Hydrogen engines to decarbonise heavy duty vehicles and machines

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RICARDO

HORIBA

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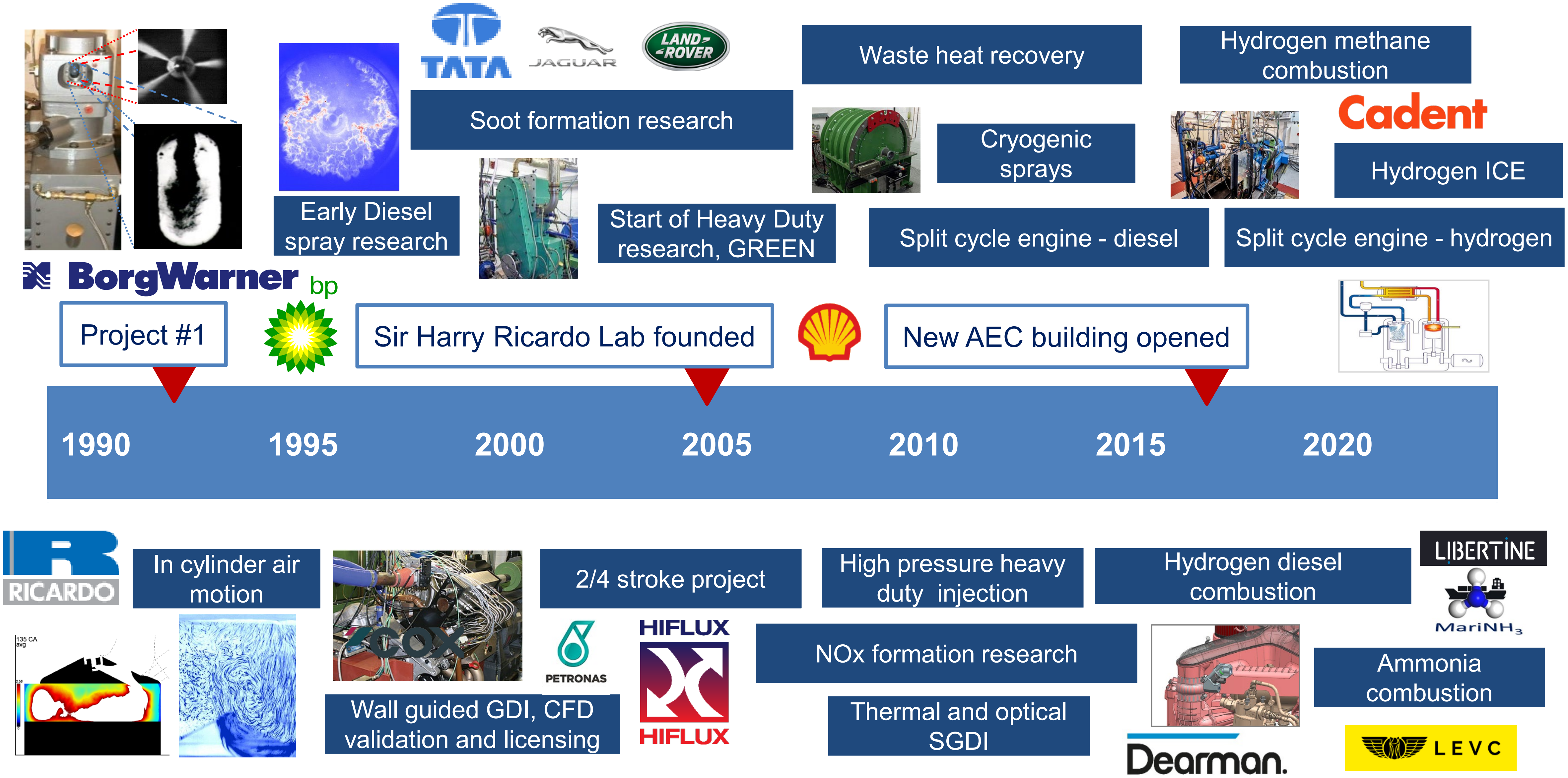
The Advanced Engineering Centre at University of Brighton has a long history of combustion engine research and industrial collaboration



Heavy duty vehicles and machines must meet operators requirements and environmental objectives

Health
Air quality emissions
NOx
Particulates

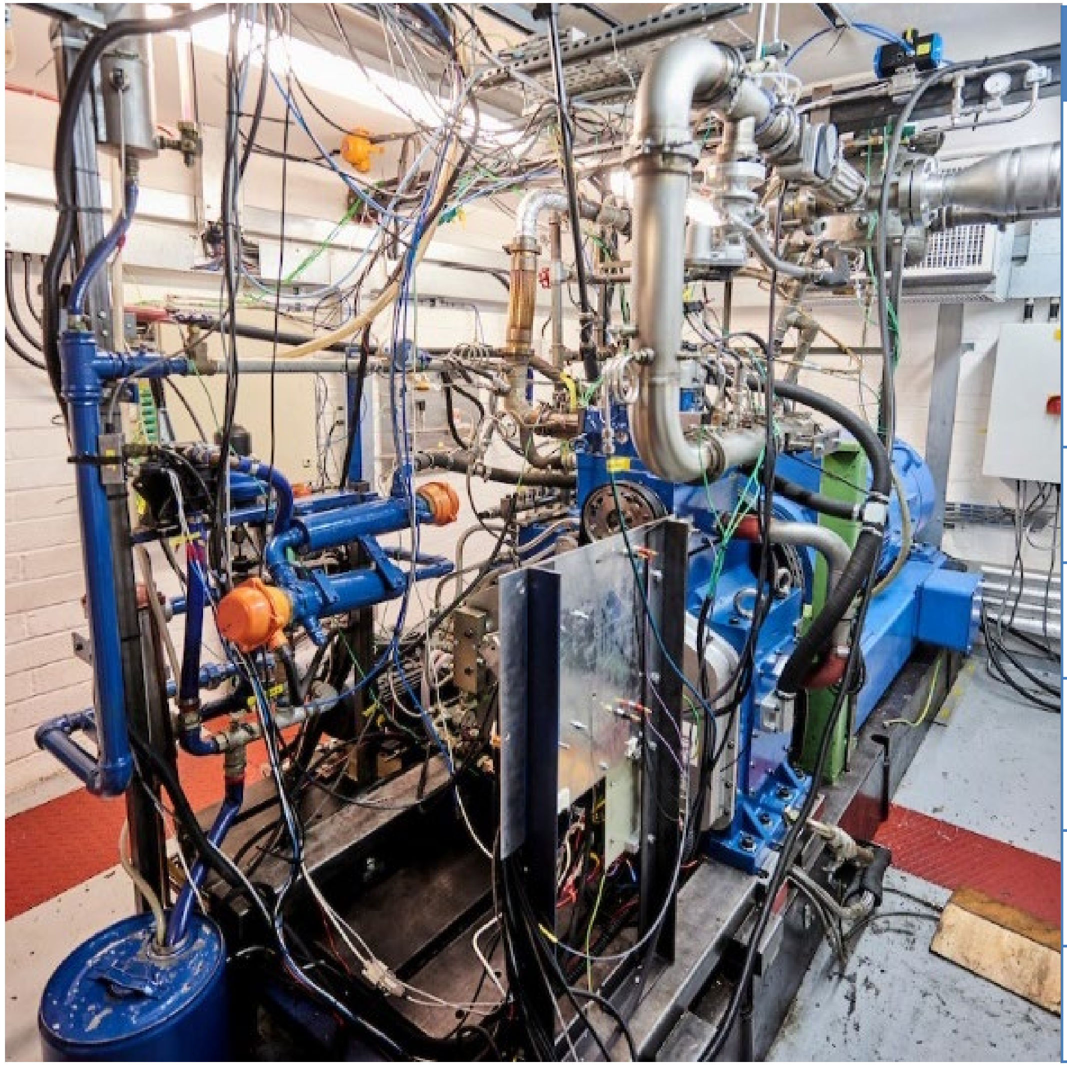
Performance
Power and torque
Range
Refuelling time

