Ashraf Emran
FEV

Hydrogen Combustion Engine
Alternative for zero emission transportation

ECT-2024 Conference

ECT-2024
15th International Conference

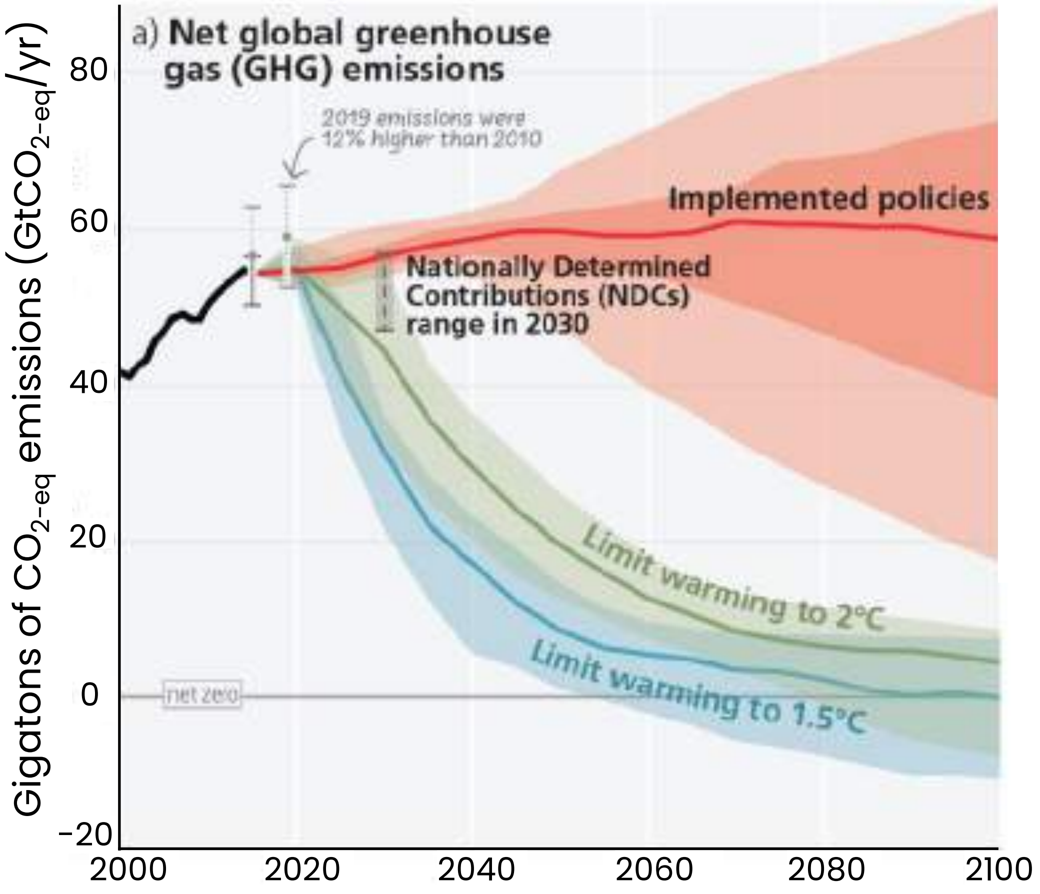
AGENDA

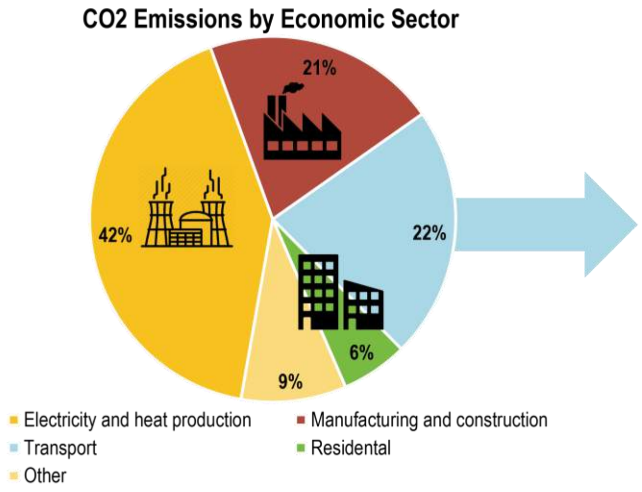
- Global Context
- Overview of H_2 engine concepts
- Key parameters of H_2-ICE
- Engine control strategies

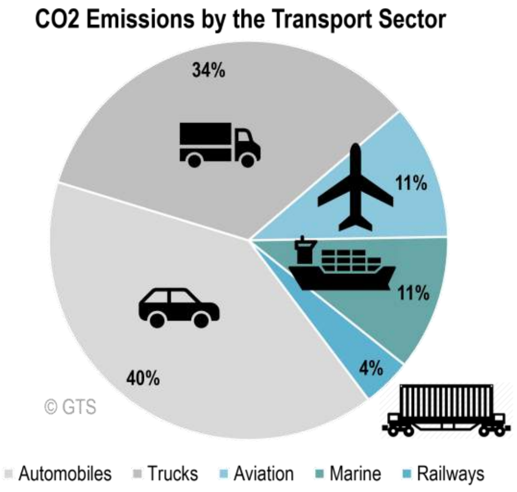
GLOBAL CONTEXT

According to the IPCC reports, limiting warming to 1.5°C and 2°C involves rapid and immediate greenhouse gas emission reductions

WITH IMPLEMENTED POLICIES, PROJECTED EMISSIONS LEAD TO WARMING OF **3.2°C**, RANGING FROM +2.2 TO +3.5°C







Source : Synthesis report of the IPCC sixth assessment report

When compared with other zero emission powertrains, H2-ICE offers many advantages we can make use of in short term

Hydrogen based vs BEV powertrain

+

- High energy storage density
- Fast refueling

−

- Fuel cost (current)
- Maintenance effort

H2-ICE based vs FC/BEV powertrain

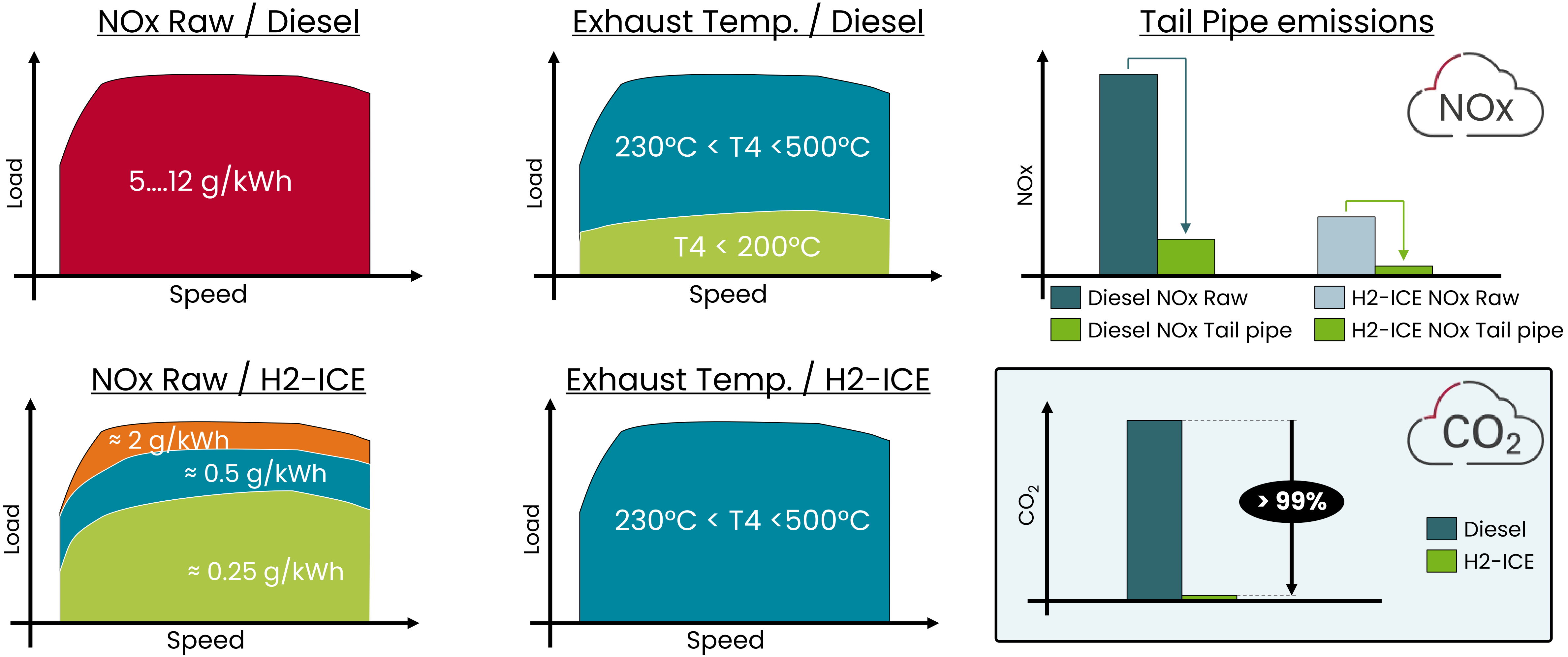
+

- Lower development and production effort, hence quicker introduction to the market
- Proven powertrain durability and less sensitive to environmental impacts
- Less stringent requirement to hydrogen purity
- Beneficial efficiency in high load operations

−

- Engine out NO_x emissions require EATS
- Powertrain noise level (still lower than diesel)

