Hydrogen combustion engines

Market trends and development road map

Düsseldorf, 17th of September

Virnich

Session:

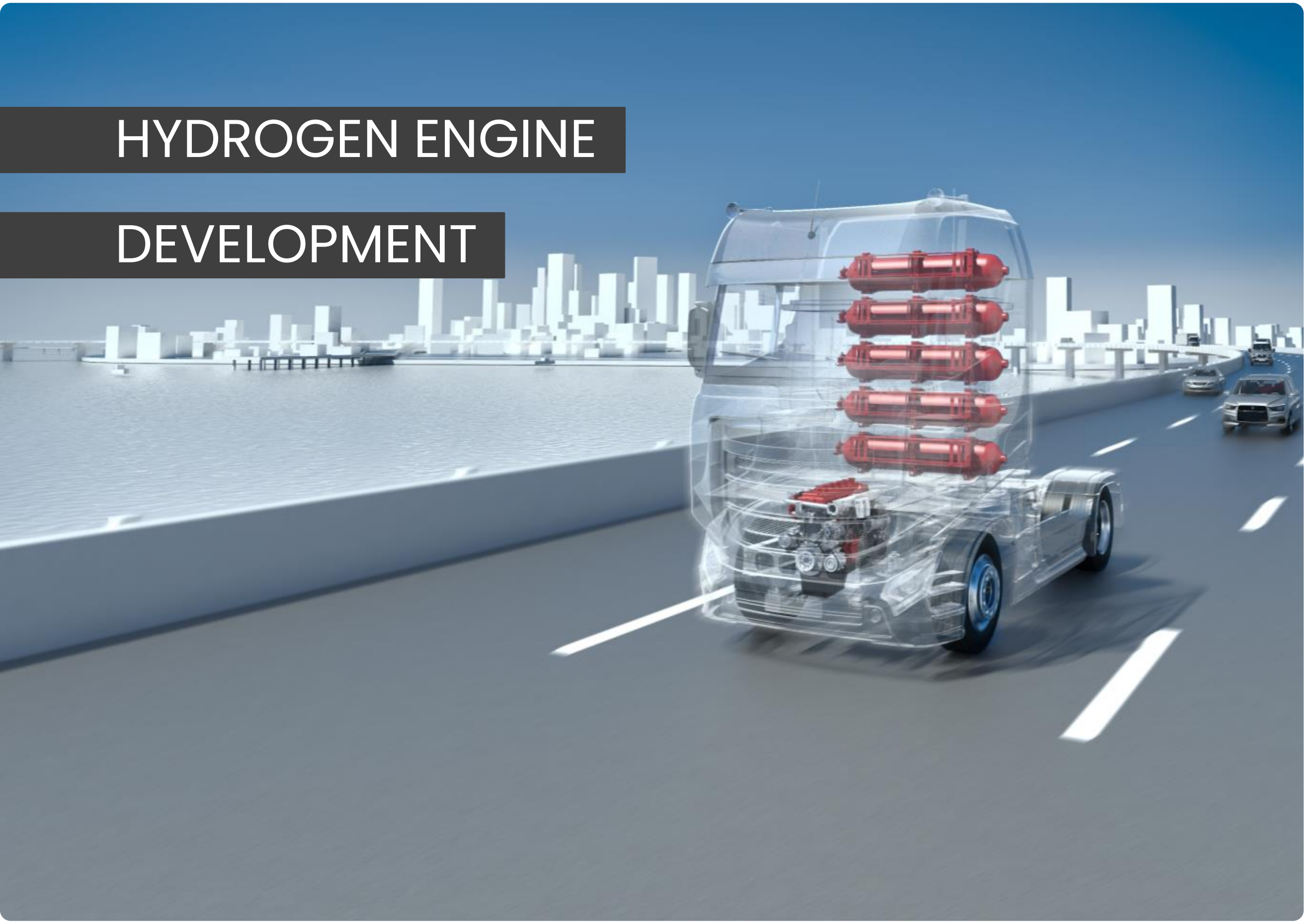
Technology Trends in Future Fuels for Maritime, Energy & Power Generation