Heavy Duty vehicles and machines

GHG Emissions
from fuel and vehicle
production and use
Climate change

Vehicle cost
Fuel cost
Durability
Cost of ownership

This presentation explores potential for Hydrogen ICE to meet these requirements, including Brighton Ricardo test results and literature evidence



Component	Hydrogen Proteus Conversion
Piston and bottom end	Volvo D13 12.8L diesel, 131mm bore, 158mm stroke D13 piston machined to give a plain bowl shape and reduced compression ratio
Cylinder Head	Scania OC13 CNG unit head modified for direct injection
Ignition system	Custom spark ignition system using AEM smart coil
Injection System	Borg Warner prototype H2 injector (35 bar injection pressure)
Throttle	Throttle located pre-intake manifold.
Compression ratio	12.62:1

The single cylinder test is investigating direct injection hydrogen combustion over a range of EGR and air fuel ratios, across the operating range

- Instrumentation
  - High speed logging – intake and exhaust manifold pressure, cylinder pressure, spark and ignition timing
  - Low speed logging – engine and test cell temperatures and pressures, cylinder head temperatures, fuel flow rate (Bronkhorst F113-AC mass flow meter)
  - Emissions – 2 Mexa 7000s intake and exhaust, plus prototype Horiba HyEVO hydrogen analyser

- EGR system
  - Cooled EGR (~70^{o}C to maintain water content)
  - Rate calculated from intake and exhaust O_2 content

$$EGR\ rate\ (\%) = \frac{O2air - O2intake}{O2air - O2exhaust}$$

- Air flow rate controlled by critical flow nozzles to avoid pulsations, fuel by injector opening time

- For each test condition, spark timing adjusted to give 50% MFB at 8^{o}ATDC, fuel and air flow rates are adjusted to give required BMEP and AFR

The need for zero impact air quality emissions means that very low NOx is vital, work shows that this is possible

- Reducing combustion temperatures via high AFR, EGR and water injection have been shown to reduce NOx for H2 ICE

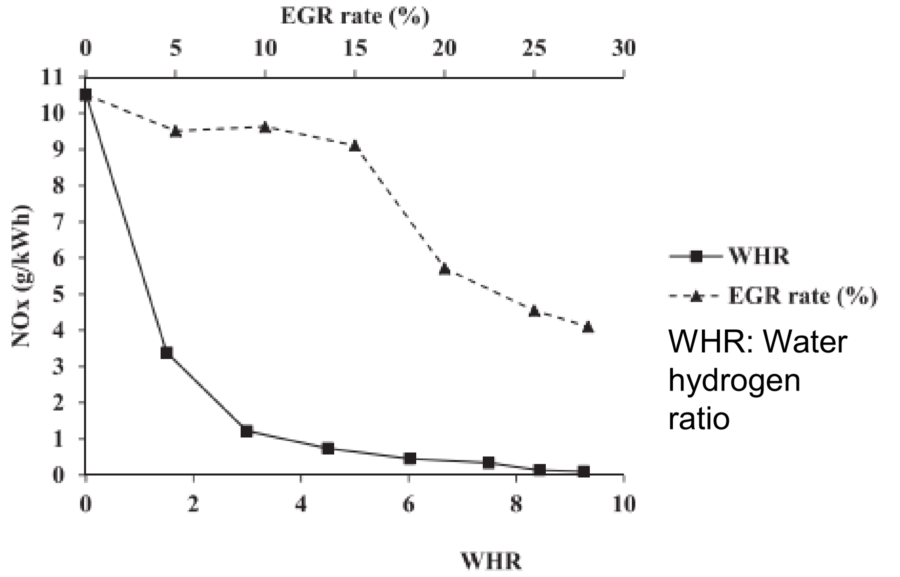
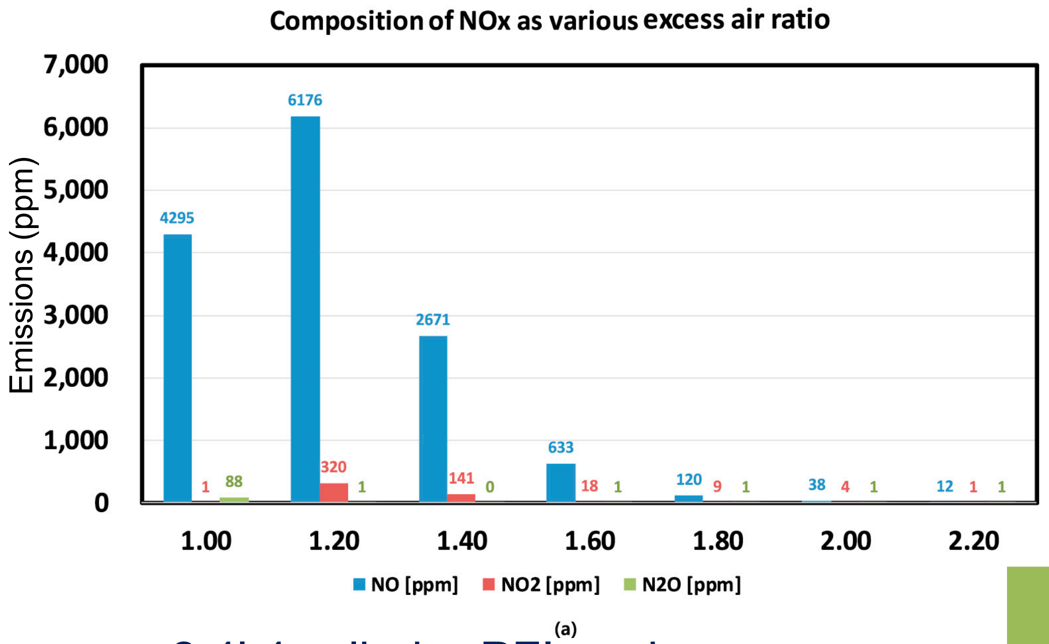


Fig. 12 – Variation of NOx emission with EGR rate and water injection.

28kW 4 cyl, PFI engine

Source: https://doi.org/10.1016/j.ijhydene.2019.01.129



2.4l 4 cylinder PFI engine

Source: https://doi.org/10.1016/j.ijhydene.2019.07.181

Health	Performance
GHG emissions	Cost of ownership

Research also shows that hydrogen injection properties can also affect NOx emissions

- Research at the Tokyo Research Centre for High Efficiency Hydrogen Engine and Engine Tribology showed potential performance for a direct injection hydrogen engine
    - Results from 1L per cylinder single,100% load at 1000rpm, 100 bar hydrogen injection pressure

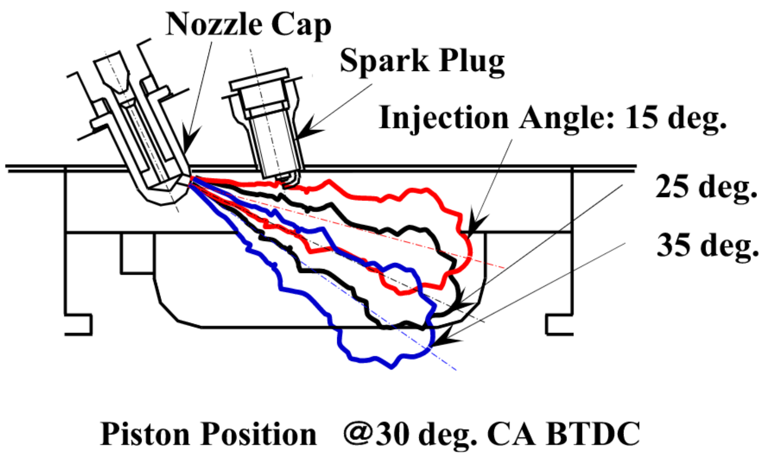


Fig. 8 — Conceptual geometry to show location of injected jet relative to combustion chamber wall for changes in injection angle.

