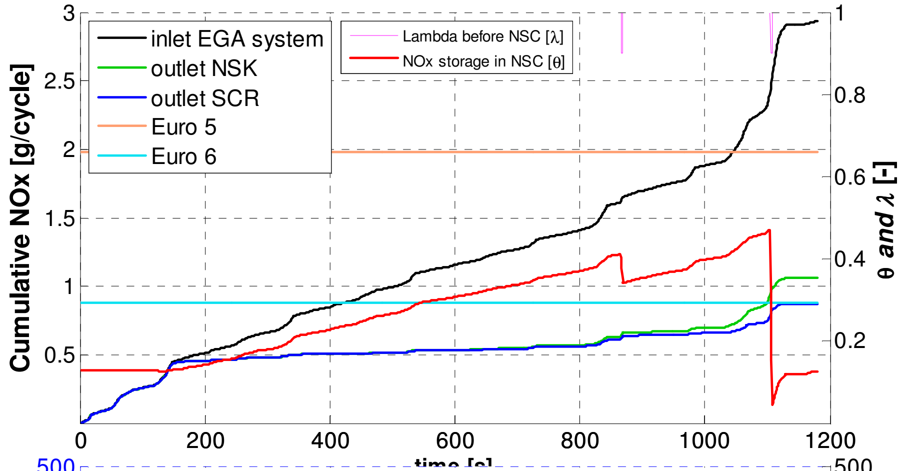
simulative analysis:
- → *principal system behavior*
- → *improves system understanding*
- → *identification of critical operating conditions*

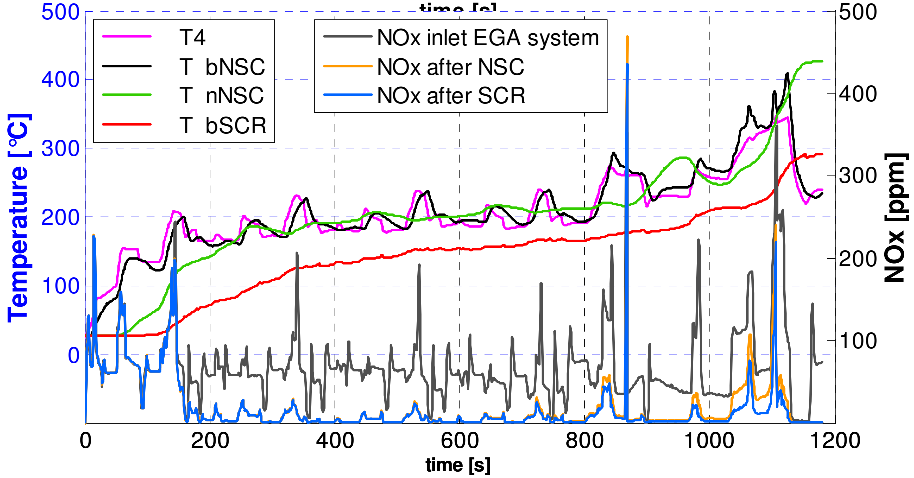
no SCR-benefit due to poor NH_3-generation

see: Chatterjee (Daimler AG) SAE2010-01-0887 and Catalysis Today 151 (2010) 395–409

BlueTec I (NSC Technology) Detailed analysis of the cycle

- Thermal aging of NSC corresponds to 80.000km
- Initial NOx loading in NSC → θ_{NSC}= 0.13 (max NOx loading 170 mol/m³)
- NH_3 pre-storage in SCR → θ_{SCR}= 0.04 (max NH3 loading 773 mol/m3)
- 2 standard regenerations at 865 and 1104 sec with duration of 3 sec





- NOx absorption starts after 150 sec
- Practically all NOx emitted between 150 sec and 800 are completely absorbed
- conversion in SCR after 800 sec due to low temperatures

➡ NOx conversion in NSC 62%

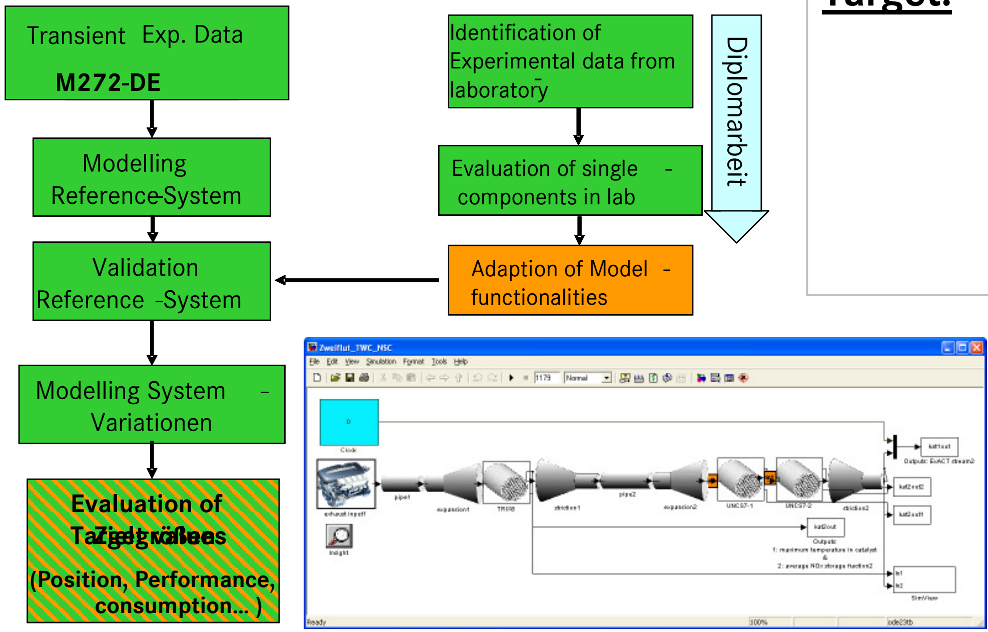
➡ NOx conversion in SCR 8%

➡ BlueTec I has the potential to meet Euro 6 targets

Coupling engine emission data with 1D EGA simulation

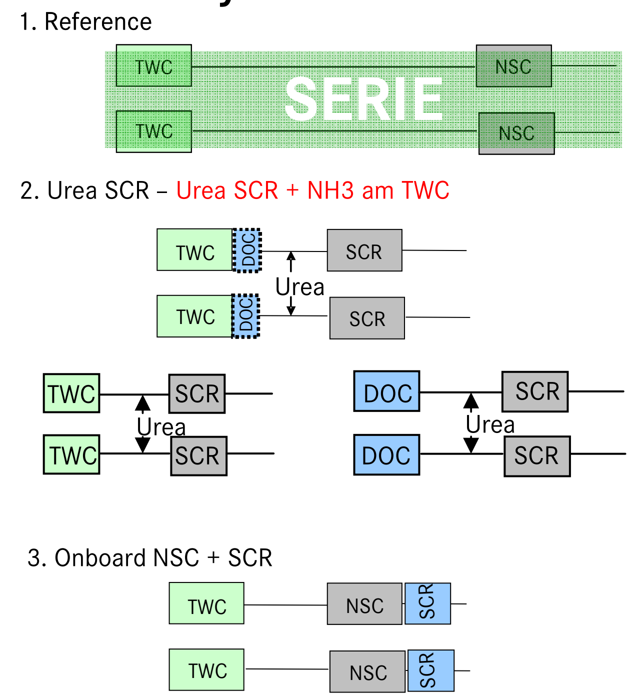
T. Rappe

EGA-Simulation DI-Gasoline: Study of different Systems



Target:
- cat-design, position
- NOx performance, urea consumption Fuel-consumption ((NEFZ, FTP)
  - crucial points
  - operation strategy
  - ageing

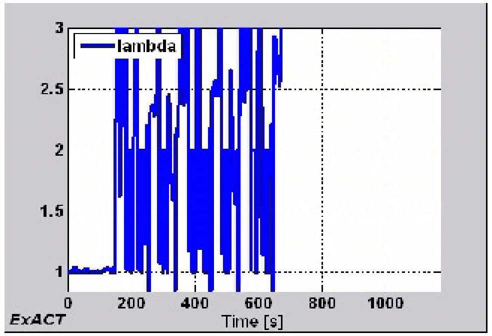
System-Variations:

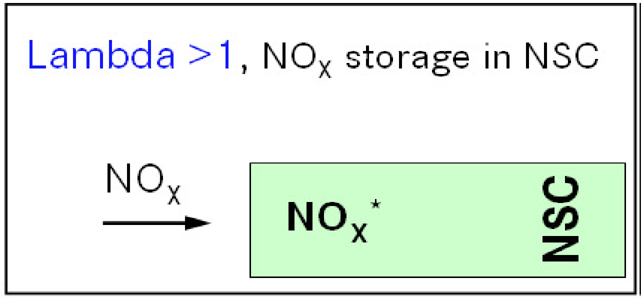


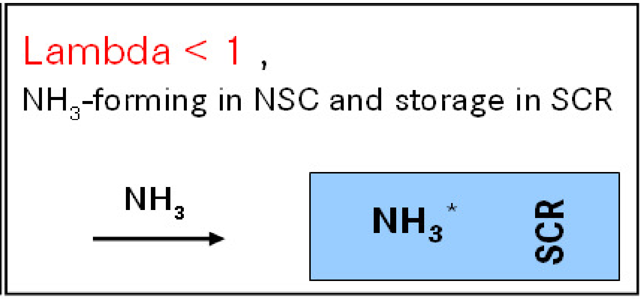
Parameters:
Temperature (catalyst position),
NOx raw emission,
NO/NO2 ratio,
NH3 pre-storage,
Urea dosing strategy,
NSC Reg.-Strategy, cat-volume

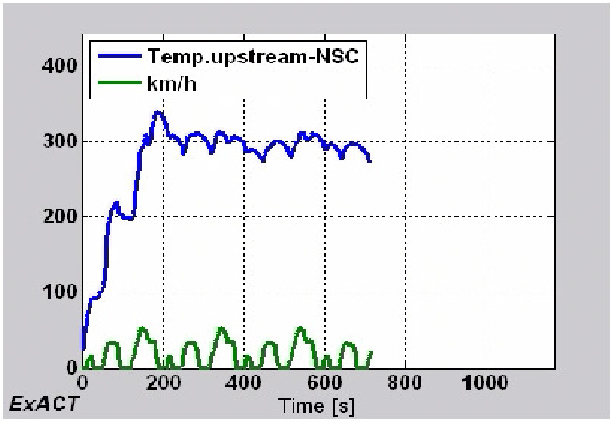
Numerical NEDC-Simulation of axial NO_X and NH_3 profile with **3s** rich spikes

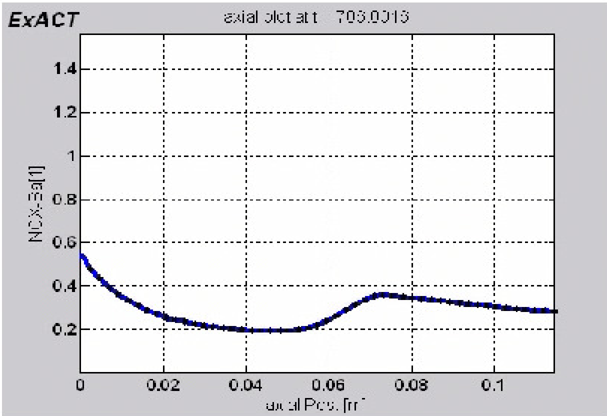
START

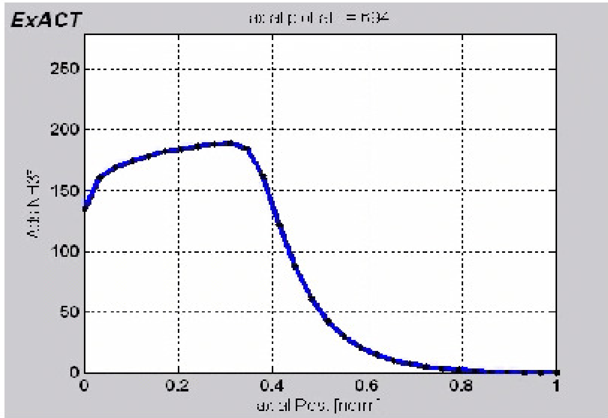












- Temperature upstream NSC
- Velocity [km/h]

