The Way of Industrialization for the H_2 ICE

ECMA Conference - 3rd November 2023

Dinesh Goyal

The Way of Industrialization for the H_2 ICE
Agenda

1

Generation 1 H_2-ICE

- ❖ Corresponding technology building blocks MPI / DI
- ❖ Achievements of generation 1 H_2-ICE

2

Way to SOP

- ❖ Challenges and solutions
- ❖ AVL tool chain: From concept to production
- ❖ Technology readiness of main components
- ❖ Dedicated H_2-Software
  - ❖ OBD for H_2-ICE
- ❖ H_2-fuel system H_2 vehicle

3

Summary

Conclusions and Outlook

The Way of Industrialization for the H_2 ICE
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- Corresponding technology building blocks MPI / DI
- Achievements of generation 1 H_2-ICE

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- Challenges and solutions
- AVL tool chain: From concept to production
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The Way of Industrialization for the H_2 ICE
Alt. Fuels: Production | Properties | Predominant Application

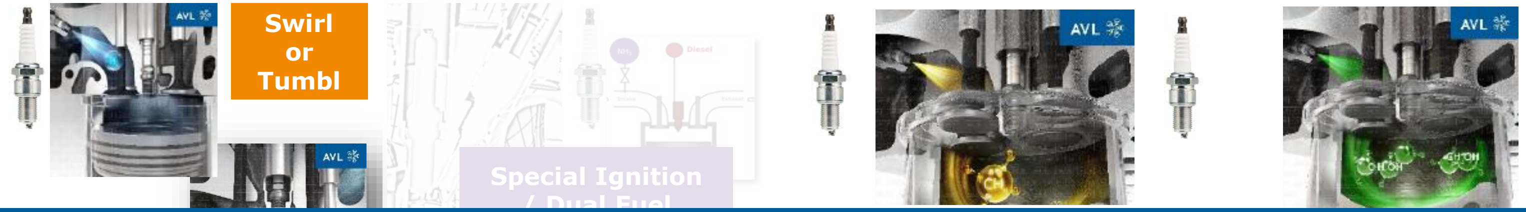
	Hydrogen H_2	Ammonia NH_3	Methane CH_4	Alcohols CH_3-(CH_2)-OH	Paraffins C_nH_{2n+2}
Opportunities	Lean burn capabilities Flame speed	Low reactivity…	High knock resistance Low tendency to pre-ignition Robust properties	Adequate knock resistance High latent heat Lean burn capability	Diesel carry over BTE potential
Challenges	Combustion irregularities Pre-ignition Mixture formation (LP-DI)	High demand for ignition energy Low laminar flame speed High ignition delay Problematic emission behavior (especially NH3)	CH_4 slip → no lean burn TWC requires stoich. approach EGR tolerance TMF lifetime Valve, seat wear,…	Liquid w/ low volatility Wall wetting (port/liner) Mixture formation Cold start potential Corroded or dissolved materials Sensitivity to pre-ignition	Peak cyl. pressure - HCF

Cooling

Ignition

Injection

best cooling on spark plug and fire deck



H_2 ICE will play a major role in India's way towards de-carbonisation

The Way of Industrialization for the H_2 ICE
Gen.1 Diesel to H_2 MPI conversion approach

Fuel system, ignition and controls

- Hydrogen injectors incl. H_2 specific engine control unit
- Fuel supply components (rails, pres. regulators, etc.)
- Hydrogen ignition system (cold spark plugs, hydrogen ignition coils)

Cylinder head & Combustion system

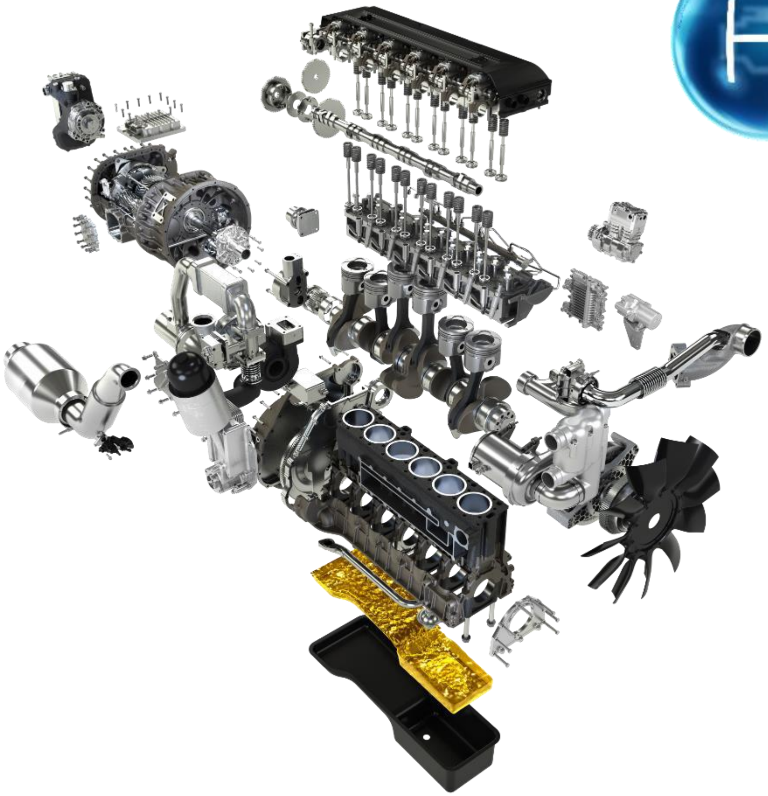
- Spark plug integration
- Valve and seats check/optimization
- Material proposals for valve and seat for gas operation
- Pistons (CR adaptation, plain surface geometry, etc.)

Intake manifold and charge air system

- Intake pipe design (runner length)
- Intake throttle arrangement
- MPI injector arrangement
- Turbocharger (for H_2 optimized air excess ratio)

