Driving Cleaner Performance

Westport™ Fuel Systems

NGVTF: Westport's HPDI™ Omni-fuel Technology

January 2023

Overview

- Overview of Westport Fuel Systems
- HPDI™: What is it?
- Hydrogen Combustion with HPDI

Alternative Fuel Capabilities

Broad Range of Products that Deliver Emission Reductions

LPG

Liquefied Petroleum Gas / Propane / Autogas

- Components and complete systems
- Light-duty applications – vapor and liquid LPG
- Monofuel, bi-fuel, dual fuel solutions
- The most commonly used alternative fuel in the world

CNG

Compressed Natural Gas

- Components and complete systems
- Light- and medium-duty applications
- Monofuel, bi-fuel, dual fuel solutions

LNG

Liquefied Natural Gas

- Complete systems
- Heavy-duty and high horsepower applications
- Monofuel and dual fuel solutions

H_2

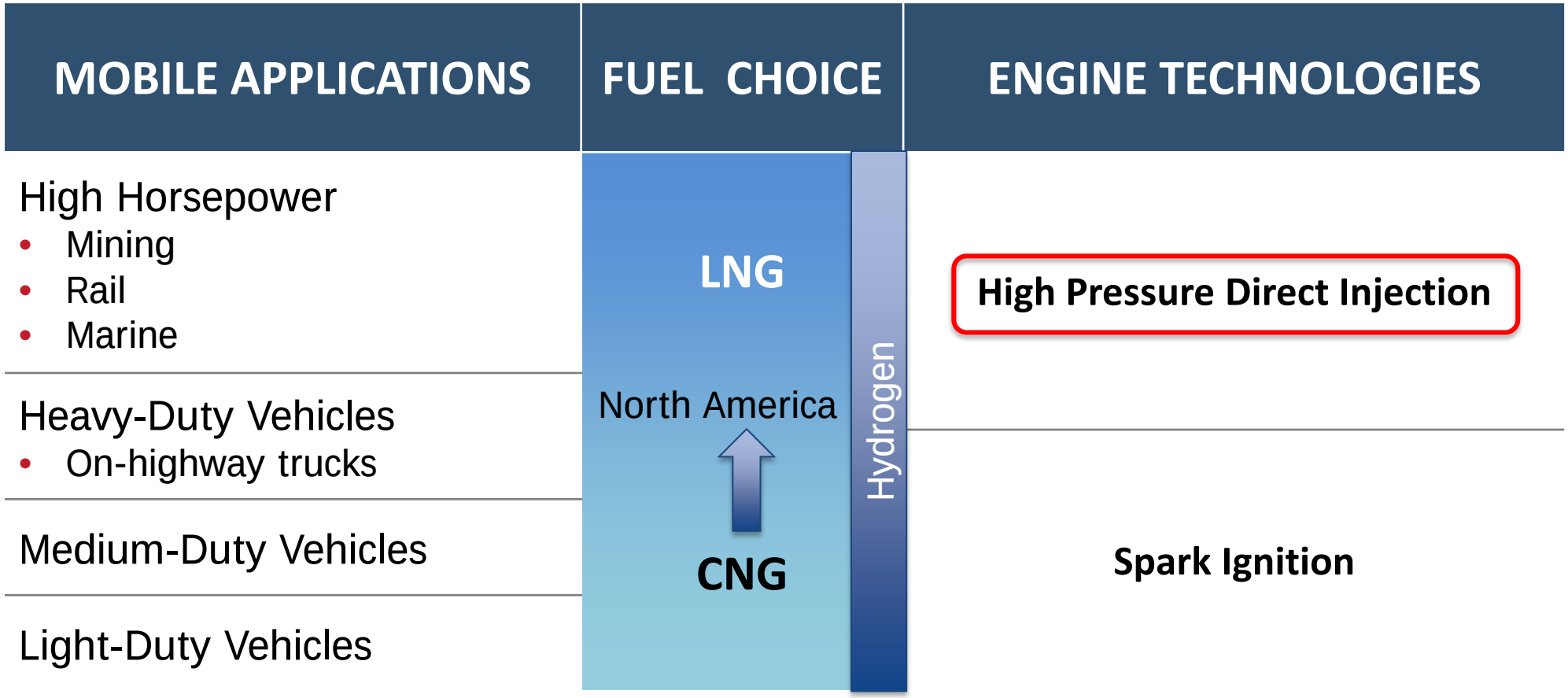
Hydrogen

- High- and low-pressure components
- Light- to heavy-duty and industrial applications
- Hydrogen/CNG blends or pure hydrogen

All Available as Renewable Fuels

Substitute for fossil based fuels

Technology Application




Westport HPDI™
So... What is HPDI and why is it different?

What Is Westport HPDI™ ?

High Pressure Direct Injection of Natural Gas is the most efficient approach to reducing CO_2 emissions using natural gas

Key enabling components are:

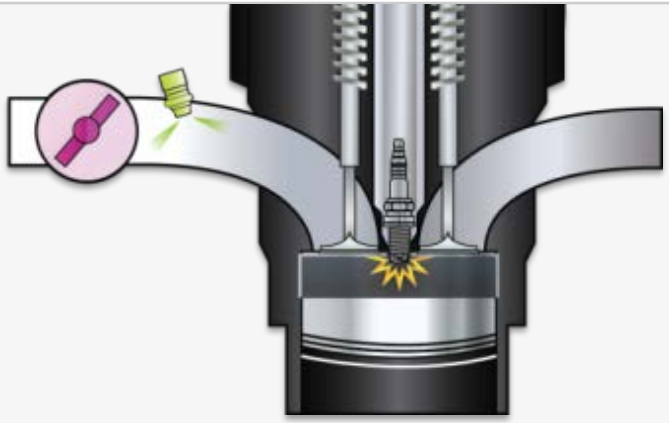
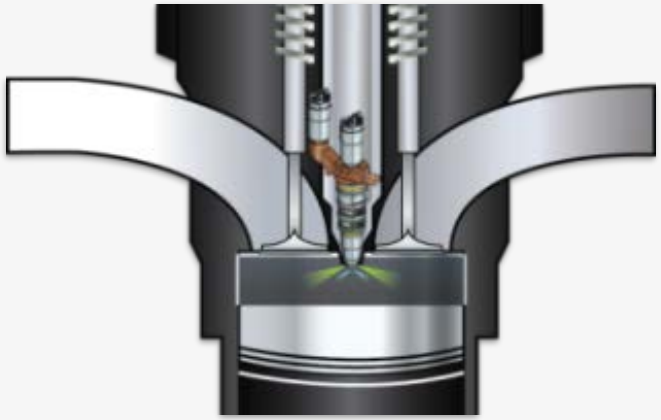
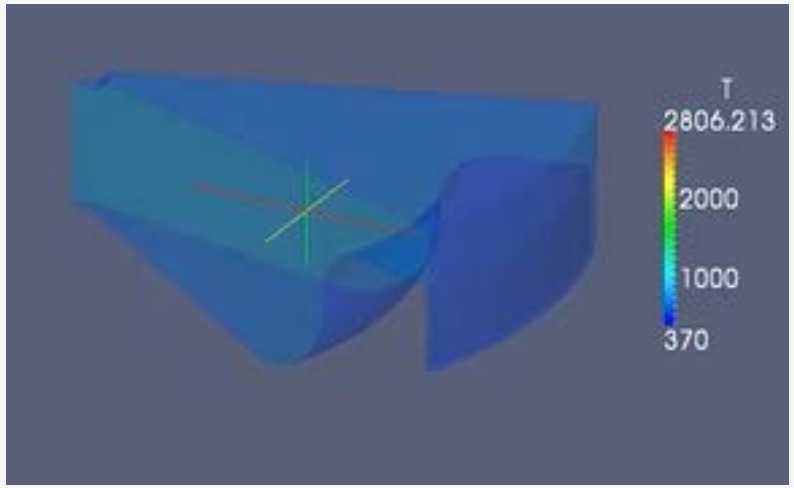
- Unique injector with a diesel pilot
- Fuel regulator
- An LNG or CNG system to provide natural gas to the engine

Engine Performance remains

- Matches diesel engine power and torque curves
- Matches diesel fuel efficiency (within 1%)
- Full diesel engine drivability and engine braking performance
- Within diesel engine mechanical and thermal limits

GHG benefit 20% over diesel engine (>85% on renewable gas with suitable blends)

Technologies – HPDI & Spark Ignited Natural Gas

	 **Spark Ignited**	  **Compression Ignition (HPDI)**
How it works	• Fuel & air pre-mixed at low pressure • Dedicated natural gas (100%) • Ignition from spark plug • Reduced compression ratio to avoid knock • Simple 3-way catalyst • Otto cycle (Stoichiometric)	• High pressure direct injection of gas into combustion chamber • Compression Ignition from diesel pilot • Same compression ratio as diesel to retain high efficiency • SCR & DPF (same as diesel) • Diesel cycle - high substitution (~94% on typical road cycle)

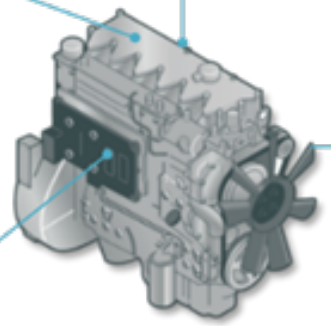
Westport HPDI™ HD Truck Solution – A Look Forward

On Engine

High Pressure Direct Injector

Gas Rail

OEM Engine



Revised Gas Conditioning Module (GCM)

On Chassis

Integrated Gas Module

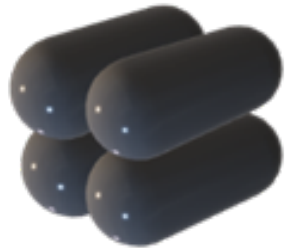
HPDI Control Software

Off-Engine System

Teaser

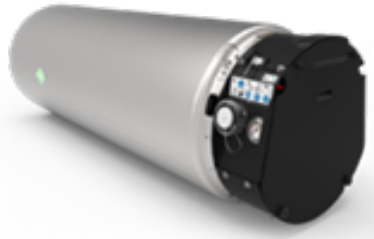
H2 / CNG

H2 Compressor
Adaptable for CNG



H2 Smart Tank Array

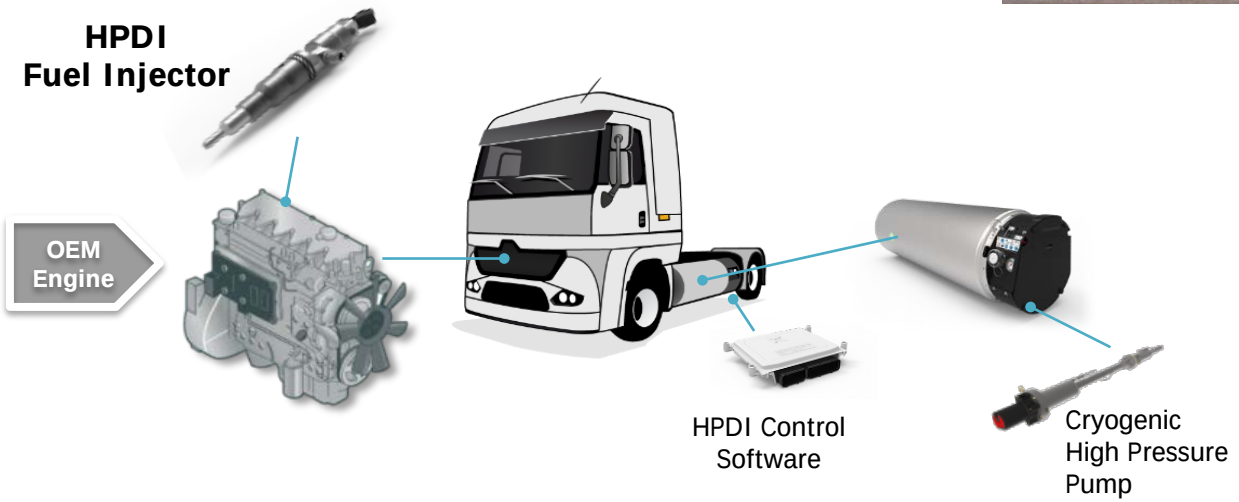
LNG



Cryogenic High Pressure Pump

A Few LNG Examples on the Road Today in Europe

- One UK customer started with 2 HPDI-equipped LNG trucks in 2018
- This year they will grow to close to 800 HPDI-equipped LNG trucks at 18 locations
- The final phase will see almost 1000 trucks all on bioLNG at 22 locations



HPDI – The Story has Just Begun

The current iteration of HPDI has proven to be a popular choice in Europe due to the diesel-like performance and efficiency coupled with the Greenhouse Gas reduction