NSC: axial profile NO_X [-]

NO_X-Ba = 1 => theoretical max. NO_X capacity

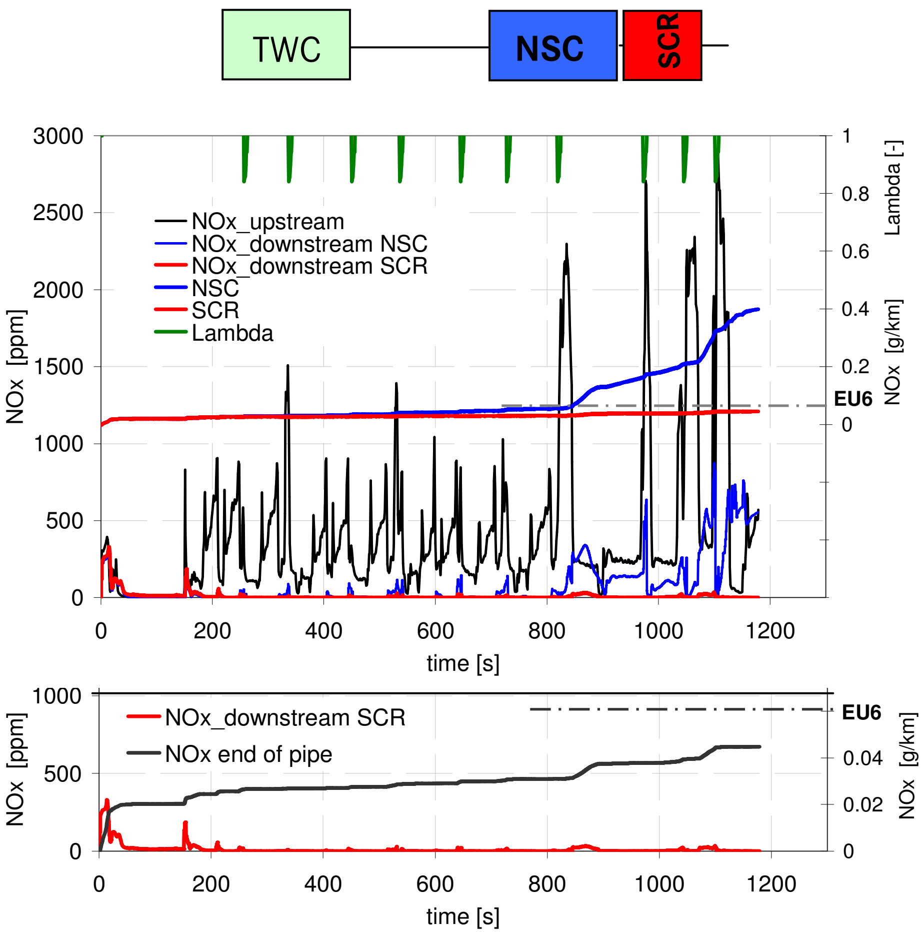
SCR: axial profile NH_3 [mol/m³]

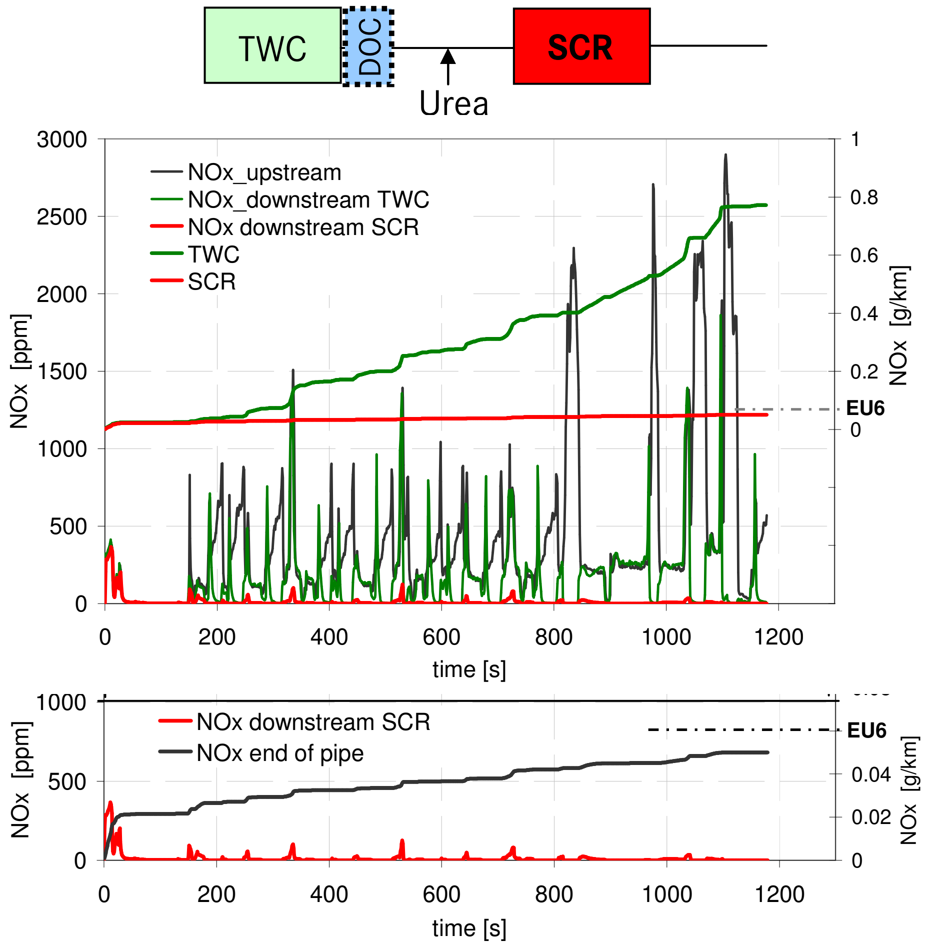
With 3s rich time NSC NO_X regeneration insufficient however for overall NO_X performance sufficient NH3 in SCR catalyst.

DAIMLER

Results: Coupling engine data with EXACT

Numerical simulation of lean gasoline vehicle to achieve EU6 regulations.





Simulation is useful to compare different EGA-systems and operation strategies.
Pre-optimizations of operation strategies can simplify test bench application.

Summary

- ***ExACT***: in-house developed and well-established 1D-simulation tool for EGA components
- description of complex exhaust aftertreatment systems possible
- simulation tasks for:
  - improved system configuration
  - improved component design and layout (catalyst size, position)
  - sensitivity analysis
  - potential estimation

Conclusion

Modeling and **simulation** will be the **key factor** for different applications of engine-vehicle combinations on markets around the world.

ExACT „virtual testbench“:
DCU-methodology for TP/PME

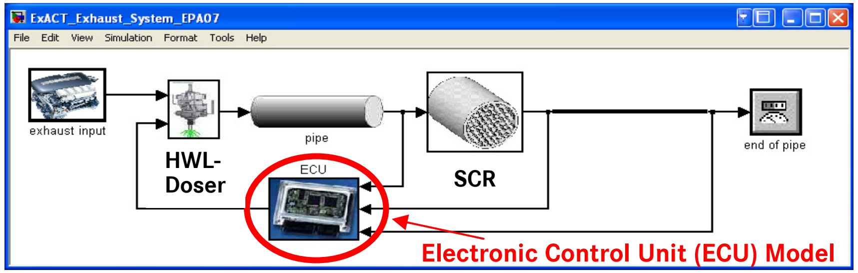
Dr. F. Hofmann

DCU-Methodology

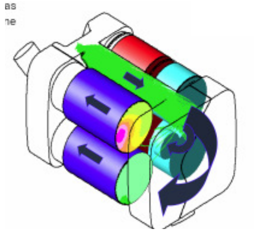
Model based DCU*-development for EURO6 and DCU-calibration with *ExACT*

***DCU: Dosing Control Unit**

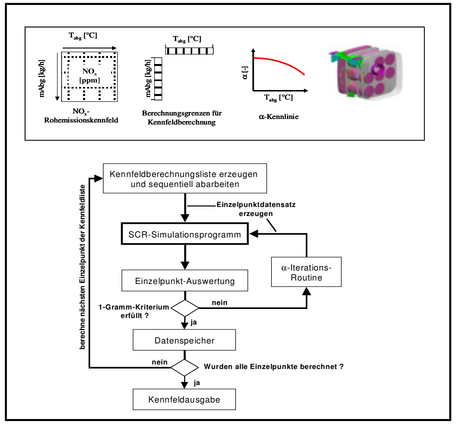
1) Development and testing of control algorithms with *ExACT*



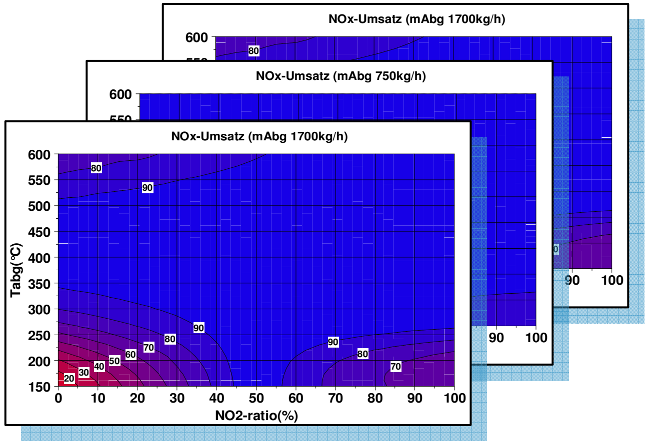
Truck EGA-box



2) Generation of NH_3-dosing-maps with *ExACT*

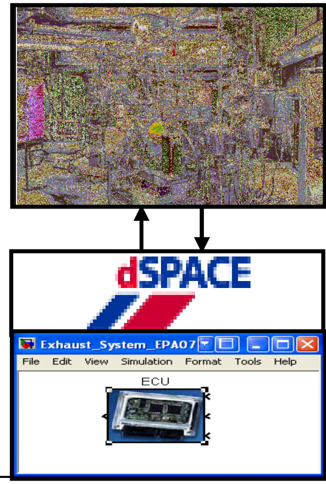


α-maps



3) Adaptation to real system

test-bench



- ***ExACT* „virtual testbench“: combined DCU and EGA simulation**
- **DCU control algorithm testing & precalibration of a-maps**

  → precalibration saves approx. 1-2 months in development time

**DCU: Dosing Control Unit*

DCU-Methodology

Further Development of Urea-Dosing Strategy for Cu-SCR based on ExACT

Motivation:

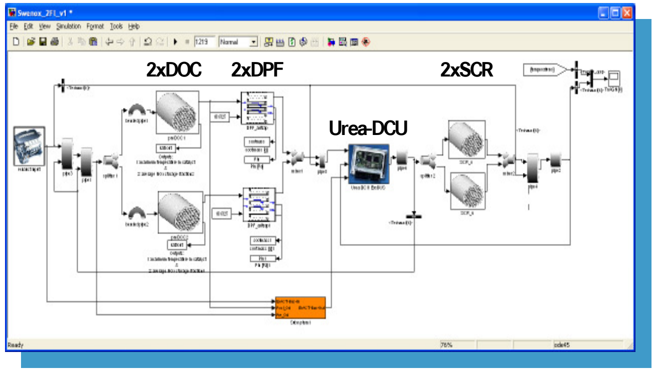
SCR NO_x conversion depends on <u>NH_3 storage</u> (θ_{NH3}) (*Cu-SCR !*)