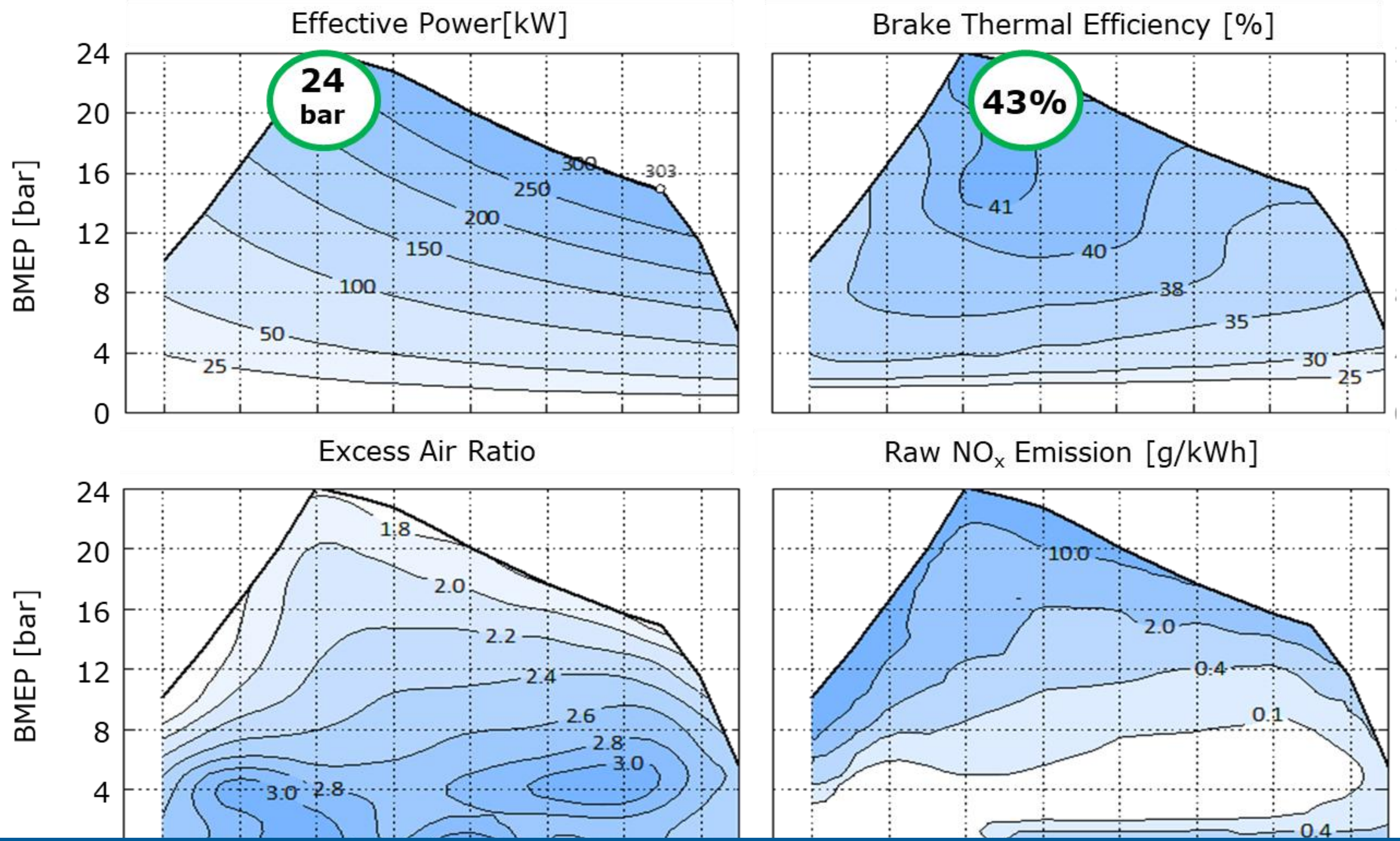
Active closed crankcase ventilation

Exhaust aftertreatment system adaptation: (D)OC, SCR*



* Diesel DOC and SCR can be carried over

The Way of Industrialization for the H_2 ICE
The AVL Hydrogen Engine: EAR, BTE, BMEP and raw NO_x



Key success factors

Maximum similarities to base engine with MPI injection

Firedeck & spark plug cooling

Outstanding performance targets with reasonable technology packages achieved on **AVL's Gen.1 Hydrogen Engine**

The Way of Industrialization for the H_2 ICE
The AVL Hydrogen Engine: Transient performance

Key success factors

Maximum similarities to base engine with MPI injection

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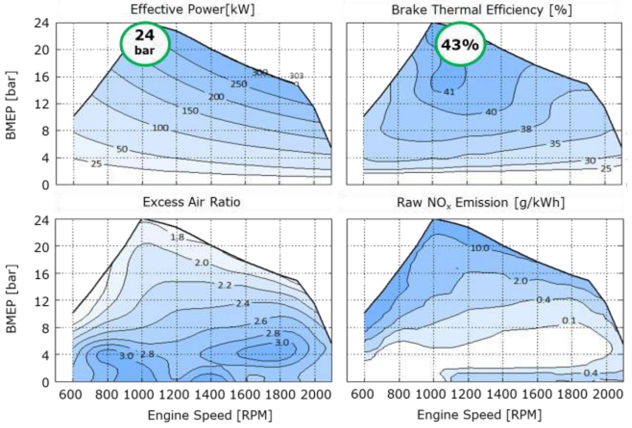
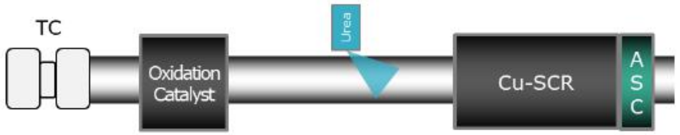
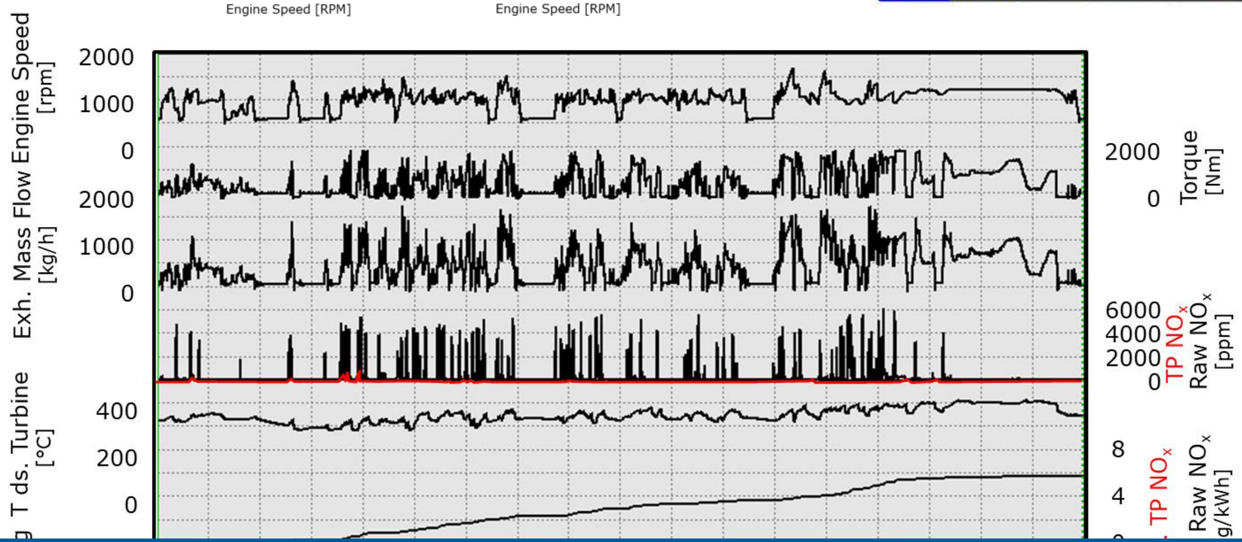


Bharat Stage VI EAS layout



Results EO

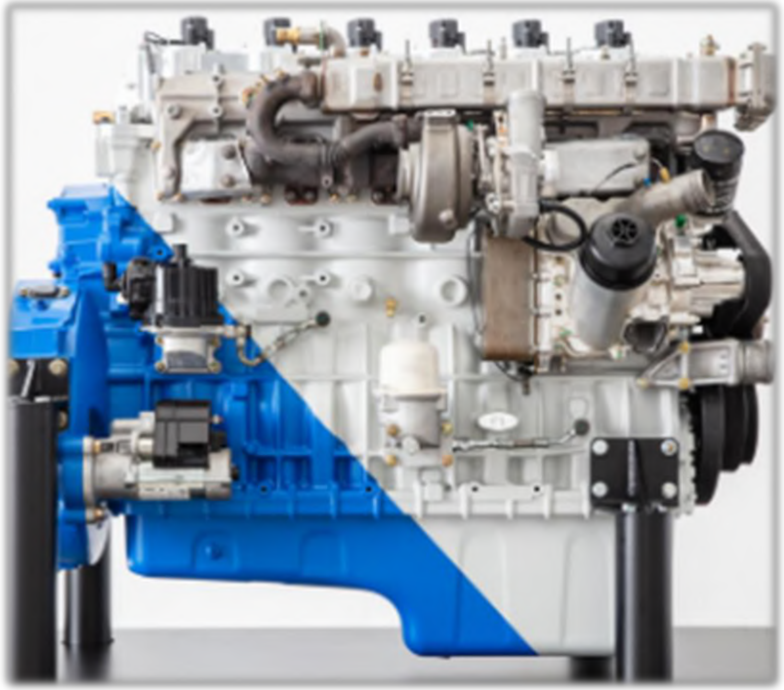
NOx	H2O	H2	CO2_Oil	THC	CO	BSFC	NOx Tailpipe
g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
5.84	802.90	1.23	0.23	0.005	0.01	83.33	0.06



Transient operation (similar to base engine) and **Bharat Stage VI** emissions demonstrated on **AVL's Gen.1 Hydrogen Engine**

The Way of Industrialization for the H_2 ICE
H_2 Activities at AVL India Tech Center (Gurgaon)

- **ITC is already conducting** Thermodynamic / Design Studies for **Diesel to H_2 ICE conversions** (MPI)
- Training for the skill transfer in progress between Graz & ITC
- **ITC Test Facility** upgrade ongoing
  - Key parts for test bed upgrade ordered
  - H_2 ICE facility to be **operational by October 2023**
- **Focus areas of service:**
  - Feasibility study
  - Demo engine / vehicle
  - Component development
  - Mechanical & functional development



Testing Infrastructure and skilled design, simulation, development and calibration engineers at **AVL's Indian Tech Center** ready to take the challange