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



*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

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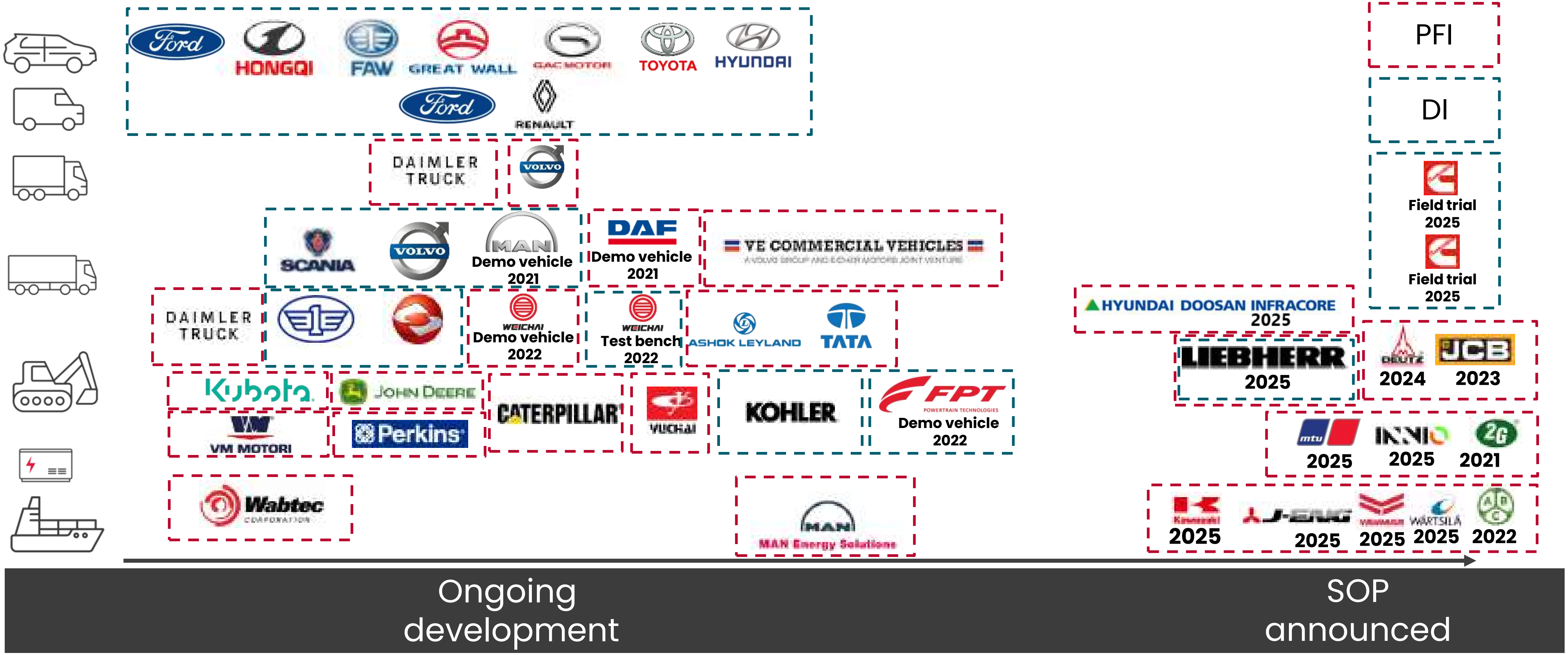
NON-EXHAUSTIVE



Source : FEV

OVERVIEW OF H_2 ENGINE CONCEPTS

Hydrogen has unique characteristics impacting the design of the combustion chamber layout as well as the engine control

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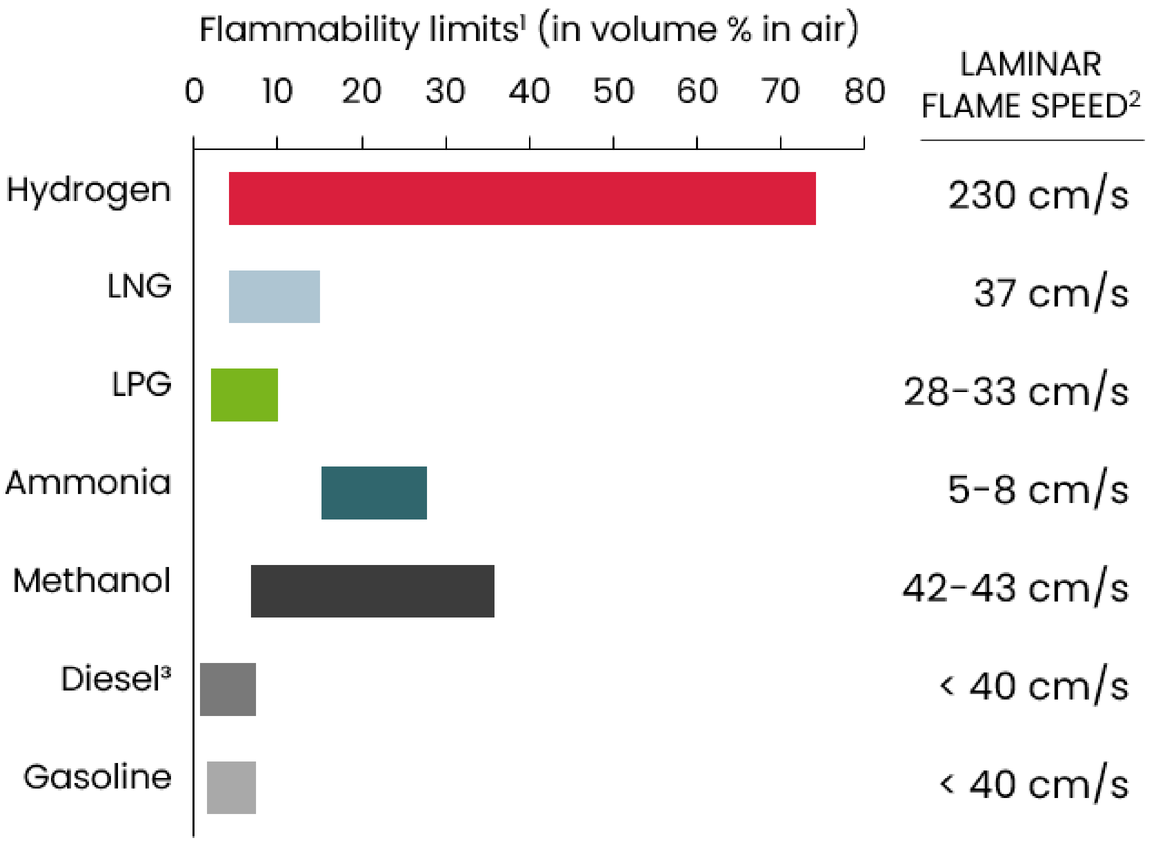
FUEL PROPERTIES

Property	Unit	Gasoline	Diesel	Methane	Hydrogen
Density @ 15°C	kg/m³	≈ 760 (l)	≈ 835 (l)	0.68 (g)	0.09 (g)
Stochiometric air demand	kgA/kgF	14.0	14.5	17.2	34.3
Lower heating value	MJ/kg	42.5	42.8	50.0	120.0
Gravimetric energy content	kWh/kg	11.1	11.7	13.9	33
Volumetric energy content	kWh/L	9.25 *liquid, 20°C, 1013mbar*	9.74 *liquid, 20°C, 1013mbar*	2.25 *gaseous, 20°C, 200bar*	0.85 *gaseous, 20°C, 350bar* 1.42 *gaseous, 20°C, 700bar* 2.34 *liquid, -253°C, 1013mbar*
Auto ignition temp.	°C	230-450	> 225	595	585
Minimum ignition energy	mJ	0.24	0.24	0.29	0.02
Flammability limits	λ	0.4-1.4	0.5-1.4	0.6-2.1	**0.13-10**
Laminar flame speed	cm/s	< 40	< 40	≈ 42	≈ 230

FLAMMABILITY



1) Flammability limits at atmospheric pressure and 25°C ; 2) At stochiometric conditions, 300 K and 1 bar; 3) No laminar combustion - Source: DNV GL; FEV

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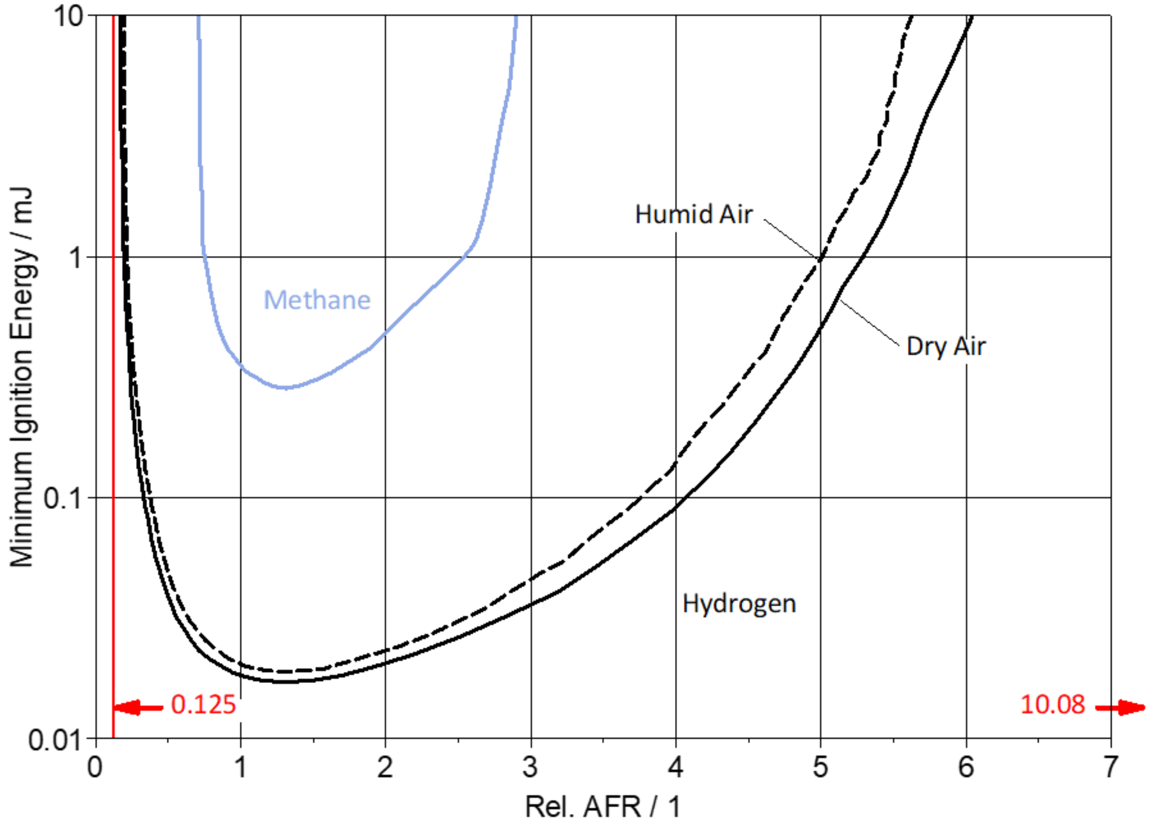
MINIMUM IGNITION ENERGY



Several different combustion system options exist for H_2-ICEs; suitability varies by application and depends also on availability of enabling technologies