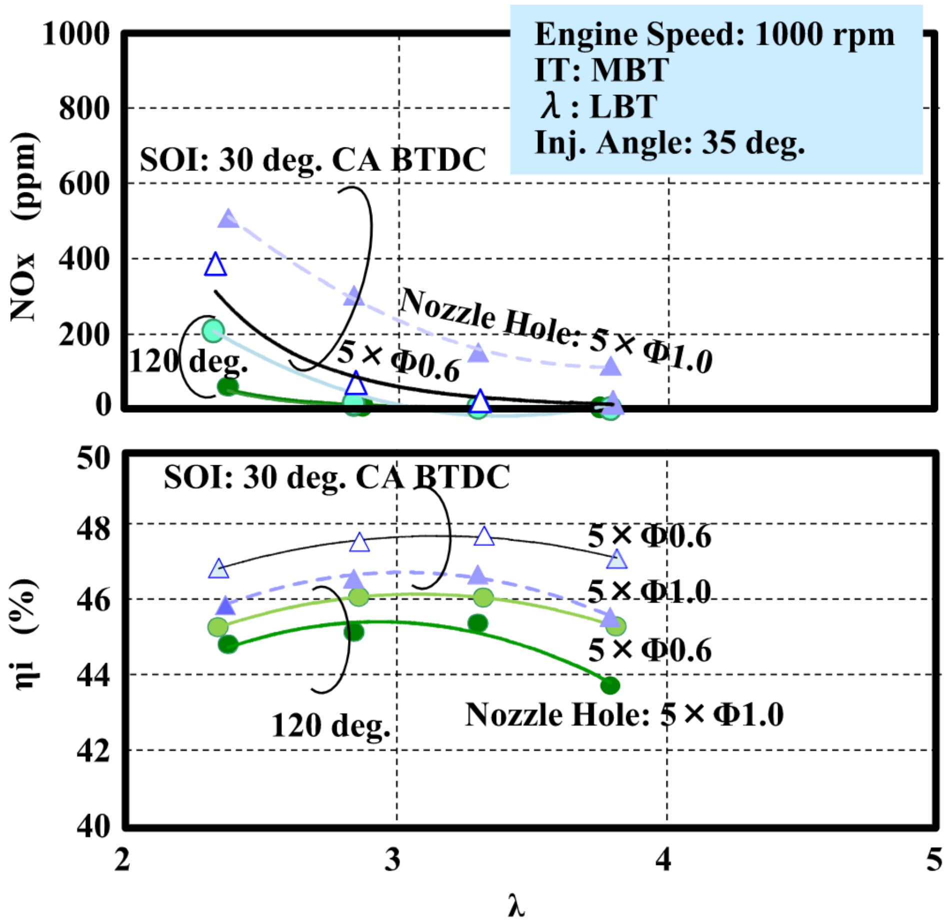


Fig. 11 — Effect of nozzle hole diameter on thermal efficiency and NOx formation for varied SOI.

Source: Yasuo Takagi, Masakuni Oikawa, Ryota Sato, Yoshihisa Kojiya, Yuji Mihara, Near-zero emissions with high thermal efficiency realized by optimizing jet plume location relative to combustion chamber wall, jet geometry and injection timing in a direct-injection hydrogen engine, International Journal of Hydrogen Energy, Volume 44, Issue 18, 2019, https://doi.org/10.1016/j.ijhydene.2019.02.058.

Brighton and Ricardo test work shows that very low NOx emissions in an HD representative engine are possible, with 35 bar direct injection

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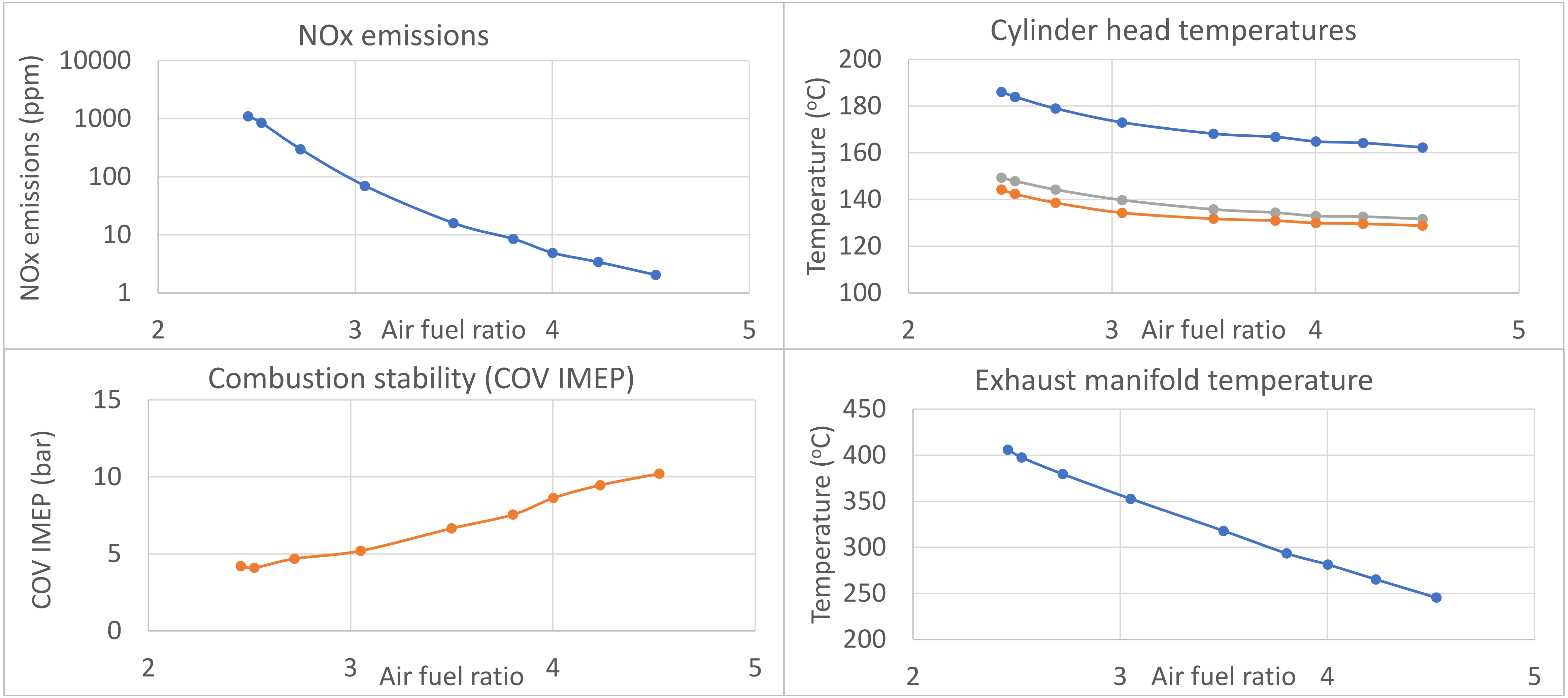
NOx emissions, 900 rpm, 14 bar GIMEP, lambda sweeps