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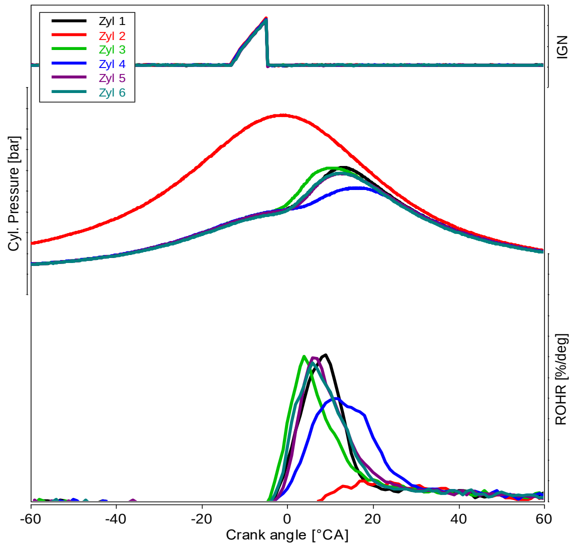
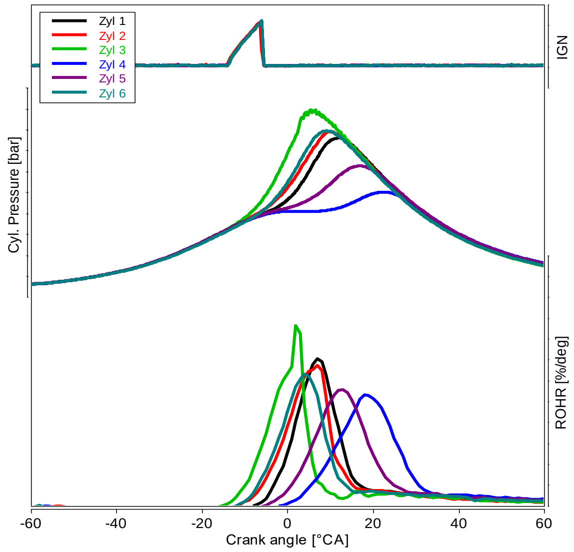
Combustion Irregularities in a H_2-ICE: Challenges and Solutions

Early Pre-Igniton



Dedicated hydrogen ignition system

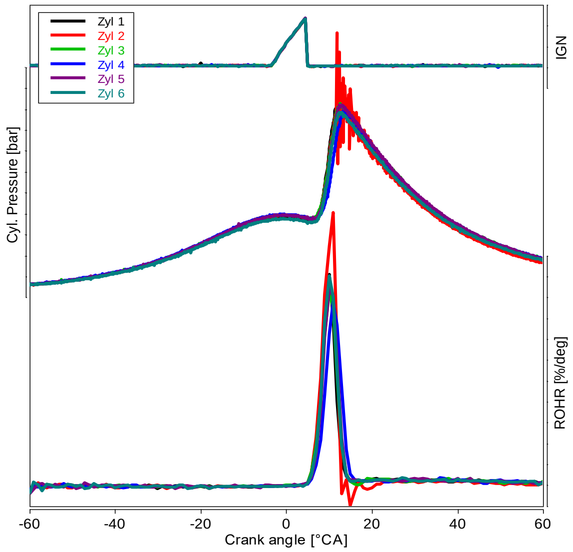
Late Pre-Ignition



Avoid hotspots

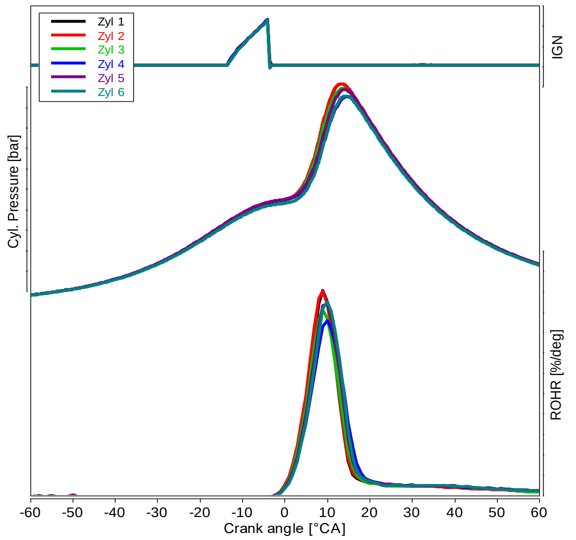
dedicated spark plugs

Knocking



Stoich. operation is very sensitive

Optimized Setting



For control of hydrogen combustion

Combustion Irregularities have to be addressed during **Engine Development AND Validation**

The Way of Industrialization for the H_2 ICE

Combustion Irregularities in a H_2-ICE: Challenges and Solutions

Design Integration & Combustion Development

H_2 Conversion & Design Integration

- Injector positioning & jet targeting
- Spark plug & coil selection
- Cylinderhead cooling, …

Fuel Homogenization

Operation Strategy

Etc., …

Simulation tasks
(In-cylinder CFD, Water Jacket CFD, Piston cooling, etc. …)

H_2 ICE DVP

Thermal survey (Cylinder head, valves, liners, piston, spark plugs)

Oil carry over measurement

Lube Oil consumption screening

P&E w/ aged components (e.g.: oil ash deposit)

Verification & Validation

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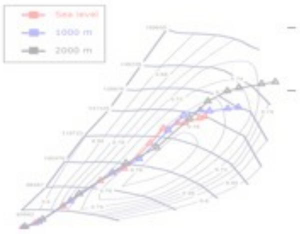
Combustion Irregularities in a H_2-ICE: Workflow



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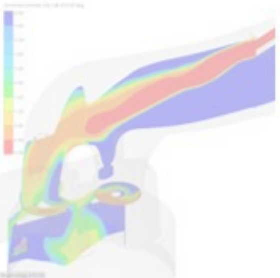