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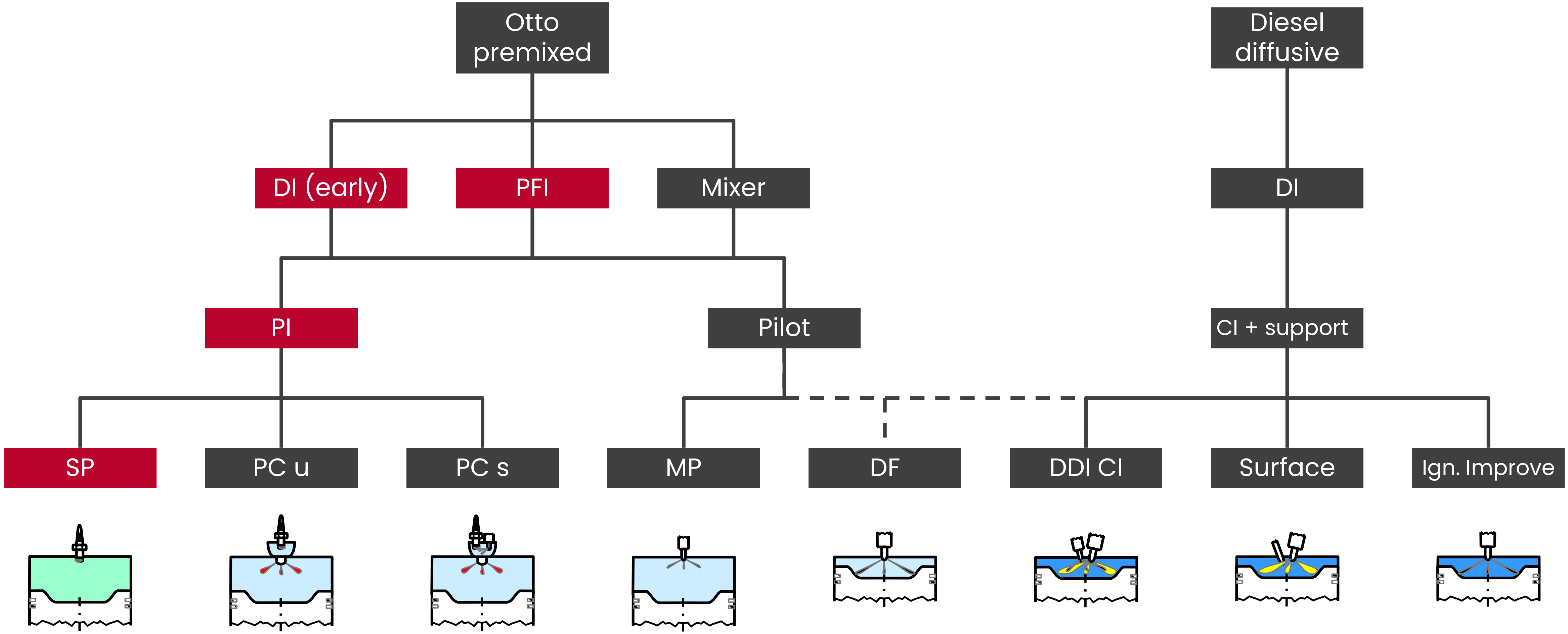
ASSESSMENT OF POTENTIAL COMBUSTION SYSTEMS – OVERVIEW

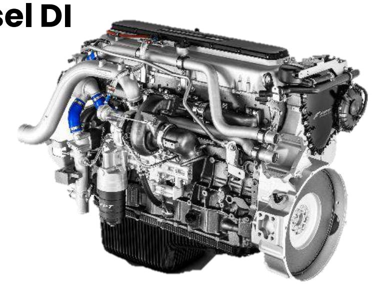


DI: Direct Injection; PFI: Port Fuel Injection; CI: Compression Ignition; PI: Positive Ignition; DDI CI: Dual Direct Injection Compression Ignition; Ign.: Ignition; DF: Dual Fuel; MP: Micro Pilot; SP: Spark Plug; PC u: Pre Chamber unscavenged; PC s: Pre Chamber scavenged
Source: TME, FEV

There are multiple mandatory hardware/software changes from a base diesel or NG engine to a hydrogen-fueled engine

CHANGED PARTS BETWEEN DIFFERENT FUEL SYSTEMS FOR HD CV - OVERVIEW

Current diesel DI



Changed parts: Diesel → H_2

- Piston, compression ratio, valves, seat rings
- Cylinder head (ignition system, DI injectors)
- H_2 Fuel supply (pipping, pressure regulator)
- **Turbocharger**
- **Exhaust aftertreatment catalyst (DOC, SCR)**
- Control system

Estimated efficiency delta: ≈ -1 %

Future PFI/DI H_2

Current PFI NG

Changed parts: Natural gas → H_2

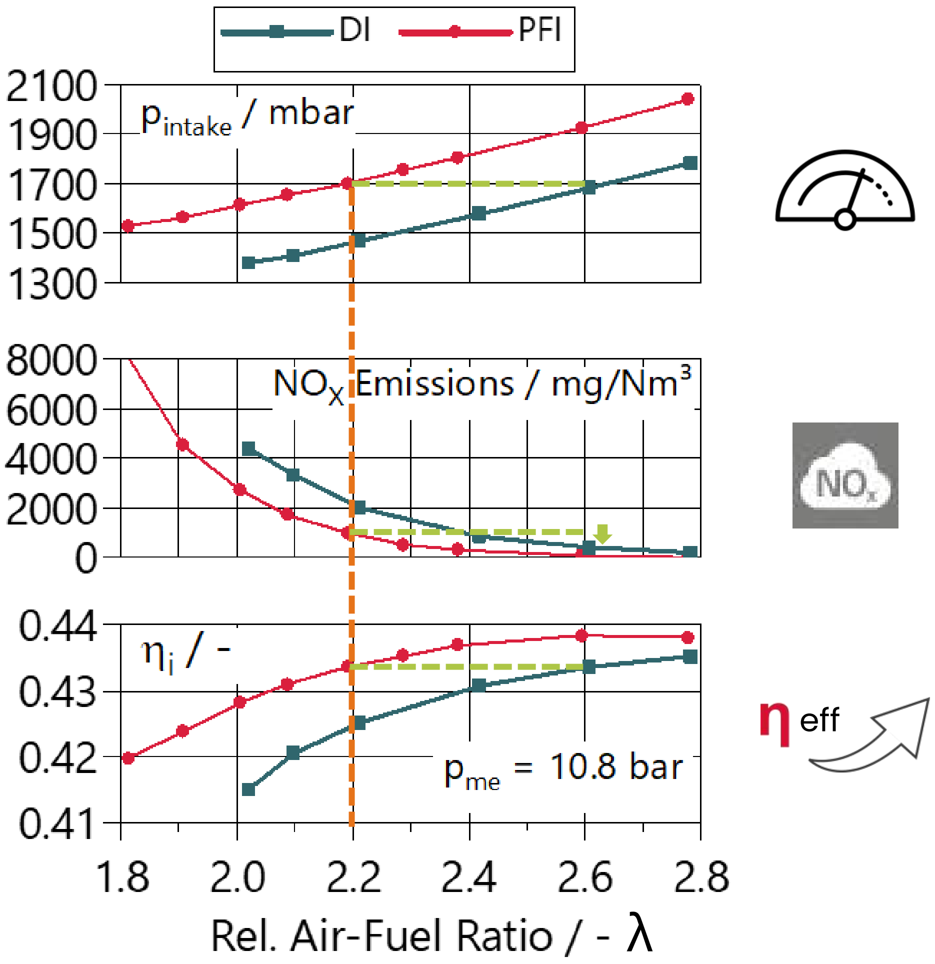
- **Piston, compression ratio**
- **Cylinder head (DI injectors)**
- H_2 Fuel supply (pipping, pressure regulator)
- Turbocharger
- Exhaust aftertreatment catalyst (DOC, SCR)
- Control system

Estimated efficiency delta: ≈ +3 %

Source: FEV

DI technology offers benefit in NOx emissions at constant boost pressure at same efficiency as PFI in addition to improved transient performance

HYDROGEN DI APPLICATION REACHING EFFECTIVE EFFICIENCIES OF 44 %

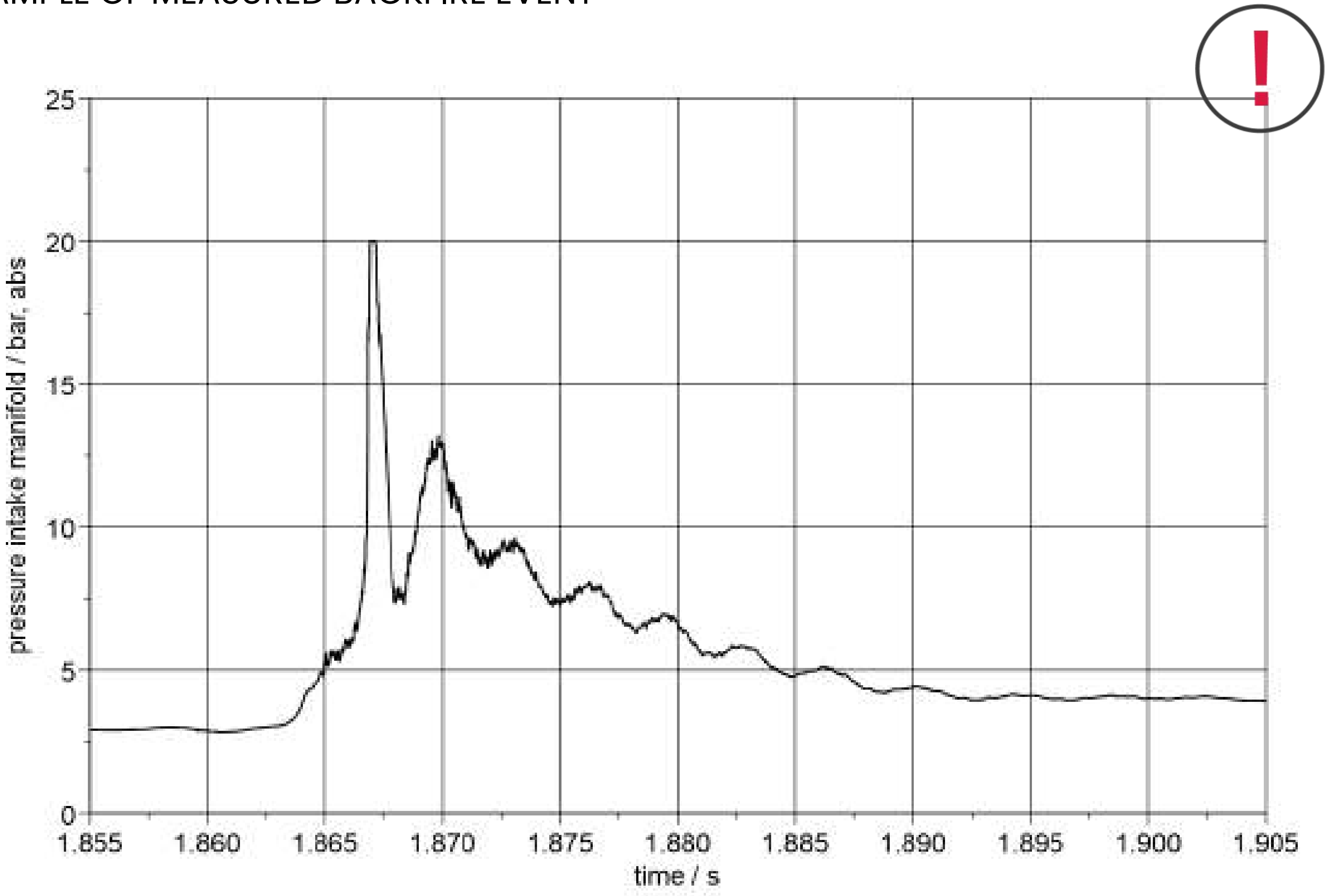


- For comparison on constant BMEP level and constant lambda, DI technology has drawback on engine NOX emissions and engine efficiency
- For real engine operation comparison on same boost pressure level more realistic, here DI offers benefit in NOx at same engine efficiency level
- Further improvement in mixture homogeneity will even raise DI benefits