Adding EGR allows further NOx reductions, although combustion stability reduces at EGR rates above 35%

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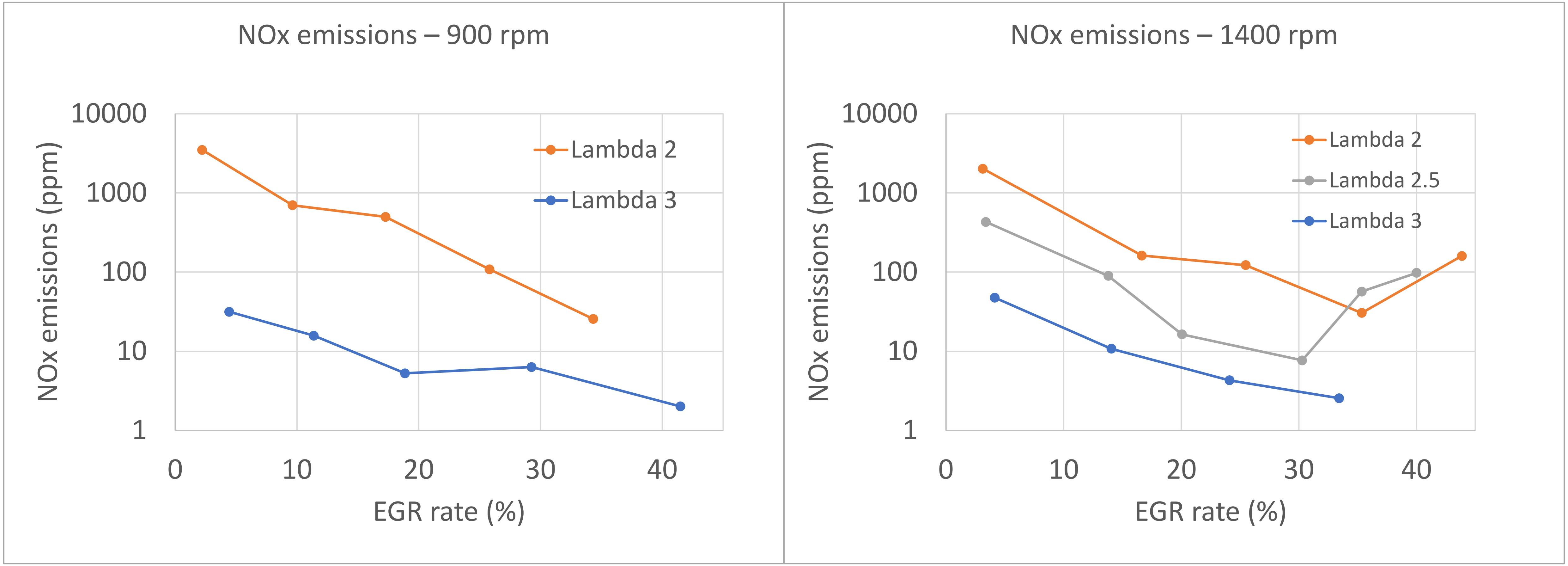
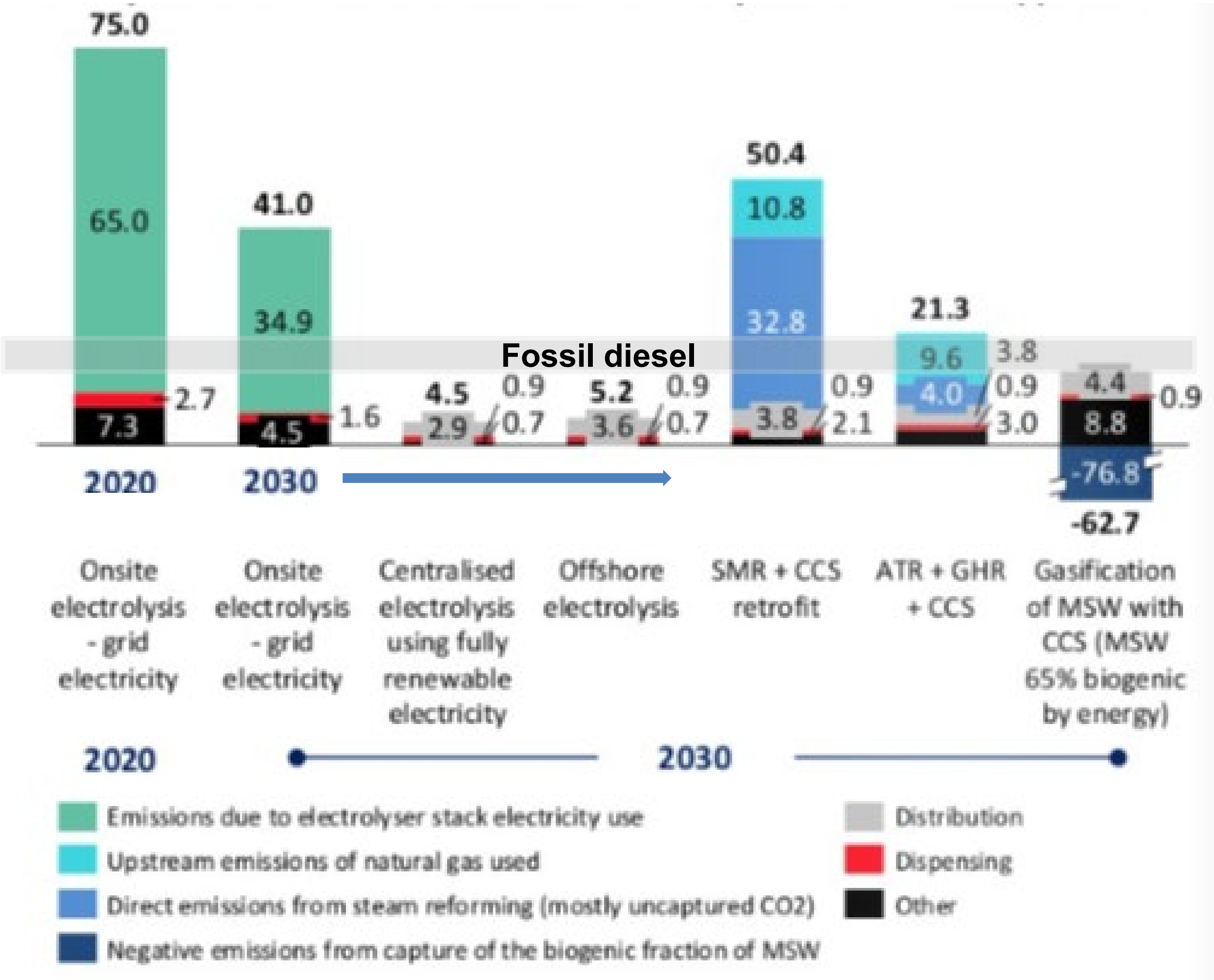
NOx emissions, 900 rpm and 1400 rpm, 9 bar GIMEP, lambda and EGR sweeps



Consideration of well to wheels greenhouse gas emissions is vital to ensure hydrogen use gives climate benefits