LUBRICANT EXPO EUROPE

FEV

FEV delivers turnkey hydrogen engine development across all applications

FEV



Technical & Strategic Consulting

Layout & concept definition

Procurement

Verification & Validation

40+ years of experience

Design & Simulation

Prototype Workshop

Software for H2 combustion control

Safety

H_2-ICEs are increasingly considered as ZEVs by overarching regulations; some markets still do not include H2-ICEs but might adapt in future

H2-ICE – REGULATORY CONSIDERATION AS ZEV

EU

3 types of ZEVs:

1. No combustion engine
2. Combustion engine with less than 3 g/tkm[1)] or 1 g/pkm[1)] emissions from fuel according to Vecto simulation
   – Fulfilled by monofueled H_2-ICE
3. Combustion engine with less than 1 g/kWh tailpipe emissions according to EU 595/2009
   – Revised UN R49 (underlying test methodology) may define monofueled H2-ICE as 0g/kwh

UK

- UK does not (yet) plan to recognize H_2-ICE as ZEV as regulation excludes vehicles that emit any CO_2 or "harmful pollutants"
- Allowance of H_2-ICE may occur due to industry interest and expected developments in EU

US

- Federal:
  – As of now not considered as ZEV
  – New EPA proposal for CO_2 emissions defines H_2-ICE as ZEV and considers it to be relevant for heavy-duty applications
- ACT states:
  – As of now H2-ICE not considered as ZEV by CARB
  – Recently, discussions started to account H_2-ICEs as ZEVs

CN

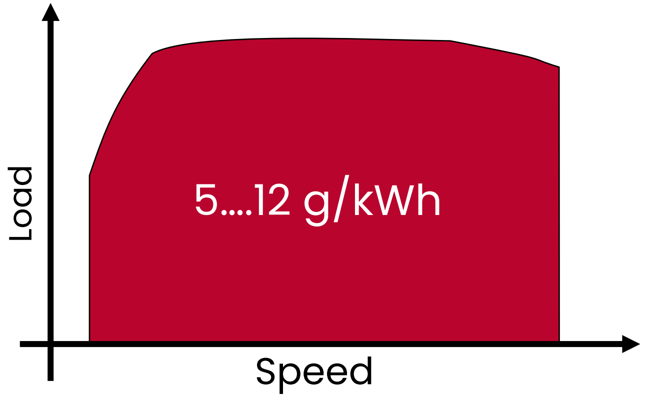
- Currently, H_2-ICE is not recognized as NEV in China
- Calculation of CO_2 emissions using life cycle assessment (LCA) calculation is currently under discussion (would benefit H_2-ICE)
- Draft LCA calculation already released for passenger cars
- Introduction of LCA calculation for commercial vehicles is possible

H2-ICE = ZEV?	EU	UK	US	CN
	✓ New EU emission regulation defines H_2-ICE as ZEV	? Not defined as ZEV yet – future alignment with EU regulation possible	✓ EPA GHG emission proposal (04/2023) ? CARB is actively discussing H_2-ICE	? Currently not defined as ZEV but possible introduction of LCA emission calculation would benefit H_2-ICE

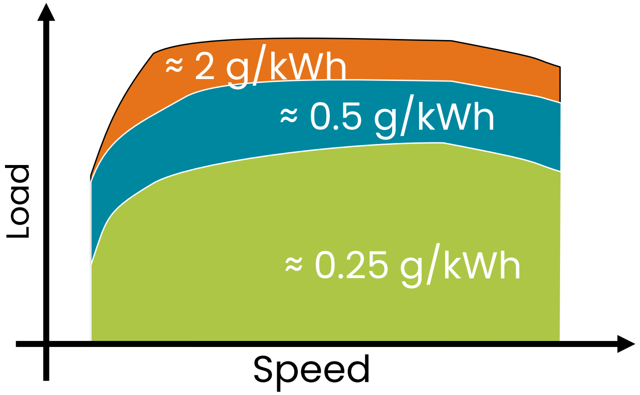
1) Final value still under discussion
2) ACEA /DG CLIMA: Based on calculated zero emissions from fuel consumption (ignoring carbon in lubricant oil & SCR)