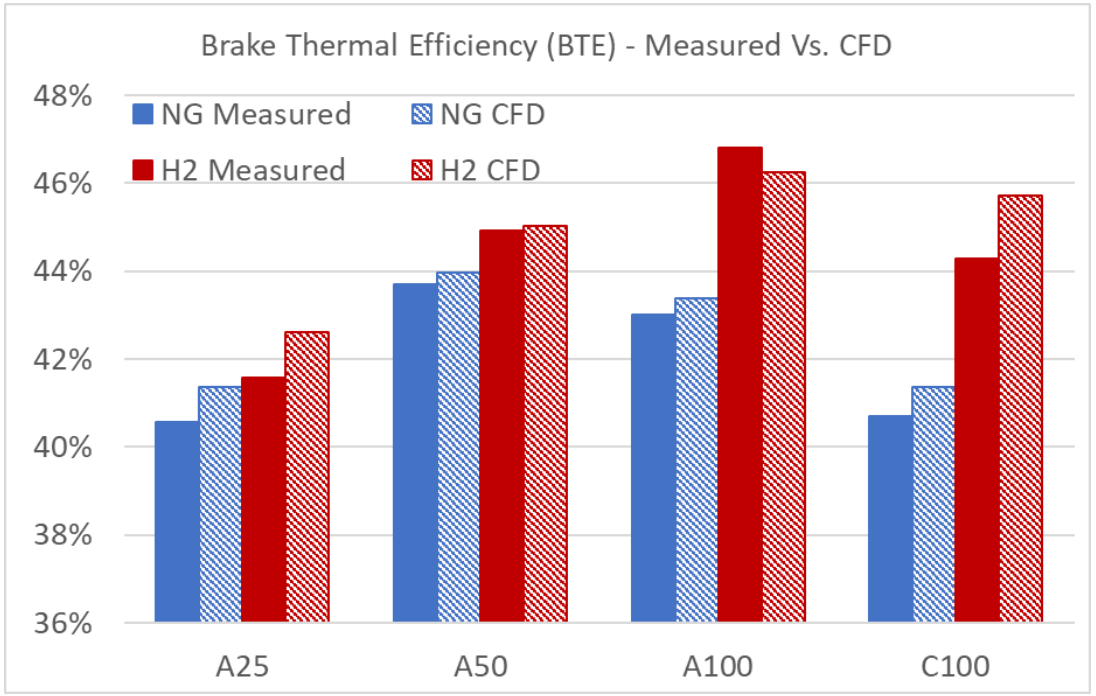
- Strong market demand for trucks fueled by LNG and biomethane as effective and affordable lower carbon solutions
- Continuously improving fuel availability

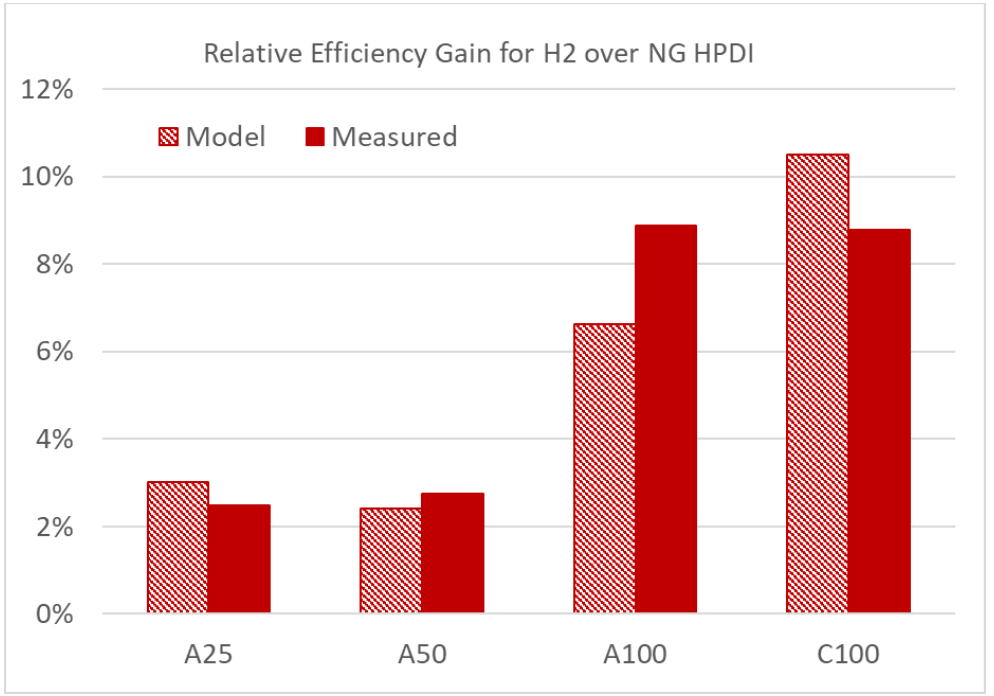
A great start, but this is just the beginning...

