H_2 HPDI: A Gamechanger in the H_2 Society

September 2022

We're Changing the Way the World Moves

Delivering advanced, proprietary, market-ready alternative-fuel systems for today's combustion-powered vehicles that lower fuel costs and cut carbon emissions without sacrificing performance.

Tier 1
Transportation supplier with diverse business units

Manufacturing
7 global locations

Accessing
Full suite of renewable and alternative fuels

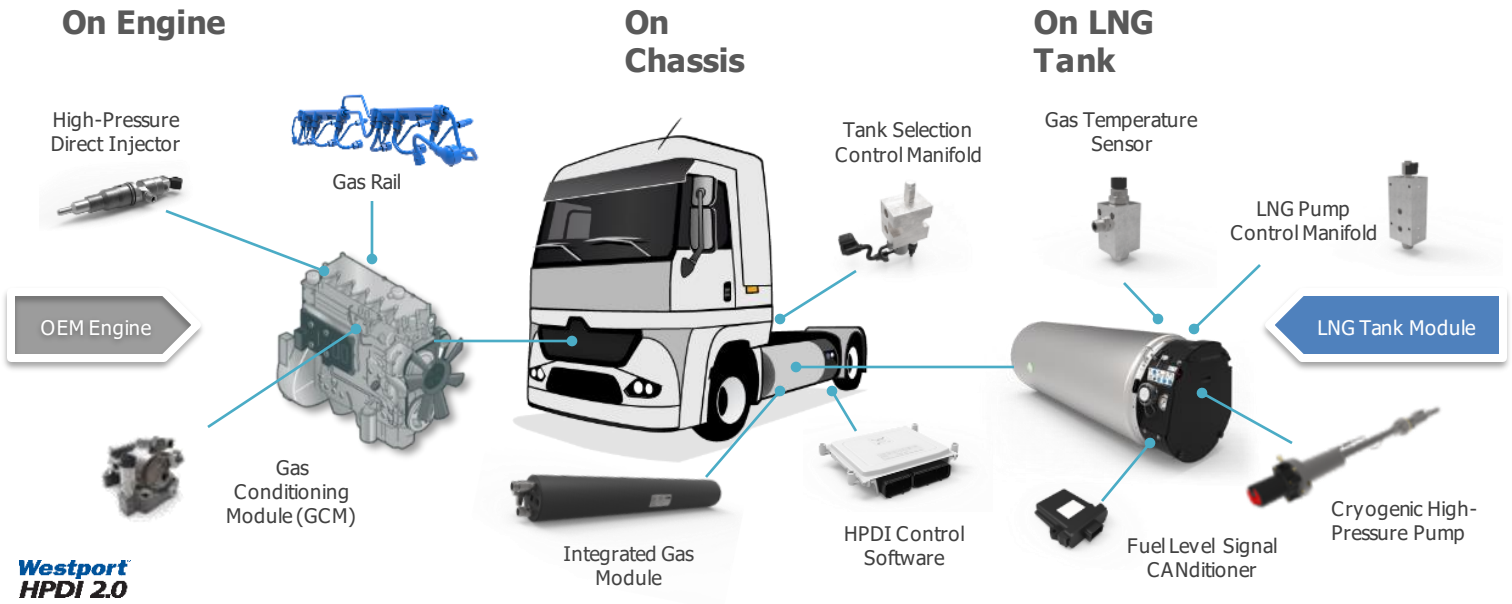
Sales in 70
countries, strong global footprint

>100
Global distributors worldwide

>1,400 Patents & Applications
Robust patent portfolio

We design, engineer, and manufacture clean fuel systems and components that address the challenges of climate change and meet stricter carbon emissions regulations.

HPDI HPDI 2.0™ is a High-Performance, Low-Emissions Fuel System Solution for Today's Combustion-Powered Heavy-Duty Trucks



HPDI: Cost-effective

HPDI is the most cost-effective way to reduce CO_2 in long-haul trucking and other high-load, long-haul applications.