<u>approach:</u>

1.) control of NH_3 loading

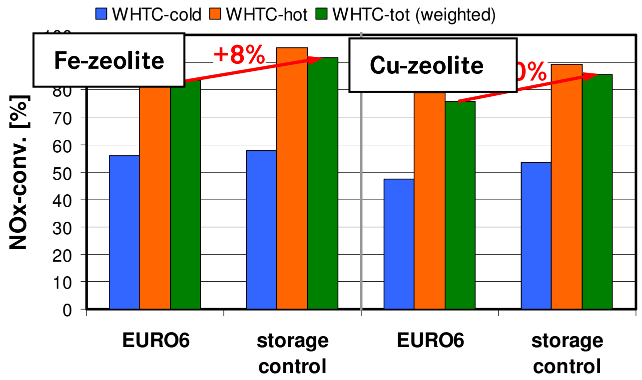
2.) accelerated NH_3 loading by overdosing at cold-start

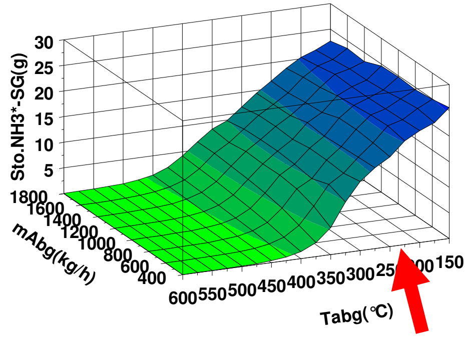
→ development of loading control and testing: with ExACT



Simulation Results:

- θ_{NH3} control
  → <u>increased</u> NO_x-conversion
- for both: Fe- or Cu-SCR
- generation of NH_3 storage map based on ExACT





Calculated calibration map: maximum NH3 load[2]

Next Step:

- Validation on engine test bench

higher NO_x-conversion due to improved dosing control

→ enables higher NO_x raw emissions & reduced fuel consumption:

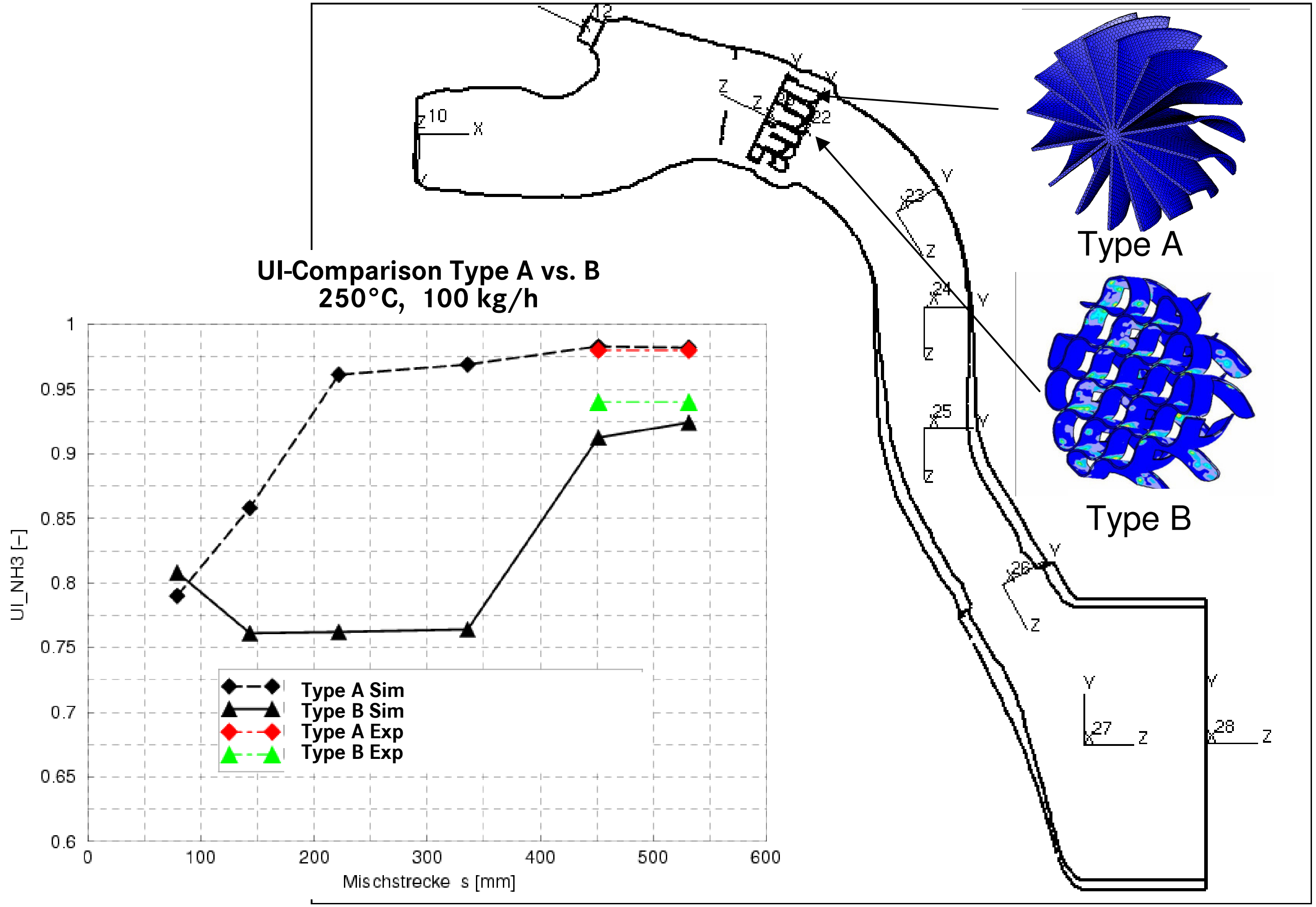
[U NOx] max
NH3 slip min

2) Model: DW3006 Fe-zeolite, fresh

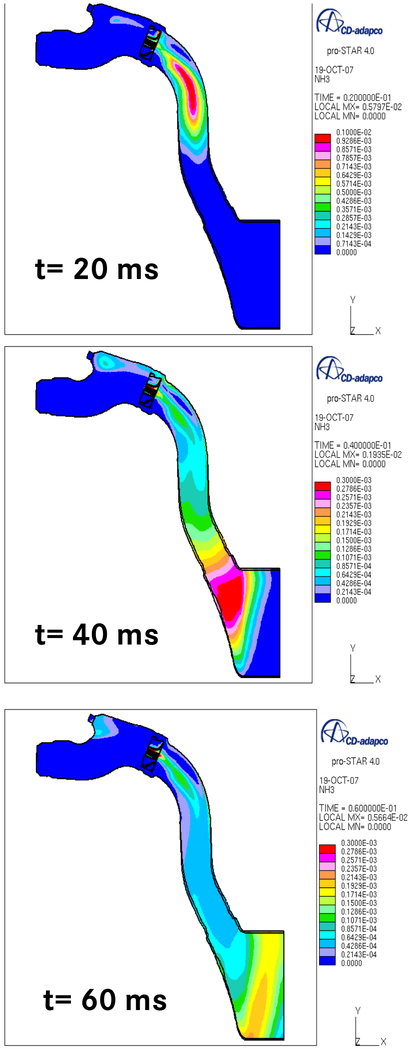
3D-CFD-Modeling
&
1D-3D coupling

Dr. Schöffel, H. Echtle

3D Simulation AdBlue Processing
Example: different mixer designs

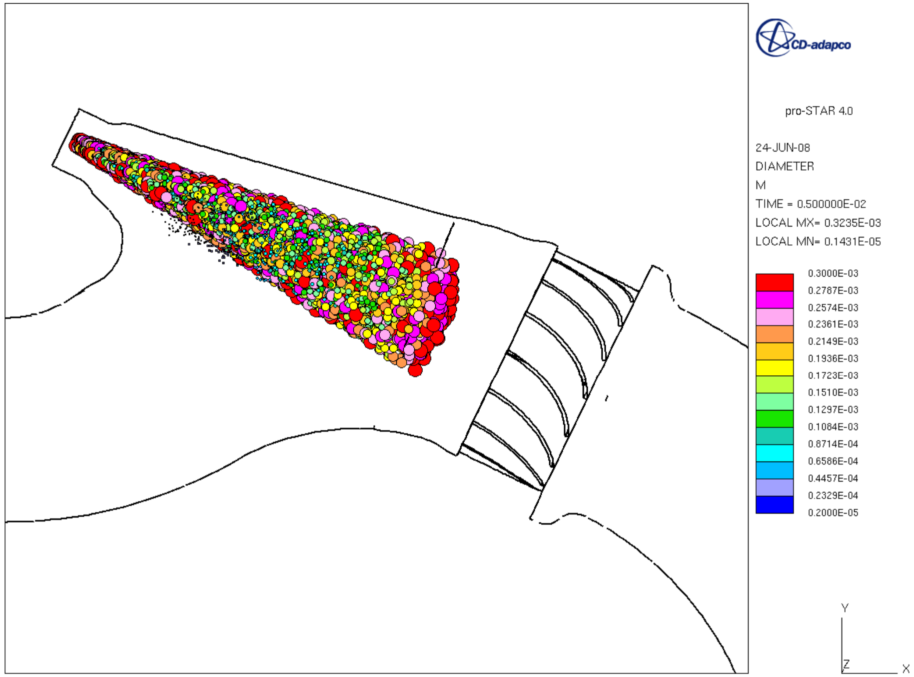


Type B: HNCO-fraction after start of dosing:

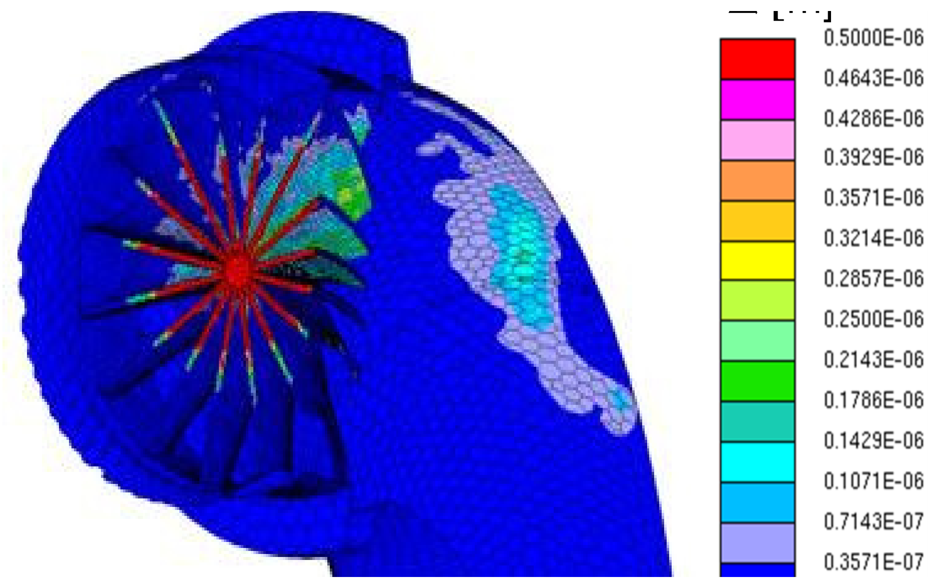


3D-model of AdBlue processing successfully applied for mixer specification

3D Simulation AdBlue Processing
Example: mixer optimization



Spray Droplets (OP2)



AdBlue Wall Film (OP2)

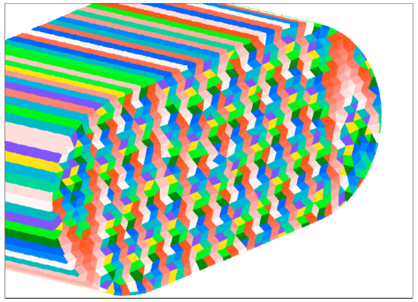
- reduced mixer length → investigating reason for less uniform distribution (350°C, 200kg/s)
- reason: wall film formation due to decreased overlap of blades → poor evaporation

