HD Hydrogen Combustion from Concept to Series Development

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

Regulation and drivers for future technology

H₂ 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
Most important vehicle classes for EU CO₂ reduction are 4, 5, 9, 10
Significant CO₂ reduction for long-haul applications required
All alternative fuels and BEV scenarios require a push through legislation and major investments

EU CO₂ 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:
- Euro VI E
- Euro VII (assumed)

USA:
- EPA/CARB Ultra Low NOx (Phase In 2024-2031)

EU „Vision Zero“
Climate neutral Europe by 2050

- 2020
- 2030
- 2040
- 2050

Year

EU 2050 goal:
60% cut in transport emissions

CO₂ is our main challenge … and our main technology driver!

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Long-haul Truck with Diesel engine, Tank-to-Wheel

Successive increase of technology efficiency and penetration rate from year to year

30 % CO₂ reduction cannot be achieved with a „Diesel-only“ strategy
## Agenda

### Regulation and drivers for future technology

**H₂ and other future e-fuels**

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### Summary and Outlook
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\textsubscript{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

**Boundaries:**
- $I = 1.8$
- $I_a = \text{const.}$
- $\eta_e = \text{const.}$
- $T = \text{const.}$

<table>
<thead>
<tr>
<th>Mixture formation</th>
<th>PFI</th>
<th>DI early LP-DI</th>
<th>DI during comb. HP-DI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power potential [%]</td>
<td>-</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Efficiency potential [%]</td>
<td>-</td>
<td>++</td>
<td>+++</td>
</tr>
</tbody>
</table>

(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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\( \text{H}_2 \) and other future e-fuels

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Summary and Outlook
IAV Model-based Development Methodology
Alternative Powertrain Development (H₂ Combustion and Fuel Cell)

- Long-term experiences with the state-of-the-art technologies PFI to HP-DI H₂ combustion to fuel cell development
- Complete H₂ development tool chain: sophisticated testing environments, component and system models etc.
IAV Uniqueness and Highlights: Hydrogen Combustion Engine
Hydrogen Combustion and After-Treatment Development

**H₂ single-cylinder (2 l) used by IAV**
- Deflagration system (to protect from H₂ back-fire)
- Low-pressure indication (intake and exhaust sides)
- 6 x injectors with 8 bar injectors on a ring (up to 12 possible)

**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 H₂ engine testing and calibration (13 l class)
- Well validated IAV 1D and 3D CFD own models for H₂ combustion, NOₓ 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 + NH₃-SCR) in cold cycles for UL-NOₓ
- Initiating and conducting of about 2.3 Mio. EUR research projects on Hydrogen combustion and after-treatment dev.
- Multiple dedicated H₂ 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 from HPDI to PFI concepts.
H₂ Single Cylinder Testing
Summary of H₂ investigations

Assembly and setup of hydrogen PFI engine

Combustion and emission investigations
- Particle number and NO₅ 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
- NO₅ 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

**H₂ 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. NOₓ emissions

ème indicated mean effective pressure of 22.4 bar reached with PFI concept!

Emissions and exhaust gas temperature as a function of the relative air-fuel ratio, n= 1100 & 1250 1/min, IMEP=11 bar
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
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IAV Activities and Expertise on HD Hydrogen Combustion Development
Model validation results

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\textsubscript{x} emissions and particle number as a function of the relative air-fuel ratio, n= 1100, IMEP= 8 bar
- High gradient in NO\textsubscript{x} emission below Lambda 2 and no significant NO\textsubscript{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\textsubscript{x} and particle emissions and relative air-fuel ratio observed.
H₂ Engine, Cold-start FTP Results, Transient Simulation

H₂ engine transient simulation results

Can future ultra Low NOₓ legislations be achieved using heavy duty H₂ engine?

- Low NOₓ emissions during ‘steady’ periods
- Evaluation of transient NOₓ 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 NOₓ, in transient cold start NOₓ 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
**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 \( \text{NO}_x \) emissions during ‘steady’ periods

→ From concept to function development!
→ Also model-based calibration!
H₂ Engine, Cold-start FTP Results, Transient Simulation

Evaluation of H₂ engine for future Ultra Low NOₓ

- Transient emission results on cold FTP cycle
  - Evaluation using holistic simulation and multiple engine calibrations
  - Compared to baseline EU VIId 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

Influence of engine calibration

Investigated EAT layouts for H₂ engine

Cu-Zeolite SCR (with non coated particulate filter)

Cu-Zeolite SCR (with non coated particulate filter)

Transient emission results on cold FTP cycle

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H₂-ICE After Treatment Technology
H₂-DeNOₓ Investigation in IAV’s Physical-chemical Laboratory

Evaluation of alternative technologies – H₂ DeNOₓ

• H₂-DeNOₓ technology catalyst tested on synthetic gas test bench to show DeNOₓ behavior under different temp. and concentration levels

• Catalyzed NOₓ reduction under stoichiometric or rich conditions by hydrogen using TWC and LNT

• Under purely lean conditions, high NOₓ conversions can be achieved even in low-temperature range

Results

• Promising NOₓ reduction efficiency of >80% reached at low temperatures, but in small temperature window

• N₂O formation observed due to reaction of H₂ and NOx on PGM → Development needed!

• Catalyst technology is not optimized, so that further reduction of the N₂O 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

IAV is enhancing its 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**
- B07: 330 kW / 1,400 Nm
- B08: 220 kW / 934 Nm
- B09: 460 kW / 981 Nm
- C01: 330 kW / 700 Nm
- G09: 500 kW / 1,000 Nm
- G10: 235 kW / 1,000 Nm
- G15: 550 kW / 1,100 Nm
- G16: 500 kW / 1,000 Nm
- 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**
- B14: 660 kW / 3,500 Nm
- B15: 780 kW / 5,000 Nm
- C02: 650 kW / 3,500 Nm
- G07: 550 kW / 2,500 Nm
- G14: 660 kW / 3,500 Nm
- U01: 660 kW / 3,500 Nm

**Heavy HD Test Bench**
- 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
IAV is enhancing its 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
- \( \text{H}_2 \) supply possible via tank and trailer
- \( \text{H}_2 \) 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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Summary and Outlook
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- 30 % CO₂ reduction cannot be achieved with a „Diesel-only“ strategy
- There is a need for zero CO₂ alternative propulsions
- Hydrogen mobility (FC and ICE), e-fuels, electrifications
- First investigations performed with the HD single-cylinder engine
- Promising results for NOₓ reduction using lean burning
- Development of an IAV H₂ combustion model
- Still challenges with combustion anomalies, like pre-ignition
- Hydrogen direct injection can improve the combustion behavior
- Promising first results on H₂-DeNOₓ catalyst

→ Promising results and continuous improvement of H₂ engine & EAT
Hydrogen Combustion Publication List


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