Source: Hydrogen WTT Pathways Study - Full Report (zemo-ebooks.org.uk)

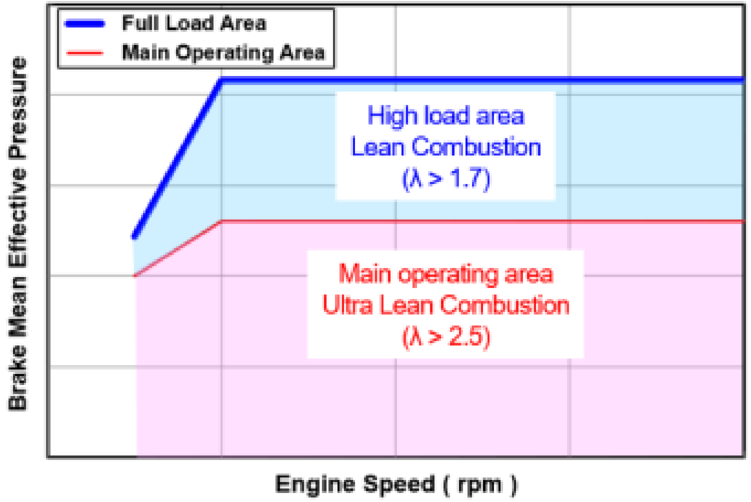
Hydrogen has no tailpipe emissions, but consideration of fuel production emissions is vital to ensure genuine climate benefit

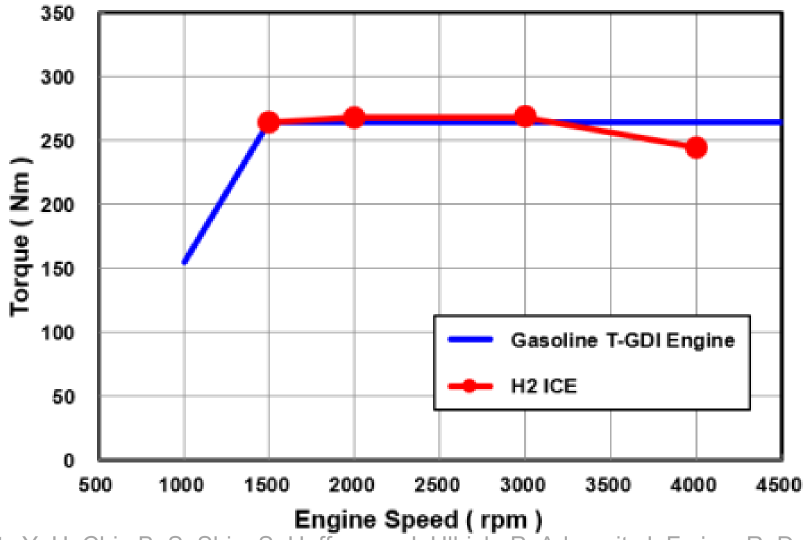
This data from ZEMO shows WTT emissions for hydrogen dispensed at 350 bar
Note that fossil diesel WTT emissions are 15-20 g CO_2/MJ

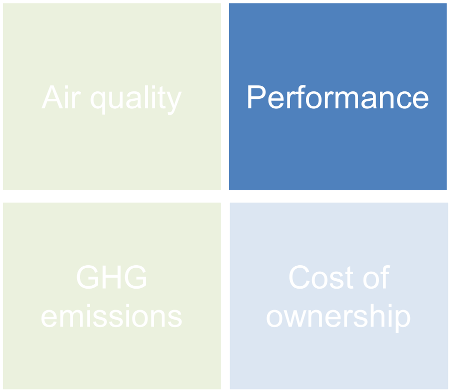
Health	Performance
GHG emissions	Cost of ownership

For heavy duty vehicles and machines, performance is not desirable it’s essential to complete the work

- Heavy duty engines must be able to produce high power and torque required by operator duty cycles
- For hydrogen engines, there are particular challenges for high load operation including injection system capability for high flow rates, high air flows for the high lambda needed for low NOx and increased likelihood of adverse combustion
- For a light duty engine, Chi et al used 2 VGTs with an electric supercharger to give high power operation with reduced air fuel ratio, high speed torque was limited by knock (more later)

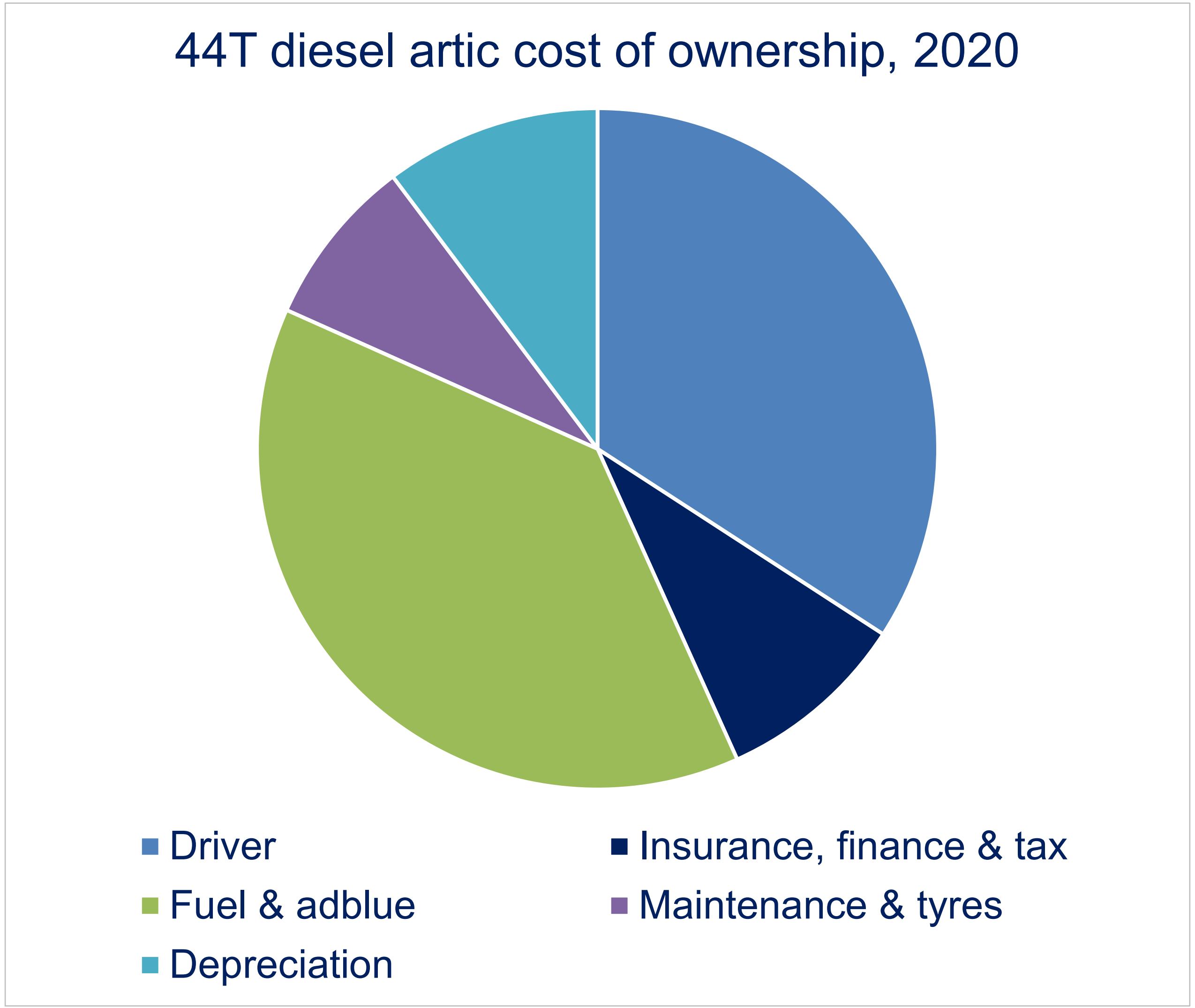






Source: Hydrogen Internal Combustion Engine: Viable Technology for Carbon Neutral Mobility Y. H. Chi , B. S. Shin, S. Hoffmann, J. Ullrich, P. Adomeit, J. Fryjan, R. Drevet Thiesel 2022, Conference on Thermo and Fluid Dynamics of Clean Propulsion Powerplants

