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HD Hydrogen Combustion from Concept to Series Development

Dr. R. REZAEI, T. Schmidt, Kick Off, CV Südwest 9th July 2021

Agenda

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Regulation and drivers for future technology

H_2 and other future e-fuels

Hydrogen HD combustion engine development

- Model based concept development
- Single cylinder testing and example results
- Hydrogen combustion and emission modeling
- Full engine test bench for proof of concept

Summary and Outlook

Enabler for Alternative Powertrain Structures
Commercial Vehicles On-Road

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CO_2 is our main challenge … and our main technology driver!

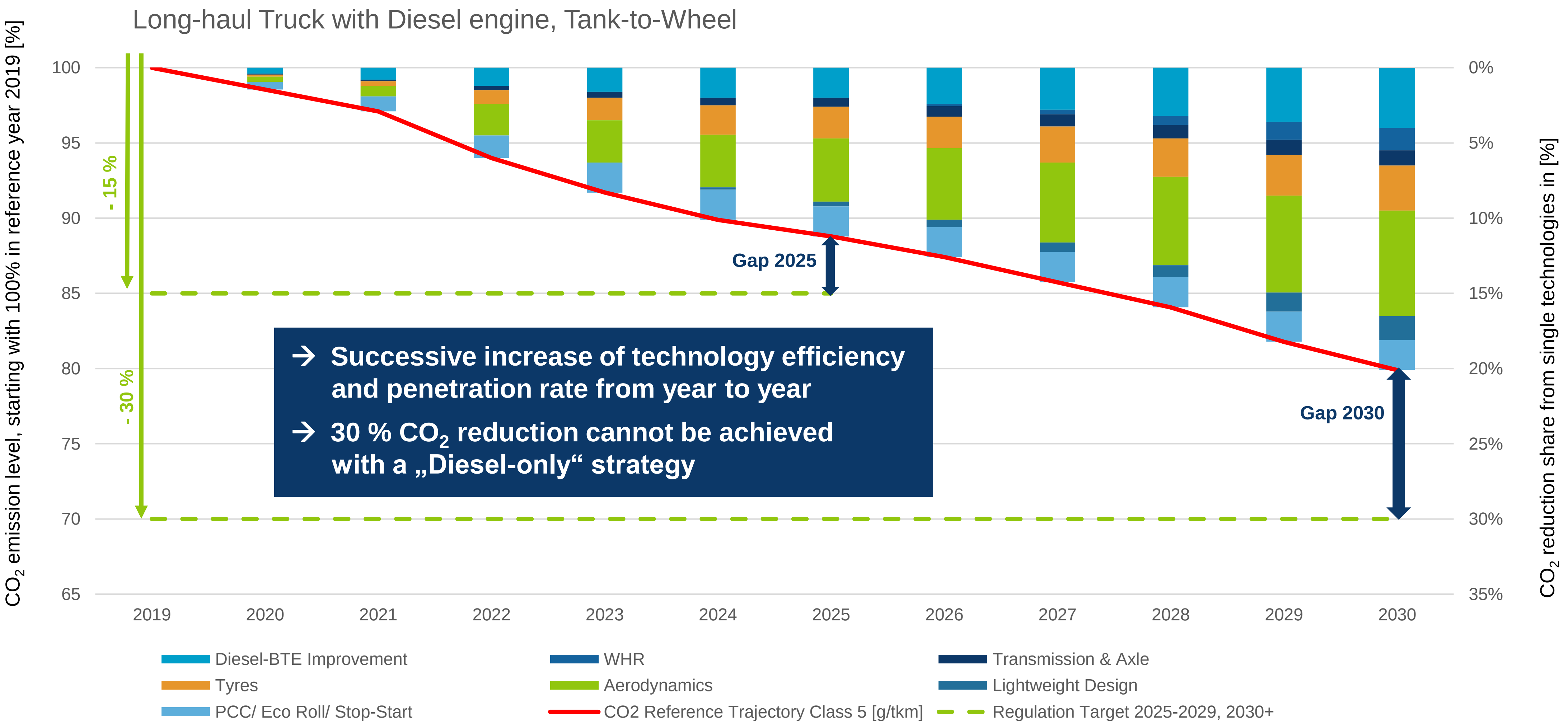
EU „Vision Zero“
Climate neutral Europe by 2050

2020 — **2030** — **2040** — **2050** — **Year**

EU CO_2 regulation HD trucks	*EU: **Fleet reduction** targets: (reference MY2019)*	**-15%** / 4,500 EUR* ; **-30%** / 6,800 EUR* 2% min. fleet share of LEV/ZEV (trucks only, Buses & coaches excluded) minimum share of clean vehicles in public procurement and service contracts
Emission legislation HD trucks	*EU:* *USA:*	Euro VI E ; Euro VII (assumed) EPA/CARB Ultra Low NOx (Phase In 2024-2031) *EU 2050 goal: 60% cut in transport emissions*

- → **Most important vehicle classes for EU CO_2 reduction are 4, 5, 9, 10**
- → **Significant CO_2 reduction for long-haul applications required**
- → **All alternative fuels and BEV scenarios require a push through legislation and major investments**

Enabler for Alternative Powertrain Structures Commercial Vehicles On-Road



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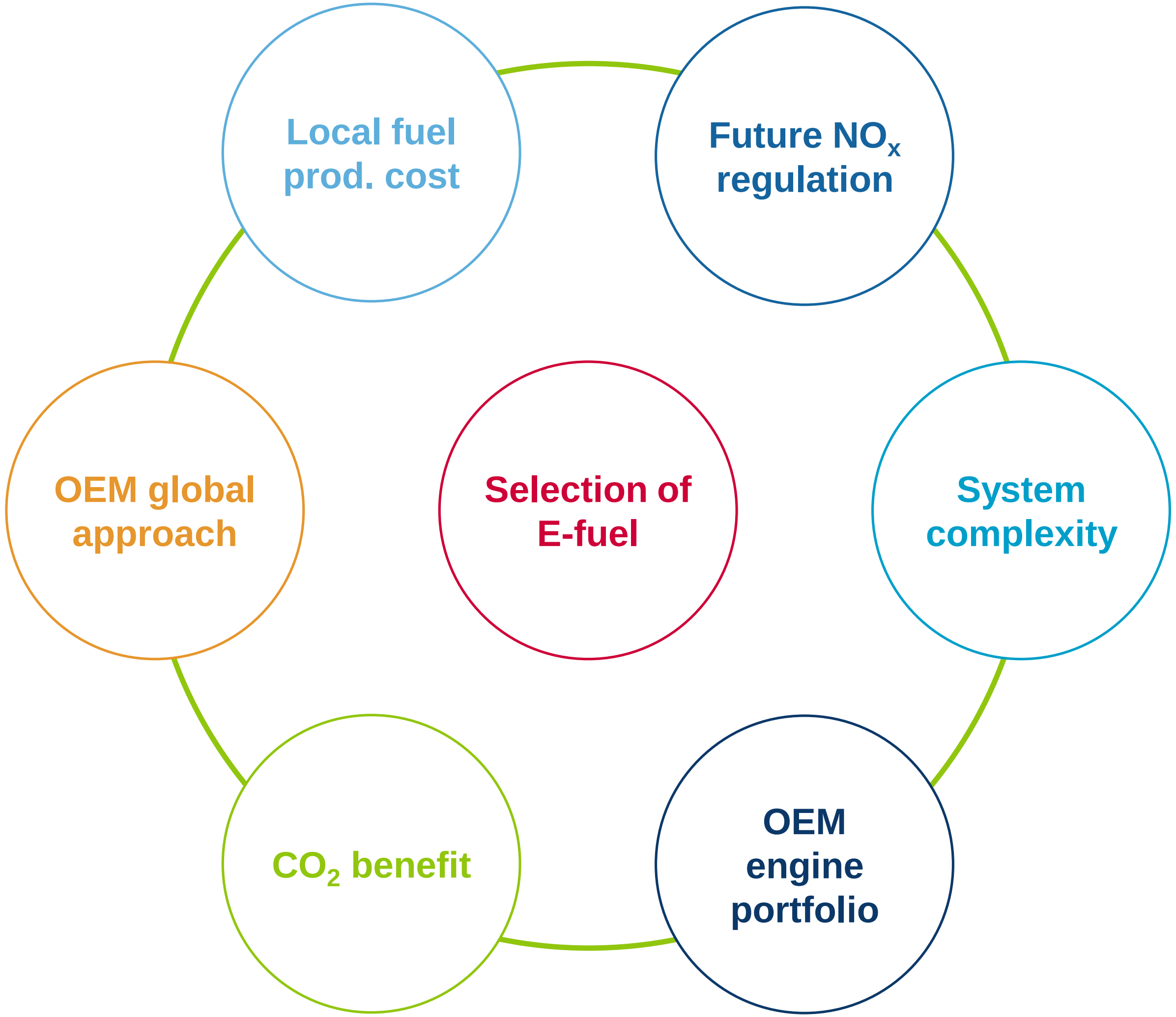
Selection of E-fuel
Considering Regulation and OEM Boundary Conditions



Which e-fuel is the most appropriate?