In comparison to conventional fuel type engine, the emissions abatement potential of H2-ICE is substantial

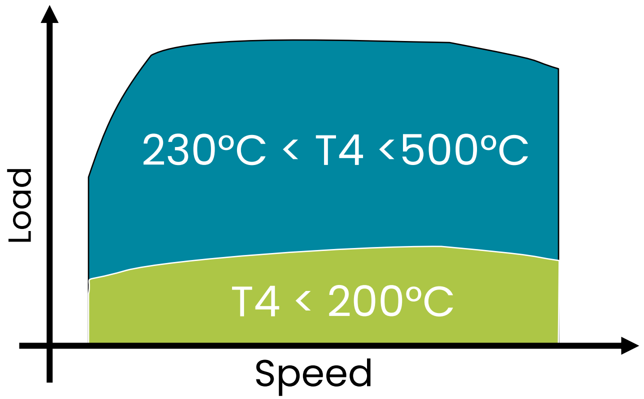
NOx Raw / Diesel



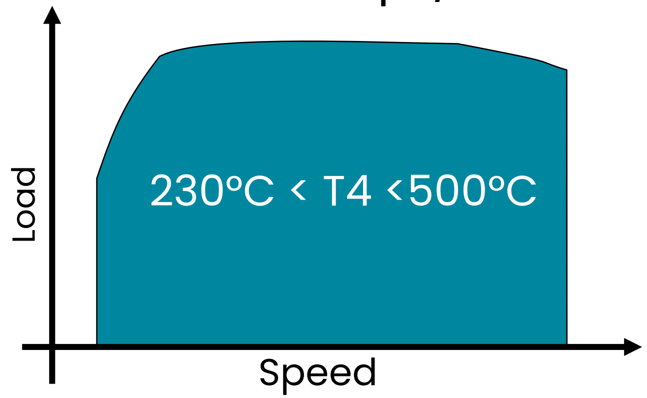
NOx Raw / H2-ICE



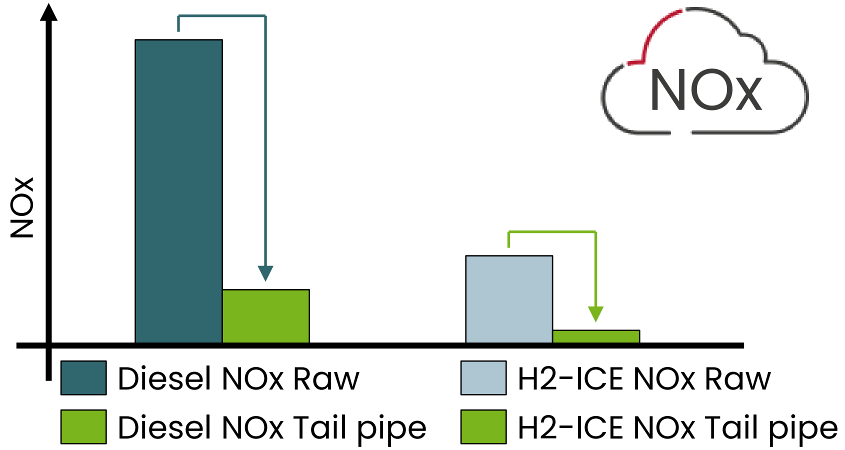