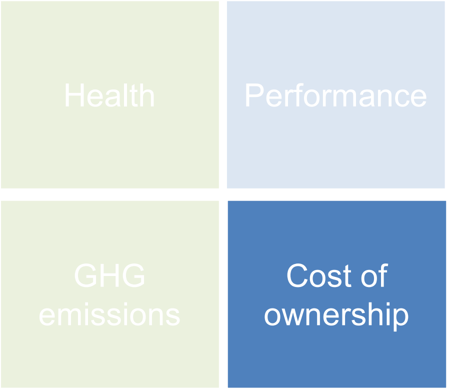
The commercial environment for heavy duty operators is tough, with low profit margins, so cost of ownership is very important



Cost of ownership is dominated by fuel costs, which means that fuel efficiency is important

Driver costs are the second largest contributor, so lowering driver productivity (eg through longer refuelling times) will have a significant negative impact

Vehicle purchase cost, depreciation and life span are also important contributors

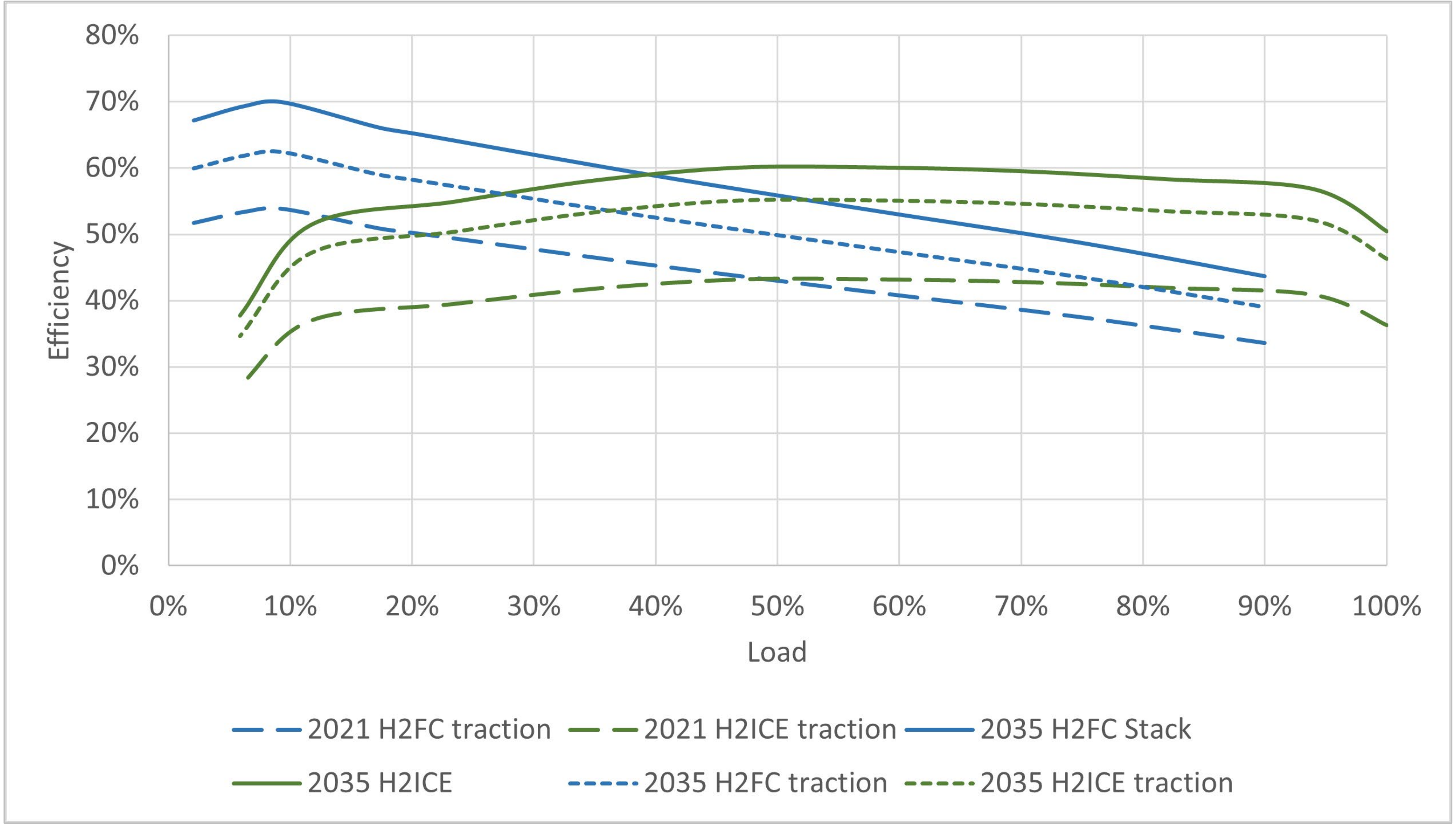


Hydrogen ICE could offer a cost advantage over H2FC reducing vehicle cost

System/cost	2025		2035	
	H2ICE	H2FC	H2ICE	H2FC
Engine/fuel cell system	41[b] $/kW @350kW[d]	195 $/kW[a] @190 kW[e]	42[b] $/kW @350kW[d]	80 $/kW[a] @190 kW[e]
	$14.4k	$37.1k	$14.4k	$15.2k
Fuel tanks	365 $/kg[a] @70kg[c]	365 $/kg[a] @70kg[c]	200 $/kg[a] @70kg[c]	200 $/kg[a] @70kg[c]
	$25.5k	$25.5k	$14k	$14k
Battery	N/A	97 $/kWh[a] @ 73 kWh[e]	N/A	63 $/kWh[a] @ 73 kWh[e]
	-	$7.1k	-	$4.5k
Total	$39.9k	$69.4k	$28.35k	$33.7k

Table 1 – Cost estimates for H2FC and H2ICE powertrains in 2025 and 2035. Cost estimates are based on the following references:
a. Advanced Propulsion Centre roadmaps 2020
b. Ricardo analysis
c. 2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf (transportenvironment.org)
d. Volvo FH Powertrain Specifications | Volvo Trucks
e. Hyundai Xcient specification (Hyundai Motor's Delivery of XCIENT Fuel Cell Trucks in Europe Heralds Its Commercial Truck Expansion to Global Markets – Hyundai Hydrogen Mobility (hyundai-hm.com))

On the road fuel consumption data for H2FC and H2 ICE shows that H2 ICE could give lower fuel costs for higher load applications



Hydrogen slip impacts efficiency and potentially greenhouse gas emissions, data shows increases with lambda and EGR