HPDI: LNG

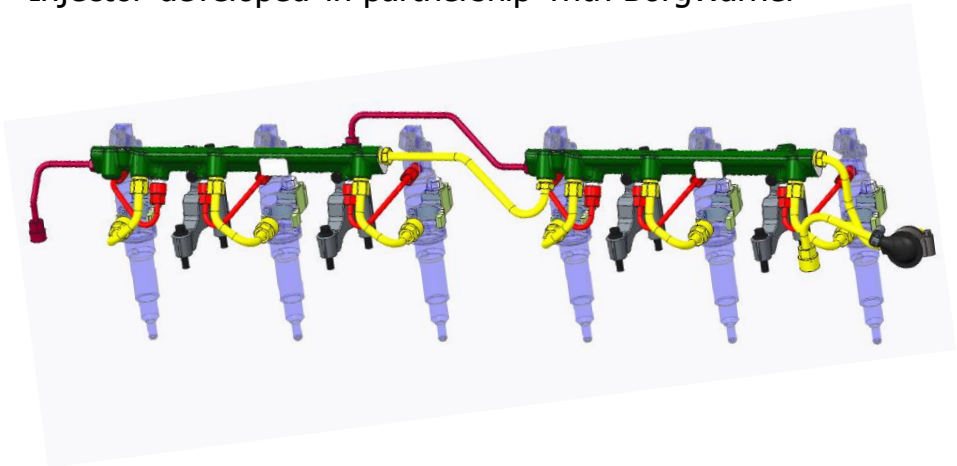
- Same torque, efficiency, and reliability as diesel engines
- **20% CO_2 reduction tailpipe**
- **100% CO_2 reduction with bio-LNG**
- No change to vehicle or engine architecture

H_2 HPDI

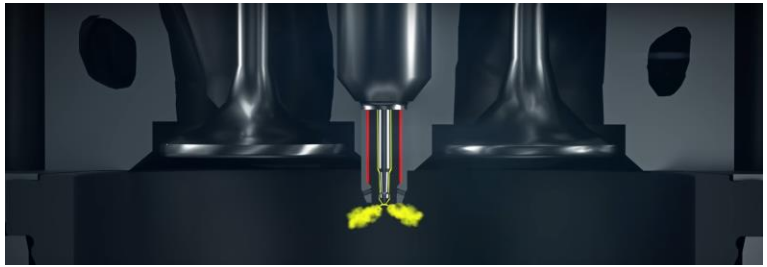
- 20% more power, 15% more torque
- **Near Zero CO_2 emissions**
- **Lowest cost to CO_2 compliance**
- Preserve existing engine manufacturing

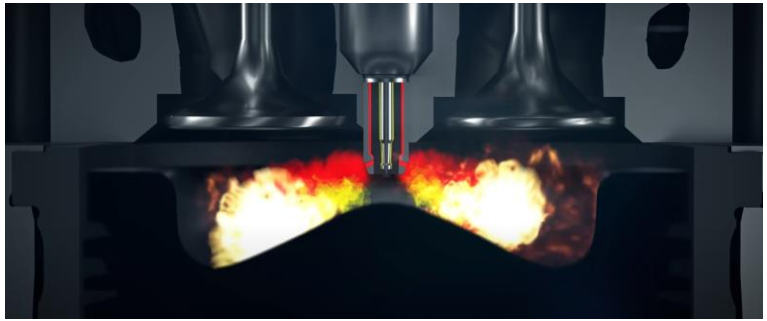
Injector and Rails

- Fits in a wide range of HD engines
- Improved reliability and durability
- Reduced cost
- Injector and rail designed for 500 bar capability
- Certified to R110
- Injector developed in partnership with BorgWarner