- There are many e-fuels under development
- Main motivation is the CO_2 regulation. For which regulation (well-to-wheel, tank to wheel, etc.) which e-fuel strategy is better?
  - Develop. of future emission scenarios
- There are multiple OEMs working on different e-fuel in EU, USA, etc.
  - Having a market overview is beneficial
- Selection of the most promising e-fuel should be selected based on OEM needs and requirements, market, regulations, etc.
  - Individual definition of e-fuel required

→ IAV can support on all above points

→ The first step is technology and regulation survey “tailored” for customer

Power Density of Hydrogen Depending on Mixture Formation

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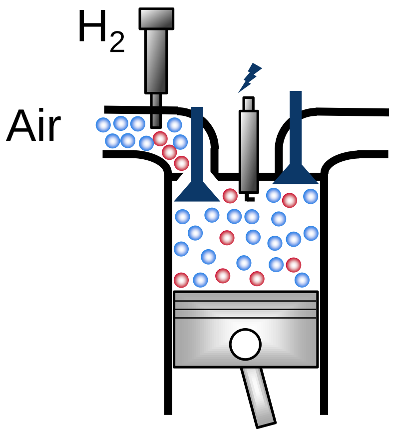
Boundaries:

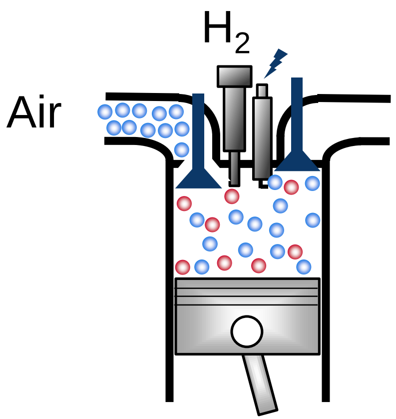
$l = 1.8$

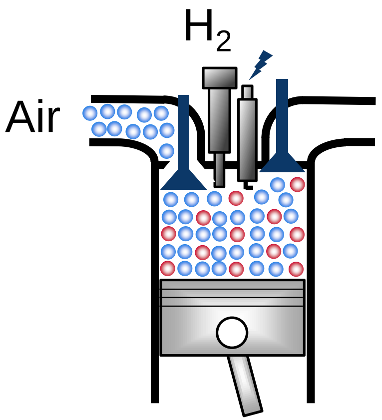
$l_a = \text{const.}$

$\eta_e = \text{const.}$

$T = \text{const.}$







Mixture formation	**PFI**	**DI early LP-DI**	**DI during comb. HP-DI**
Power potential [%]	–	+	++
Efficiency potential [%]	–	++	+++
(compared to Diesel, theoretical)			
Risks			
Back fire			
Pre ignition			
Knocking			

→ **For CV applications, depending on boundary conditions (e. g. retrofit from Diesel baseline) PFI or LP-DI are good options. HP-DI is on the research level due to the current technical feasibility.**

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IAV Model-based Development Methodology
Alternative Powertrain Development (H_2 Combustion and Fuel Cell)

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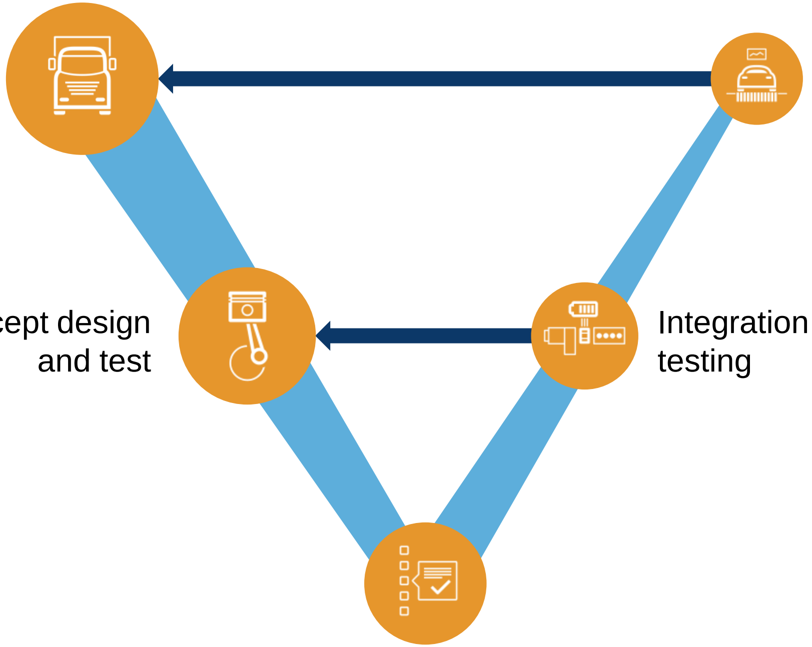
Overall system simulation

IAV testing environments

References and development process

Requirements analysis

System testing



Concept design and test

Integration testing

Concept implementation

SW development

H2 fork lift / GANE fuel test

- → **Long-term experiences with the state-of-the-art technologies PFI to HP-DI H_2 combustion to fuel cell development**
- → **Complete H_2 development tool chain: sophisticated testing environments, component and system models etc.**

IAV Uniqueness and Highlights: Hydrogen Combustion Engine
Hydrogen Combustion and After-Treatment Development

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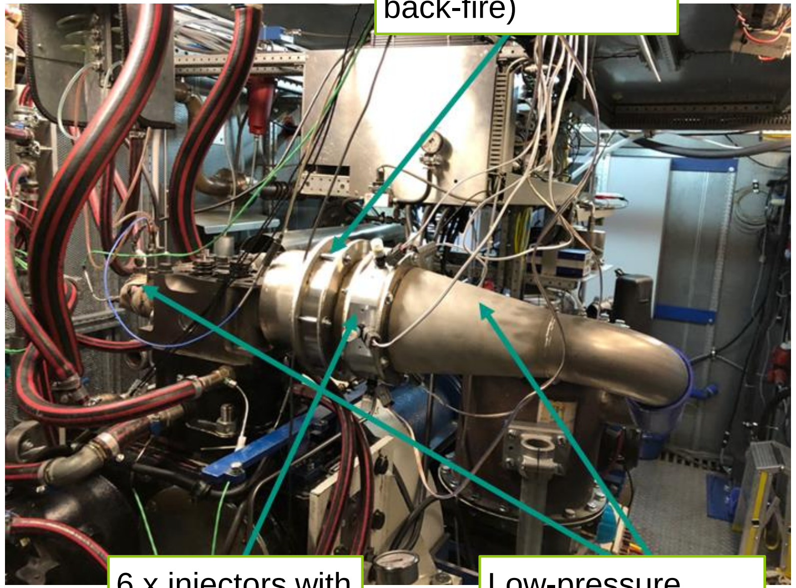
H_2 single-cylinder (2 l) used by IAV



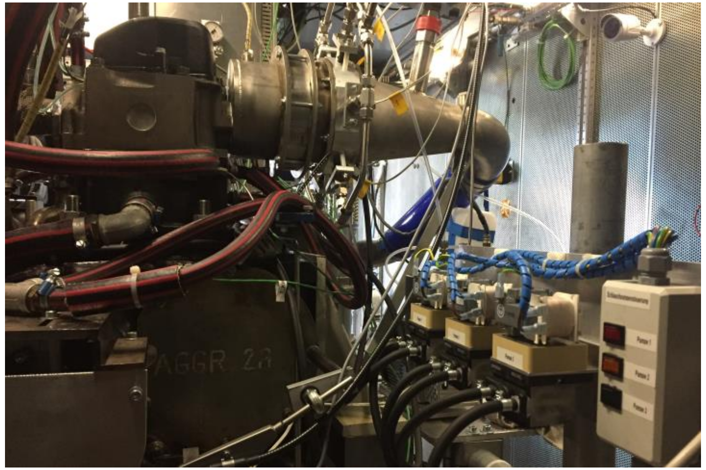
Highlights / USPs: Combustion + EAT

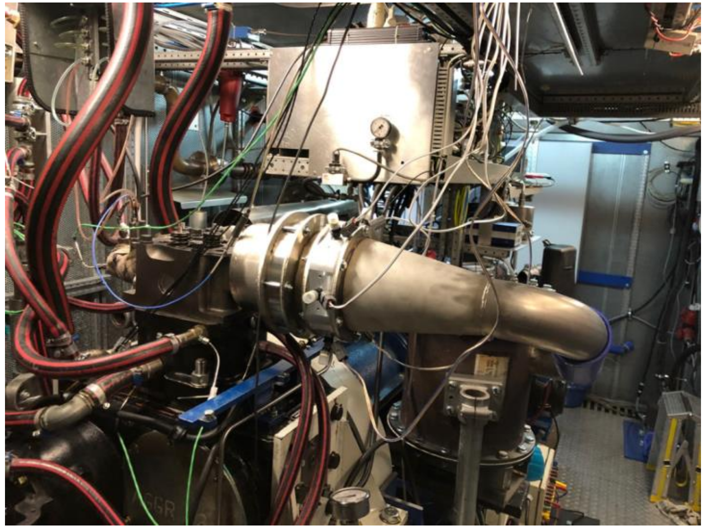
- Single-cylinder testing of innovative hydrogen combustion:
- PFI / SI, water injection, LP-DI and HP-DI / CI up to 300 bar
- Full H_2 engine testing and calibration (13 l class)
- Well validated IAV 1D and 3D CFD own models for H_2 combustion, NO_x and knocking using detailed reaction kinetics
- Synthetic catalyst testing (in PCL) and modelling of H2-SCR tech.
- Holistic engine + EAT system optimization to define EAT structure (H2-SCR + NH_3-SCR) in cold cycles for UL-NO_x
- Initiating and conducting of about 2.3 Mio. EUR research projects on Hydrogen combustion and after-treatment dev.
- Multiple dedicated H_2 single cylinder engines available in different size categories HD (2.X l), MD (1.X l), LD (0.5 l)