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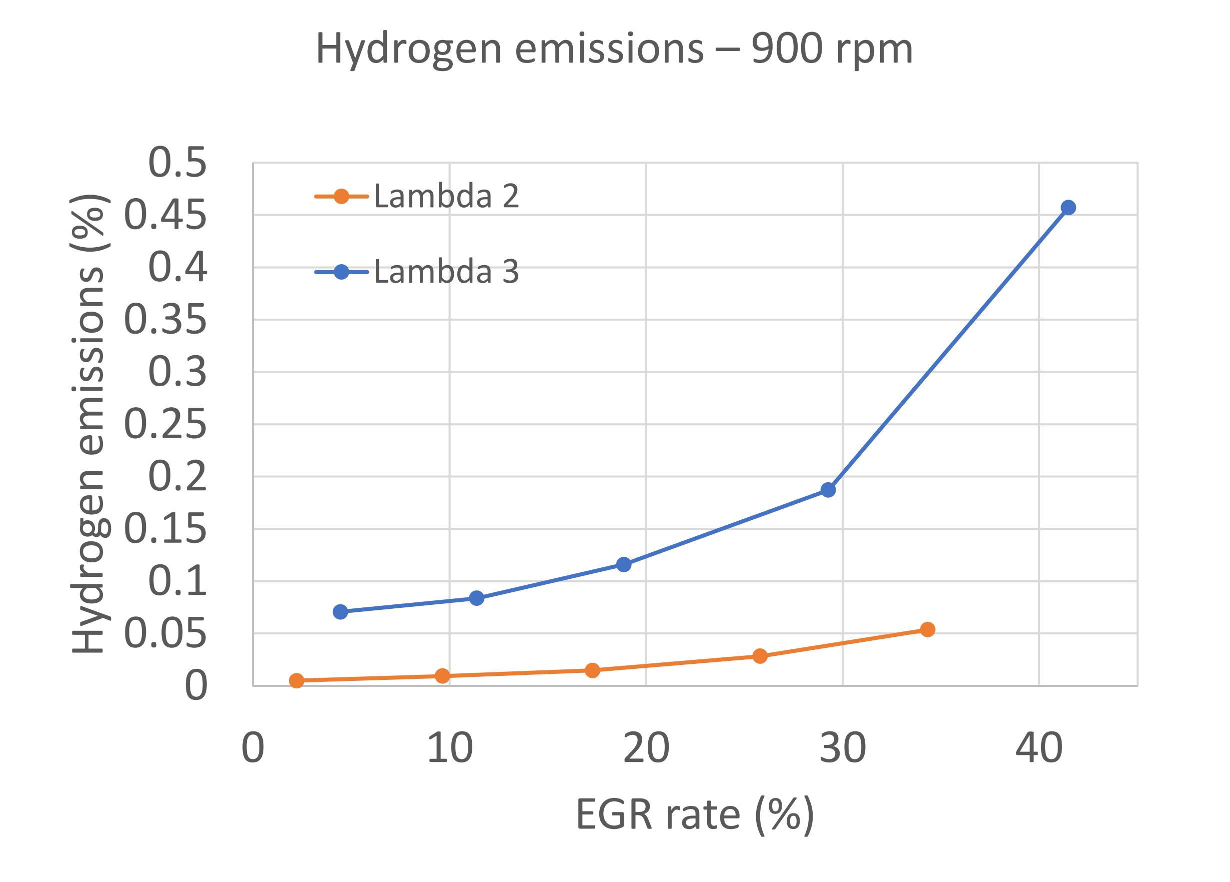
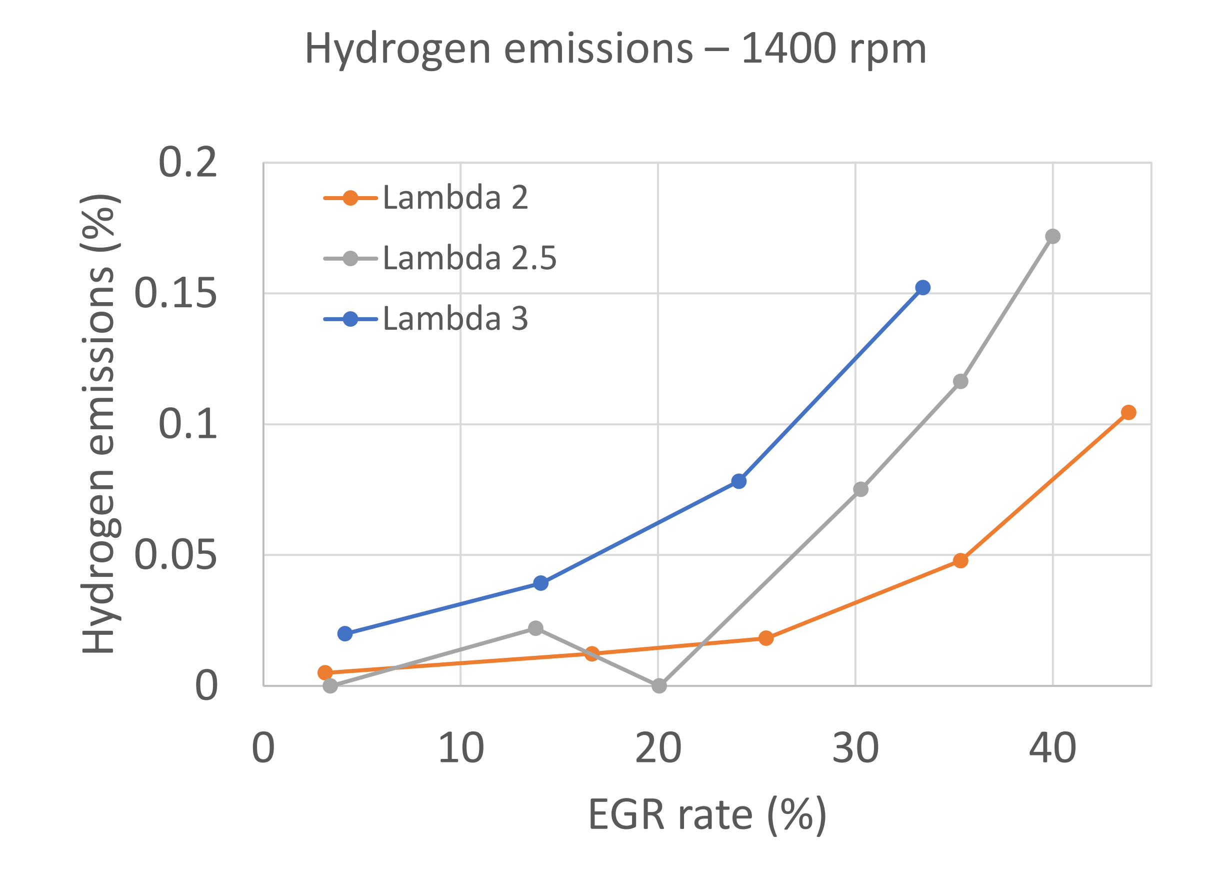
H_2 emissions, 900 rpm and 1400 rpm, 9 bar GIMEP, lambda and EGR sweeps





Adverse combustion conditions such as knock, misfire and backfire all need to be managed to maintain durability

- A combination of low ignition energy and wide flammability range means that hydrogen combustion is particularly susceptible to adverse combustion conditions

- Spark ignition - knock caused by random ignition of end gas with influence of in cylinder pressure waves

- Compression ignition – knock related to combustion rate, occurring at the beginning of combustion

- Likelihood of knock affected by a range of factors: compression ratio, intake temperature, air fuel ratio, ignition timing, combustion chamber hot spots, mixture homogeneity and turbulence, engine speed