Exhaust Temp. / Diesel

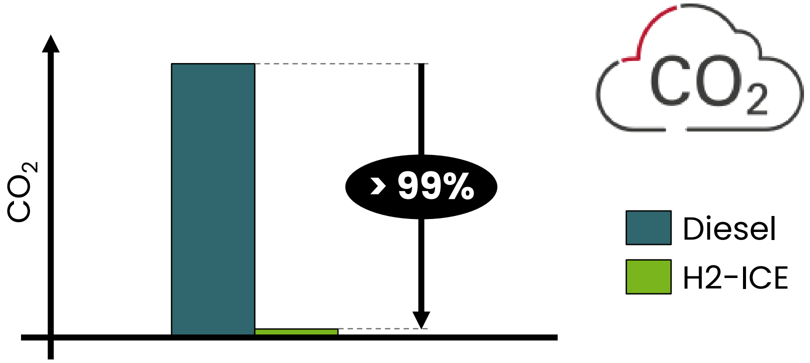


Exhaust Temp. / H2-ICE



Tail Pipe emissions



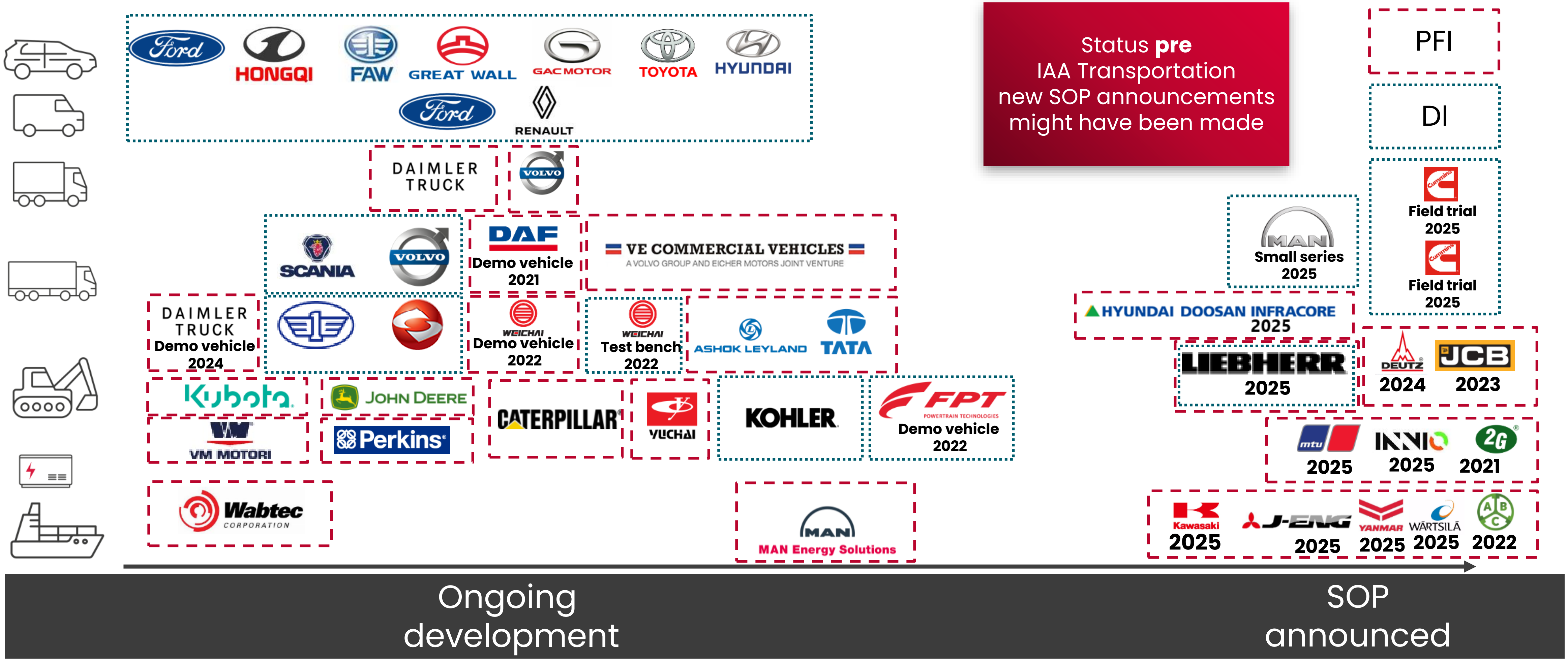


*The emission of HC and CO are not shown as their emissions are within the analyzer accuracy range