→ **Overall system development of engine to EAT: From pure research to series preparation!**

→ **The new IAV HD 2 l single-cylinder with possibility to measure <u>from HPDI</u> to PFI concepts.**

H_2 Single Cylinder Testing
Summary of H_2 investigations





Assembly and setup of hydrogen PFI engine

Combustion and emission investigations

- Particle number and NO_x emissions
- Variation of rel. air-fuel ratio (lean burning)
- Variation of EGR ratio and comp. to lean burning
- Knock and pre-ignition tests for model dev.
- Variation of compression ratio

Ignition system variation

- Pre-chamber spark plug
- Conventional spark plug

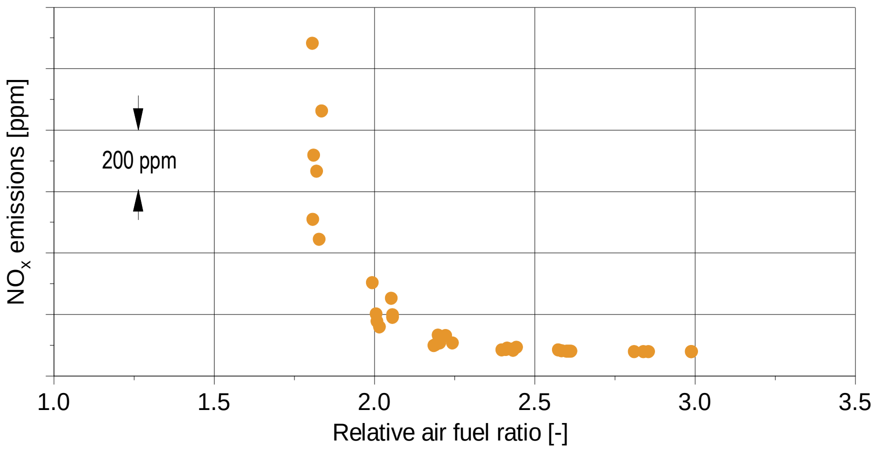
Water injection

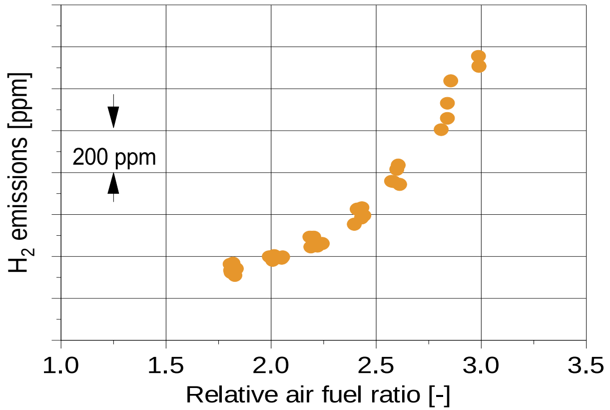
- Improvement of pre-ignition and fuel efficiency
- NO_x reduction, esp. under transient conditions

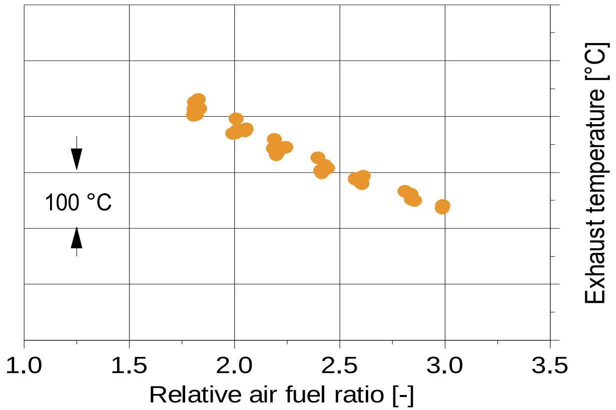
→ **Definition and test of further concepts in collaboration possible.**

→ **All options from HPDI (300 bar) possible with the new SCE**

HD Hydrogen Combustion Development Overview – Measurement Data







Emissions and exhaust gas temperature as a function of the relative air-fuel ratio, n= 1100 & 1250 1/min, IMEP=11 bar

H_2 experimental investigations

Intensive measurement at HD single-cylinder engine

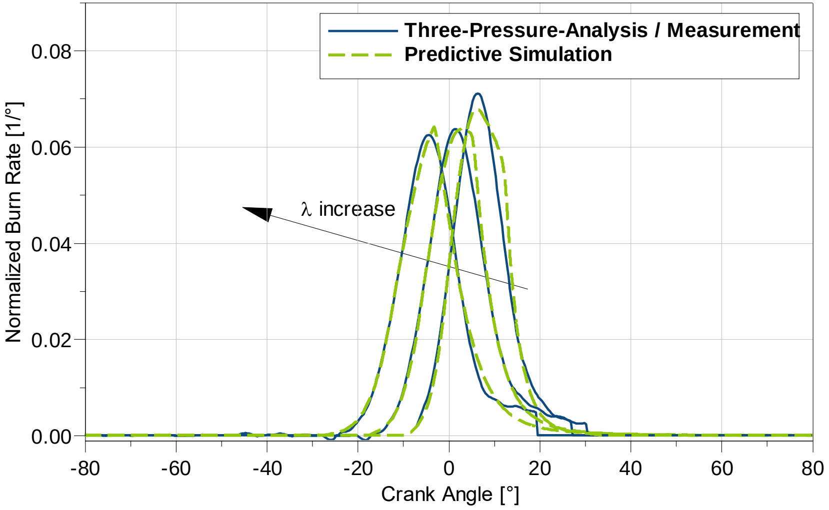
Variation of following parameters (exemplary):

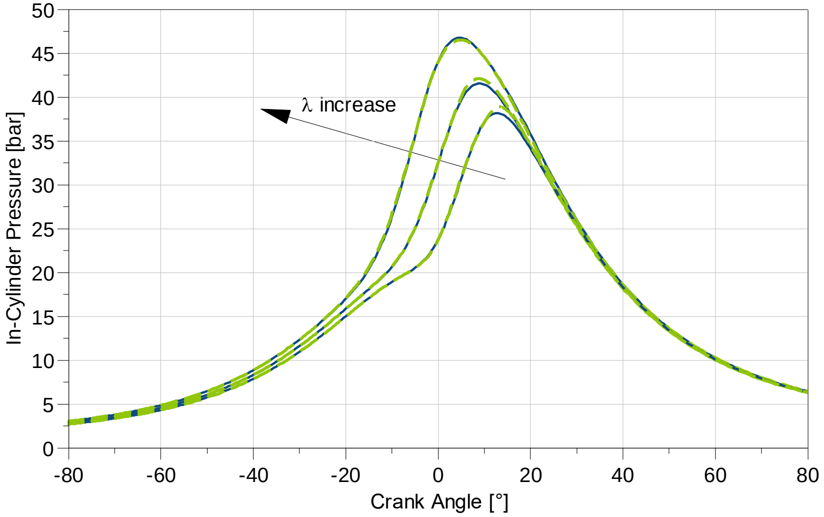
- Engine speed: 1100 and 1250 rpm
- IMEP: 5 .. 22 bar
- Torque for 3 l: 525 Nm
  Torque for 12 l: 2100 Nm
  (at 1250 rpm)
- Boost pressure: up to 3.3 bar
- Rel. A/F ratio: 1.8 .. 3.4
- EGR rate: 0 .. 15 %

Impact of operation parameters on emission behaviour e.g. NO_x emissions

→ **Indicated mean effective pressure of 22.4 bar reached with PFI concept!**

IAV Activities and Expertise on HD Hydrogen Combustion Development Summary





Simulation results with the IAV combustion model

Measurement data – single-cylinder research engine

- Measurement data based on 2 l hydrogen single cylinder engine
- Totally over 130 operating points available with indication data
- Engine speed from 1100 rpm and 1250 rpm
- Indicated mean effective pressure from 5 – 22 bar

Simulation data – predictive combustion and emission modelling

- IAV developed new combustion model based on reaction kinetics modelling of laminar burning velocity.
- The normalized burn rate as well as the In-cylinder pressure results simulated by the calibrated SI turbo model show very good match to the measurement results.