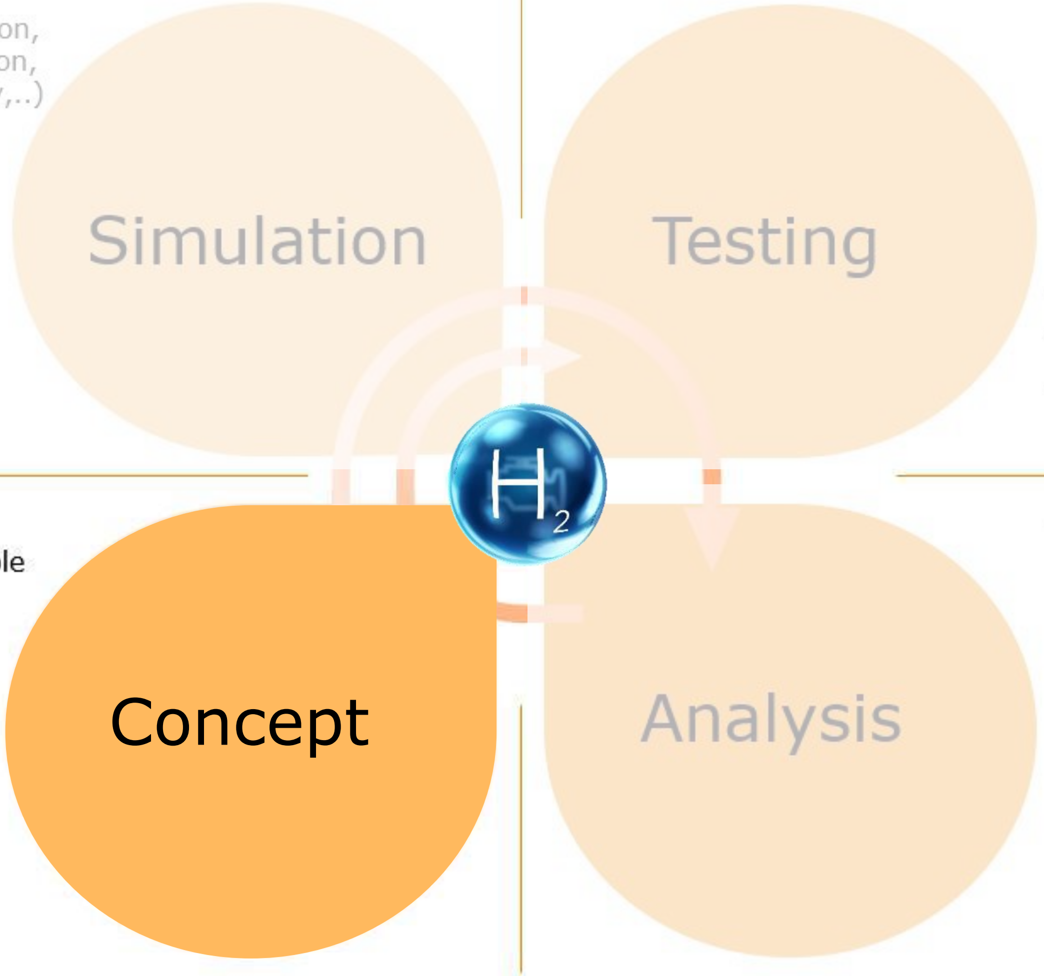

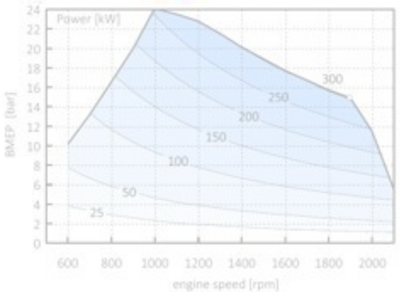

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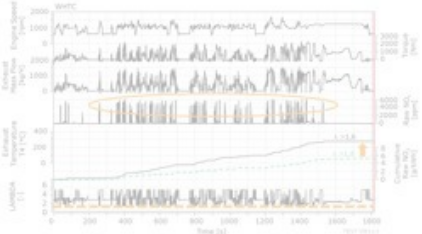
- Load response and transient cycles
- Operation borders (e.g. Pre-ignitions)



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- Charge motion: swirl / tumble
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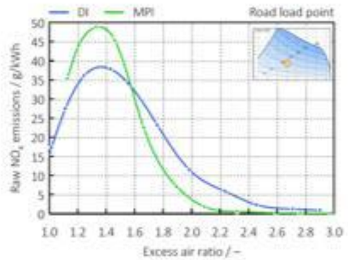
- Design constraints



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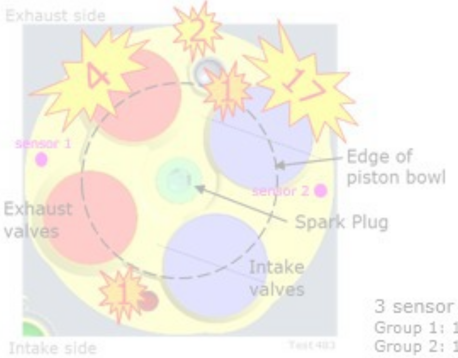

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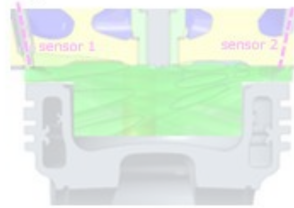

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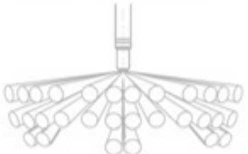

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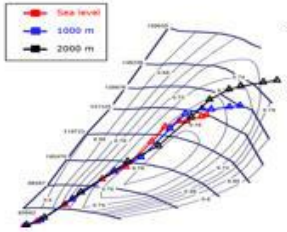

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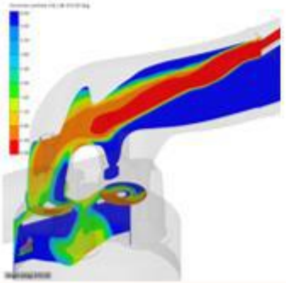
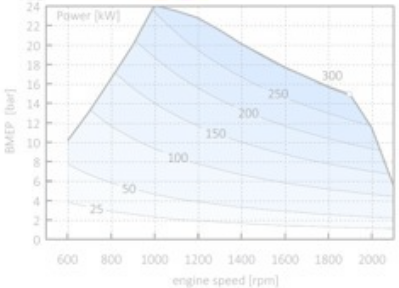


AVL FIRE®

Simulation

Testing



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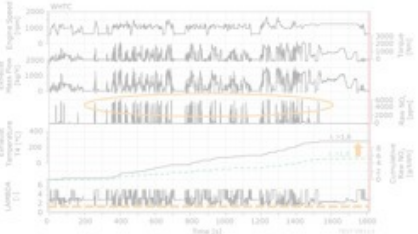

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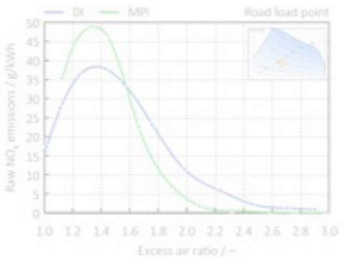

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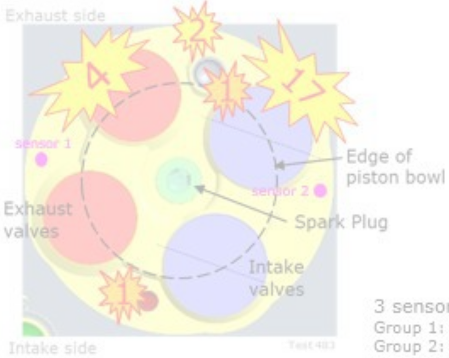

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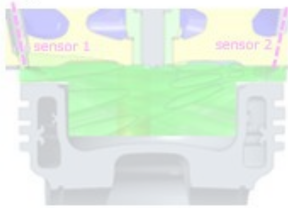

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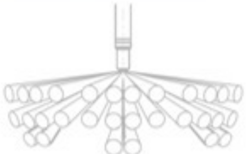
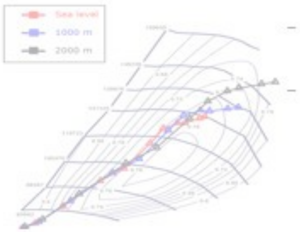


The Way of Industrialization for the H_2 ICE

Combustion Irregularities in a H_2-ICE: Workflow



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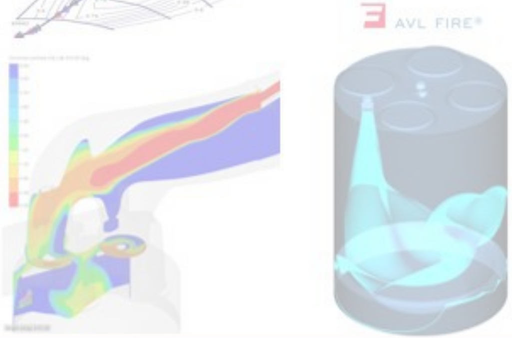

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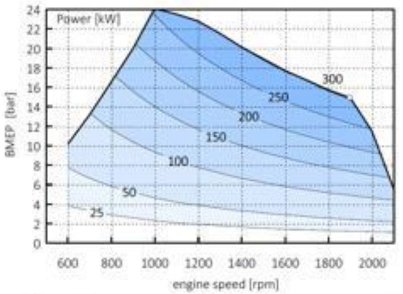

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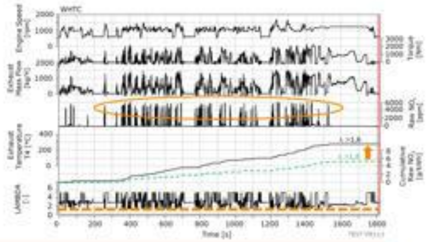

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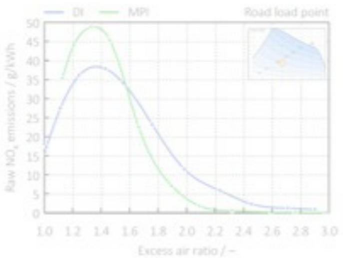

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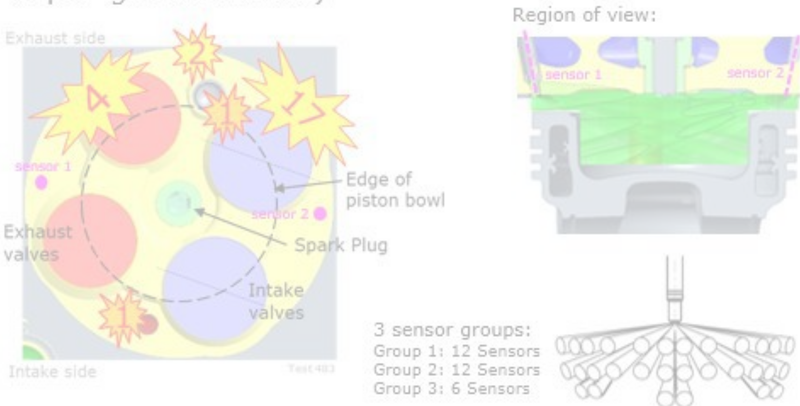