Source: Data extracted from FEV engine benchmark database to assess/compare engine metrics between Diesel engine and H2-ICE

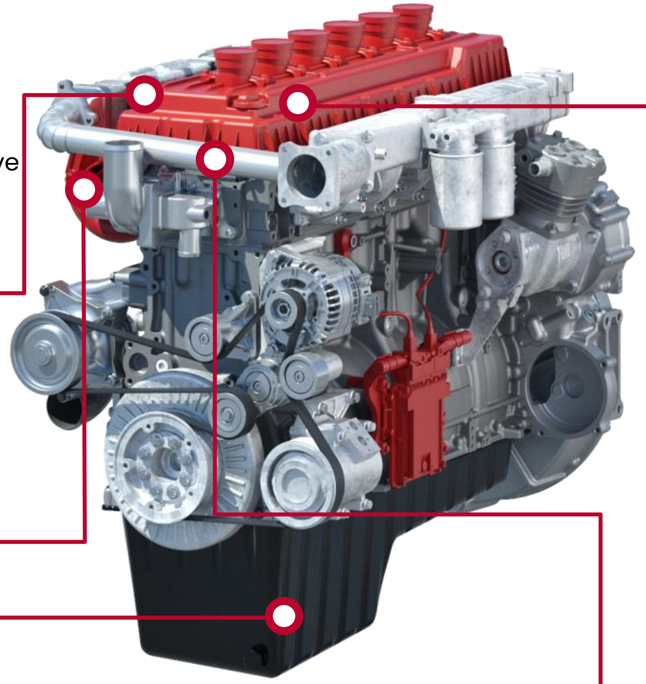
Publicly announced interest and investment in H_2-Engine development is now growing strongly amongst on-and off-highway industry players

FEV



Multiple hardware and software changes need to be applied to convert an existing engine to a hydrogen operation

OVERVIEW OF NEW / ADAPTED PARTS



Head design: Pent roof or flat head

- For Gen1 engines pent roof not in focus
- HD truck oems focus on Hydrogen as the only alternative fuel, therefore flat head design acceptable
- Off road industry forced to widen the scope for various alternative fuels, stronger push for pent roof design

Turbocharger: Wastegate or VTG?

- Trend towards VTG
- Some HD truck OEM still using WG+EGR

Crankcase ventilation: Active?

- Benefit for water in oil topic
- More robust in case of failure

Injection system: DI or PFI?

- Drawback in power density can be compensated during steady state operation quite successfully. But quite some customers now facing challenges during transient load built up.
- Maturity benefit of PFI not existing anymore since announcement of MAN SOP H2 ICE DI.