→ **IAV combustion model can well predict the hydrogen combustion**

IAV Activities and Expertise on HD Hydrogen Combustion Development
Validation of H_2 Combustion Model

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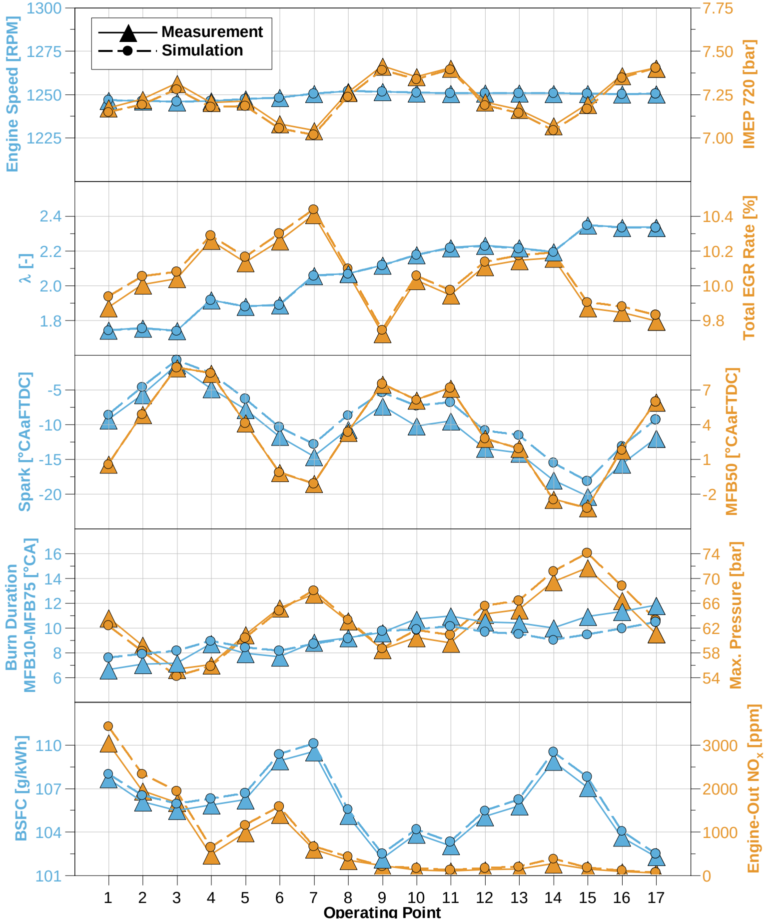

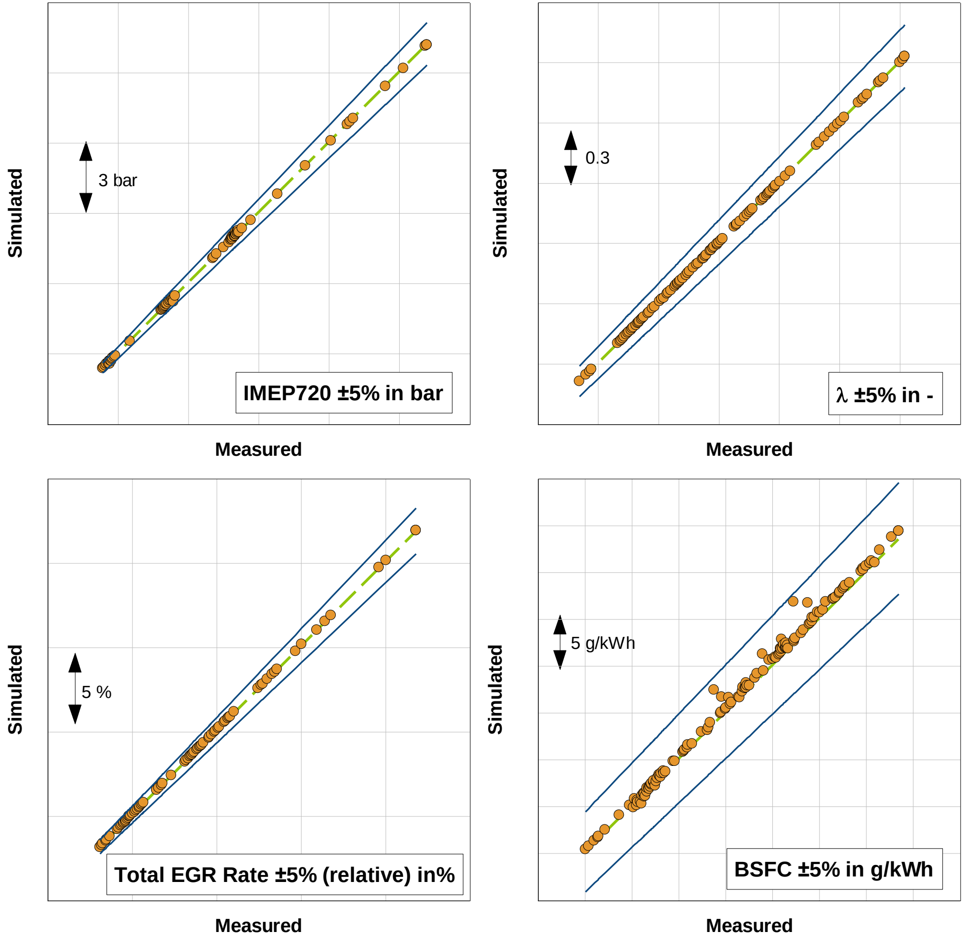

→ **IAV combustion model can well predict the hydrogen combustion**

IAV Activities and Expertise on HD Hydrogen Combustion Development

Model validation results

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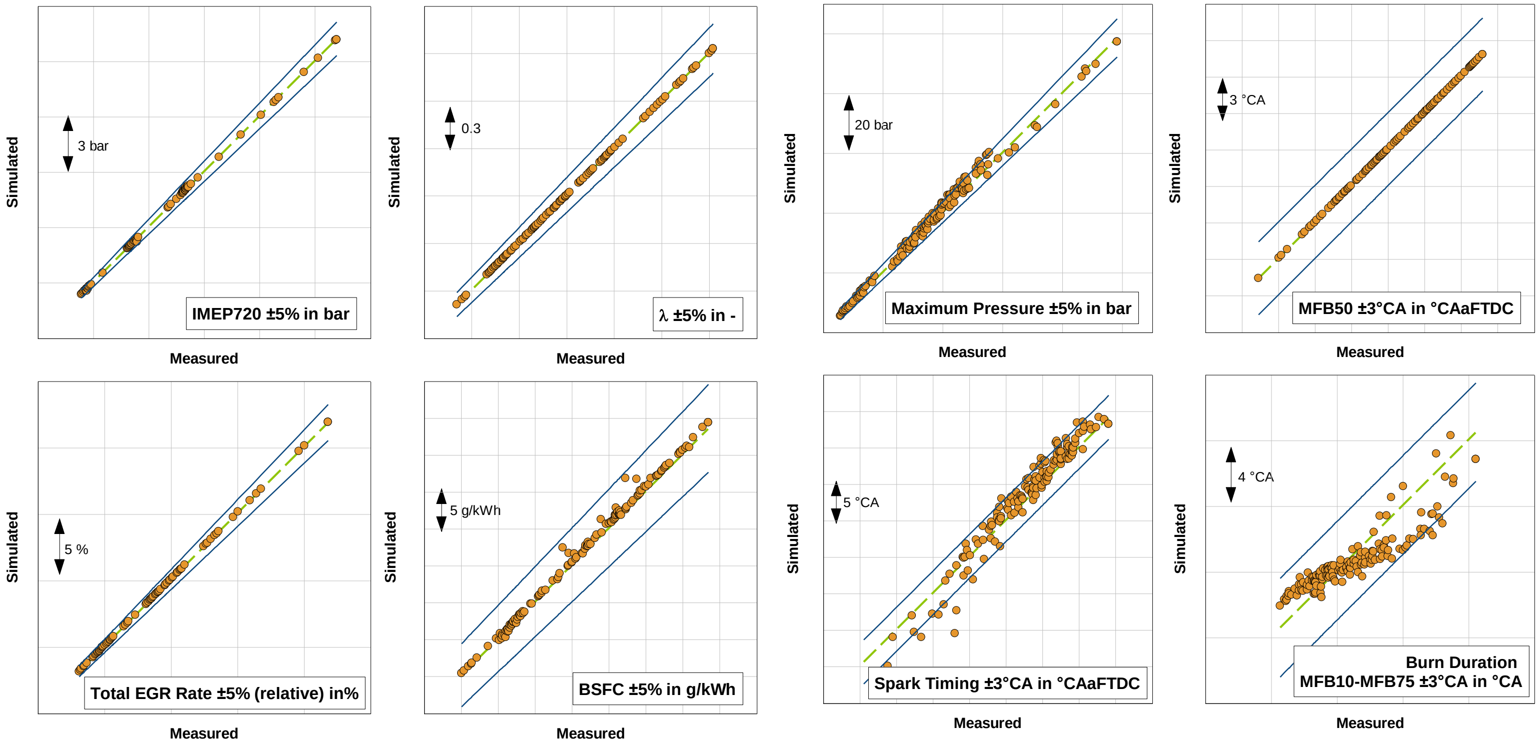
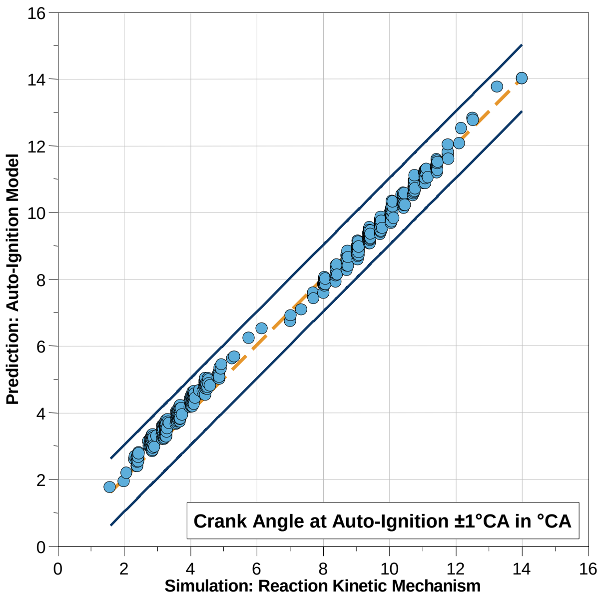
Prediction of Combustion Characteristics