  → ***3D-Simulation applied for diagnostics and optimization***

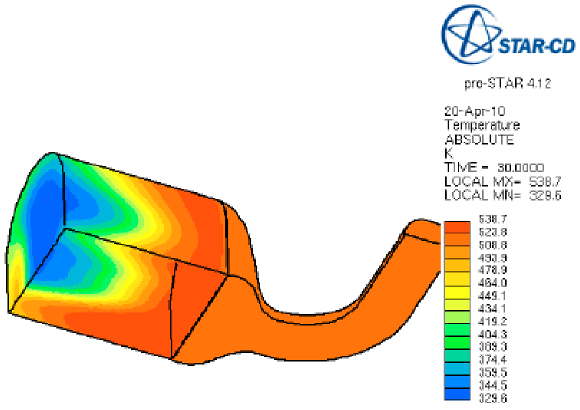
1D-3D coupling

Cooperation with CD-adapco

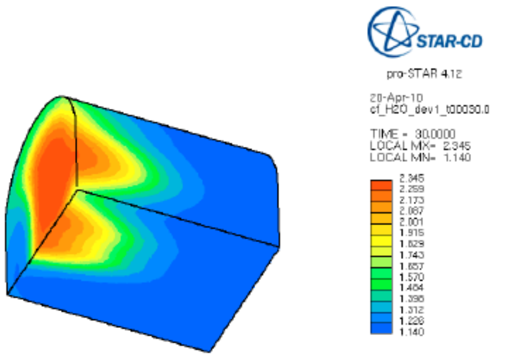
Monolith with fine representative channel subdivision



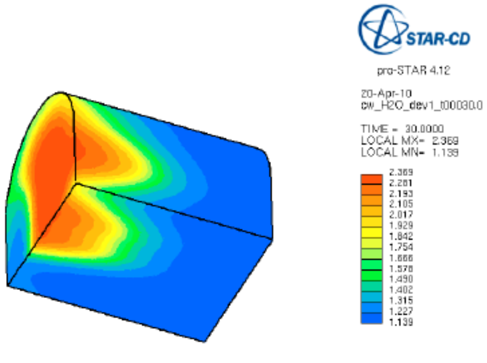
Example: water condensation on DOC



Temperature



H2O Gas



H2O Wall

M. Weaver, CD-adapco, CLEERS-Workshop 2010

- integration of DOC 1D-reactions validated → model compatibility 1D – 3D
- pilot application for test bench simulation in progress
- next steps: integration DPF and SCR reactions

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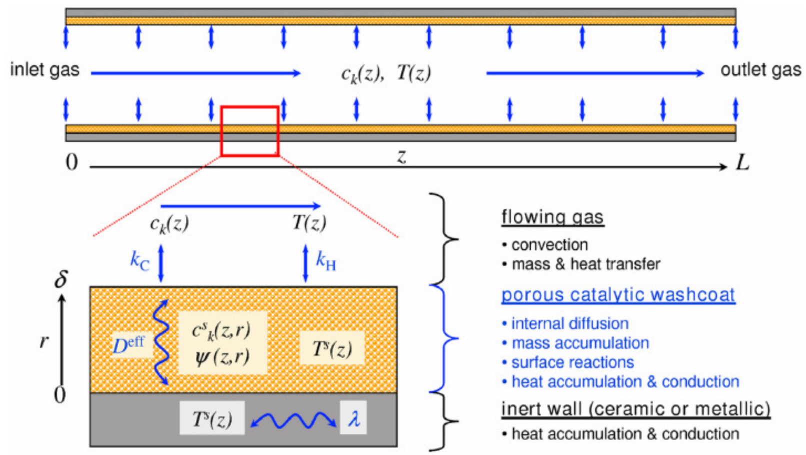
Control-oriented SCR-Model (COM)
Methodology (HiL, SiL, ..)

Dr. Frank Hofmann

SCR Modeling ExACT und COM

Modeling ExACT

1D-Model



Reactions*):

$$NH_3^* + NO + \frac{1}{4}O_2 \rightarrow N_2 + \frac{3}{2}H_2O$$ Standard-SCR

$$NH_3^* + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$ Fast-SCR

... up to 12 Reactions considered

Model-equations*):

$$\frac{\partial C_j}{\partial t} = -\frac{v}{L}\frac{\partial C_j}{\partial z} - \frac{4}{d_h}k_{mt,j}\left(C_j - C_j^S\right)$$ Mass-transport Gasphase

$$\frac{\partial C_j^{wc}}{\partial t} = D_{eff,j}\frac{\partial^2 C_j^{wc}}{\partial x^2} + R_j$$ Washcoat Diffusion/Reaction

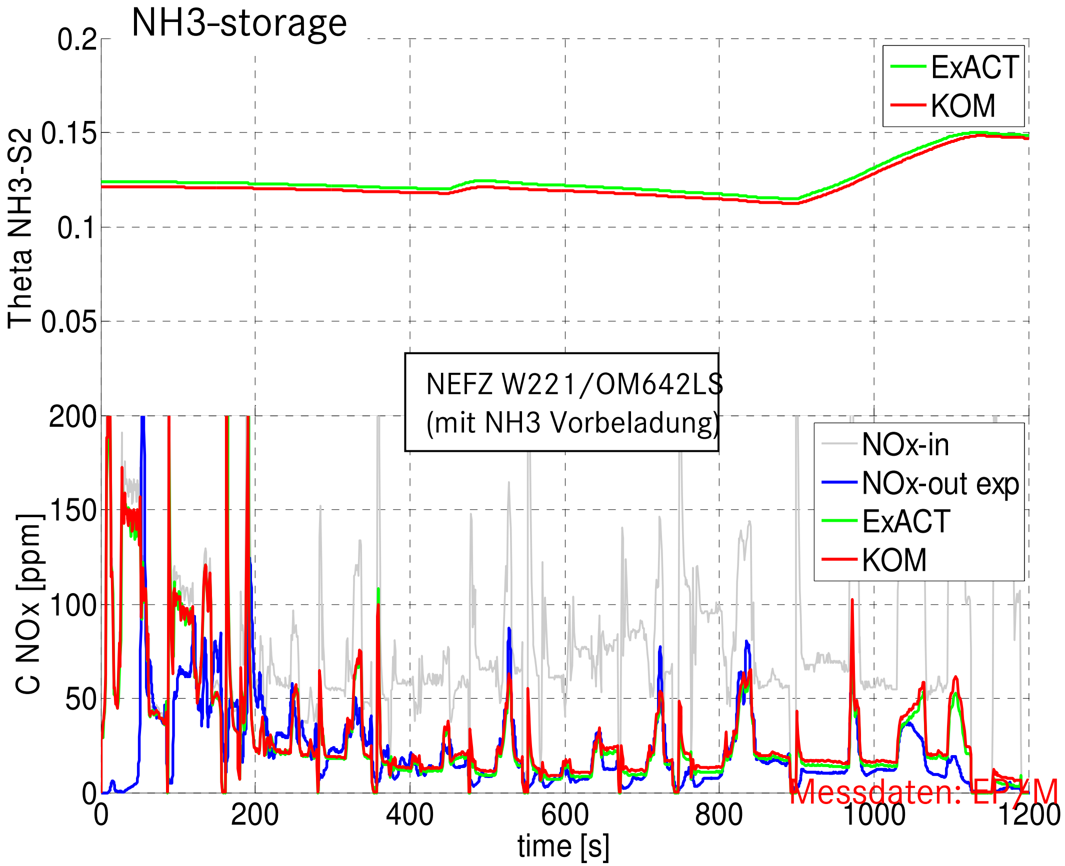
Simplifications*):

- Radial mean-value of washcoat-Concentrations
- Analytcal solutions of model equations (DGLn)

COM

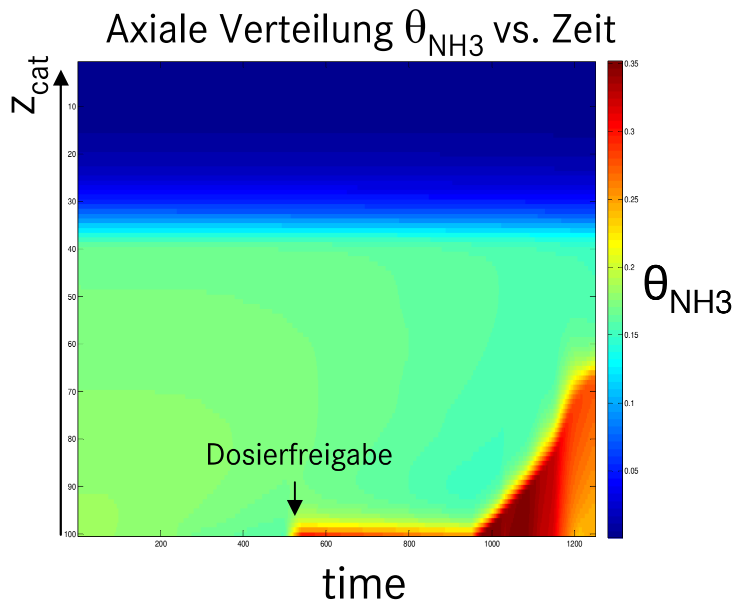
- Chemical/physcal reactions in the catalyst are described with high accuracy by the ExACT model.
- Control-oriented model derived by model simplifications of ExACT

Example: Comparison COM vs. ExACT in NEDC with Cu-SCR-catalyst



ExACT: 100 Segmente
COM: 10 Segmente

For improved dosing strategy the axialedistribution θ_{NH3} is considered



- Results of ExACT are reproduced by the control-oriented model with high accuracy.

Summary

- For the **overall system simulation** of future powertrain concepts there is no alternative to EGA-simulation (conventionel & e-Drive)
- **ExACT** is physical/chemical based and effective for **predictive simulation**
- **ExACT** + 3D-Simulation urea process in exhaust is used intensively for application work in the **product development**
- The use for **model-based control** and ECU capable models is of increasing importance
- And will be **further developed** together with our academic and industrial partners

Outline

- **Introduction**
  - **- Emission Standards – Motivation - Challenges**
- **Modeling Challenges**
  - **Exhaust Gas Aftertreatment Simulation**
    - **BlueTEC Technology for Passenger Cars**
  - **"Virtual Powertrain" - Engine emission modeling**
- **Full Vehicle Simulation**
- **Summary - Conclusion**

Virtual Powertrain – engine emission modeling

Dr. R. Steiner et. al. in cooperation with ETH Zürich

Engine Emission Modeling

General Modeling Requirements:

Overall system simulation (and sub-models!) needs to be

- **fast** for offline predictions: results for driving cycles are in focus!
- **real-time** for HiL applications (for total system: time steps <10 ms, <100 HZ)
- **very fast** when using an engine air-path model: time steps <1ms, <1000HZ)

Compromise between computational efficiency and accuracy:

As accurate as needed, as simple and fast as possible!!!

Accounting for most relevant physics-based process variables!