Hydrogen Combustion with HPDI

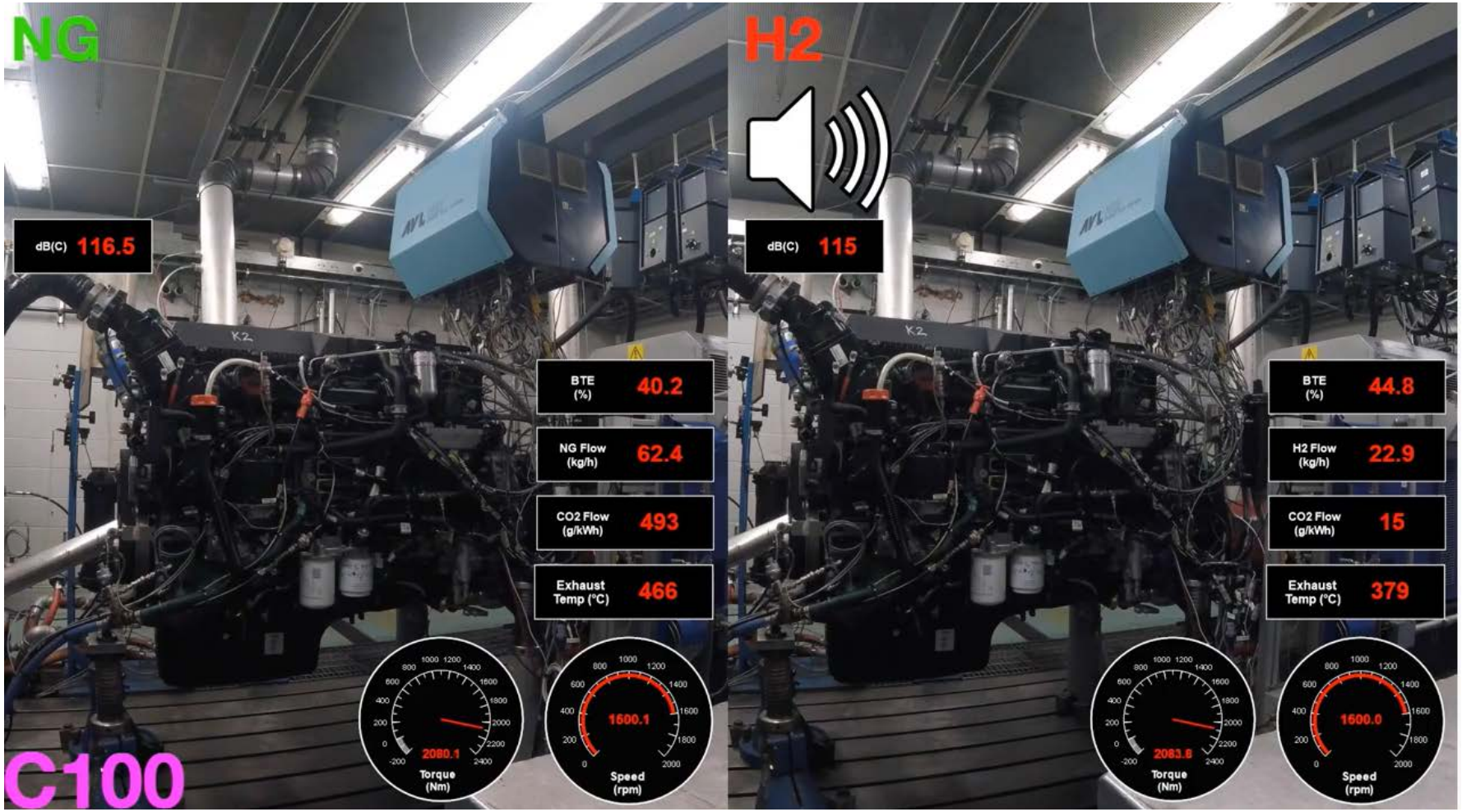
Engine Test Data – H_2 HPDI

- WFS' preliminary combustion CFD modeling of H_2 HPDI showed very promising engine efficiency, sufficient to justify testing an existing (unmodified) heavy-duty NG HPDI engine on H_2
- Engine test data confirmed the CFD modelling, thus demonstrating the compelling performance and efficiency benefits of H_2 HPDI
  - Full load H_2 HPDI BTE ~46-47%, vs. 41-43% for NG HPDI
  - Relative efficiency gain (H_2 vs. NG) is larger at high load points





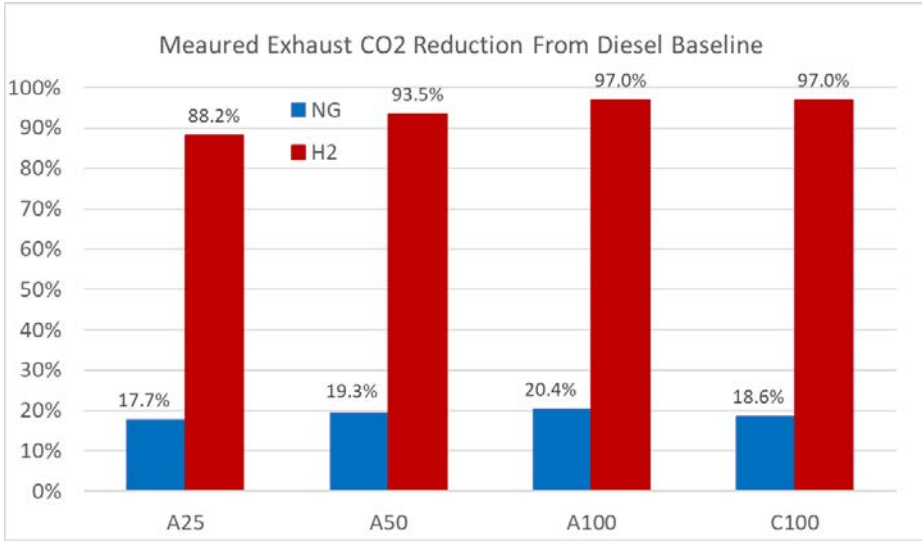
WFS Currently Operating H_2 HPDI in Vancouver Test Cell



https://www.youtube.com/watch?v=E3FZjMoDRZ0

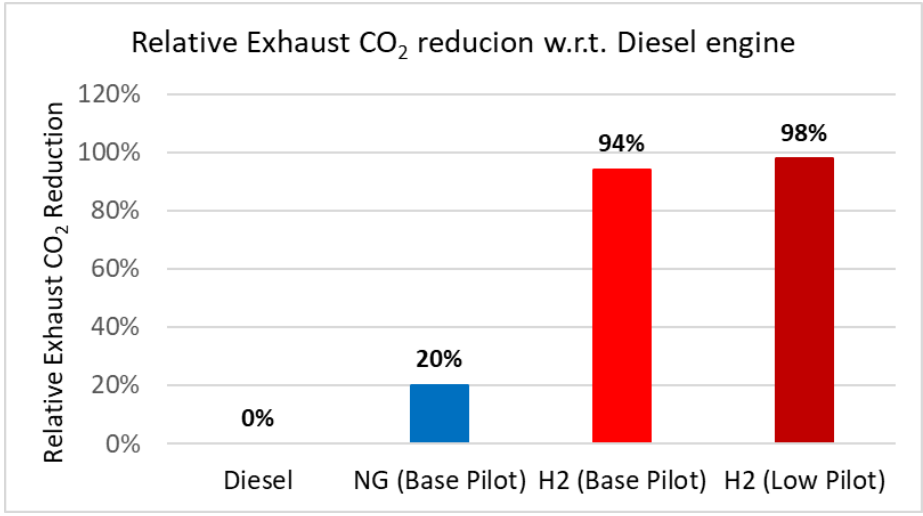
H_2 HPDI - Tailpipe CO_2 Reduction

Pilot Qty	Pilot Energy%	Main Fuel	Brake Specific CO2	CO2 %Reduction	Ignition Stability
mg/Str			g/kW.h		
	NA	Diesel	597	0.0%	Baseline Diesel
5.34	2.09%	NG	482	19.3%	Baseline NG HPDI
5.34	2.09%	H2	13.2	97.8%	Baseline H2 HPDI
2.67	1.04%	H2	6.6	98.9%	Little Impact
1.34	0.52%	H2	3.3	99.4%	Little Impact
0.67	0.26%	H2	1.7	99.7%	Longer Ign. Delay, Little HRR Spike
0.33	0.13%	H2	0.8	99.9%	Longer Ign. Delay, HRR Spike



Options exist to lower the residual CO_2 emissions from the H_2 HPDI engine by reducing pilot fuel quantity, or utilizing a low/zero-carbon content pilot fuel.