CoC: Center of Combustion

Damaging backfire event can be explained thanks to gas exchange analysis. Avoiding their occurrence, with PFI optimization suppresses the risk

EXAMPLE OF MEASURED BACKFIRE EVENT



DESCRIPTION

- Intake manifold
  - filled with homogenous mixture
  - AFR 2.3
  - 8…10L volume
  - Single point injection
- Intake manifold pressure sensor limited to 20 bar, real pressure mostly higher
- Very short intake pressure peak of ~2 ms

Source : FEV

Different injection pressure levels allow different combustion process layouts with specific pros and cons

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H_2 INJECTION SYSTEMS FOR MD (5L CLASS) OFF ROAD – CONSTANT AIR FUEL RATIO

External mixture preparation | Space requirement cylinder head

	Low pressure PFI SI	Low pressure DI SI	High pressure DI SI	High pressure DI CI
Fuel Injection	Port fuel injection ~ 5-10 bar	Direct injection ~ 20-50 bar	Direct injection ~ 200 bar	Direct injection ~ 200 bar
Boost pressure[1] for 11.5 bar	~ 2.5 bar	~2.0	~2.0	~2.0
Boost pressure[2] for 14.1 bar	~ 2.9 bar	~ 2.3	~ 2.3	~ 2.3
Combustion	Stoich/Lean Spark ignited	Lean Spark ignited	Lean Spark ignited	Diffusive
Compr. ratio Min/Max	10:1 - 13:1	10:1 - 13:1	11:1 - 13:1	16:1 - 18:1
NOx Raw level g/kWh	↓ (< 0.5)	o (0.5 - 1)	↑ (1 - 2)	↑↑ (6 - 8)
Peak / cycle efficiency (NRTC) warm	o / ↓	o / o	o / o	↑ / ↑
Transient load response	↓↓	o	o	↑
Main benefit	▪ Easy to integrate, ▪ Hardware available ▪ Low failure risk	▪ Robust against back-fire ▪ Efficiency / range ▪ Power density	▪ Same as LPDI ▪ Higher power density ▪ Injector packaging	▪ Robust against back-fire ▪ Highest efficiency / range
Main drawbacks	▪ Boosting ▪ Safety	▪ Integration DI Injector	▪ Integration DI Injector ▪ High pressure generation	▪ Integration DI Injector ▪ High pressure generation ▪ NOx raw emissions

constant air fuel ratio 1) Engine PFI Demo 11.5 bar, 450Nm, 65 kW, max. power 71kW 2) Engine 2 14.1 bar, 540Nm, 91 kW, max. power 100 kW
Source: FEV

KEY PARAMETERS OF H_2 ENGINE

The NO_X raw emissions and the engine efficiency mainly depend on the relative air/fuel ratio and the center of combustion

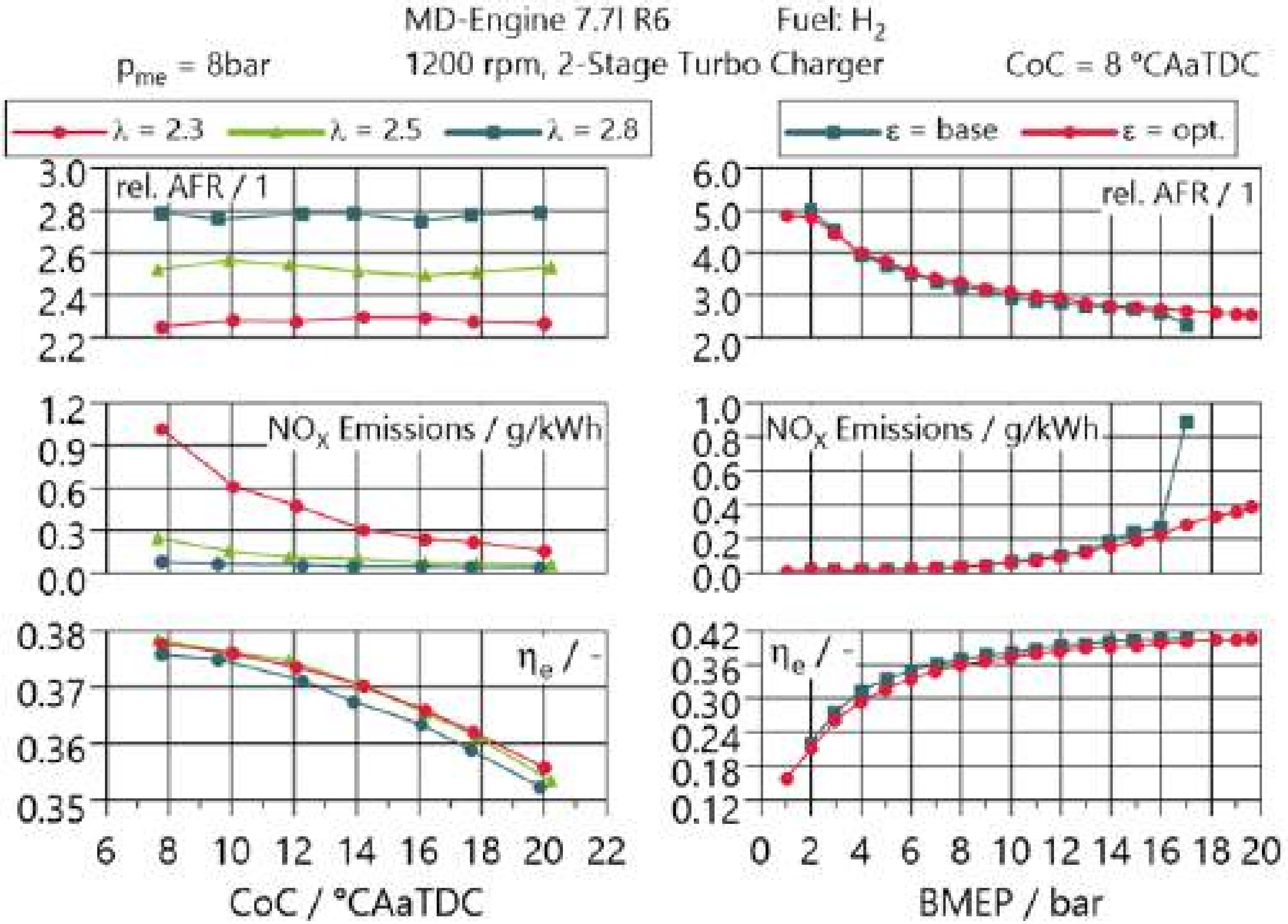
HYDROGEN HD APPLICATION REACHING EFFECTIVE EFFICIENCIES OF 42 % WITH ATTRACTIVE RAW NO_x EMISSION

Base engine:

- Stochiometric natural gas with EGR
- Single point fuel injection
- High level of charge motion
- Miller timing

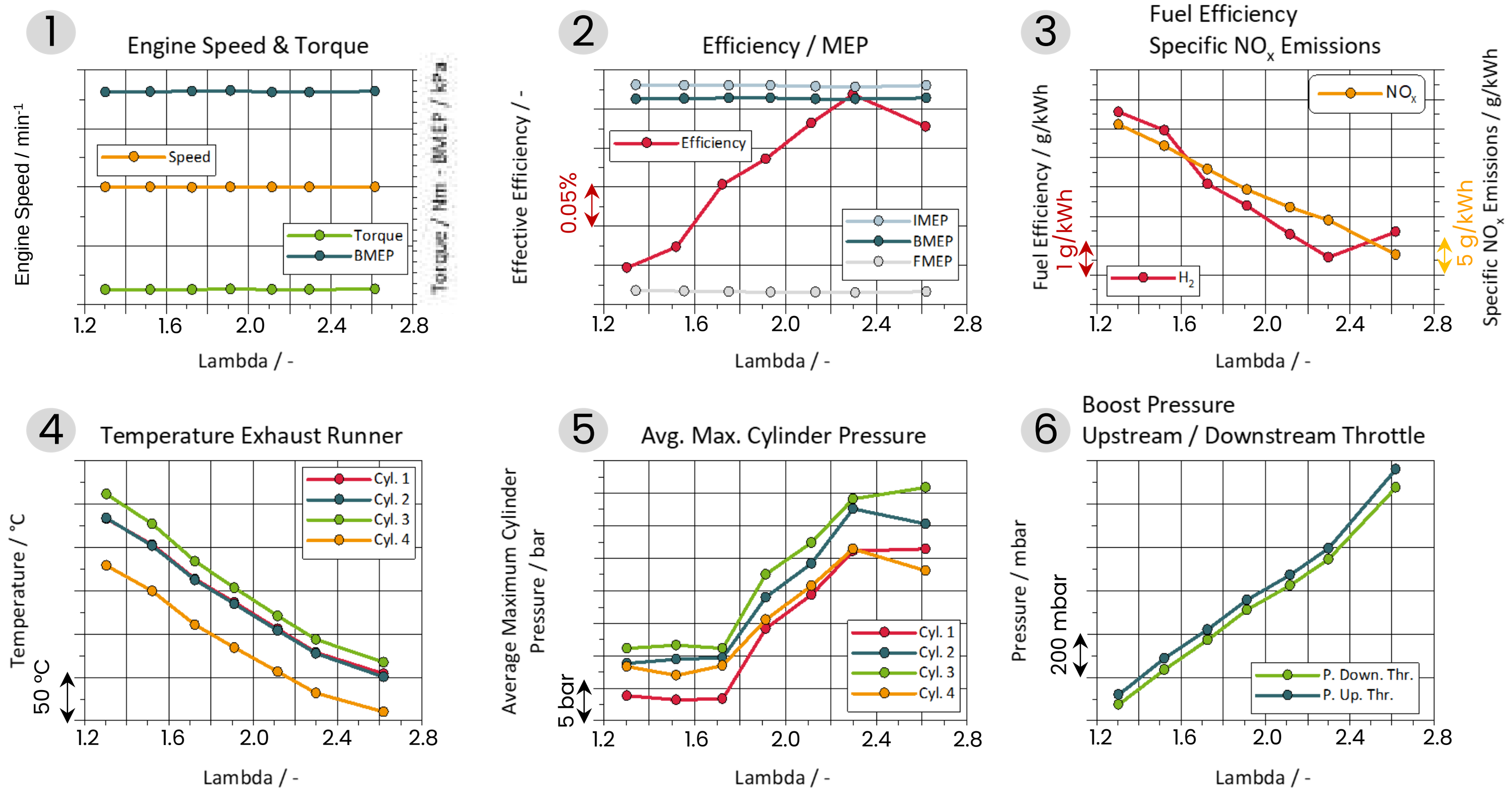
For hydrogen operation:

- 2-Stage turbocharging
- Reduced compression ratio for optimized power density
- No Miller timing



CoC: Center of Combustion

If lean combustion is targeting across a wide engine area, adaptations on engine hardware are necessary (boosting, compression ratio, EATS…)



- Lambda sweep performed on 4-Cyl H2-ICE at steady state point. 1
- Leaning out the mixture can support engine efficiency gain 2 and reduces the NOx emission. 3
- Running lean put high effort on the boosting system. 6 Consequently, the in-cylinder pressure raises. 5
- With higher AFR, exhaust temperature drops. 4 Trade-off must be found between engine out emission reduction and EATS performance.