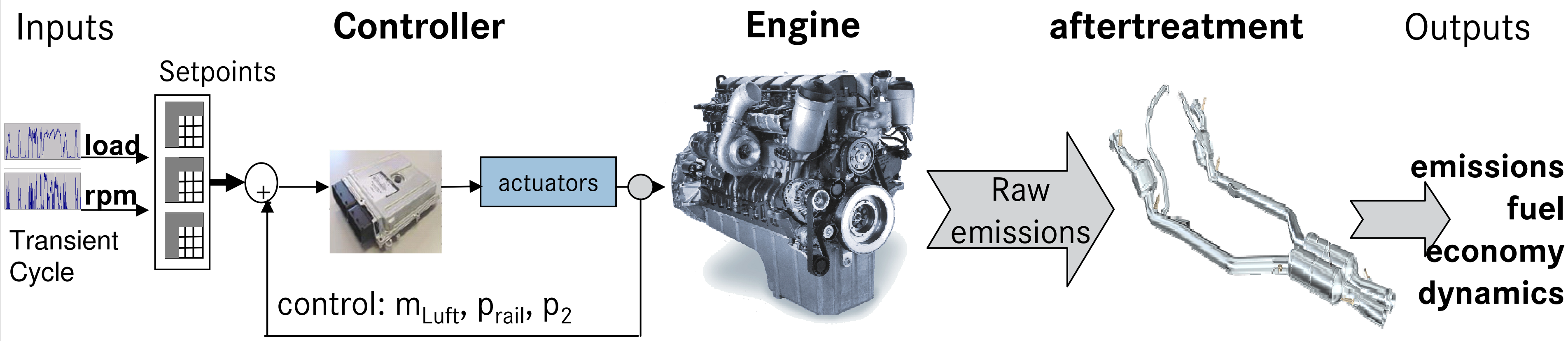
Most challenging part in sub-model development, prediction of

- transient behaviour of heat release and raw emission formation

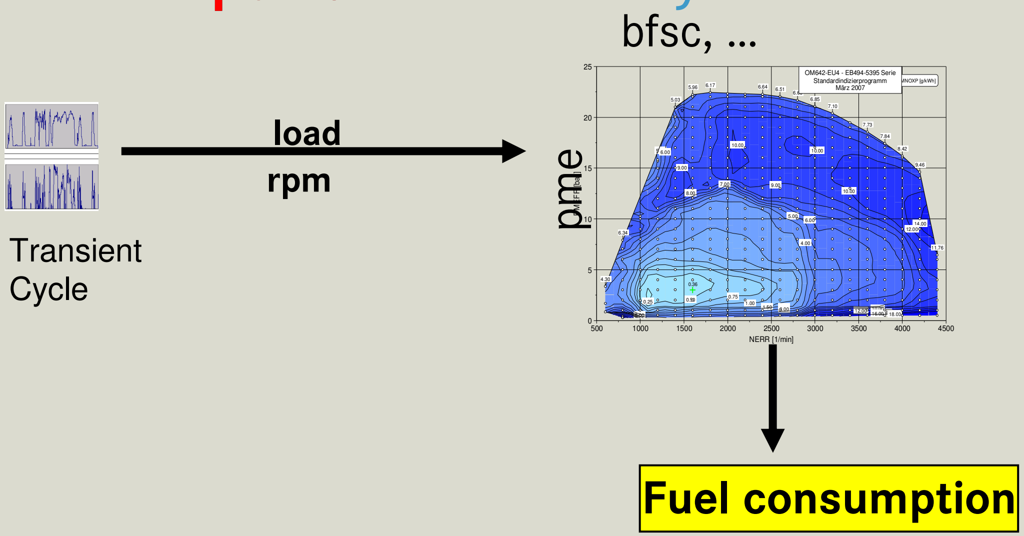
*1 :Depending on computer platform

Virtual Powertrain: State-of-Art

Hardware:



Virtual powertrain: Today: Quasi-Static Approach for **Fuel Consumption**

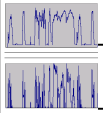


Virtual Powertrain: State-of-Art

Hardware:

Inputs	Controller	Engine	aftertreatment	Outputs

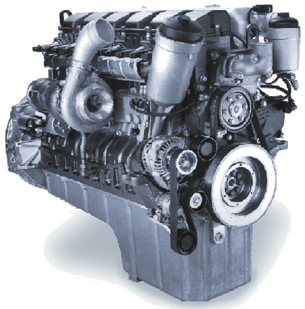
Setpoints



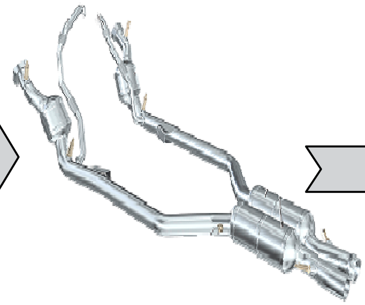
Transient Cycle

actuators

control: m_{Luft}, p_{rail}, p_2

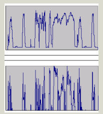


Raw emissions



emissions
fuel economy
dynamics

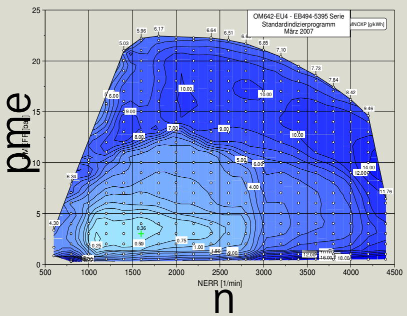
Virtual powertrain: Today: Quasi-Static Approach for **Raw Emissions**



Transient Cycle

load
rpm

e.g.. NOx, bfsc, ...



bfsc, T4, emissions

Aftertreatment Dynamics Model

Mean-Value Model

ExACT

Stationary engine maps
(critical: transient predictability,
no variation of control parameters, ...)

Control-oriented Modeling: State-of-the-art

Gas path: Mean value model for control-oriented applications (ODEs)

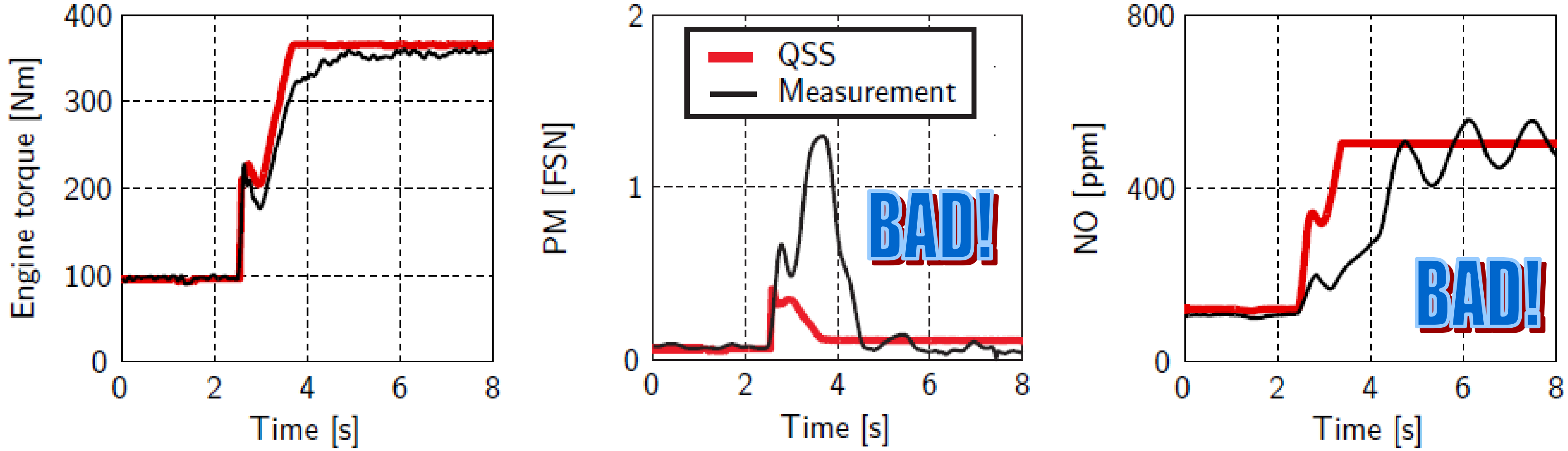
→ good compromise between computational efficiency and accuracy

Combustion: Quasi-static modeling approach

→ based on static engine maps

Raw Emissions
3D CFD models (Kiva...)
Phenomenological models (Hiroyasu...)
} Usually crank-angle based. CPU costs too high!

Empirical Models (Barba...) Large-number of measurements needed; reduced portability; very poor extrapolation capability!



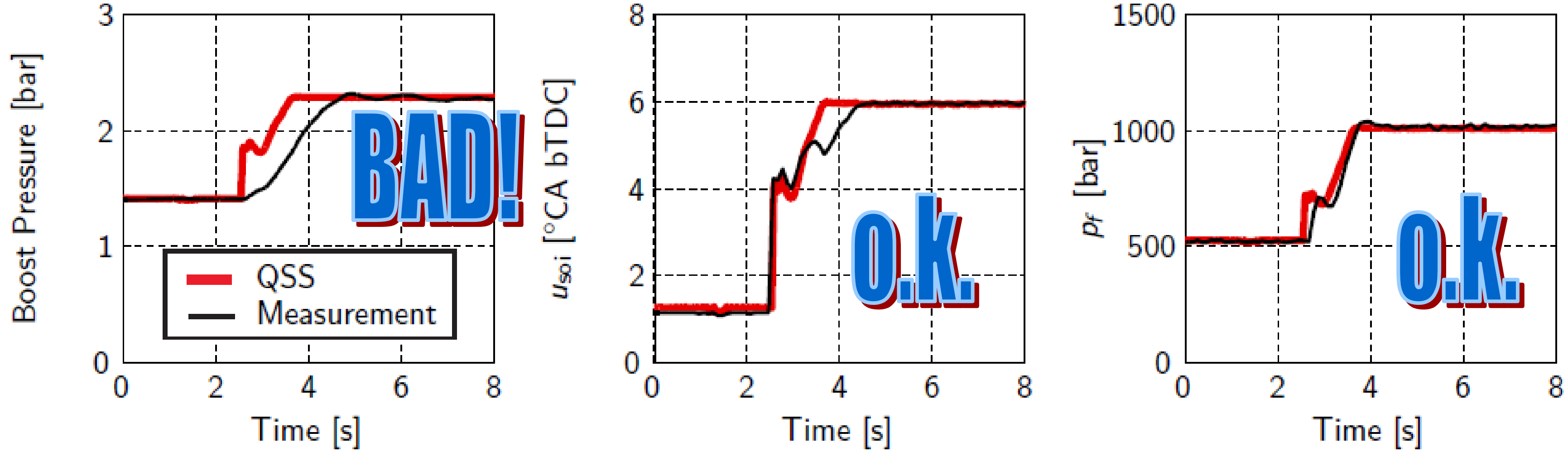
Comparison between measurement data (black) and quasi-stationary simulations (red) during a load step at constant engine speed.

Quasi-stationary modeling approach is adequate for computing torque generation (and fuel consumption) but inappropriate for predicting emissions!

Transient boundary conditions of combustion process

Differences to static engine operation

Comparison between measurement data (black) and quasi-stationary simulations (red) during a load step at constant engine speed.



Gas path → strong influence
Strong relevance on emission formation!

Fast injection dynamics → small effects
Main influence on torque generation!

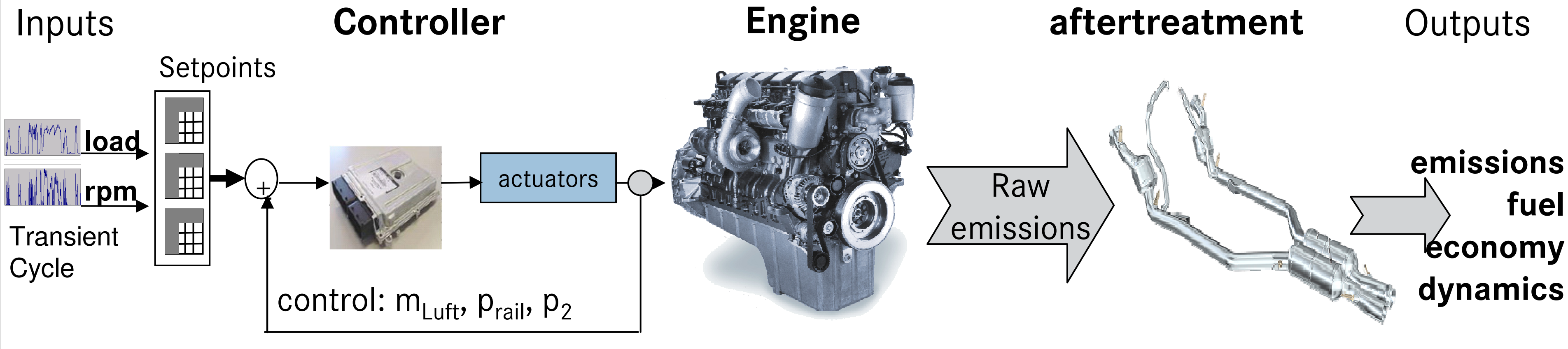
The **turbocharger inertia** causes the most relevant dynamic effects for a modern Diesel!