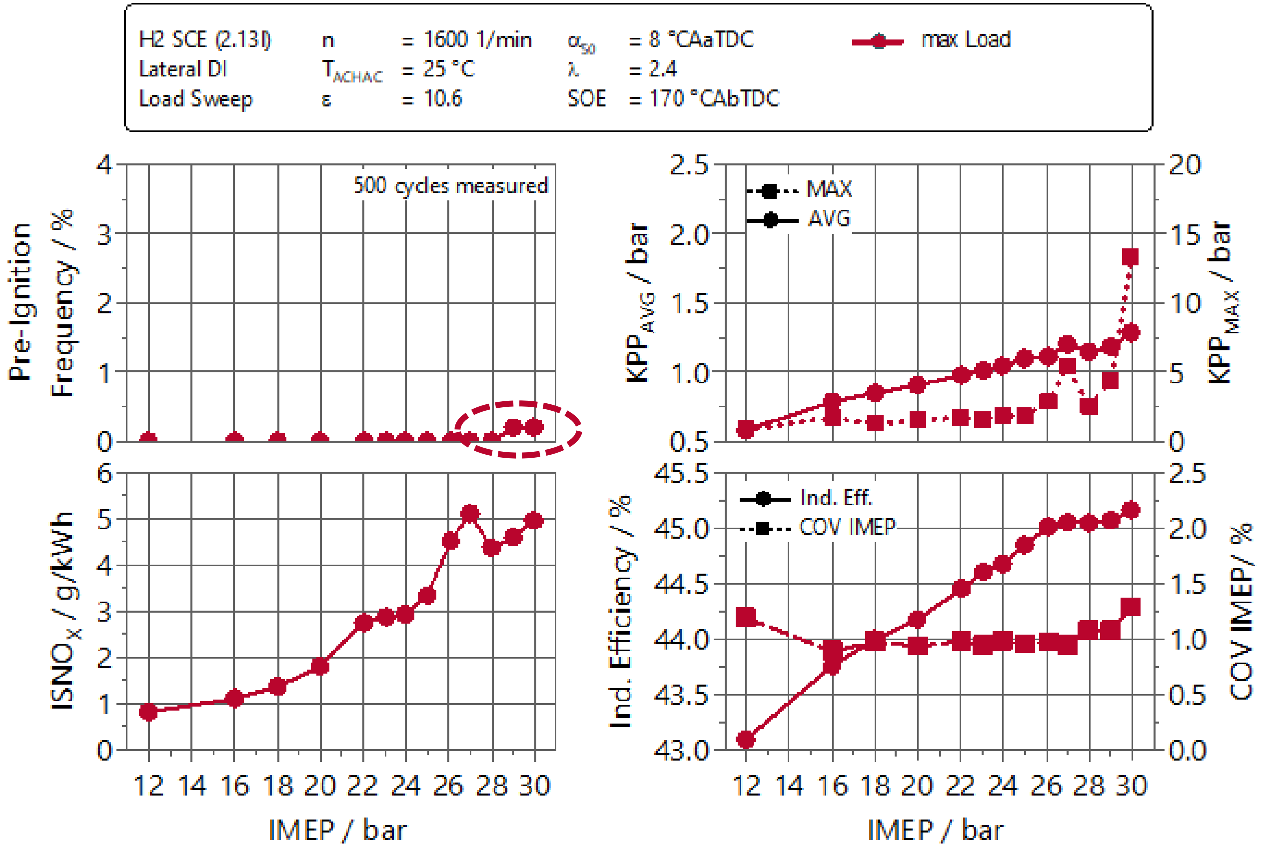
For DI: w/ or w/o Spray cap

- Spray cap required if charge motion level not sufficient to create required mixture homogeneity
- Increasing injection pressure level (· 30 bar) eases the situation w/o spray gap
- Spray gap prone to cause pre ignition at high loads

Air management: w/ or w/o EGR

- No benefit in NOx emission w/EGR
- can ease turbo charger layout especially if WG is utilized
- more likely to be used in combination with PFI

Latest results from SCE
Up to 30 bar at 1600 rpm to prove possible power density with DI



- Tailored charge motion design enables H2 ICE to reach diesel like power density level, if sufficient boost pressure is available
- Right trade-off between tumble level and volumetric efficiency is key
- Pre-ignition still limits the max. achievable load

Diesel like power density in combination with attractive engine efficiency

First assessment of the requirements for lube oil used in H_2 ICE operation shows challenges on LSPI events, water accumulation and others

IMPACTS OF **H2 ICE** ON LUBRICANTS

Not exhaustive

Major similarities to existing lubricants

- **Similar requirements of gas ICEs** regarding lube oil indicate that oil developed for gas engines can be suitable for use as baseline for operation w/ H_2-ICE
- However, further requirements and improvement potentials **need to be investigated**