H_2/air mixture is known to have substantially lower minimum ignition energy compared to natural gas/air mixture. Results are shown here for reduction in pilot fuel quantity.

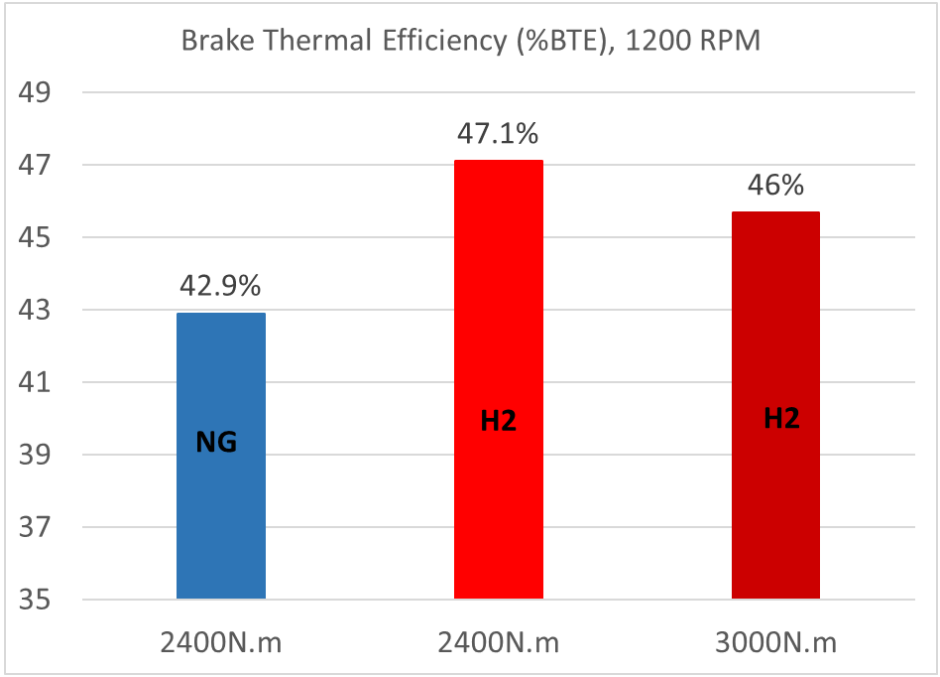


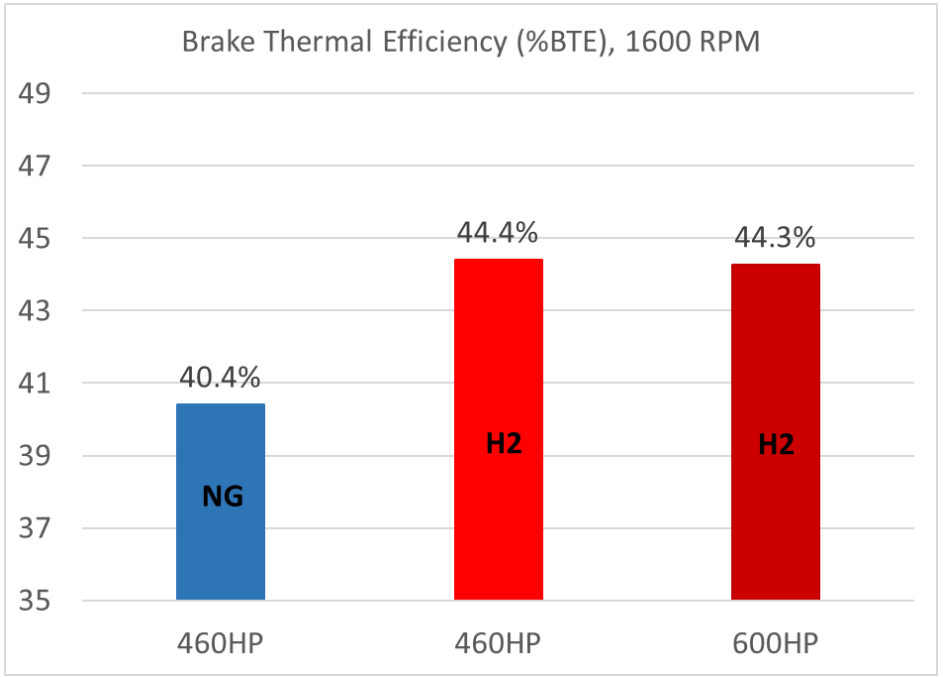
H_2 HPDI - High Performance with High Efficiency

Analysis & modeling indicated the potential for H_2 HPDI to achieve 15-20% higher BMEP than NG HPDI or diesel engines.

Testing has validated that H_2 HPDI can yield significantly higher peak torque and power than the base NG HPDI or diesel engine, by leveraging the combustion characteristics of H_2 and without exceeding engine mechanical limits.*

H_2 HPDI enables higher vehicle performance and/or significant engine down-sizing, with associated cost savings.