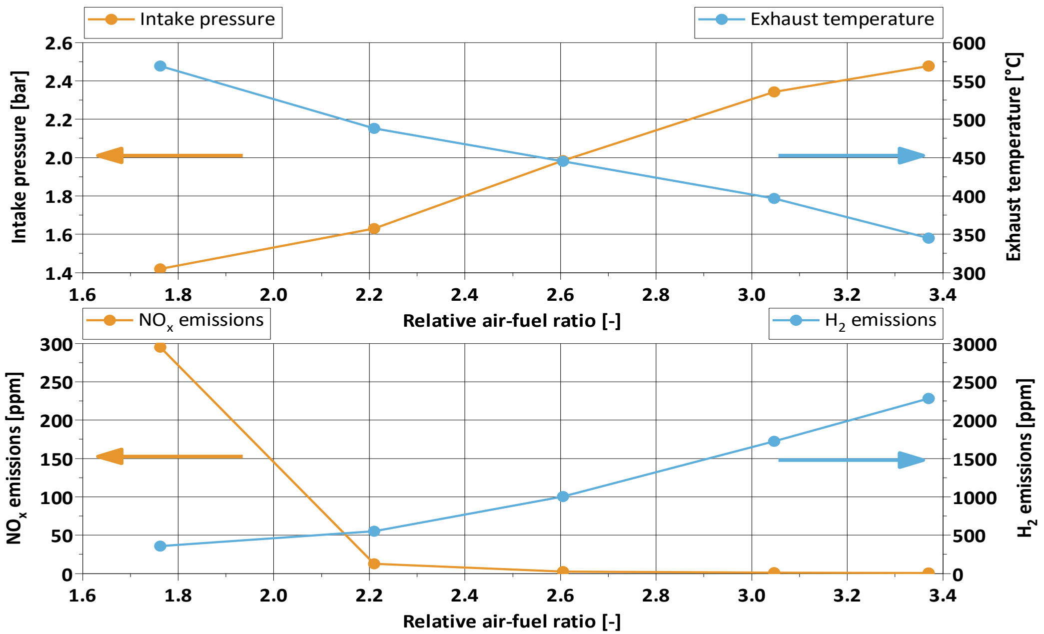


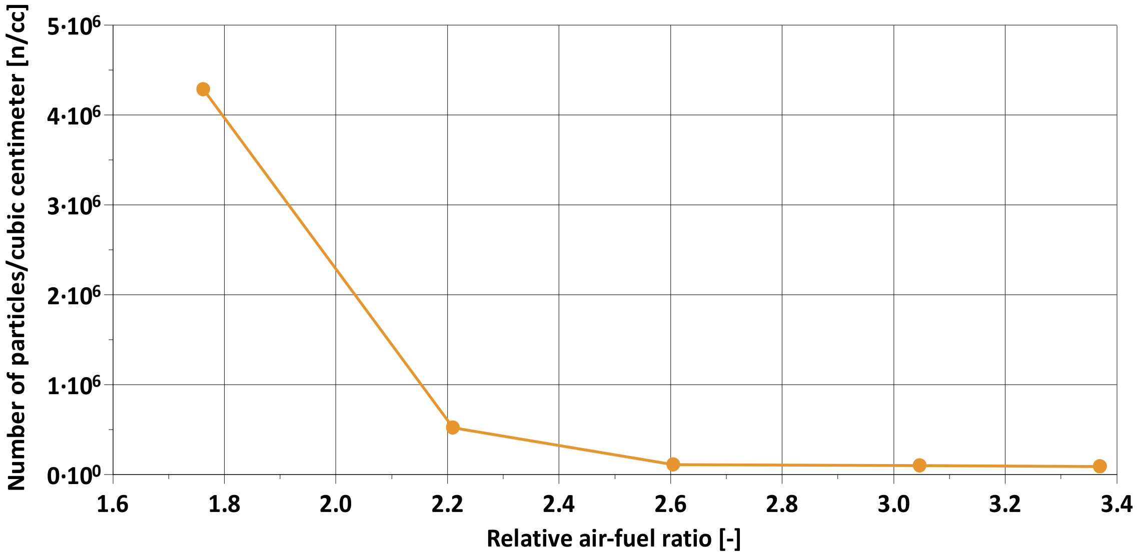
Prediction of Auto-Ignition



→ **IAV's custom combustion model can accurately predict all relevant hydrogen combustion characteristics as well as auto-ignition in the unburnt mass**

HD Hydrogen Combustion Development Overview – Measurement Data



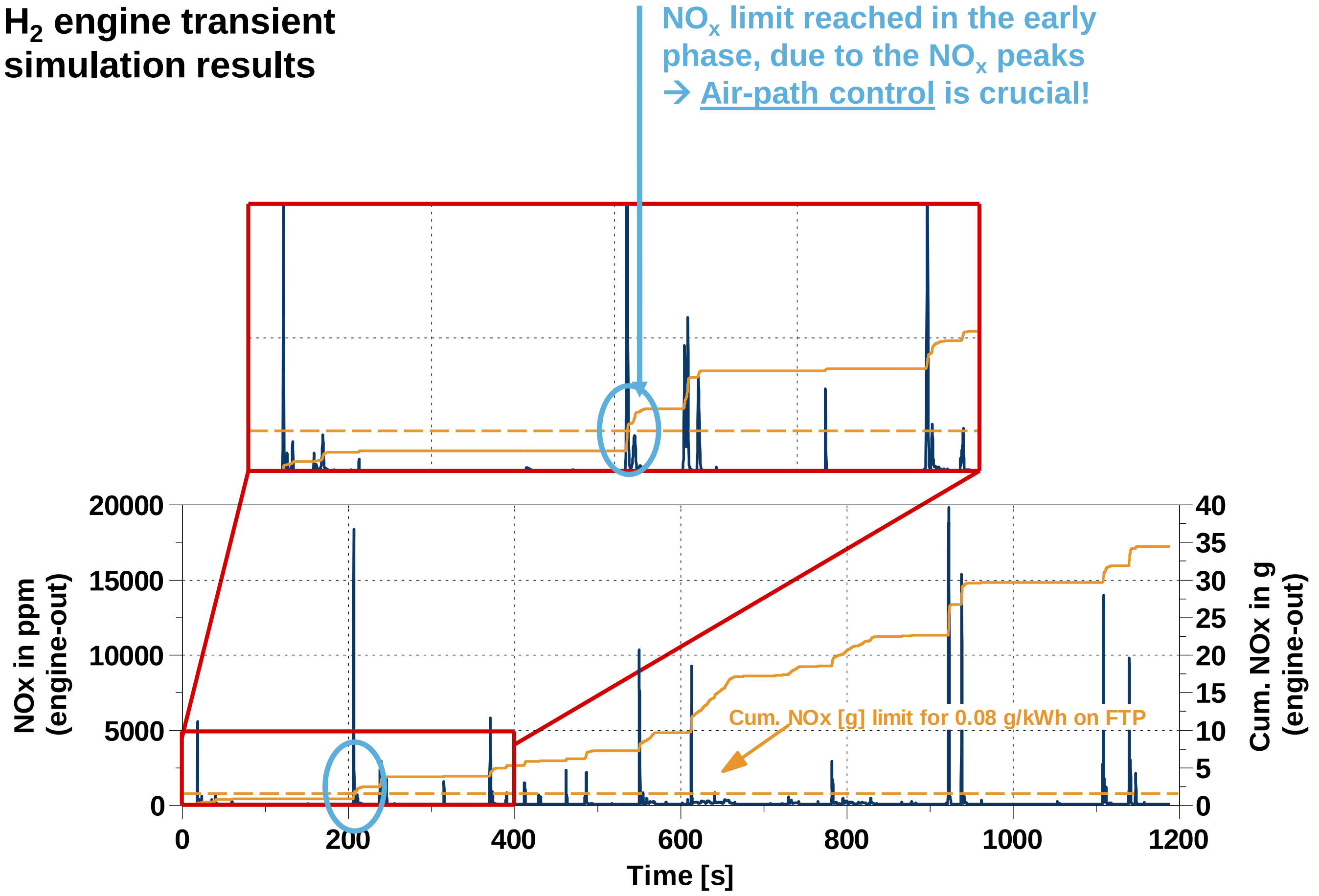


- NO_x emissions and particle number as a function of the relative air-fuel ratio, n= 1100, IMEP= 8 bar
- High gradient in NO_x emission below Lambda 2 and no significant NO_x reduction benefit with high relative air-fuel ratios
- Reduced particle numbers with higher air-fuel ratios and consequently higher intake, exhaust and in-cylinder pressure.
- Increase of hydrogen slip with lean burning

→ **A connection between NO_x and particle emissions and relative air-fuel ratio observed.**

H_2 Engine, Cold-start FTP Results, Transient Simulation

H_2 engine transient simulation results



Can future ultra Low NO_x legislations be achieved using heavy duty H_2 engine?