The relevant boundary conditions for combustion and emission formation are:

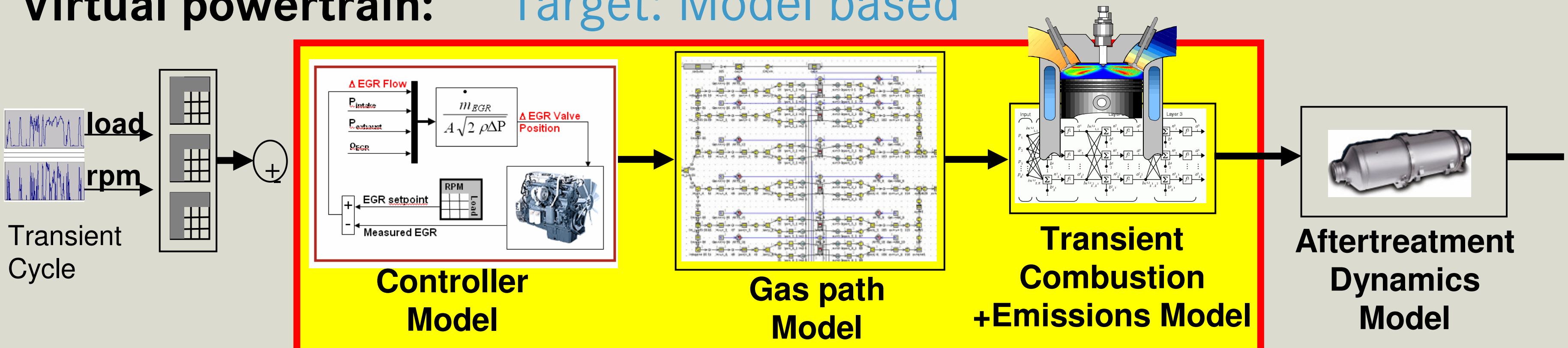
- cylinder charge at IVC (mass, gas composition, and gas temperature)
  boost pressure, exhaust gas recirculation rate and the temperature after intercooler
- injection (mass, pressure, timing)
- operating point (injected fuel, engine speed)

Virtual Powertrain: Target

Hardware:



Virtual powertrain: Target: Model based

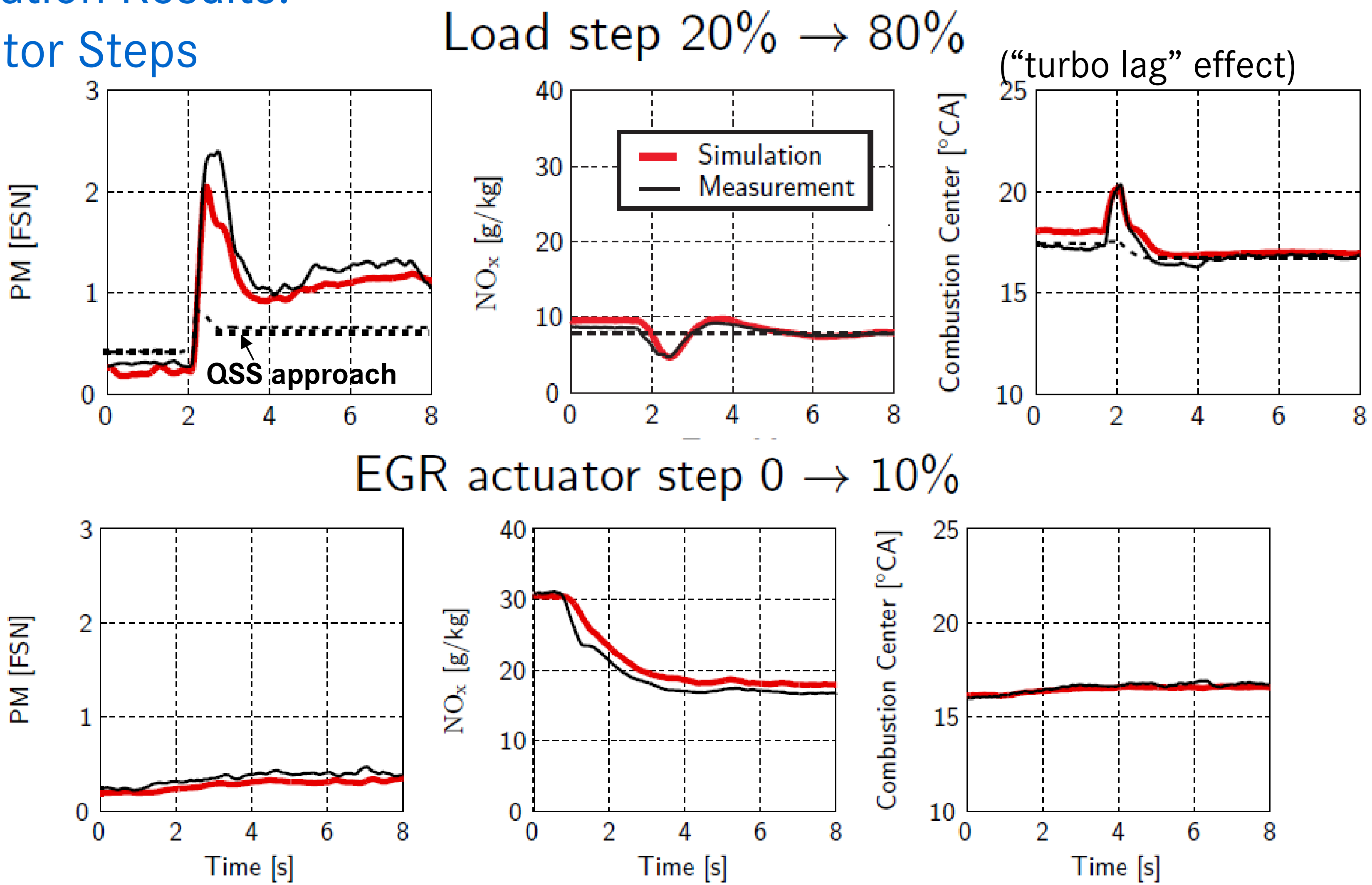


Transient control-oriented engine models

Challenge: Prediction of heat release and raw emissions

Approach ETHZ Prof. Guzzella

Simulation Results:
Actuator Steps

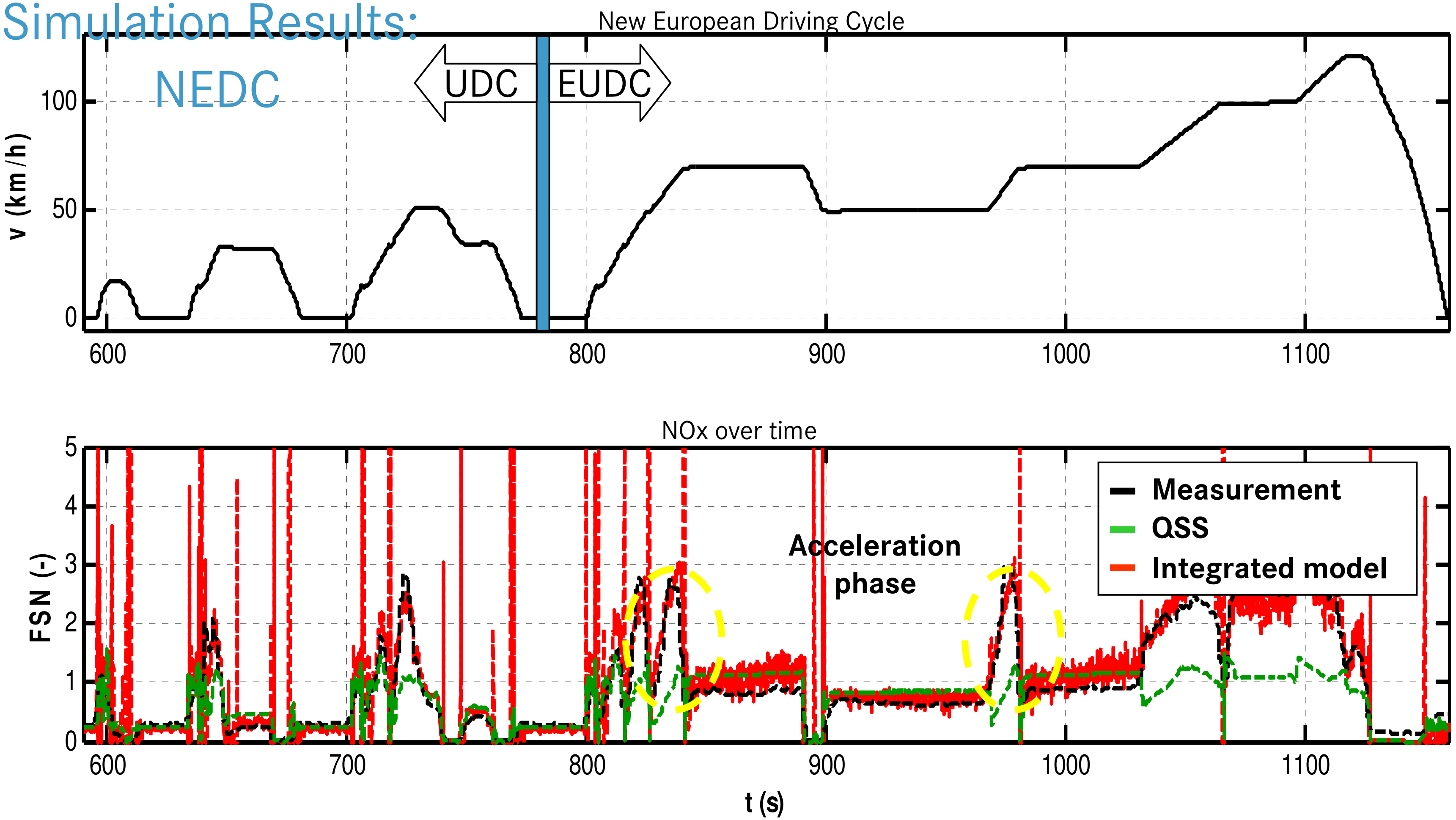


With the approach "Transient control-oriented engine models"