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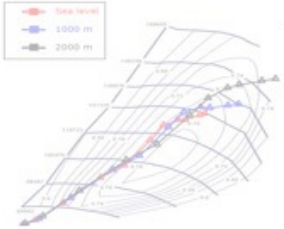

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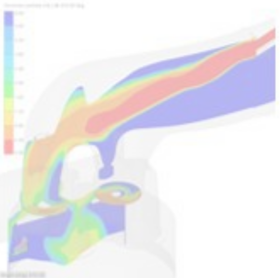

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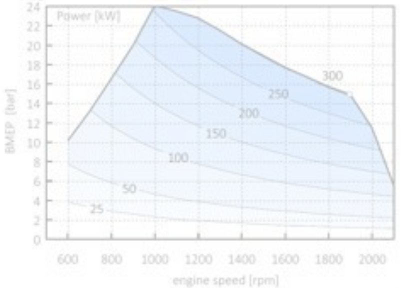

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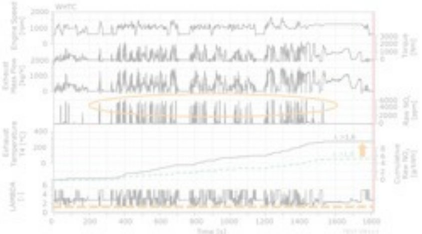

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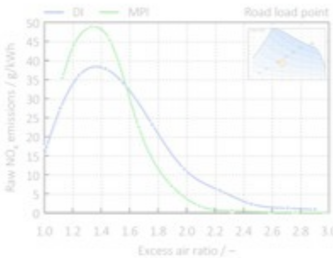

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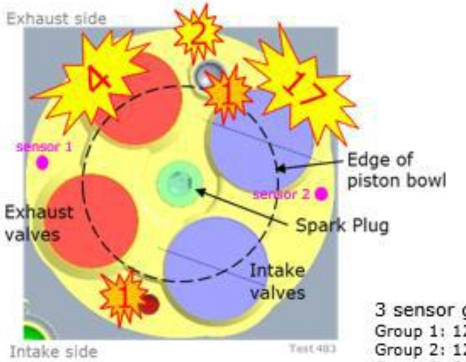

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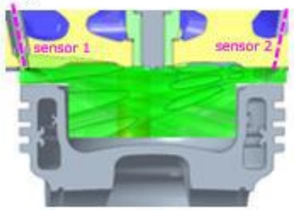

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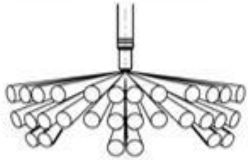

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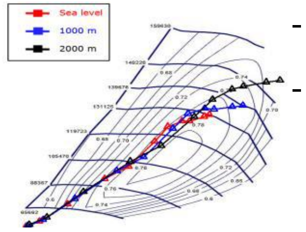

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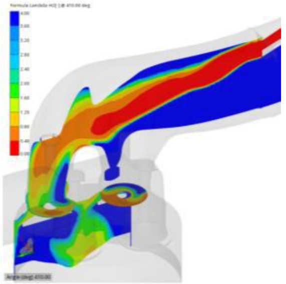

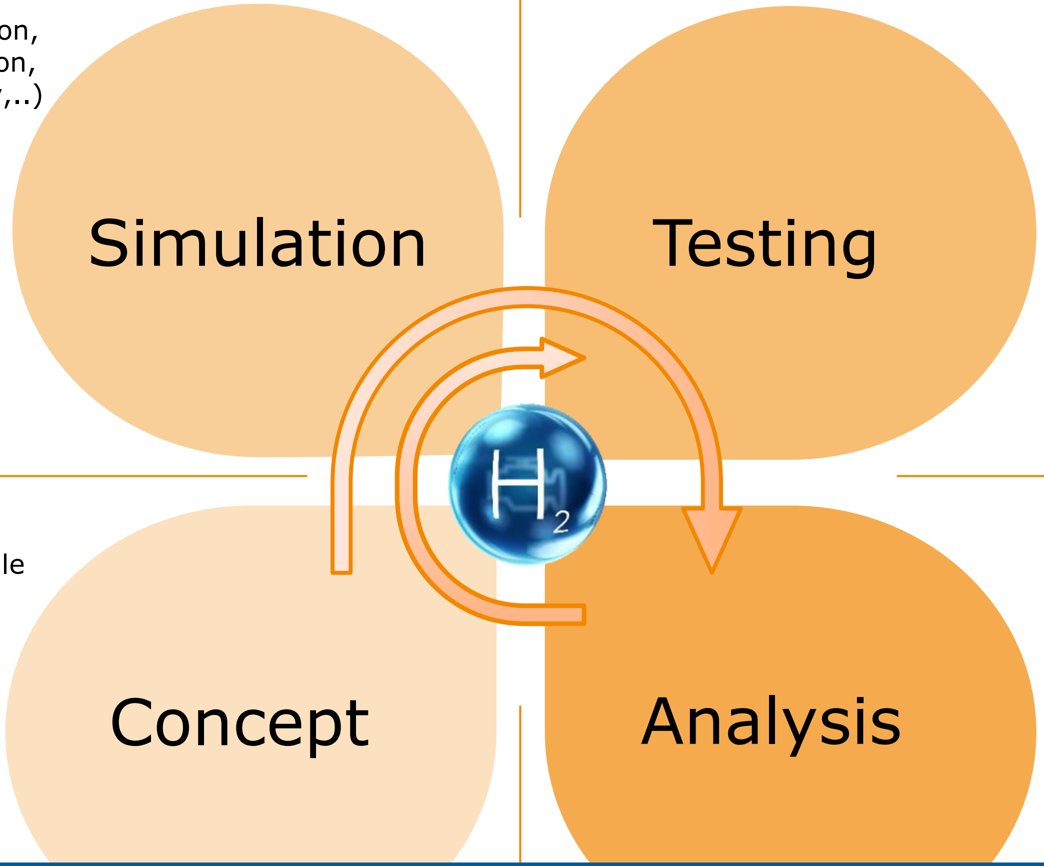

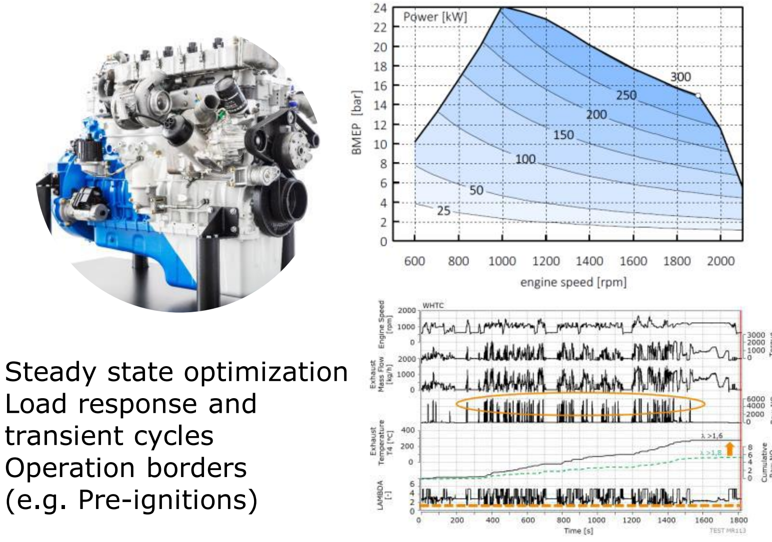

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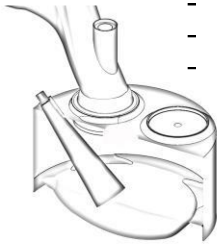

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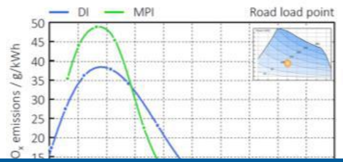

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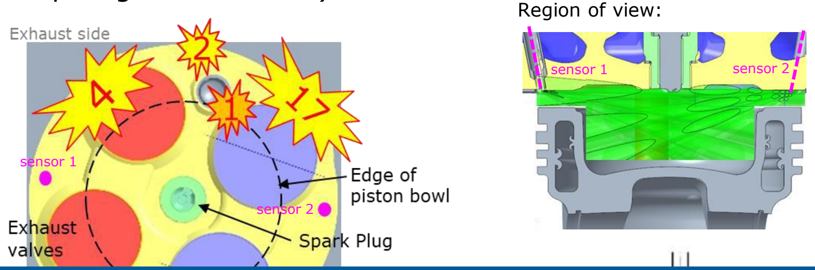