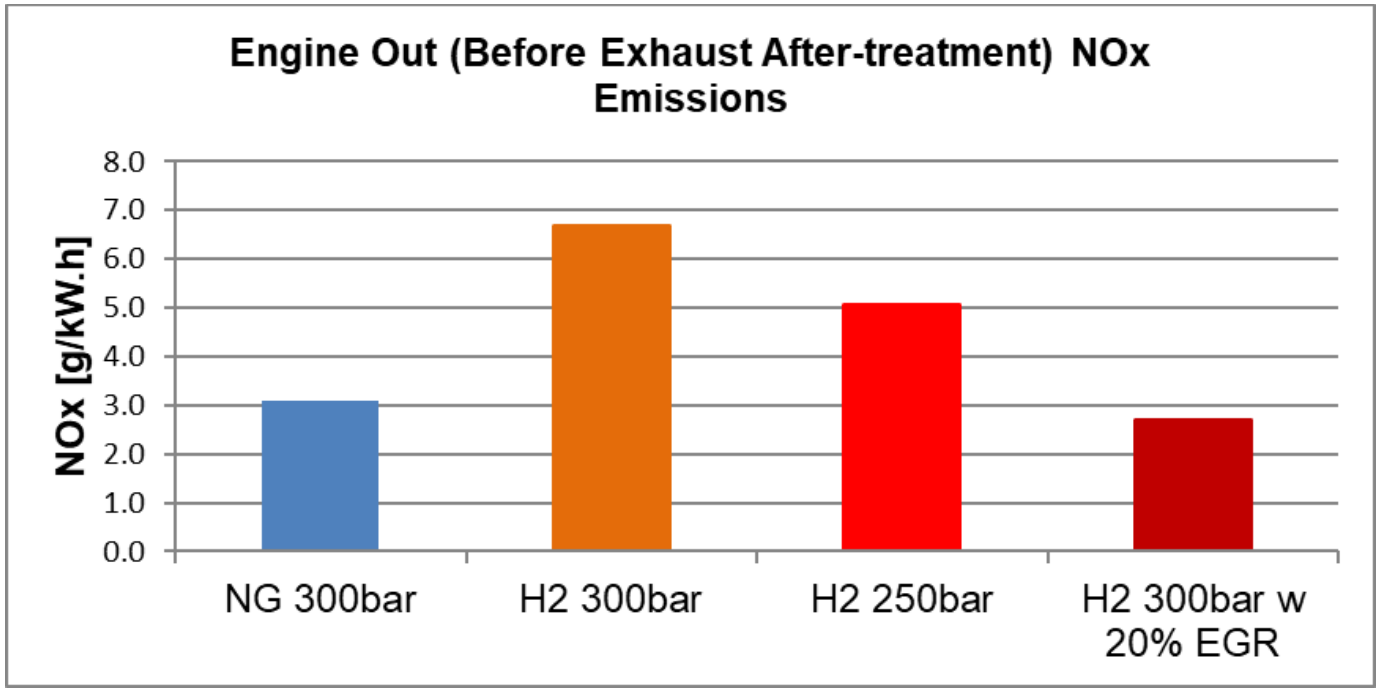


* The NG baseline values shown in the figures above should not be interpreted as an upper limit for NG HPDI, as the NG HPDI torque and power shown above are known to have room for further improvement, as demonstrated in a separate program. For guidance, the actual improvement in maximum achievable H_2 HPDI torque and power, as compared to the maximum achievable NG HPDI torque and power, is approximately 15-20%.

H_2 HPDI - Engine-Out NOx Emissions

- Higher flame temperature and more abundant excess air for H_2 HPDI increases the rate of NOx formation
- Fuel injection pressure, timing, & EGR are effective in bringing engine-out NOx down to levels similar to or lower than NG HPDI, while maintaining significant IMEP and ISFC advantages

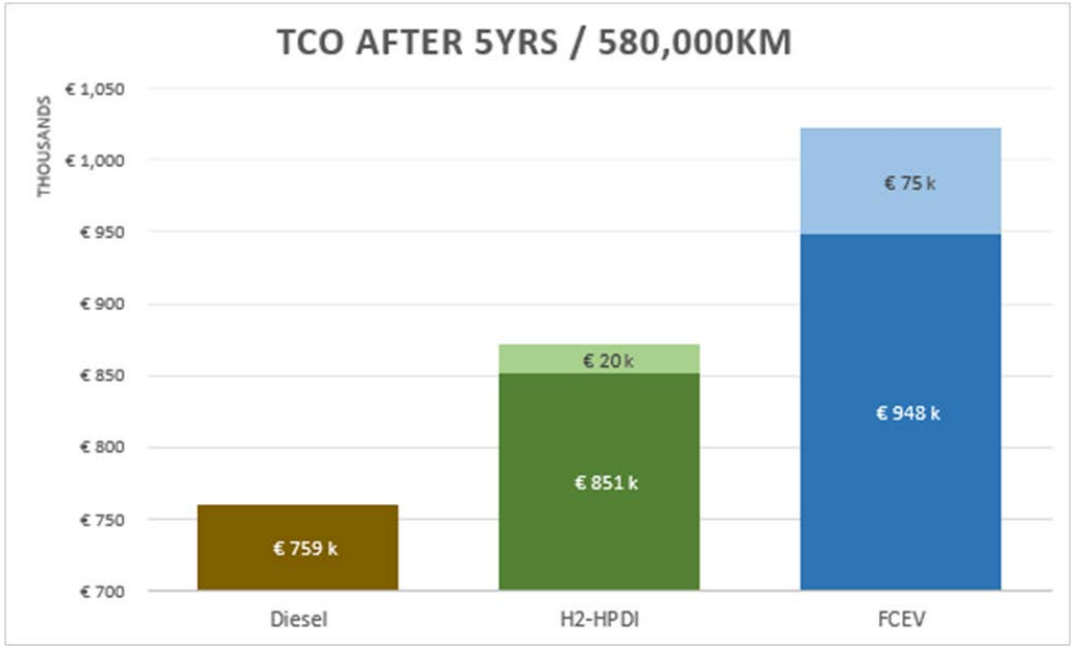
	IMEP	ISFC	NOx
	bar	g/kW.h	g/kW.h
NG 300 bar	21.6	198	3.1
H2 300 bar	24.5	178	6.7
H2 250 bar	23.0	188	5.1
H2 300 bar with 20% EGR	24.1	186	2.7