Well Prediction of heat release and raw emissions

Comparison between measurement and simulation **Soot:**

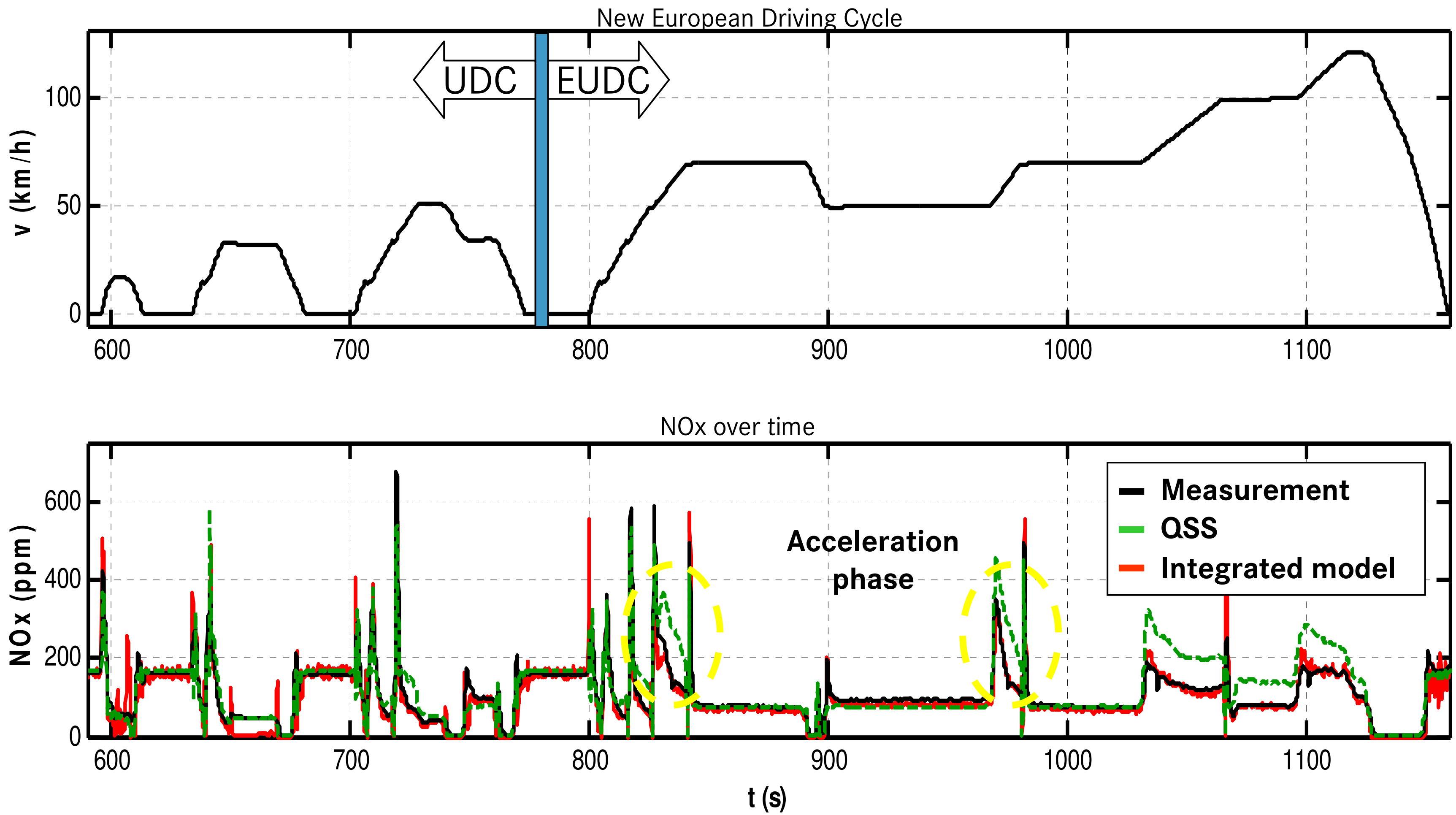
Simulation Results:



Influence of transient transitions on soot-emissions are predicted well!

UDC= urban-driving-cycle
EUDC=Extra-urban-driving-cycle

Comparison between measurement and simulation **NOx:**



Influence of transient transitions on NOx-emissions are predicted well!

UDC= urban-driving-cycle
EUDC=Extra-urban-driving-cycle

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Outline

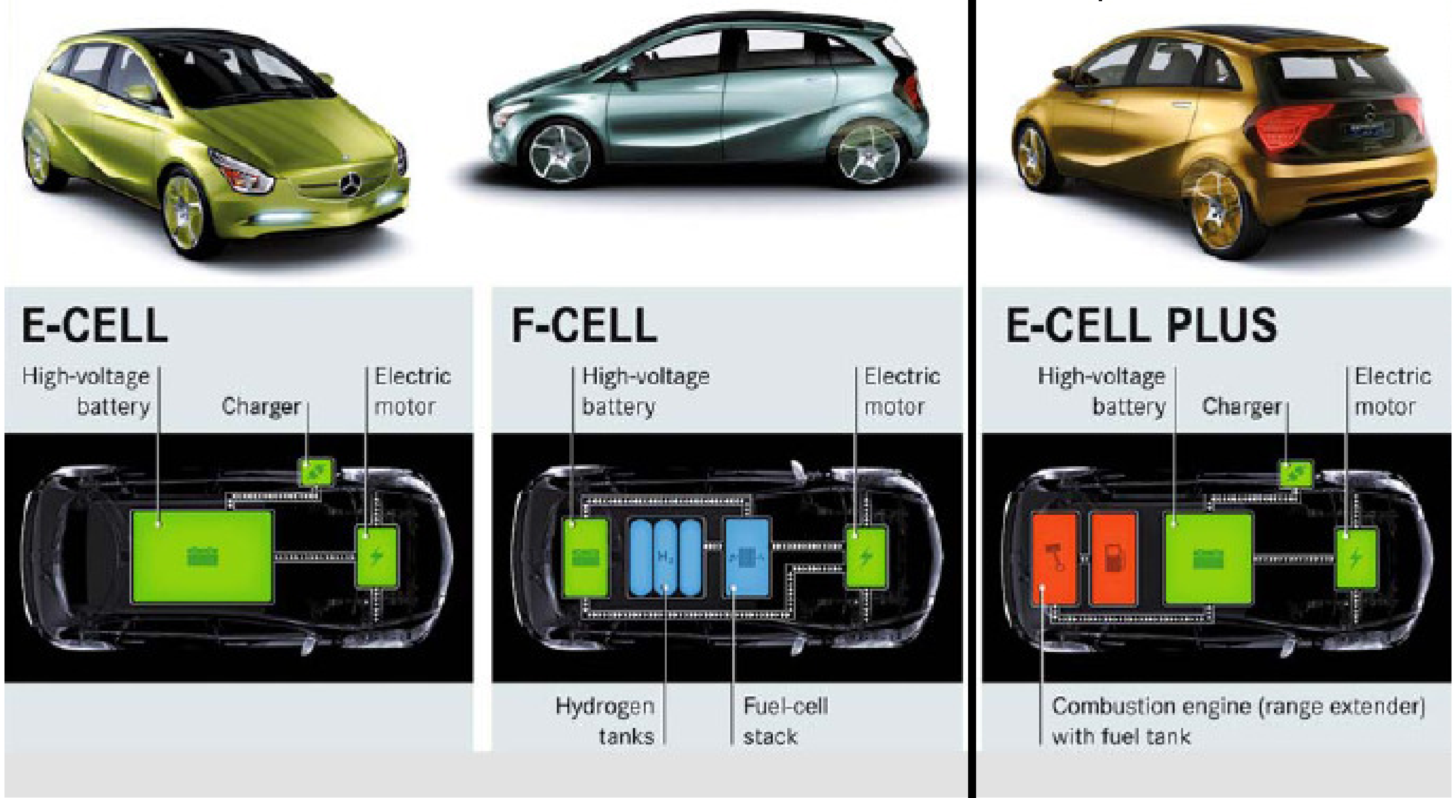
- **Introduction**

    - Emission Standards – Motivation - Challenges

- **Modeling Challenges**
    - **Exhaust Gas Aftertreatment Simulation**
        - **BlueTEC Technology for Passenger Cars**
    - **"Virtual Powertrain" - Engine emission modeling**
- **Full Vehicle Simulation**
- **Summary - Conclusion**

Example: Support within the Blue-Zero Project

Example: REX



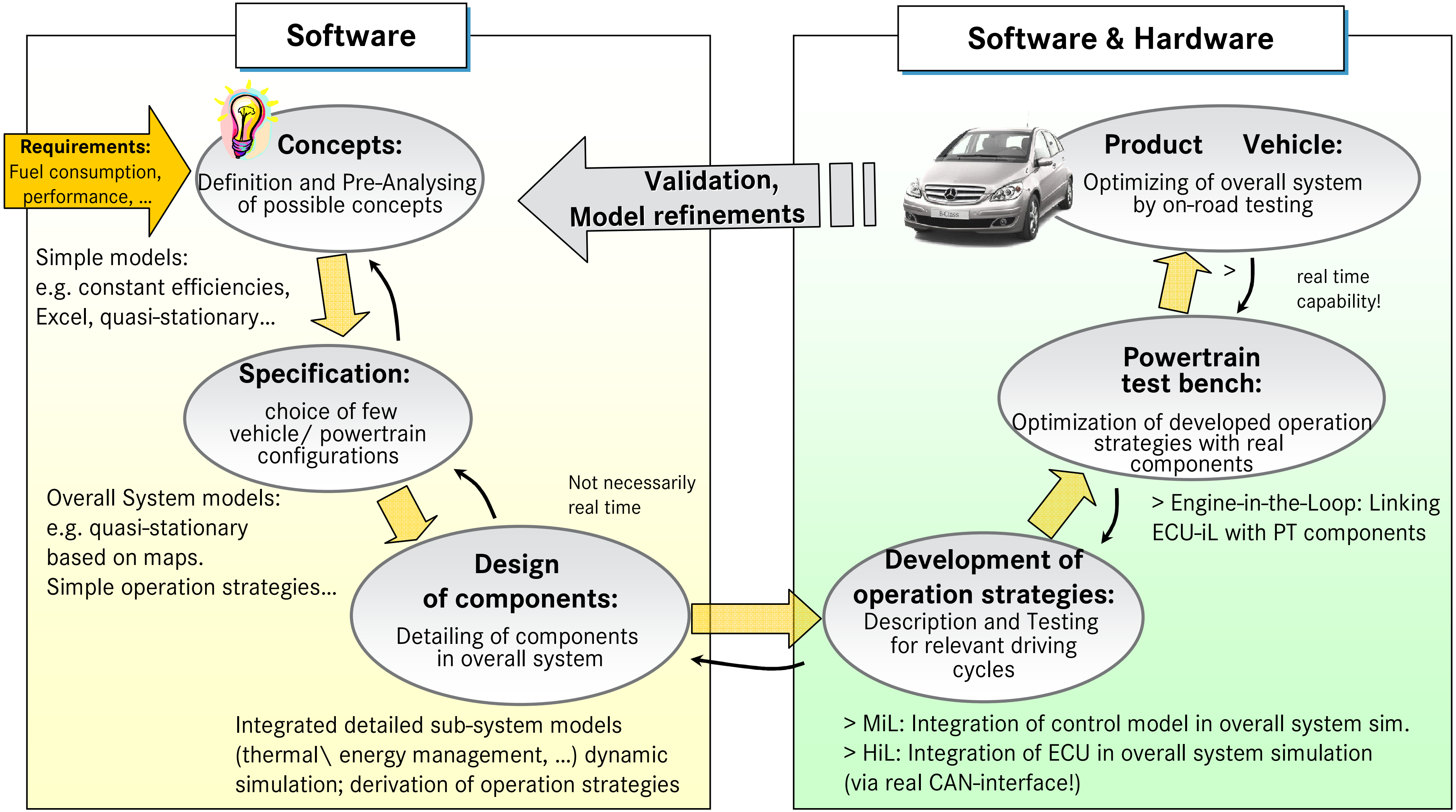
Three different powertrain system configurations in one vehicle architecture.

Main propulsion system: electric motor.

	E-Cell	F-Cell	E-Cell+
Energy supply:	battery,	fuelcell,	reduced battery+combustion engine
Total range:	200km,	400km,	600km

Complex operation strategy:
several operation modes:
> Electric drive
> Serial drive
> parallel drive
for arbitrary driving cycles!