Established **tool chains** during the whole development process as **key success factor** for challenging timeline

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Verification & Validation

The Way of Industrialization for the H_2 ICE
Mechanical Development Focus of H_2-ICE

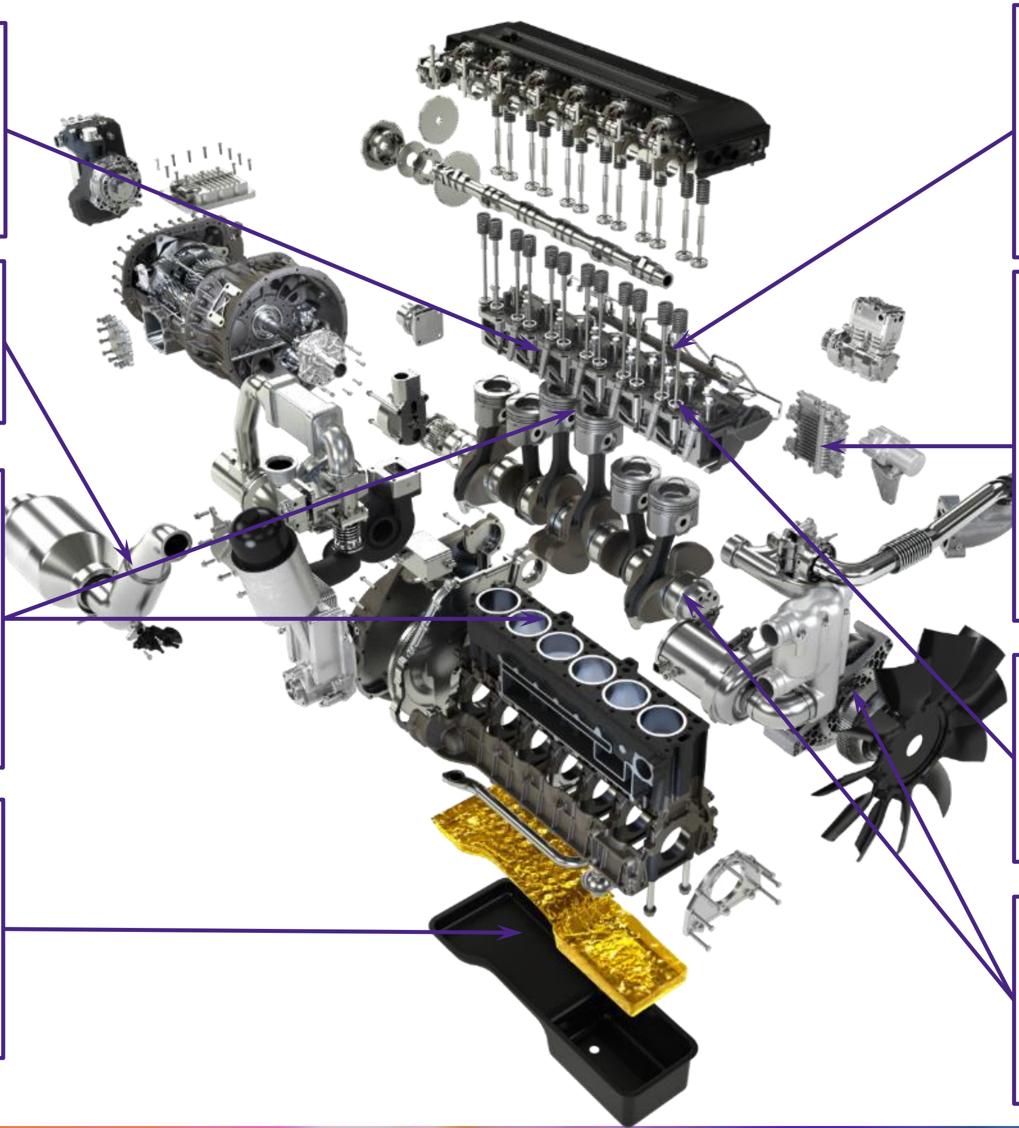
Injectors / Spark Plugs
- Pre-Ignition due to hot Spots
- Wear due to Temperature & Pressure Conditions

Exhaust System & EAS
- Water Content in Exhaust Gas
- Corrosion Topics

Piston Bore Interface
- Oil into Combustion Chamber
- Blowby Flow to Crank Case
- Oil Coking
- Friction & Wear Behavior
- Corrosion topics

Lubrication Oil
- Management of Water Content
- Oil Aging (Water & H_2)
- Specific Oil Formulations (No Soot Content Constraints, etc.)

Note: H_2 Embrittlement not critical



Cylinder Head
- Pre-Ignition due to hot Spots
- Improper function of valve stem seals (Pressure level due to Intake Throttle)

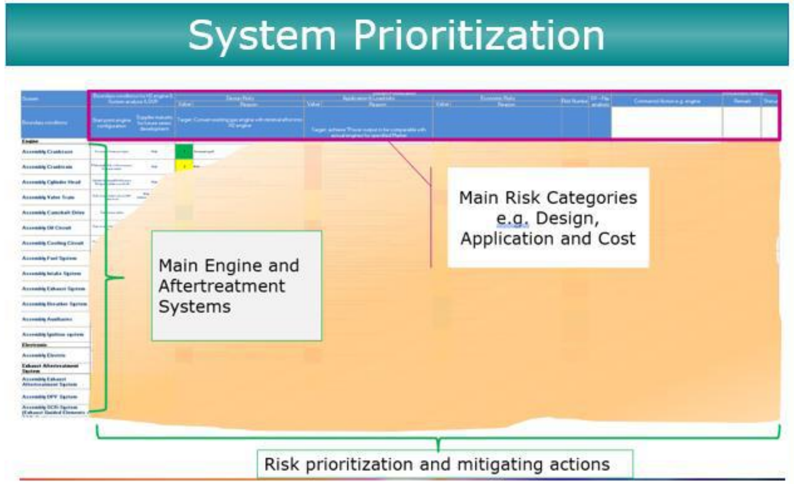
Crankcase Ventilation System & Oil Separation
- Combustion Irregularities by Oil Carry Over
- Oil Aging (Water & O_2)
- Corrosion Topics
- Condensation & Freezing

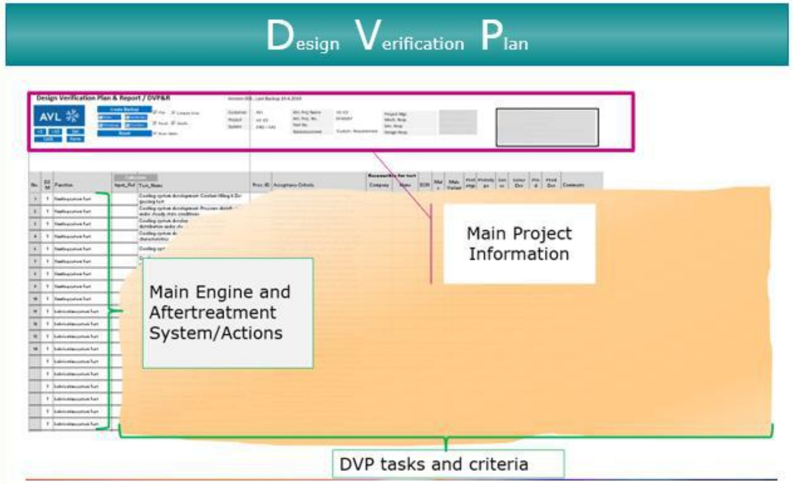
Valves & Valve Seats
- Increased Wear due to lack of lubrication property of fuel
- Pre-Ignition due to hot Spots

Crank Train Components
- Stresses due to Irregular Combustion
- Crank Train
- Torsional Vibration