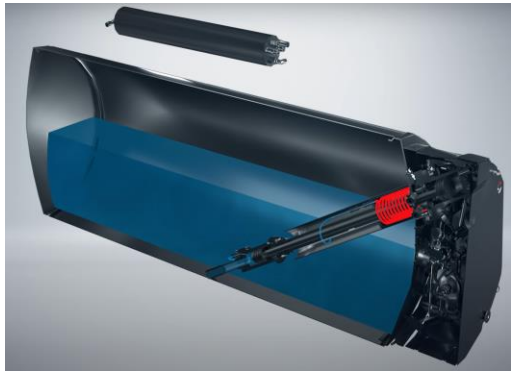


HPDI LNG & H_2





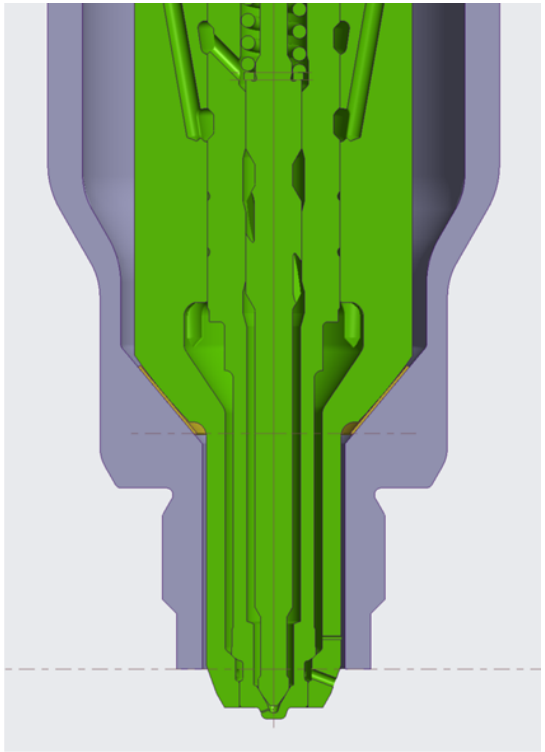
https://www.youtube.com/watch?v=KNGzgzmFIV0



Liquid LNG / H_2 Storage

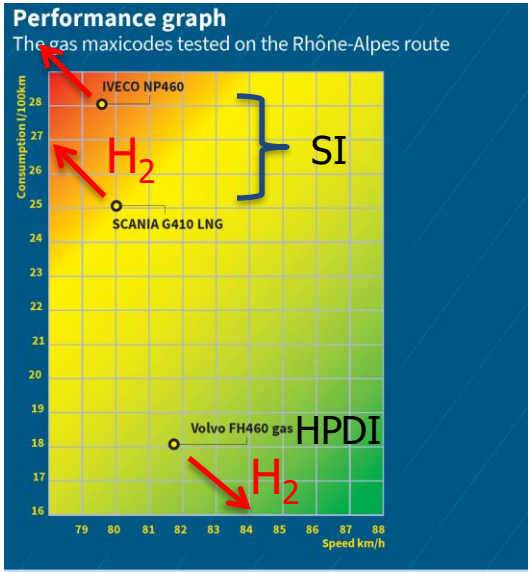
Compressed 700 bar H_2 Storage

HPDI LNG & H_2



HPDI nozzle with 2 concentrical needles

Fuel Consumption Comparision HPDI vs. SI LNG



IVECO STRALIS NP 460

Consumption: 28.1 kg gas per 100 km
Commercial speed 79.63 km/h

SCANIA G410 LNG:

Consumption: 25.1 kg gas per 100 km
Commercial speed 80.03 km/h

NEW VOLVO FH13 460 LNG:

Consumption: 18.2 kg gas per 100 km
Commercial speed 81.87 km/h
Note:
+ 1.2l/100 km of diesel
+ 1.2l/100 km of AdBlue

- Three brands were compared in a defined route by magazine "FrenchRoutes" in April 2022. HPDI has by far the lowest fuel consumption and, in the same time, the highest commercial speed during the mission

- When operating on Hydrogen (H_2), the HPDI system will:
  - Achieve higher efficiency than a fuel cell vehicle
  - Perform better than a fuel cell vehicle