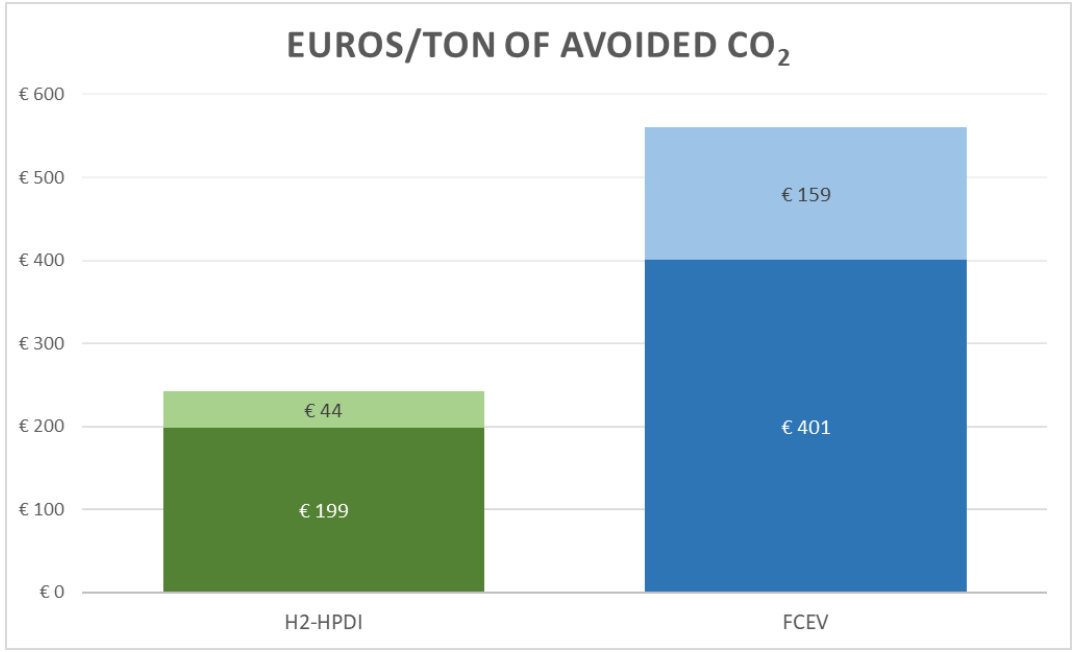


H_2 HPDI – A Cost-Effective Path to Zero Carbon

Joint WFS / AVL TCO study showed an overwhelming advantage for H_2 HPDI vs. FCEVs in terms of Total Cost of Ownership, mainly due to the significantly lower vehicle cost for H_2 HPDI, and similar operational costs.

The cost of CO_2 avoidance, relative to diesel, is also drastically lower with H_2 HPDI vs FCEV.





H_2 HPDI trucks can provide lower Total Cost of Ownership and much more cost-effective CO2 reduction than fuel cell trucks.

Study: Westport Fuel Systems - Westport Fuel Systems and AVL Joint Paper Assesses Total Cost of Ownership for Hydrogen Internal Combustion Engines (wfsinc.com)

WFS and H_2 HPDI are Well Positioned for Commercial Success

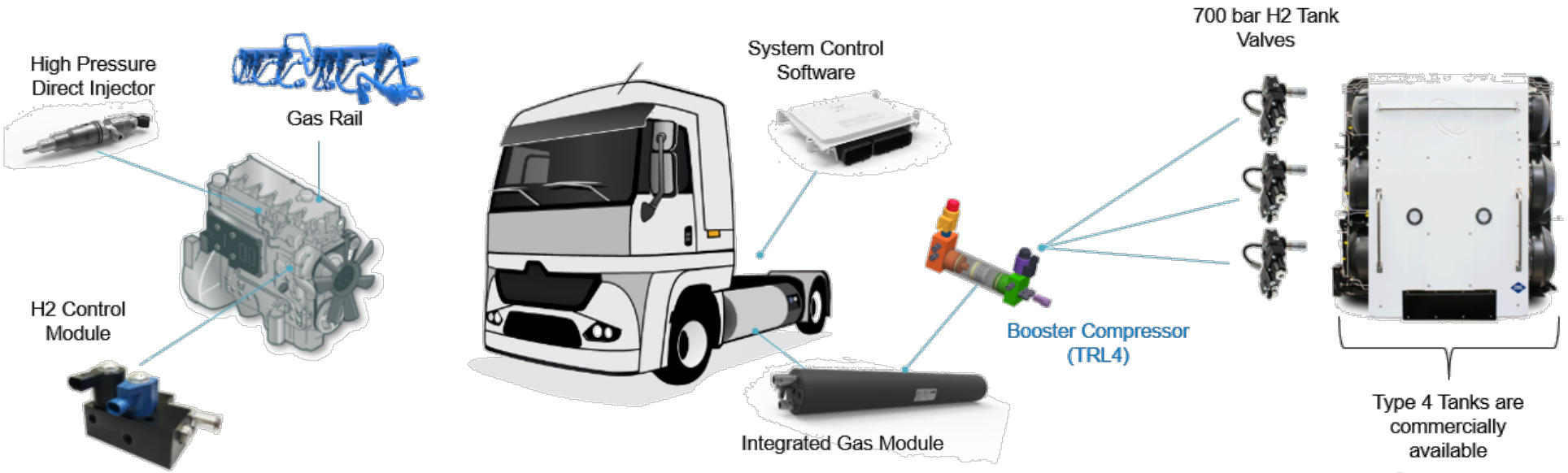
H_2 HPDI can leverage the same on-engine fuel system components we sell today

H_2 HPDI can leverage the same off-engine storage system as FCEVs, plus a booster compressor