Major impacts / differences of H_2 ICEs on oil lubricants

- **Low-speed pre-ignition (LSPI) events** occur more frequently in H2 ICE compared to diesel, due to (mainly) the low ignition energy and high diffusion
  - **Increased LSPI events** will impact the durability and performance of H2 ICEs
  - Oils specifically developed for H2 ICE may decrease LSPI events vs. low SAPS diesel oils (e.g. TotalEnergies)
- The combustion of hydrogen leads to an **increased** presence of **water in the oil**
  - **Increased generation of water** during the combustion and thus also presence of water in the exhaust gas and blow-by (e.g. reducing the performance of the lube oil)
  - **Lower coolant water & oil temp**. will lead to increased tendency of water accumulation in the oil
  - **Higher temperatures at** the **wall** are expected (combustion is closer to the cylinder wall)
- **H_2** in the combustion chamber could **deteriorate the "self-healing"** effect of ICE **oils**
  - Theoretically, the H_2 radicals generated may also react with the ICE oil fragments, preventing them from linking up with each other and thus reducing the ability of the oil to repair itself; → **Still**, this needs **to be tested & proven** (does the H_2 molecule has an impact on the oil?)
- As H_2 ICE combustion is "**soot free**", there is no / limited lubrication from the soot on certain parts (e.g. valve seat contacts), which may have an **impact on wear**
- Potential USP in the context of zero-CO_2 combustion: **carbon-free / low-carbon lubricant**
  - Oil components such as sulfur & phosphorus might receive more focus ("low pollutant" fuel)

Source: FEV

FEV has a large variety of H_2 engines, developed and ready for oil testing

FEV

Passenger cars

- 0.5L SCE (1.0L PC equivalent)
- DI / PFI possible
- Tumble charge motion
- Adjustable CR (10.8 to 11.5)

Medium duty

- 7.7L & 6-cylinder
- PFI possible
- 2-stage turbo charging
- Compatibility: H_2 & CNG

Heavy duty

- 2.13L SCE (13L HD equivalent)
- DI / PFI possible
- Tumble w/ intake port chamfer or no charge motion
- Compatibility: H_2, MeOH, NH_3, DME, OME & CNG

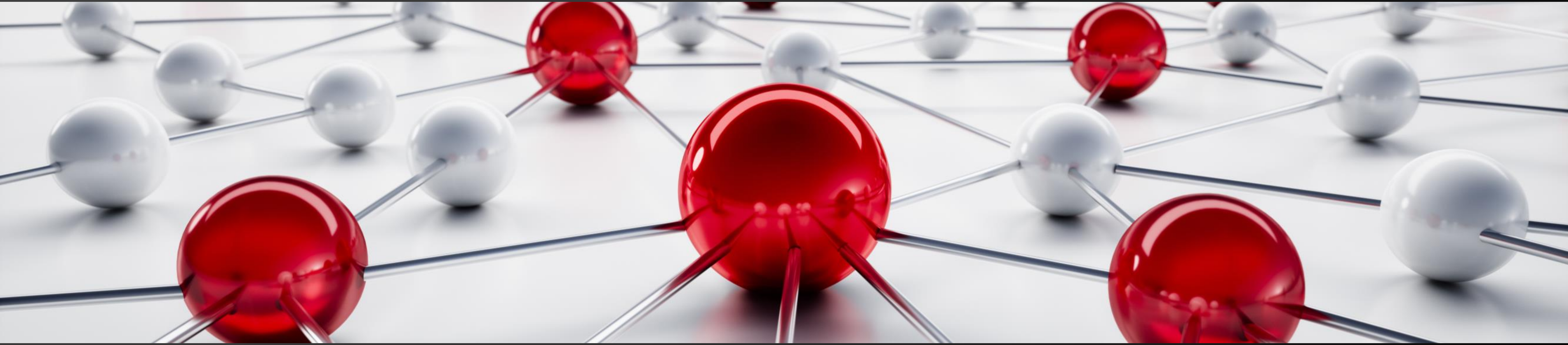
Pre-ignition

Water in oil

Durability

Lube oil emissions

DI = Direct Injection; PFI = Port Fuel Injection; SCE = Single Cylinder Engine



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