Source : FEV

With a PFI configuration, SOI and EOI are key calibration parameters to influence the mixture formation and the combustion quality

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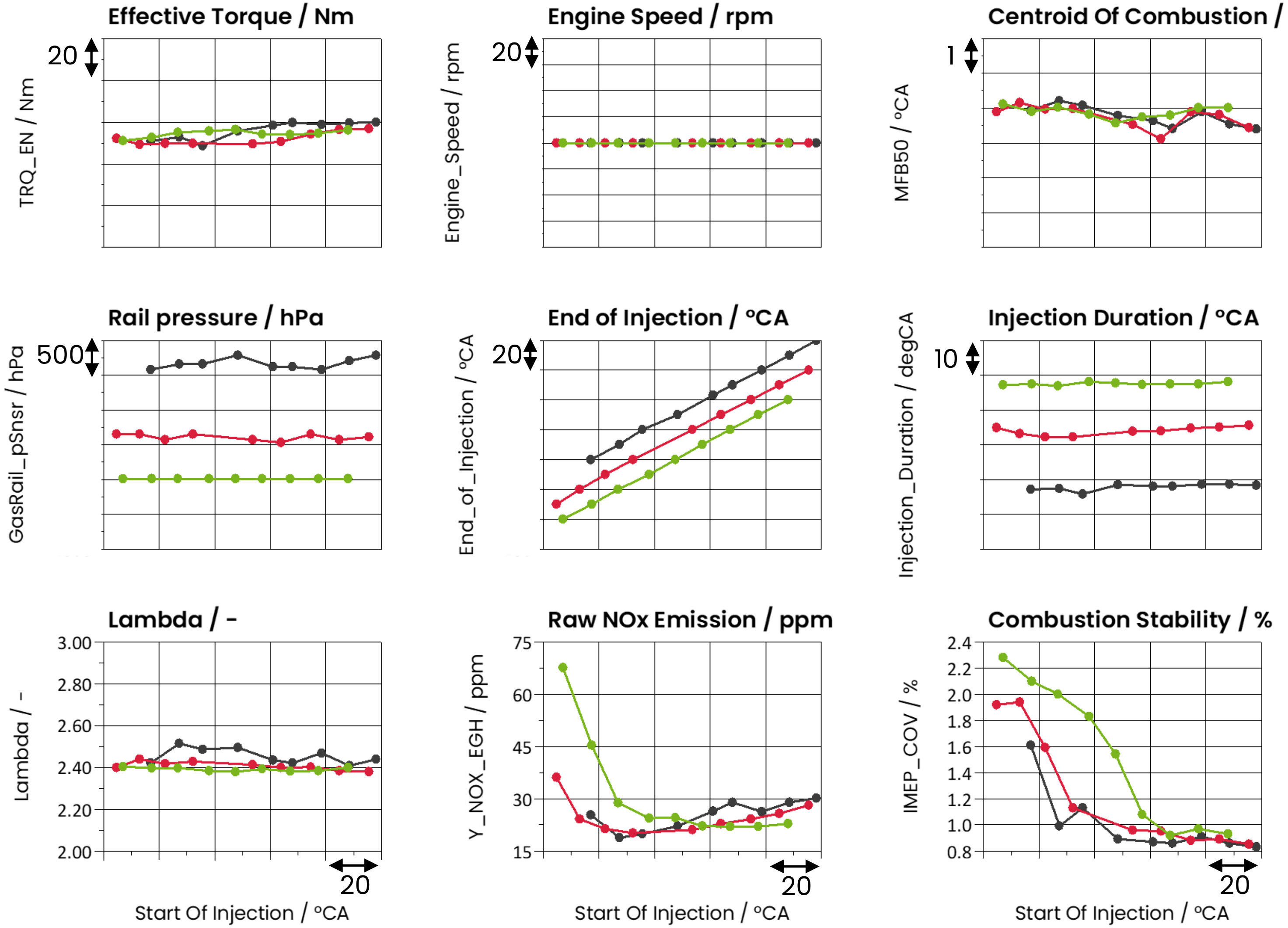


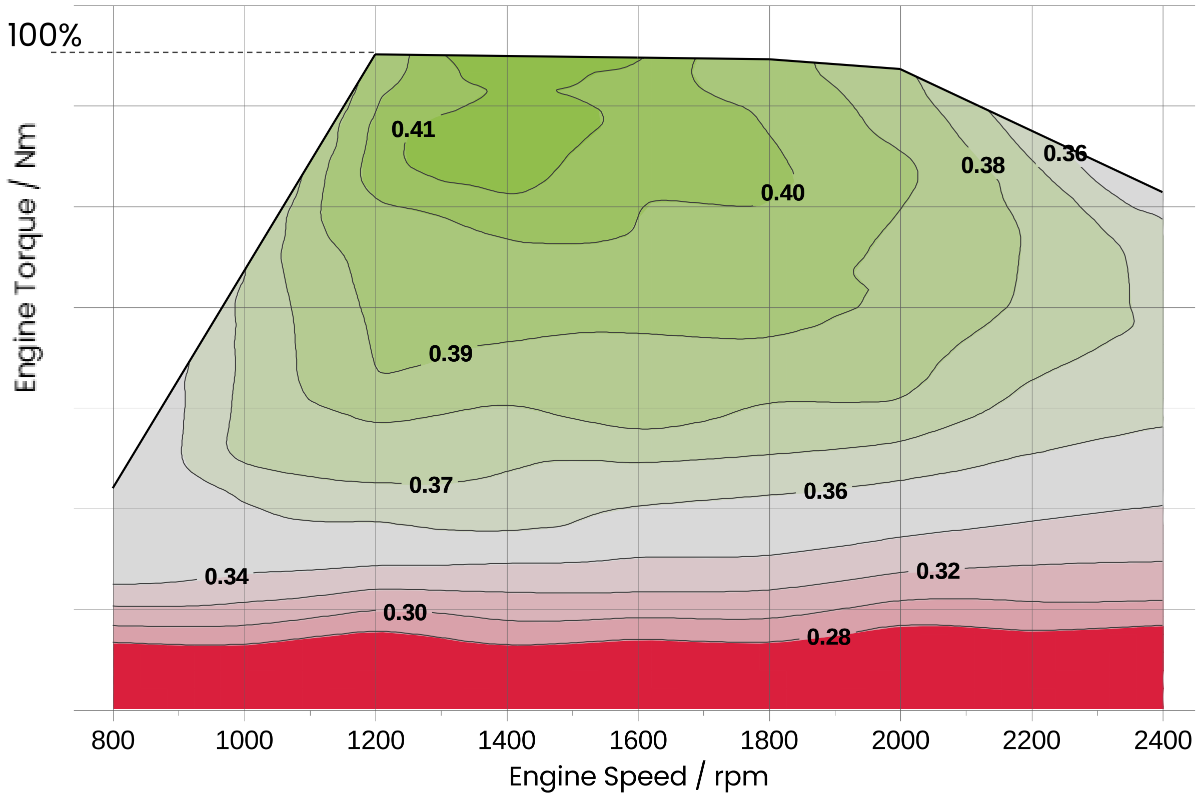
[redacted]

- SOI and EOI are closely linked to the camshaft timing.
- A “sandwich” approach, composed of three layers of fresh air - air/H_2 mixture - fresh air is beneficial for :
  - suppressing the hot spot into the cylinder
  - delivering properly mixed air/H_2 mixture
  - scavenging the intake port and keeping lowest H_2 concentration

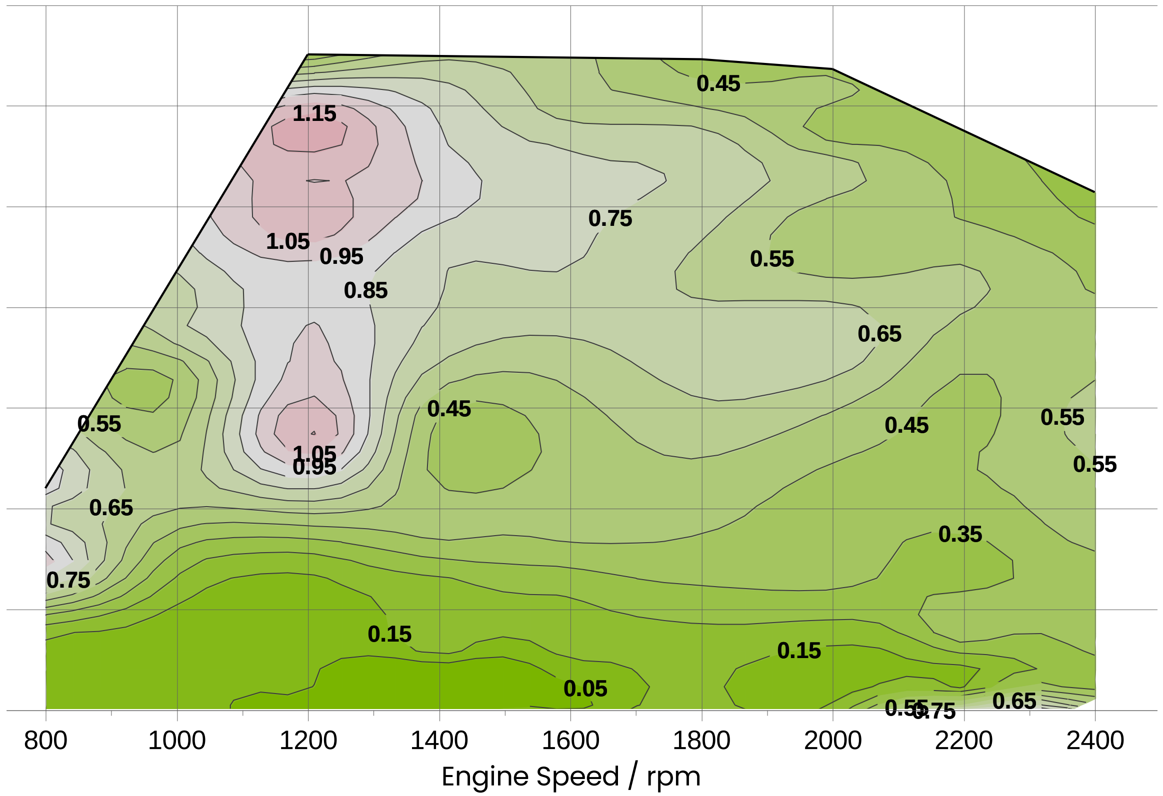
For the whole engine area, attractive BTE and raw NOx emissions are achievable. Exemplary results are given for a retrofitted PFI engine