The Way of Industrialization for the H_2 ICE

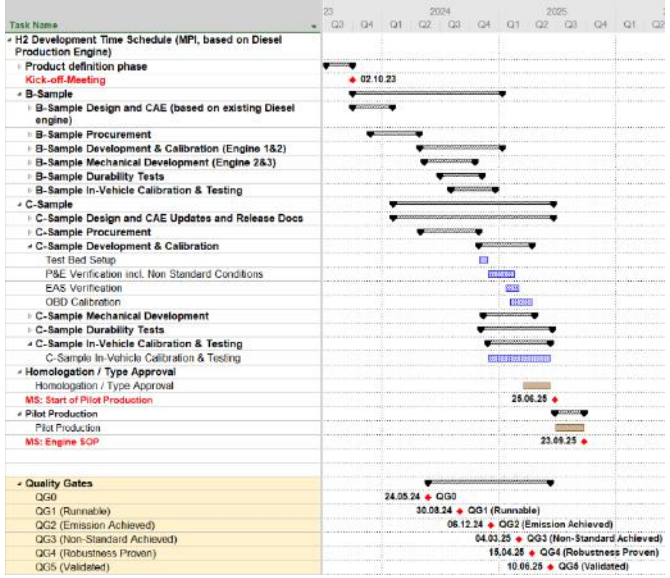
Verification & Validation of H_2-ICE





Component / System / Location	Potential Failure / Issue	Simulation Tasks	Verification & Validation (Hardware Testing) Tasks
Combustion chamber (cylinder head, valves, spark plug, liner & piston)	Pre-ignition due to hot spots in combustion chamber	• 3D cylinder CFD simulation • Water jacket CFD simulation • Piston cooling CFD simulation • Head block compound simulation (FEA) • Piston FEA • Spark plug FEA (by supplier)	• Thermal survey (cylinder head, valves, liner, piston & spark plug) • Optical combustion investigation (Visiolution) • P&E Development
Combustion chamber/ PBI	Pre-ignition due to entrance of oil droplets into combustion chamber (PBI, valve stem seals and crankcase ventilation system)	• Ring dynamic simulation (EXITE piston & rings)	• Measurement of oil metering rate of stem seals (supplier) • Lube oil consumption/ lube oil emission measurement • Oil carry over measurement • Optical combustion investigation (Visiolution)
Combustion chamber	Pre-ignition due to carbon and/or		• P&E investigation with aged

Tailored V&V plan from Gen1 to SOP



Dedicated and tailored **Verification and Validation plan** to address H_2 specific failure modes

The Way of Industrialization for the H_2 ICE
Verification & Validation Example #1: CCV & Oil Separation

Engineering Challenges:

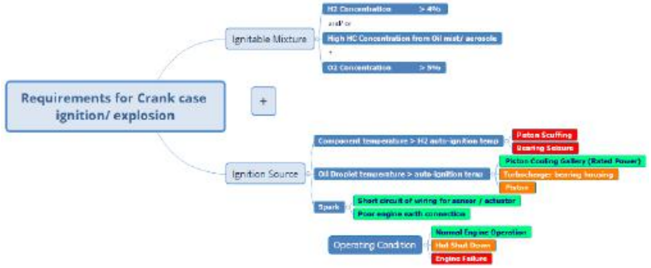
- Safety: Avoiding risk of ignition/explosion or controlling risk of Engine damage by explosion
- Minimize Oil carryover to Intake system

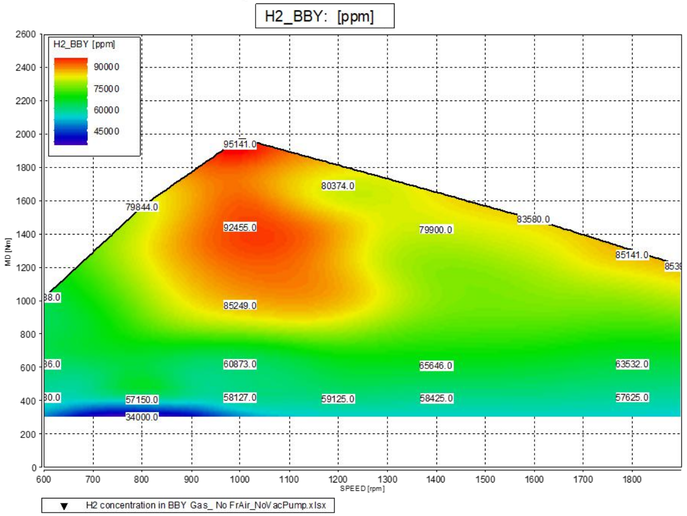
Main reasons for high H_2 concentrations in crankcase:

- Impact of the rapid pressure rise (caused by the high flame speed and resulting fast burn rate) on blowby flow rate
- Extremely low density of hydrogen gas causing high blow down volumes
- Compression of pre-mixed H_2 charge causes high H_2 concentrations in the blowby gas.

AVL V&V approach Gen1 → SoP:

- Assessment of Crank Case Ignition Risk
- Measurement of oil carry over
- Recommendation of Crankcase ventilation system
- Optimization of H_2 content in crankcase
- Reduction of Pre-Ignition / Combustion anomalies





The Way of Industrialization for the H_2 ICE
Verification & Validation Example #2: PBI

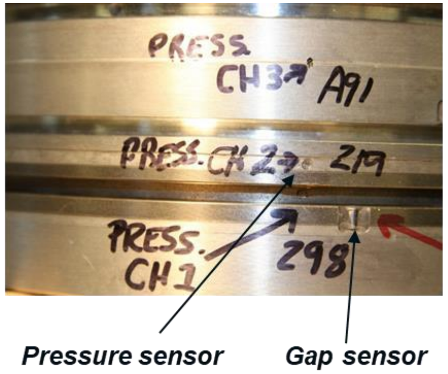
Engineering Challenges:

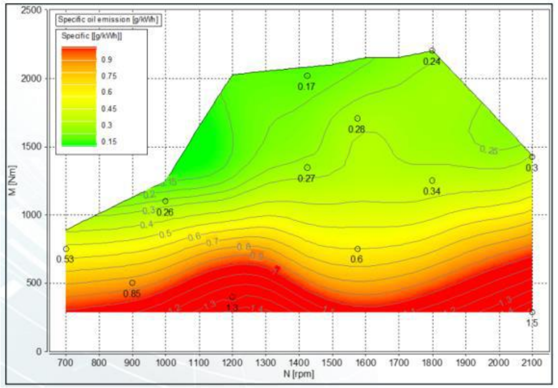
- Optimization of piston bore interface is a key topic for Hydrogen engines
    1. To reduce the oil carry over into the combustion chamber (risk of unintended ignition events)
    2. Optimize Blowby
    3. Oil consumption

- Oil coking is also an important aspect that needs attention
- Corrosion topics due to high water content
- Core component temperature optimization

AVL V&V approach Gen1 → SoP:

→ Lube oil consumption/ emission measurements
→ Blowby measurement and development
→ Core component temperature measurement (Eg: Piston telemetry, Liner temperature etc)



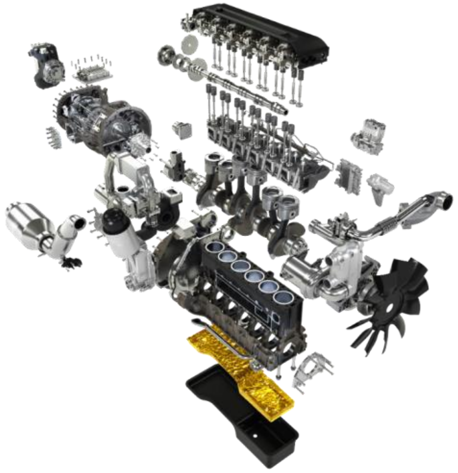


The Way of Industrialization for the H_2 ICE
Main Components, Supplier Overview and technology Readiness

Today

SoP Date expected

Q1/2025



Fuel Lines, EAS, Turbocharger *

Breather system *

MPI Injectors

BOSCH BorgWarner HOERBIGER LIEBHERR Nikki

Pressure control

BOSCH BorgWarner VENTREX

Dedicated H_2 Ignition coils

BOSCH TENNECO BorgWarner

EMS incl. H_2 specific SW

BOSCH BorgWarner AVL Westport Fuel Systems

DI Injectors

BOSCH LIEBHERR BorgWarner Westport Fuel Systems HOERBIGER DENSO

Dedicated H_2 Spark plugs

BOSCH NGK TENNECO

* Can be carried over from current available technologies with adaptations

Technology Readiness Level (TRL)

1 — 2 — 3 — 4 — 5 — 6 — 7 — 8 — 9

Technology readiness **(TRL) with MPI** given for **Indian market** introduction dates

The Way of Industrialization for the H_2 ICE
AVL H_2-engine control SW development

Diesel Control SW

- Idle Speed Control
- Start Torque Calculation
- Engine Torque Protection
- Friction Torque Calculation
- Driver Torque Demand Eval.
- Torque Coordinator
- Torque/Fuel Converter
- Fuel Pressure Control
- EGR Valve Control
- Intake Throttle Control
- Torque coordination
- Turbo Charger Control
- Non Standard Corrections
- Injection Control