- Low NO_x emissions during 'steady' periods
- Evaluation of transient NO_x emissions on cold-start HD-FTP cycle
- Extension of simulation model of 12 l HD engine for transient investigations
- In steady-state with mean value of 400 – 500 ppm NO_x, in transient cold start NO_x peaks (5000 – 8000 ppm, based on control strategy) can be seen during the dynamic torque build-up periods → Challenge for air-path control and limitations of air path, turbocharger response
- Control strategies and function development should be considered

→ **The model-based development approach could be performed from concept to function development**

H_2 Engine, Cold-start FTP Results, Transient Simulation

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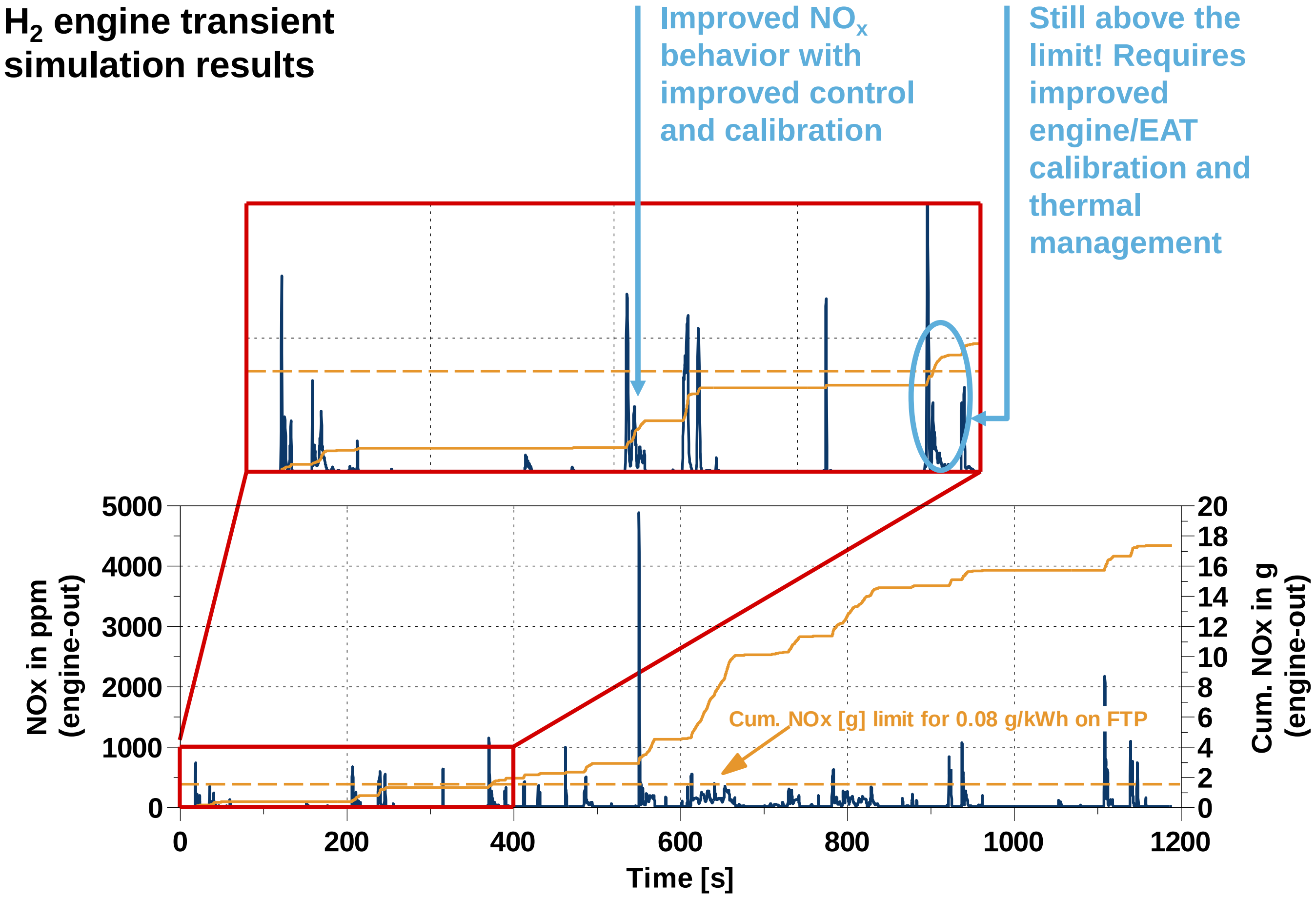
H_2 engine transient simulation results



Model-based control and calibration

- IAV has a long-terms experiences on using model-based control development and calibration
- The air-path control is directly implemented in GT-Suite model environment
- The predictive engine and EAT models in GT-Suite can be directly used as the virtual test bench to develop and calibrate the control strategies
- Low $_{NOx}$ emissions during 'steady' periods

→ **From concept to function development!**

→ **Also model-based calibration!**

H_2 Engine, Cold-start FTP Results, Transient Simulation

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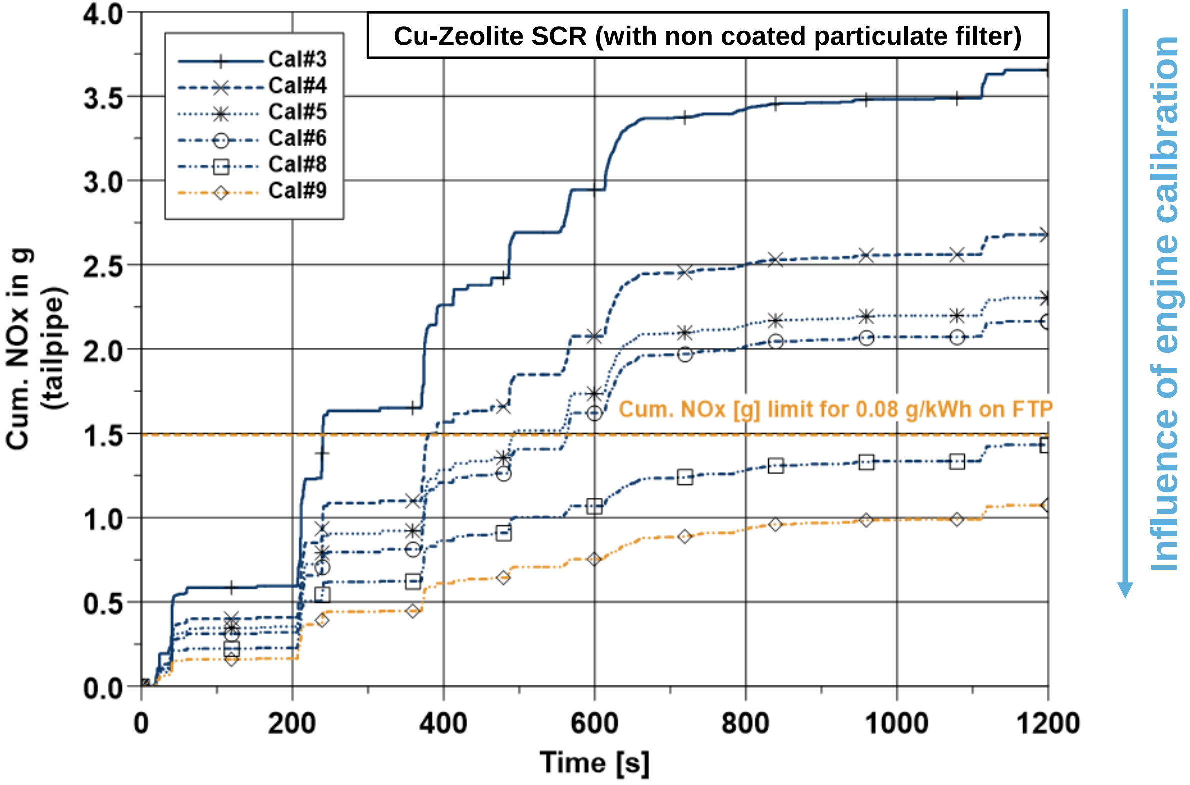
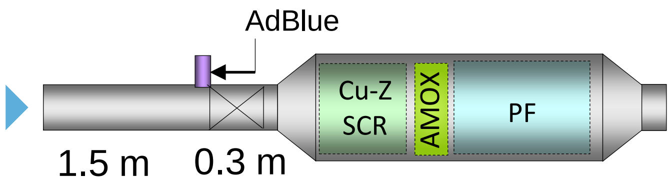
Evaluation of H_2 engine for future Ultra Low NO_x