MEASUREMENT OF ENGINE MAPPING WITH MD 6L H_2-PFI ENGINE

Break Thermal Efficiency / %



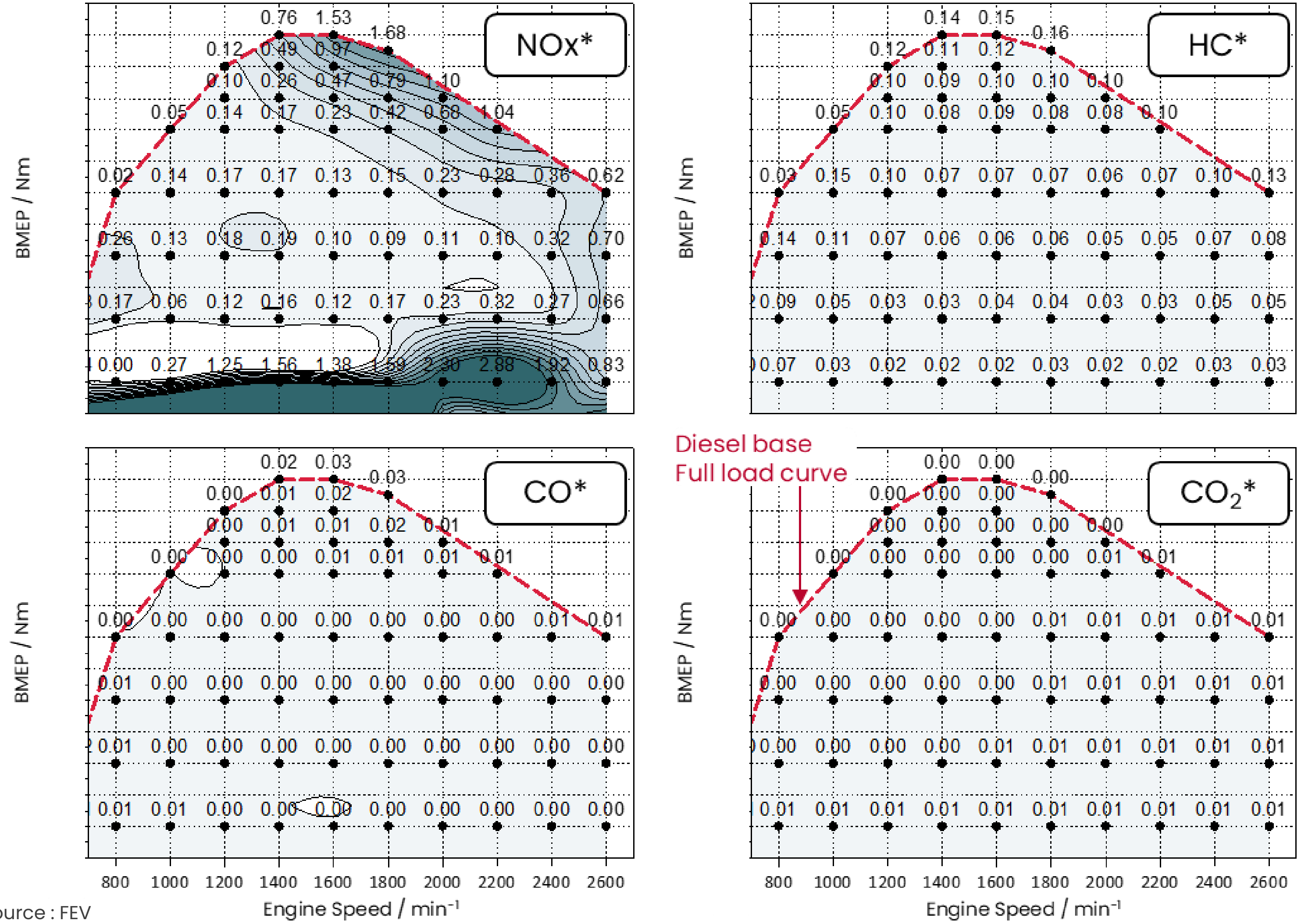
Specific Raw NOx emission / g/kW.h



Source : FEV

In comparison to conventional fuel type engine, the emissions abatement potential of H2-ICE is substantial. Exemplary results are given for DI engine

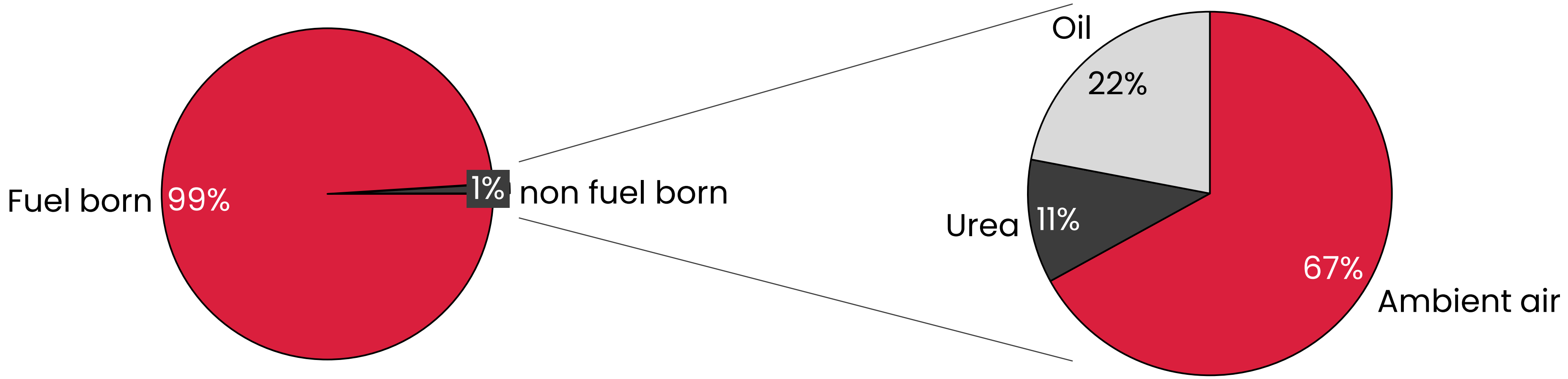
NORMALIZED ENGINE-OUT POLLUTANT EMISSIONS (H2-ICE EMISSIONS / DIESEL EMISSIONS)



Source : FEV

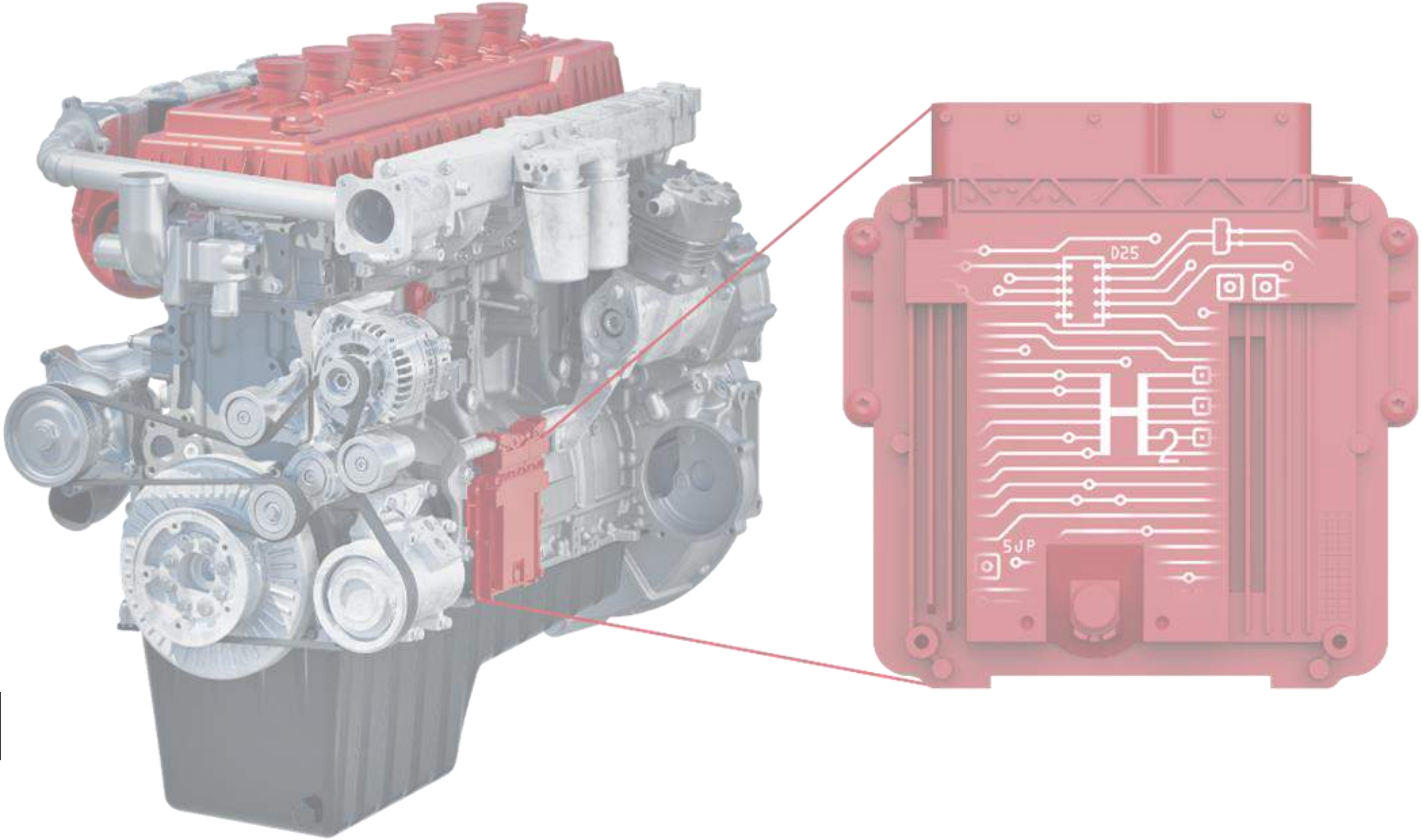
- The base Diesel is state of the art technology :
  - 2000bar fuel pressure,
  - high EGR rate capability
  - coping with Eu6 emission legislation
- The prototype H2 engine emits five times lower NOx engine-out when compared to the fully optimized diesel engine.
- Carbon based emission are only coming from the combustion of engine lubricant. Compared to Diesel, the emissions of HC, CO and CO2 show extremely low values. Their emissions are within the analyzer accuracy range.
- 100 %= emission of the series Diesel engine