- EGR and water injection have been shown to reduce knock propensity

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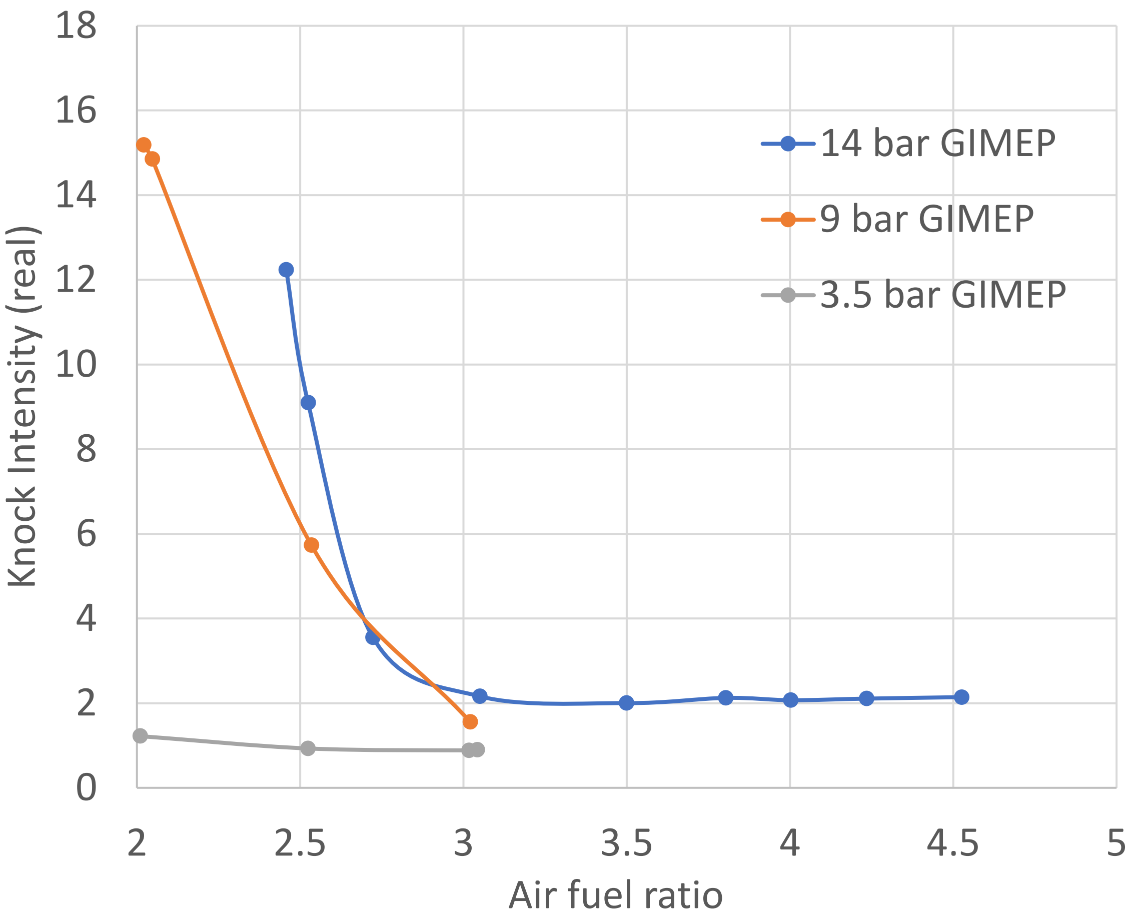
Knock intensity, 900 rpm



Note: ignition timing changes for some points

Brighton Ricardo test work has shown the relationship between backfire and preignition for this direct injection engine

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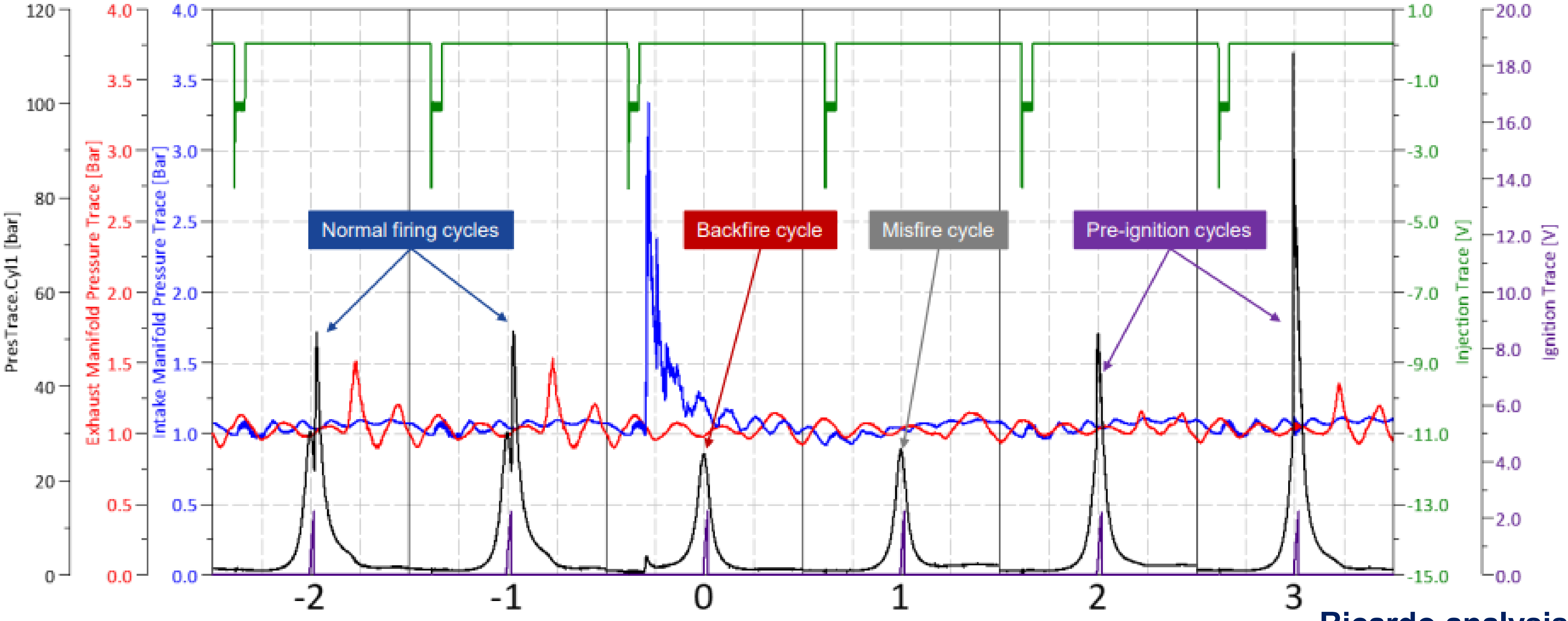
Backfire event example, 900 rpm, 9 bar GIMEP, lambda 1.1



Ricardo analysis

To succeed, hydrogen engines must meet heavy duty operator requirements and environmental objectives

- Near zero NOx emissions are possible with high air fuel ratios, EGR and water injection
- If high AFRs are used to manage NOx, the high air flow rates needed require boost system development
- Knock and preignition must be carefully managed to support durability
- WTT emissions of H_2 can mean that hydrogen powertrain WTW GHG emissions are worse than fossil diesel
- Further work at Brighton – hydrogen fuelled recuperated split cycle engine
- Thanks for your attention and questions, stay in touch: p.a.atkins@brighton.ac.uk