SI and **H_2** spec. Control Functions

AVL H_2 Control SW Library

H_2 Control SW Transformation

Customer tailored **H_2** Control SW

Diesel Control SW (Maximum carry over of current Diesel controls) → Fuel quantity-based torque control

- Lambda Based Torque Limit
- Transient Detection
- Cylinder Pressure Model
- Ignition Control
- Transient Correction
- Irregular Combustion Control
- Closed Loop Lambda Control

- Diesel S/W control structure for lowest calibration efforts and data maintenance.
- Easy and flexible SW adaptation
- Small coordination effort due to complete H2-engine control inhouse development
- Independence: Have the flexibility in cooperation with external suppliers for further software modules.
- Fast and flexible interface adaptation within SW-Release generation

Fast deriving of **H_2 specific ECU** by re-using of **proven AVL software modules** from SI or CI platforms

The Way of Industrialization for the H_2 ICE

Bharat Stage VI OBD requirements for H_2-ICE

BS-VI OBD-II Threshold Limits	NO_x (m/kWh)	PM (mg/kWh)	CO (mg/kWh)
Compression ignition engines	1.200	25	---
Positive ignition engines	1.200	---	7.500

The Way of Industrialization for the H_2 ICE
Setup of OBD-system for Bharat Stage VI H_2-ICE

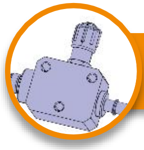
- **Air / Boost** CI
- **EGR system** CI
- **SCR catalyst** CI
- **(Diesel) Particulate Filter** CI
- **(Diesel) Oxidation Catalyst** CI
- **Lean NO_x trap** CI

- CI H_2 **Electrical Elements** SI

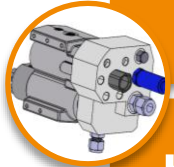
- SI **Idle speed control**
- SI **Thermostat**
- SI **Misfire Monitoring**
- SI **Variable Valve Train**
- SI **Three Way Catalyst**
- H_2 **Crankcase ventilation system**

Dedicated functionalities to **ensure CCV and H_2 fuel system safety**

The Way of Industrialization for the H_2 ICE
H_2 storage system: Schematics & Main Components



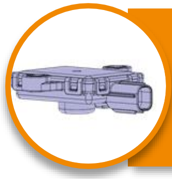
Service De-Fuel Shutoff



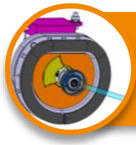
Low pressure regulator
(incl. pressure relive valve)

MPI: 7 – 15 bar
LP-DI: 15 – 30 bar

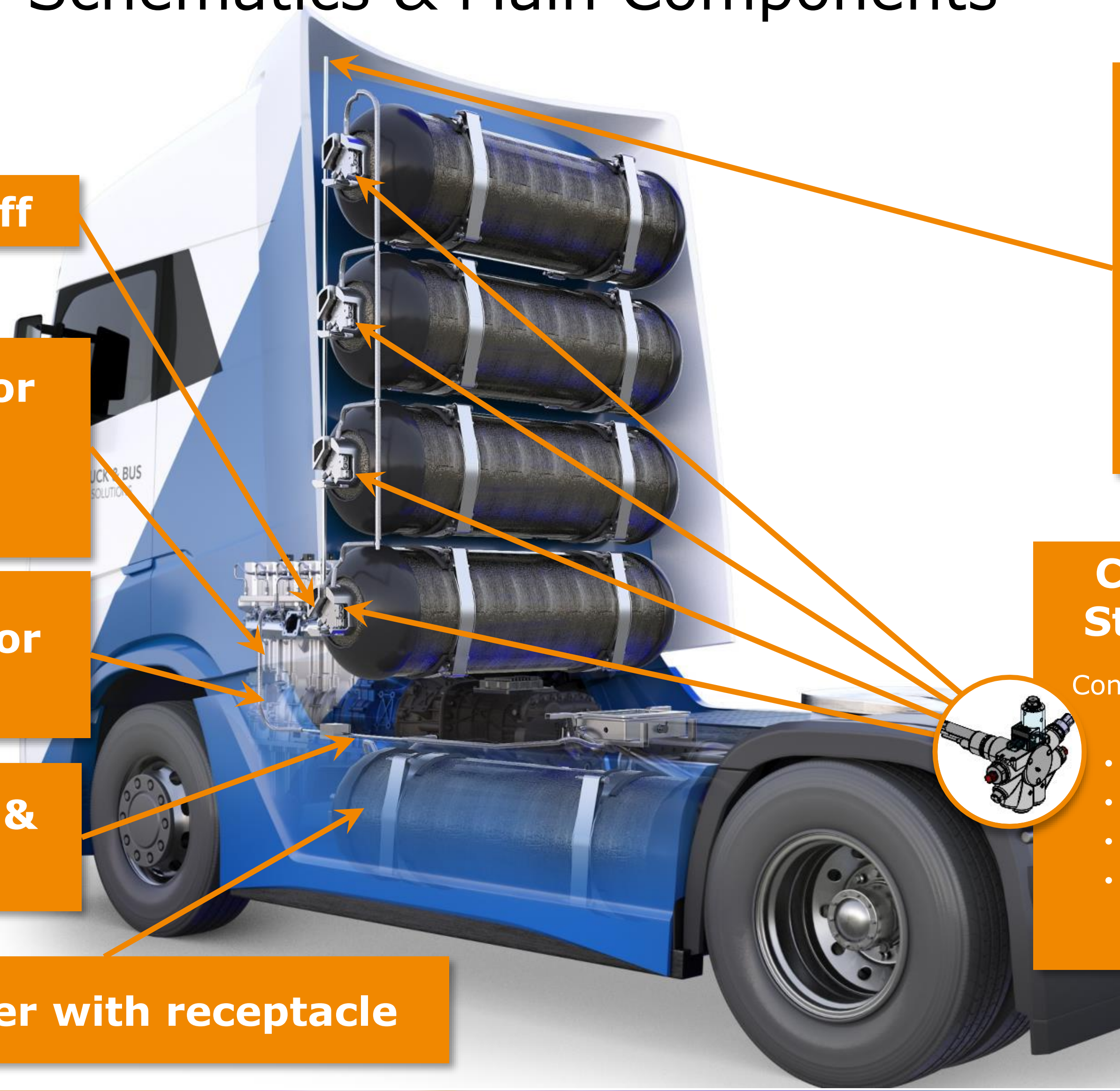
High pressure regulator
(incl. pressure relive valve)



Excess flow limitation & Full system isolation



Tank filler with receptacle



System ventilation

- Thermal pressure relief of containment vessels
- Pressure relive after pressure reducer
- Pressure relive after low pressure regulator
- Service De-Fuel Shutoff

Compressed Hydrogen Storage System (CHSS)

Containment vessels* with integrated On-Tank Valve (OTV), including:

- Thermal pressure relief device
- Check valve
- Excess flow valve
- Manual valve

* 700 bar / **350 bar**

The Way of Industrialization for the H_2 ICE
Agenda

1 **Generation 1 H_2-ICE**

- ❖ Corresponding technology building blocks MPI / DI
- ❖ Achievements of generation 1 H2-ICE

2 **Way to SOP**

- ❖ Challenges and solutions
- ❖ AVL tool chain: From concept to production
- ❖ Technology readiness of main components
- ❖ Dedicated H_2-Software
  - ❖ OBD for H_2-ICE
- ❖ H_2-fuel system H_2 vehicle

3 **Summary**

Conclusions and Outlook

The Way of Industrialization for the H_2 ICE

- **H_2 ICE** will play a major role in India's way towards **de-carbonisation**
- First **H_2 Commercial Vehicle** will enter series production in **India in 2025**
- Generation 1 targets demonstrated, **H_2-ICE industrialisation follows** as next step
- Established **tool chains** during the whole development process **key success factor** for challenging timeline
- Dedicated and tailored **Verification and Validation plan** to address H_2 specific failure modes
- **Technology readiness with MPI** given for Indian market introduction dates
- Fast deriving of **H_2 specific ECU** by re-using of **proven AVL software modules** from SI or CI platforms
- Dedicated functionalities to **ensure CCV and H_2 fuel system safety**

AVL is your one stop shop for industrialization of the H_2-ICE

LOOKING FORWARD TO YOUR QUESTIONS

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