CO2 emission mainly driven by ambient CO2, oil and urea born emissions are only one third of the CO2 tailpipe emissions of a H2 ICE



- On a conventional diesel fueled engine 99% of the tailpipe CO_2 emissions are fuel born
- For H2 ICE only the remaining 1% is relevant created by
  - Ambient air (66%)
  - Lube oil combustion (22%)
  - Urea conversion (11%)
    - Thermolysis: $CH_4N_2O \rightarrow NH_3 + HNCO$
    - Hydrolysis: $HNCO + H_2O \rightarrow NH_3 + \boldsymbol{CO_2}$

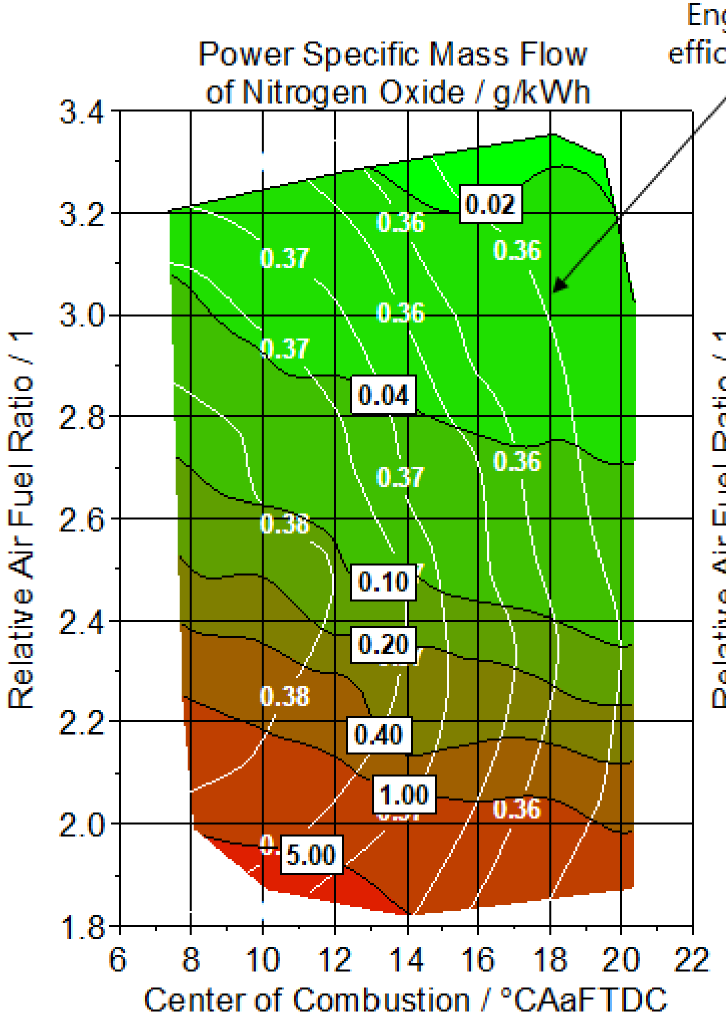
1g/kWh NOx emission causes 0.478g/kWh CO2 emissions

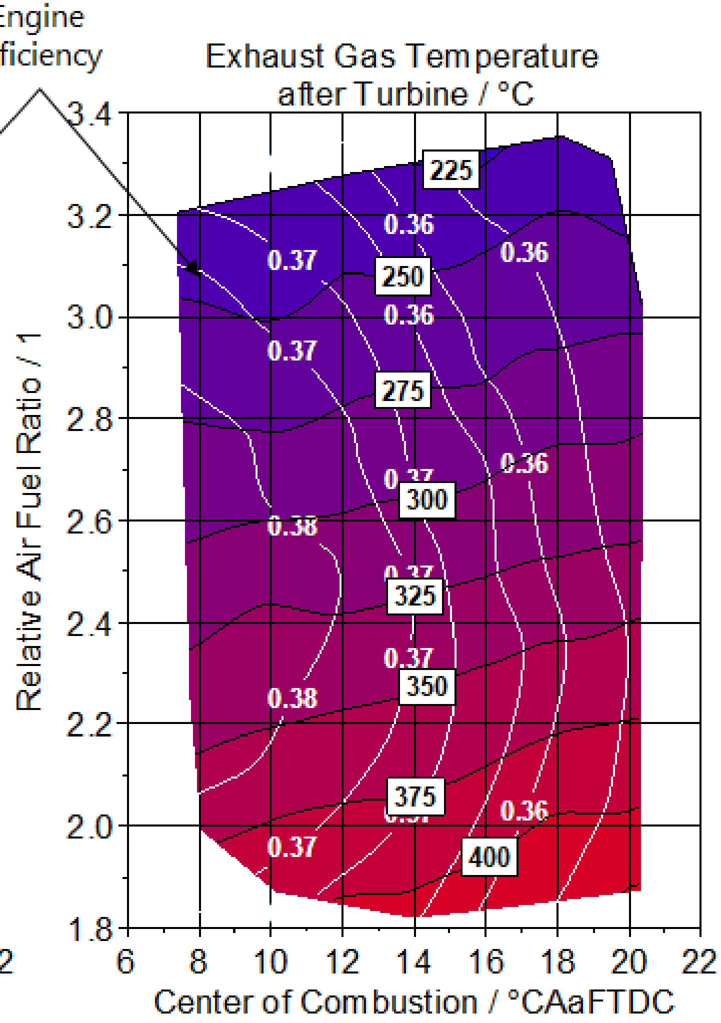


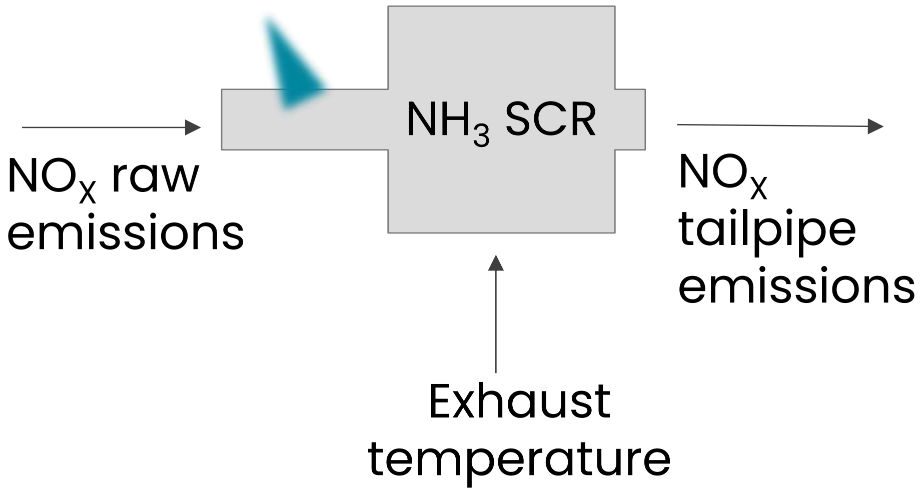
ENGINE CONTROL STRATEGIES

NO_X emissions and exhaust temperature can be strongly influenced by relative air-to-fuel-ratio and center of combustion

1400RPM/8BAR, STEADY STATE INVESTIGATION : INFLUENCE OF AIR FUEL RATIO AND CENTER OF COMBUSTION

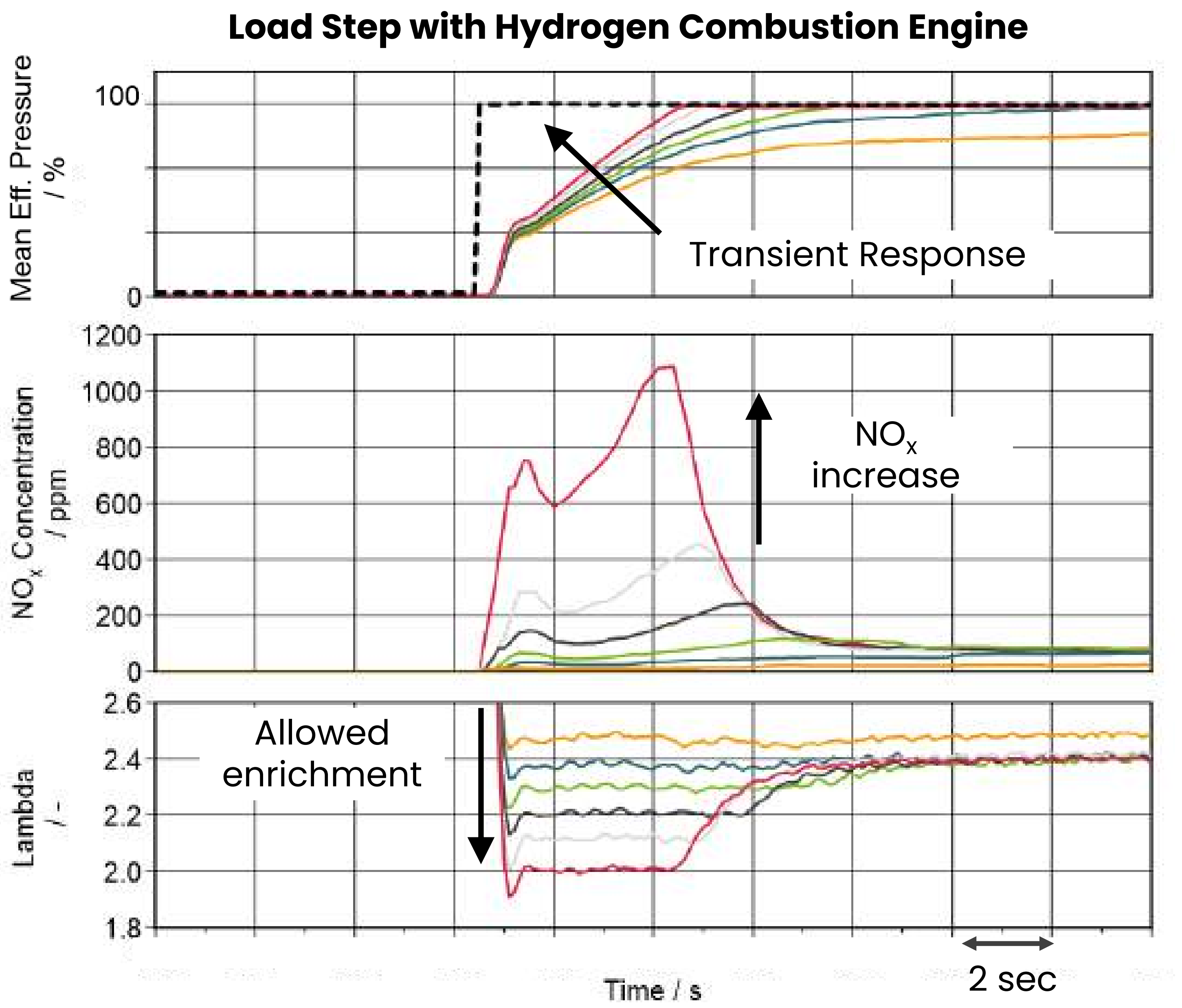






Source: FEV

H_2-ICE specific control strategies required to solve trade-off betw. NO_x emissions and transient performance