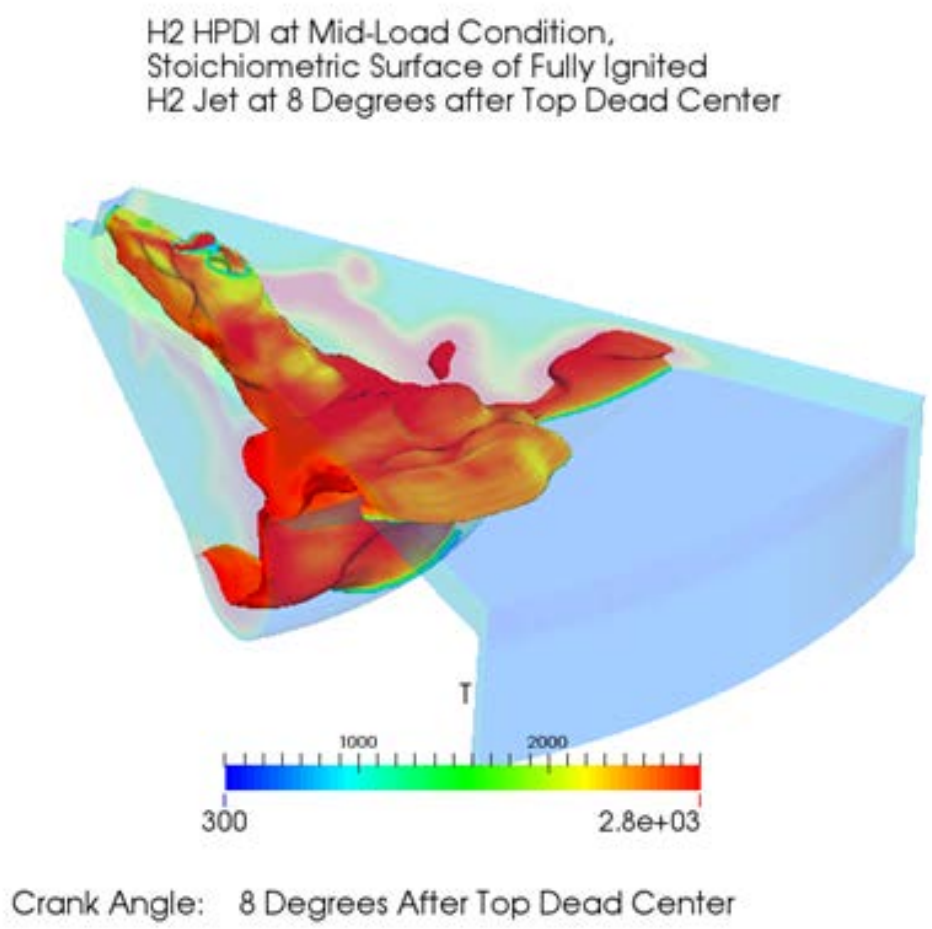
- WFS supplies H_2 tank valves, regulators, PRVs for FCEVs today, via our GFI brand
- WFS has a NG booster compressor at TRL 4. H_2 compressor development & integration are underway

Growing interest in H_2 HPDI from OEMs.

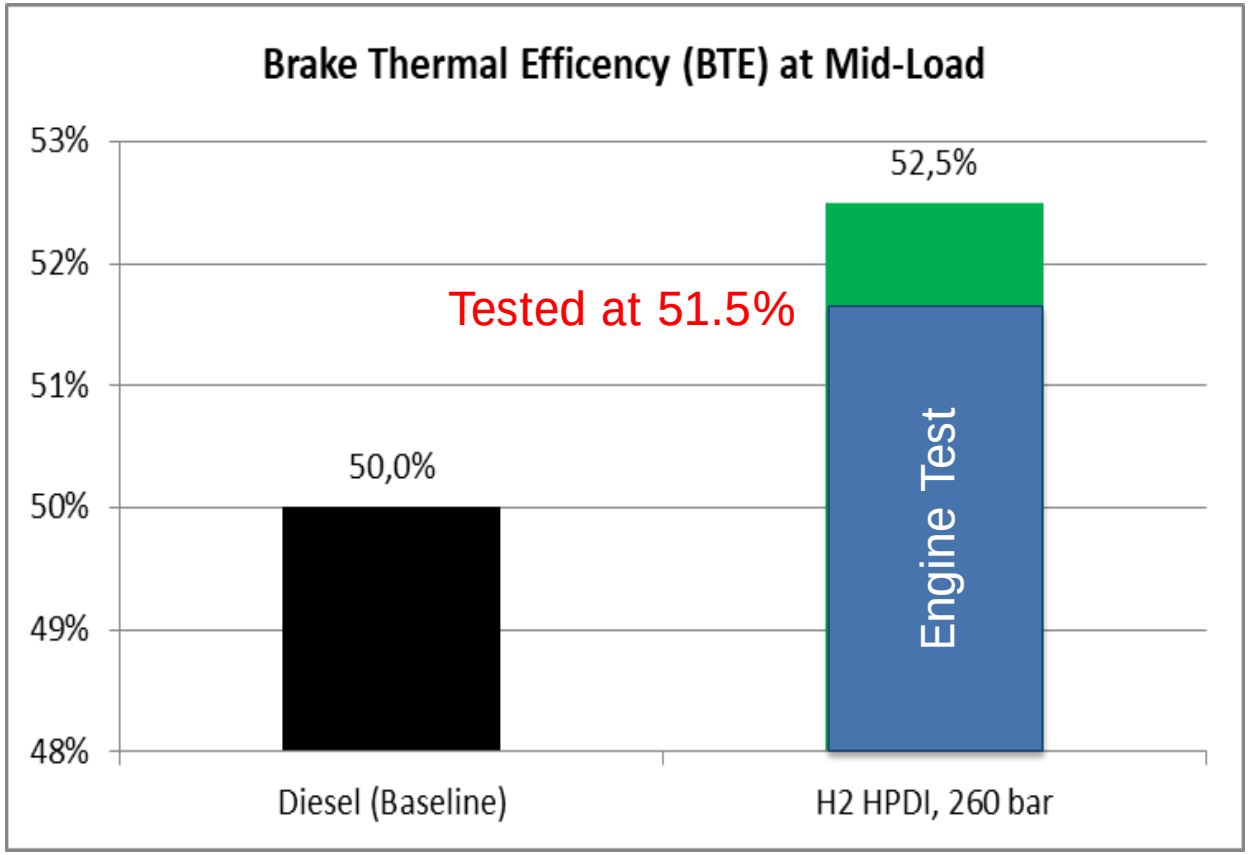
- Multiple engine programs (single and multi-cylinder) are underway with both announced and unannounced OEM customers
- These include Scania and Tupy / AVL



H_2 HPDI – Next Generation HD Engines (CFD)



CFD visualization of the fully ignited hydrogen jet at mid-load condition (50 % load at 1200 RPM).



CFD comparison between diesel and hydrogen (H_2) HPDI.

Summary & Next Steps

WFS has examined the combustion properties of hydrogen as an alternative, zero-carbon fuel for internal combustion engines for heavy duty applications.

Combustion modelling and engine testing have demonstrated that among the combustion systems investigated (PFI SI, ECDI SI and HPDI), HPDI combustion offers the **highest power density**, **highest efficiency** and is the **most robust system** for using hydrogen in an internal combustion engine for **heavy duty applications**.

H_2 HPDI provides near-zero CO_2 emissions in its current configuration, with further CO_2 reduction opportunities identified for future study and development.

H_2 HPDI offers lower TCO and more cost-effective CO_2 reductions than FCEV heavy duty trucks.

H_2 HPDI interest is growing from OEMs, with multiple H_2 HPDI development projects recently announced and underway.

Thank you.

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