Investigated EAT layouts for H_2 engine

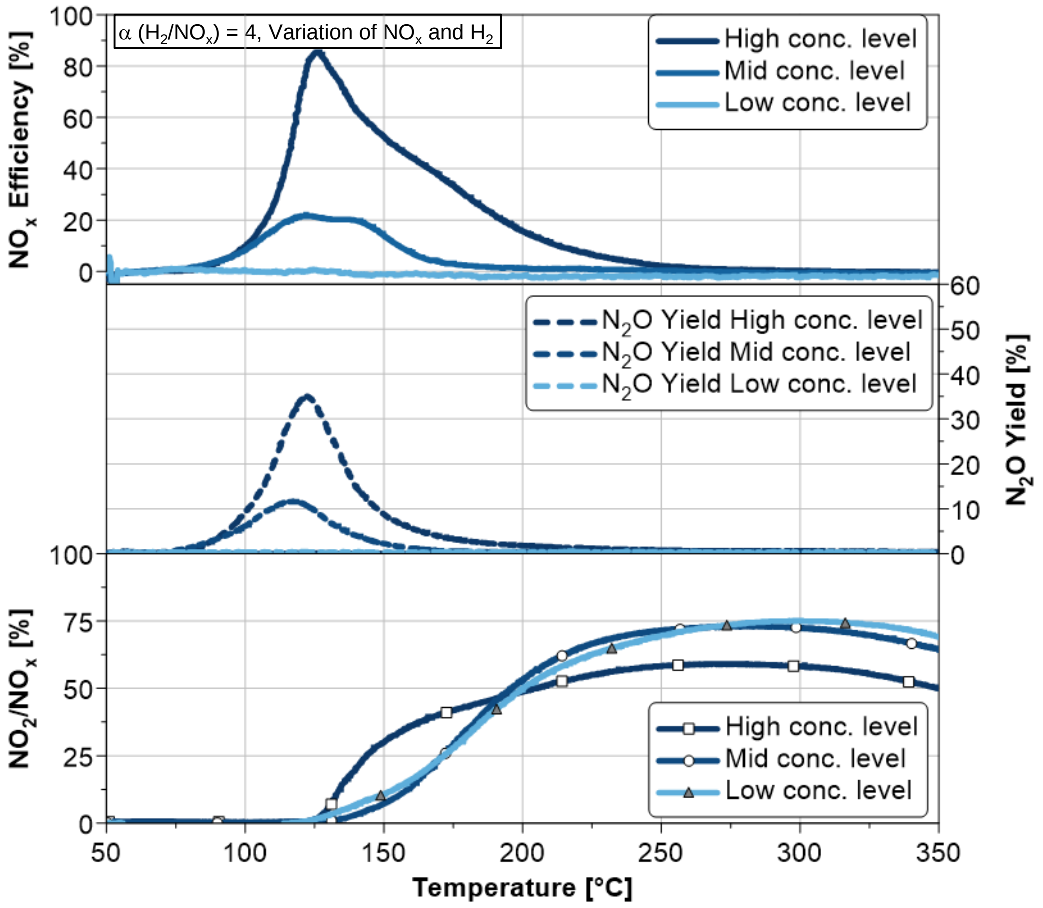


Cu-Zeolite SCR (with non coated particulate filter)

Transient emission results on cold FTP cycle

- Evaluation using holistic simulation and multiple engine calibrations
- Compared to baseline EU VId diesel EAT, the SCR was moved to an upstream position
- The necessity of an oxidation catalyst and the most suitable coating for SCR were considered.
- Other EAT variants are investigated and compared based on tailpipe emissions

H_2-ICE After Treatment Technology
H_2-DeNO$_X$ Investigation in IAV's Physical-chemical Laboratory



Evaluation of alternative technologies – H_2 DeNO$_x$

- H_2-DeNO$_x$ technology catalyst tested on synthetic gas test bench to show DeNO$_x$ behavior under different temp. and concentration levels
- Catalyzed NO_x reduction under stoichiometric or rich conditions by hydrogen using TWC and LNT
- Under purely lean conditions, high NO_x conversions can be achieved even in low-temperature range

Results

- Promising NO_x reduction efficiency of >80% reached at low temperatures, but in small temperature window
- N_2O formation observed due to reaction of H_2 and NOx on PGM → Development needed!
- Catalyst technology is not optimized, so that further reduction of the N_2O slip can be assumed
- Using holistic engine and after treatment evaluation, the optimum after-treatment architecture can be defined
- Final concept based on specific working cycles

IAV's Medium and Heavy-duty ICE Cells

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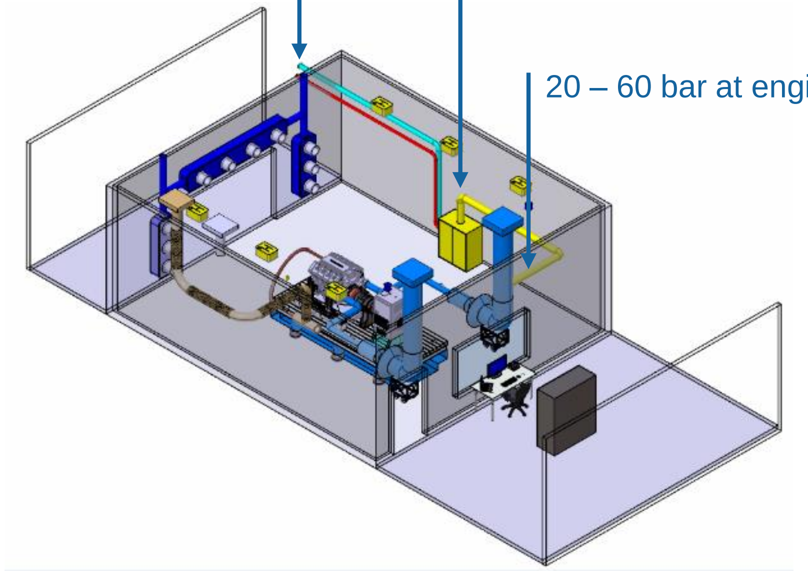

IAV is enhancing it's engine test benches for hydrogen use

- Suitable from LD to HD Commercial Vehicle engines
- Testing from component up to full engine calibration and series preparation
- IAV is investing in alternative fuels infrastructure

20 asynchronous dynos for CV out of 50 in total @ IAV

MD Test Benches

Bench	Rating	Fuel
B07:	330 kW / 1,400 Nm	
B08:	220 kW / 934 Nm	
B09:	460 kW / 981 Nm	
C01:	330 kW / 700 Nm	CNG
G09:	500 kW / 1,000 Nm	CNG
G10:	235 kW / 1,000 Nm	CNG
G15:	550 kW / 1,100 Nm	CNG
G16:	500 kW / 1,000 Nm	CNG
U02:	330 kW / 1,400 Nm	
U03:	330 kW / 1,400 Nm	
U04:	330 kW / 1,400 Nm	
J01:	265 kW / 506 Nm (business partner)	
Br03:	330 kW / 1,400 Nm (business partner)	

HD Test Benches

Bench	Rating	Fuel
B14:	660 kW / 3,500 Nm	
B15:	780 kW / 5,000 Nm	
C02:	650 kW / 3,500 Nm	CNG
G07:	550 kW / 2,500 Nm	CNG
G14:	660 kW / 3,500 Nm	H2
U01:	660 kW / 3,500 Nm	CNG

Heavy HD Test Bench — H2

G13: 1,470 kW / 7,000 Nm

Operations:
C: Chemnitz, G: Gifhorn, B: Berlin,
U: Detroit, J: Tokyo, Br: Sao Paulo