Source: FEV

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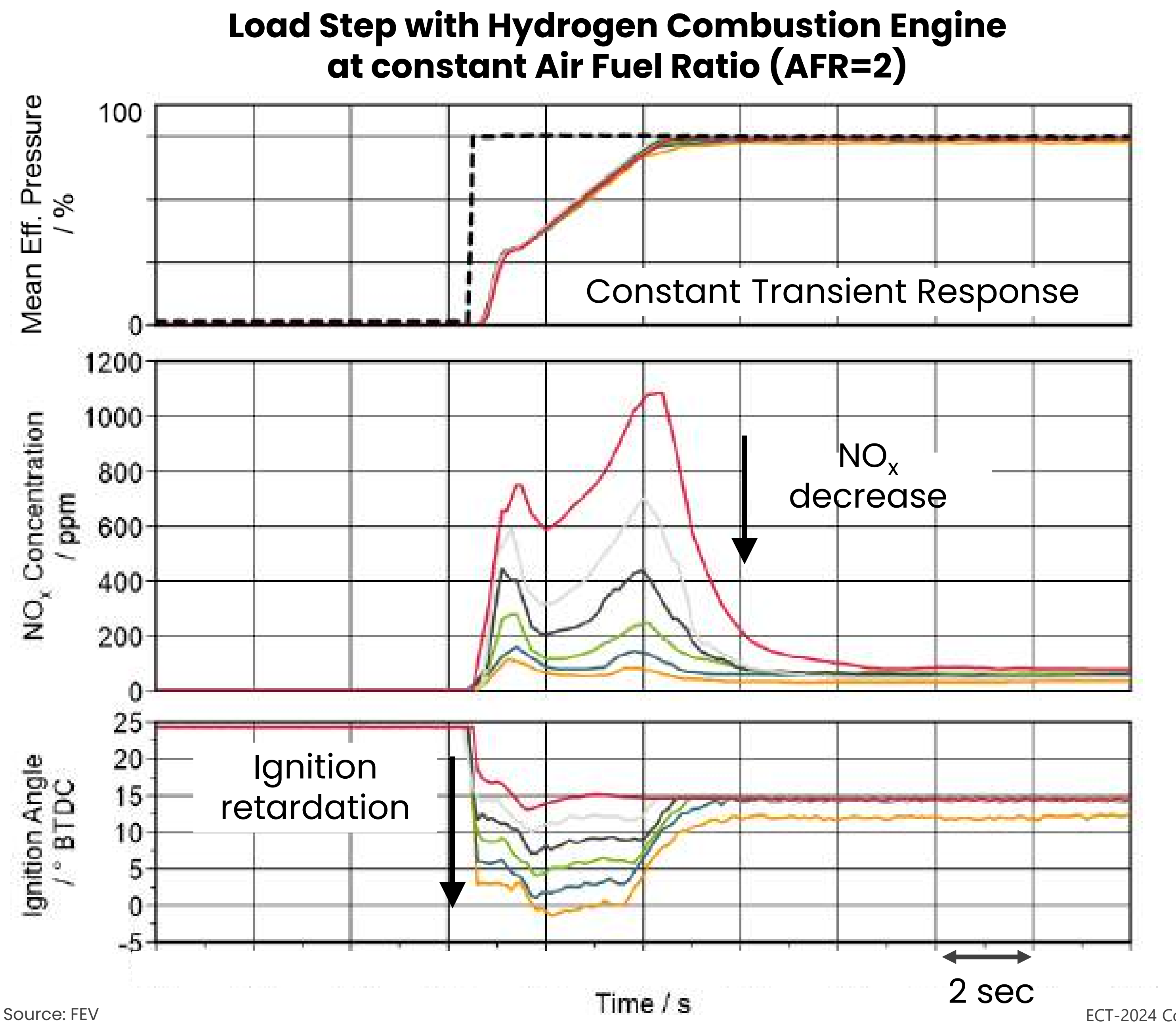

Source: FEV

With an adapted control algorithm for lambda and ignition timing, it is possible to maintain a balance between engine efficiency and NO_x emissions

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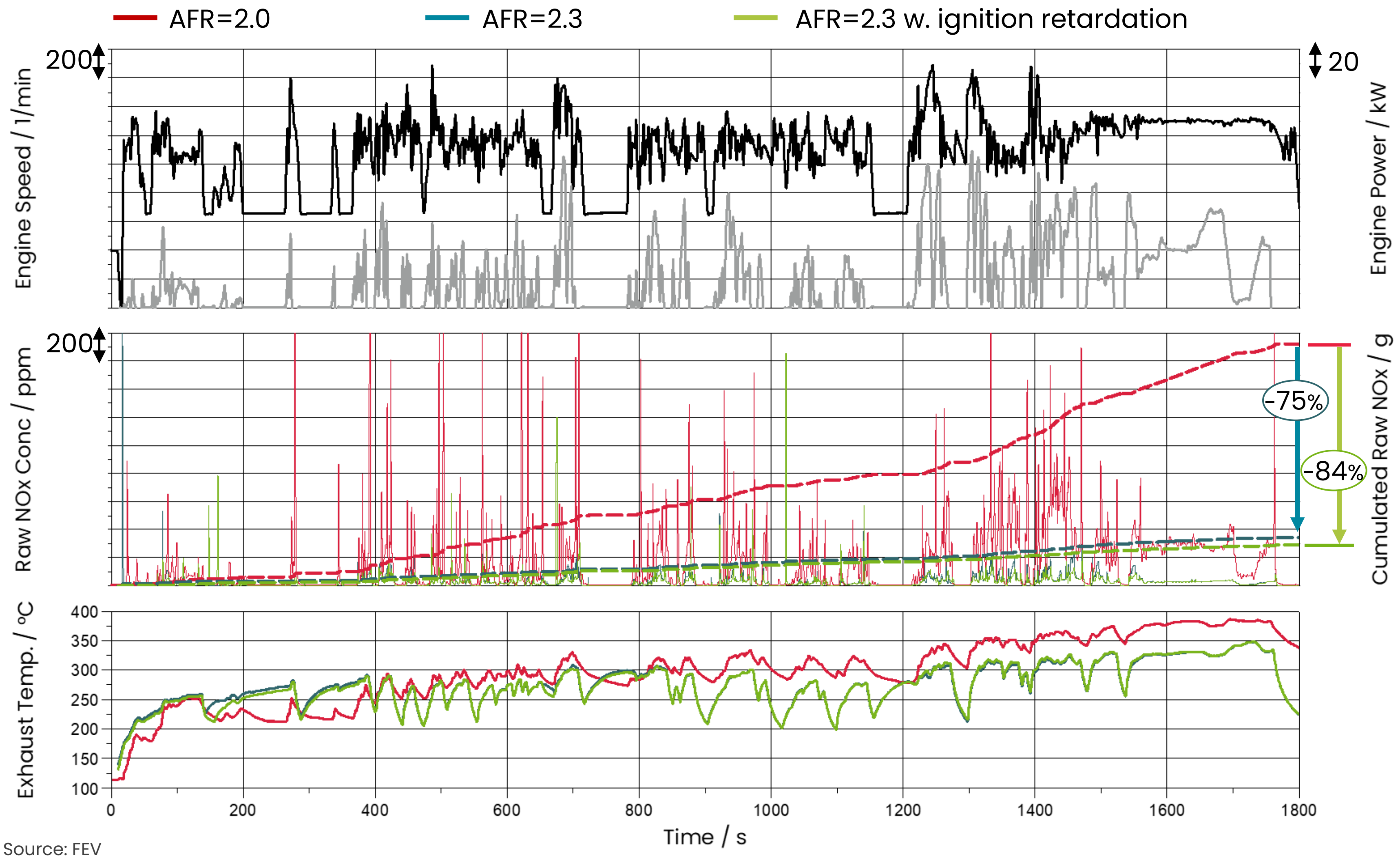
WHTC MEASUREMENT FROM MD 7.7L H2-PFI ENGINE



DESCRIPTION

- During fast load requests, an enrichment of the air/fuel ratio supports rapid load build-up but results in higher NO_x emission
- During a fast load increase the ignition timing is retarded to avoid NO_x emission peaks and knocking combustion
- Balance can be found between engine efficiency and NO_x emission

Source: FEV

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Hydrogen engine can serve as a robust, well proven energy conversion device

- **Existing Fleet** determines GHG reduction potential in the oncoming years. A **fast transition** towards **sustainable** propulsion concepts is mandatory.
- ICE with renewable fuel is one solution with a **fast-to-market** approach
- Further development are on-going to further enhance native advantages and counteract on major challenges (i.e. abnormal combustion, embrittlement, storage,..)
- The work already performed on engine converted to **H_2 operation,** demonstrates that using established technologies while maintaining minimal changes to known engine hardware offers a **reliable** and **cost-effective** solution for the **quick market introduction of H_2-ICE.**

NO MATTER WHO WILL WIN THE RACE FOR FUTURE COMMERCIAL TRANSPORT…

FEV IS READY TO SUPPORT YOUR DEVELOPMENT!

THANK YOU VERY MUCH FOR YOUR ATTENTION

Q&A : LIVE OR VIA FOLLOW UP TALK

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