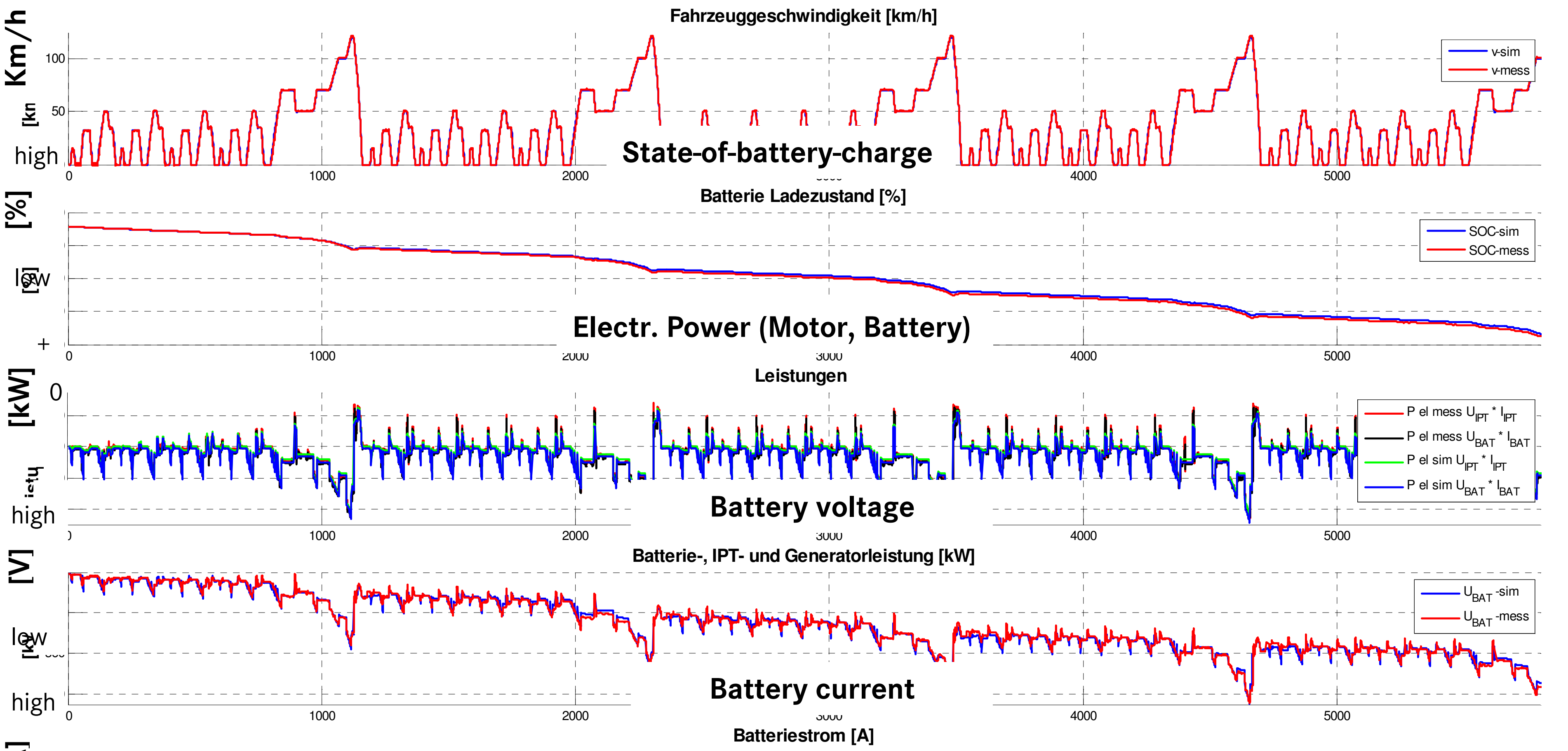
„Simulation chain“: From concept to product



Reduction of development time by strong link between soft- and hardware (Plug 'n Play)

Simulation vs roller test bench measurements:

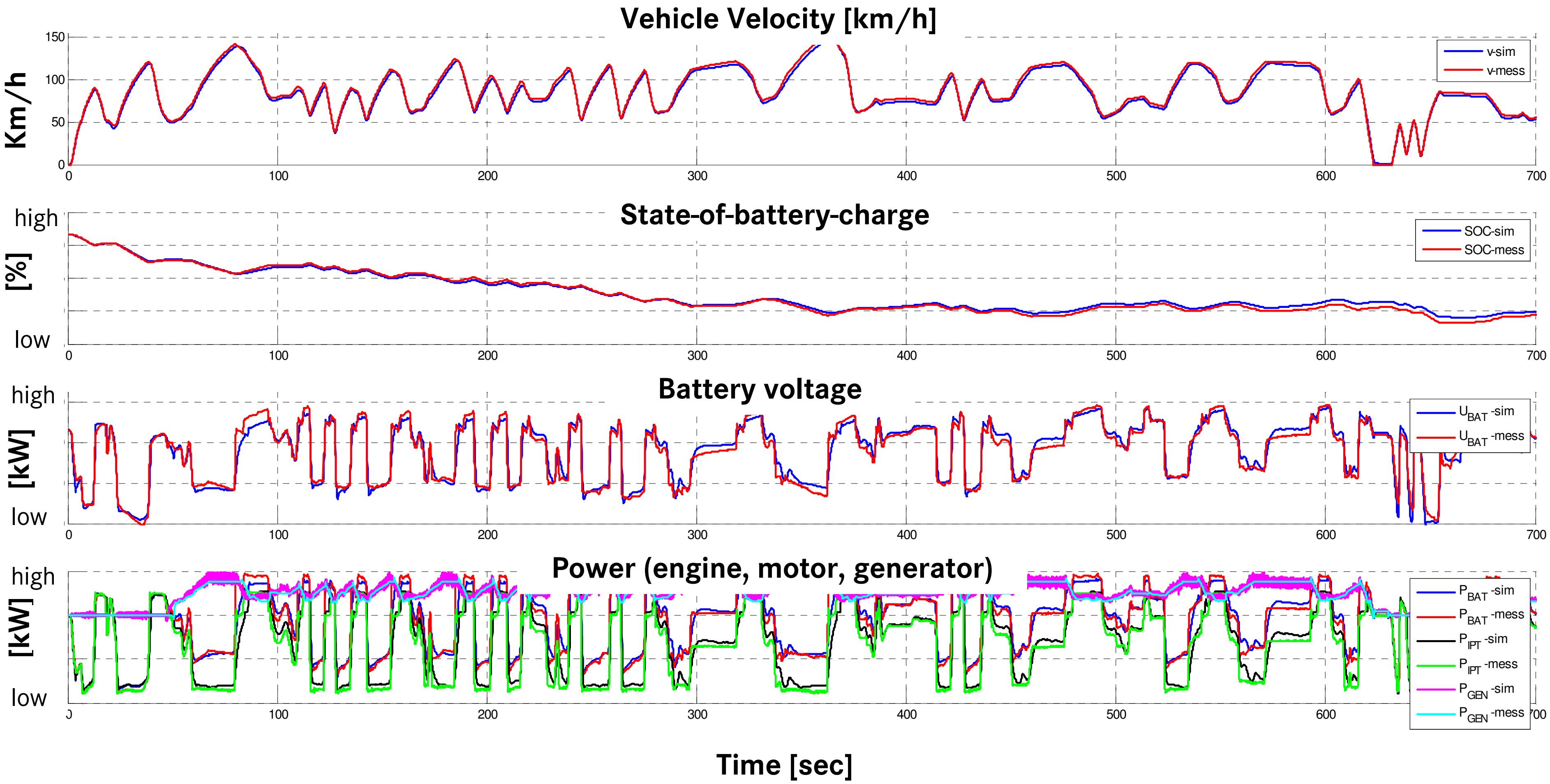
Vehicle Velocity [km/h]



Validation based on roller test bench shows good results!
Ready to use for "offline" optimization (Model-, ECU-, Powertrain-in-the Loop)!

Source: P. Macri-Lassus

Simulation vs field ride measurements:



Validation based on arbitrary driving cycle shows good results!
Ready to use for "offline" optimization (Model-, ECU-, Powertrain-in-the Loop)!

Source: P. Macri-Lassus

Summary

- The mobility of the future is dependent on a lot of boundary conditions that become more and more stringent! CO_2 and emissions are in focus!

  Future mobility is also shaped by the electrification of the powertrain!
  Portfolio of powertrain concepts and its complexity is dramatically increasing!
  Increase of levers for optimization. Operation strategies make the difference!
  Overall system optimization is the key to success!

- Without advanced simulation tools it will be impossible to meet these challenges. This includes sub-system and overall system models.

"Best components with best operation strategies!"

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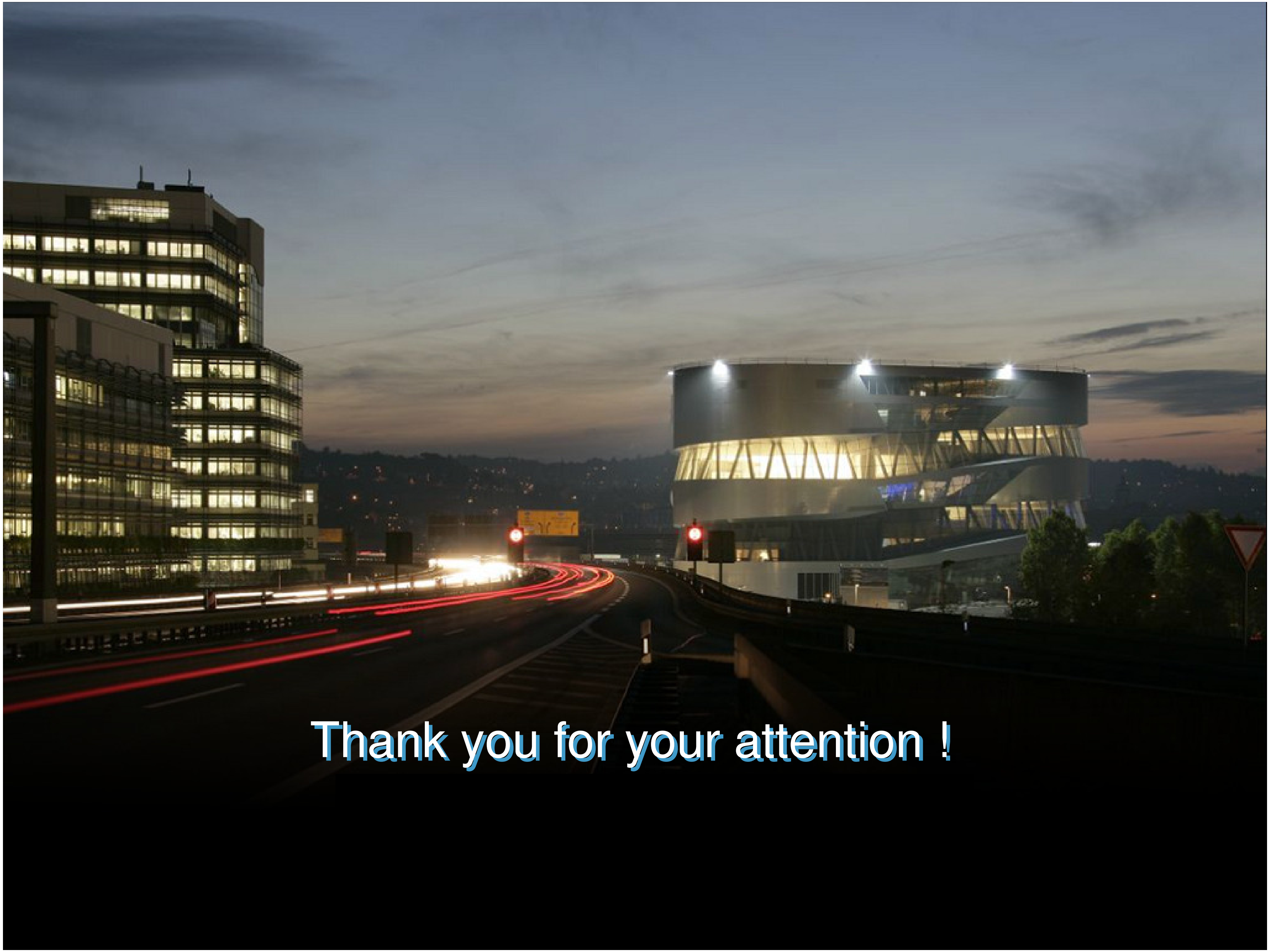
Thank you for your attention !