CNG – Natural Gas capable,
H2 – Hydrogen capable

Hydrogen Engine Test Resources at IAV
Specifications HD Hydrogen testing

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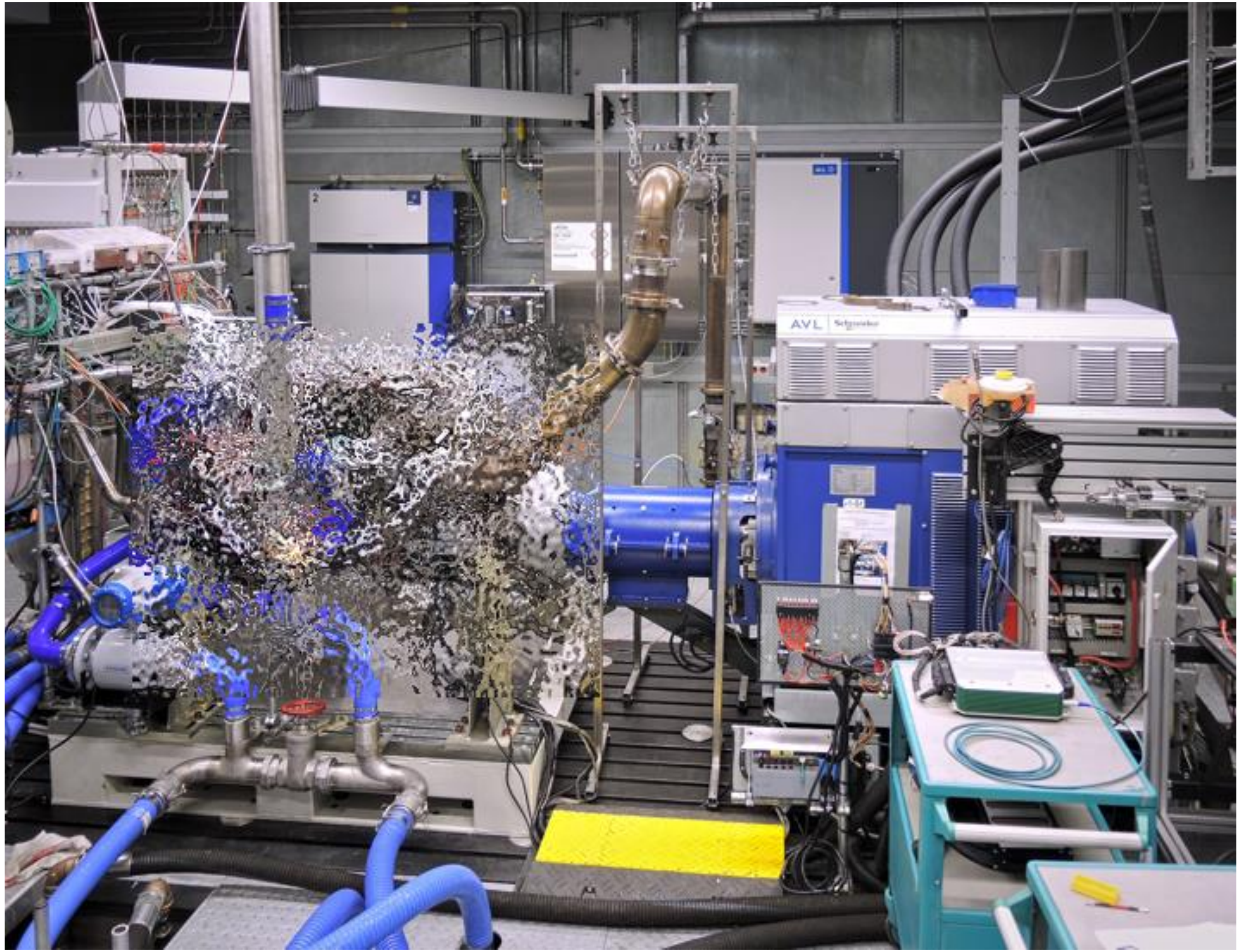

IAV is enhancing it‘s engine test benches for hydrogen use

- Suitable from Light to Heavy Duty Commercial Vehicle engines
- 2 test cells with parallel operation 660 kW / 3,500 Nm
- H_2 supply possible via tank and trailer
- H_2 pressure levels up to 60 bar (upgrade to 100 bar possible)
- Testing from component up to full engine calibration and series preparation

→ Supporting from early concept phase to series preparation!

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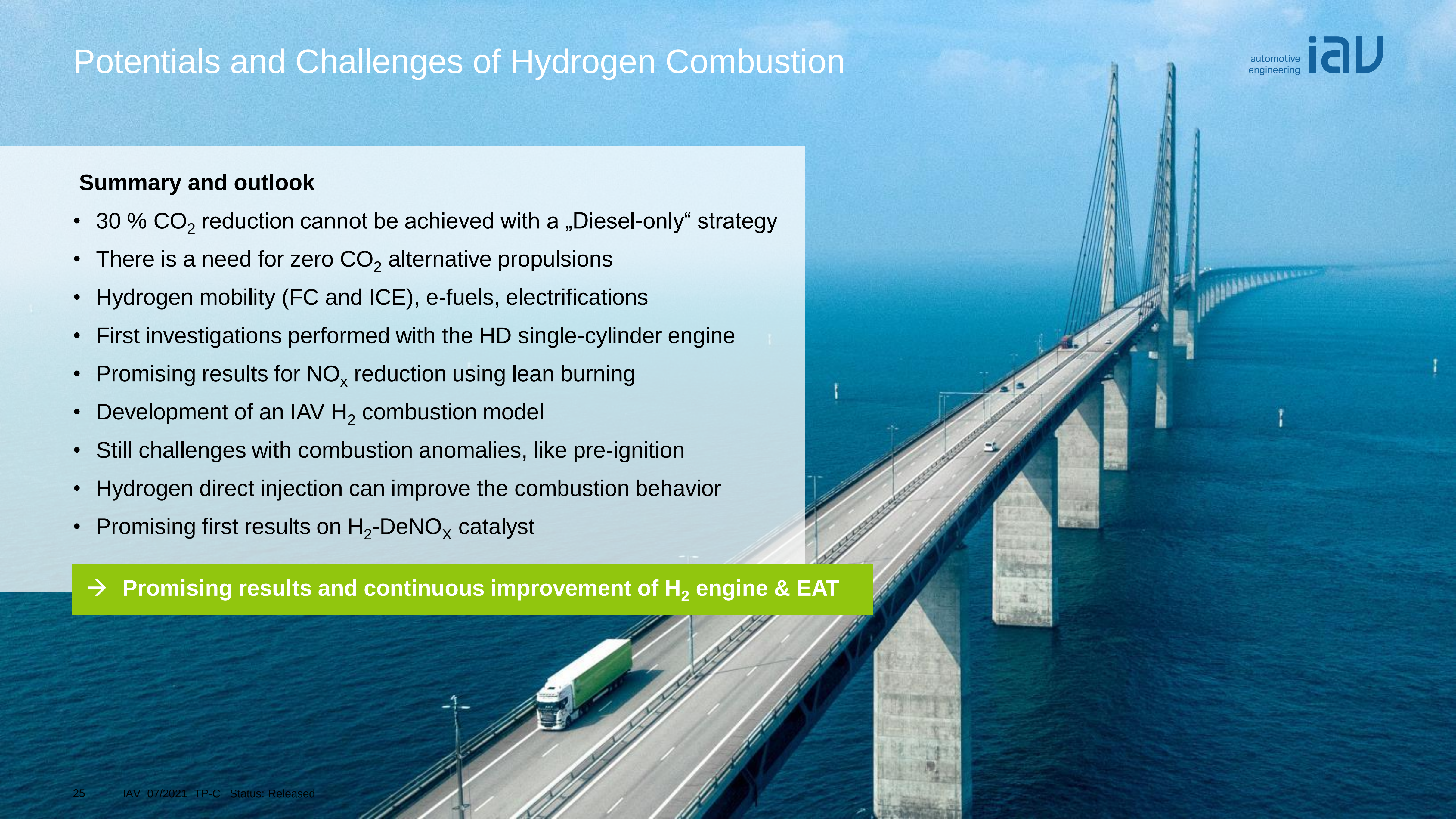

Potentials and Challenges of Hydrogen Combustion

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Summary and outlook

- 30 % CO_2 reduction cannot be achieved with a „Diesel-only“ strategy
- There is a need for zero CO_2 alternative propulsions
- Hydrogen mobility (FC and ICE), e-fuels, electrifications
- First investigations performed with the HD single-cylinder engine
- Promising results for NO_x reduction using lean burning
- Development of an IAV H_2 combustion model
- Still challenges with combustion anomalies, like pre-ignition
- Hydrogen direct injection can improve the combustion behavior
- Promising first results on H_2-$DeNO_X$ catalyst

→ **Promising results and continuous improvement of H_2 engine & EAT**

Hydrogen Combustion Publication List

- Rezaei R., Riess M., Li Q., Rolke P., Wohlrab A., Hayduk C., Bertram C.: “Decarbonization of commercial vehicles with hydrogen combustion: from concept to start of production and beyond”, 2nd World Congress on Internal Combustion Engines, China, 2021
- Rezaei R., Hayduk C., Fandakov A., Riess M., Sens M., Delebinski T.: “Numerical and Experimental Investigations of Hydrogen Combustion for Heavy-Duty Applications”, SAE World Congress, 2021
- Rezaei R., Sens M., Riess M., Bertram C.: “Potentials and challenges of hydrogen combustion system development as a sustainable fuel for commercial vehicles”, ATZ Engine Conference, Baden-Baden, 2021
- Juenemann D., Mennig M., Rezaei R., Toepfer T, Bertram C.: “Model-based development of alternative propulsions for HD off-highway applications”, 15th International MTZ Conference on Future Powertrains, Hanau, 2021
- Rezaei R., Hayduk C., Sens M., Fandakov A., Bertram C.: “Hydrogen Combustion – a Puzzle Piece of Future Sustainable Transportation!”, SIA Powertrain & Energy, France, 2020
- Rezaei, R. “Hydrogen Combustion Technologies for Future Heavy Duty Applications”, Sep. 2020, Karlsruhe, Germany
- Rezaei R., Hayduk C., Sens M., Riess M., Fandakov A. et al.: “Potentials and challenges of hydrogen as a sustainable fuel for commercial vehicles with internal combustion engines”, IAV Japan TechDay, 2020
- Rezaei R., Mennig M., Hayduk C., Bertram C. et al.: “Holistic engine and exhaust after-treatment system development for hydrogen combustion concepts”, 18th FAD Conference Challenge – Exhaust aftertretament, Radebeul (near Dresden), 2020
- Rezaei R., Hayduk C., Sens M., Fandakov A., Bertram C.: “Model-based Development Methodology for HD Hydrogen Combustion System Optimization”, ATZ Experten-Forum Powertrain 2020 „Ladungswechsel und Emissionierung“, Hanau, 2020

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