  At a fraction of the cost of a fuel cell vehicle

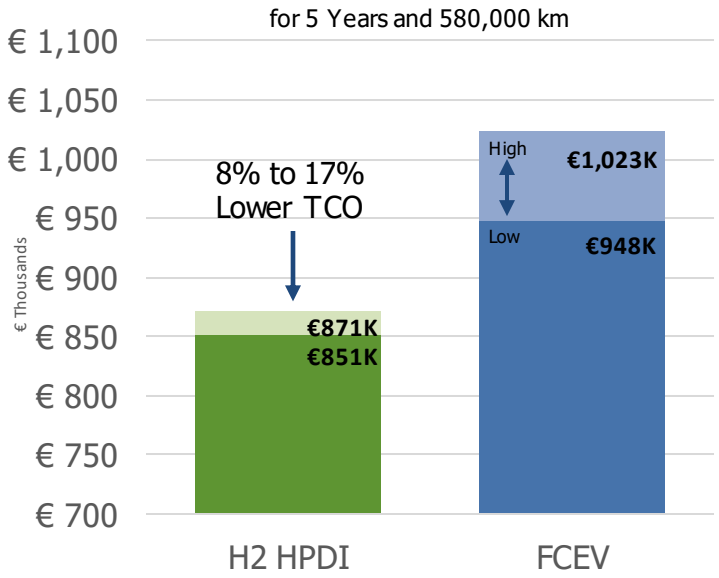
H_2 HPDI the Gamechanger

- One challenge for H_2 as a fuel in HD vehicles is range due to the low energy density of the fuel. This is valid both for compressed (700 bar) and LH2. Engine efficiency is key.
  - **H_2 HPDI 90kg H_2 => 900 km range**
- H_2 HPDI offers higher efficiency than corresponding diesel engine, **5-8% higher efficiency**
- At high load H_2 HPDI is even more efficient than a fuel cell on vehicle level.
- With the introduction of H_2 HPDI, HPDI is no longer a methane "bridge" technology and will be competitive with FCEV near and long term
- High commonality between Diesel, CNG, LNG and H2 operation. Only fuel system is exchanged.
- Ignition initiator fluid (pilot) can be significantly reduced. The latest proposal for ZEV definition will be fulfilled by the Westport H2 HPDI technology.

TCO Analysis of H_2 HPDI

H_2 HPDI: Pathway to Near-Zero Emissions

Total Cost of Ownership (TCO)



Source: AVL / Westport TCO study, 2021

Benefits vs. Fuel Cell

For the Truck Customer

- Lower upfront acquisition costs
- Proven truck design and durability
- Familiar truck operation

For the OEM

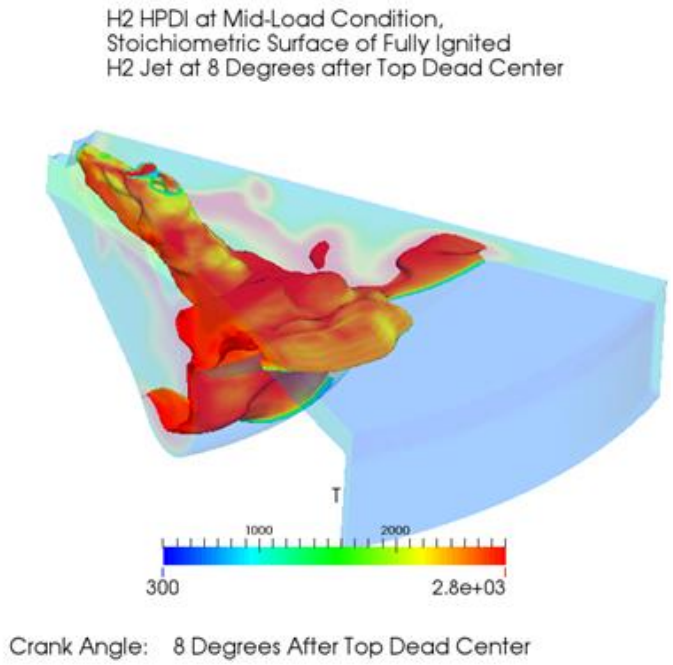
- Low product development cost
- Preserve current manufacturing, supply chain, and service infrastructure
- Avoid manufacturing investments for fuel cells, batteries, and motors

For the Environment

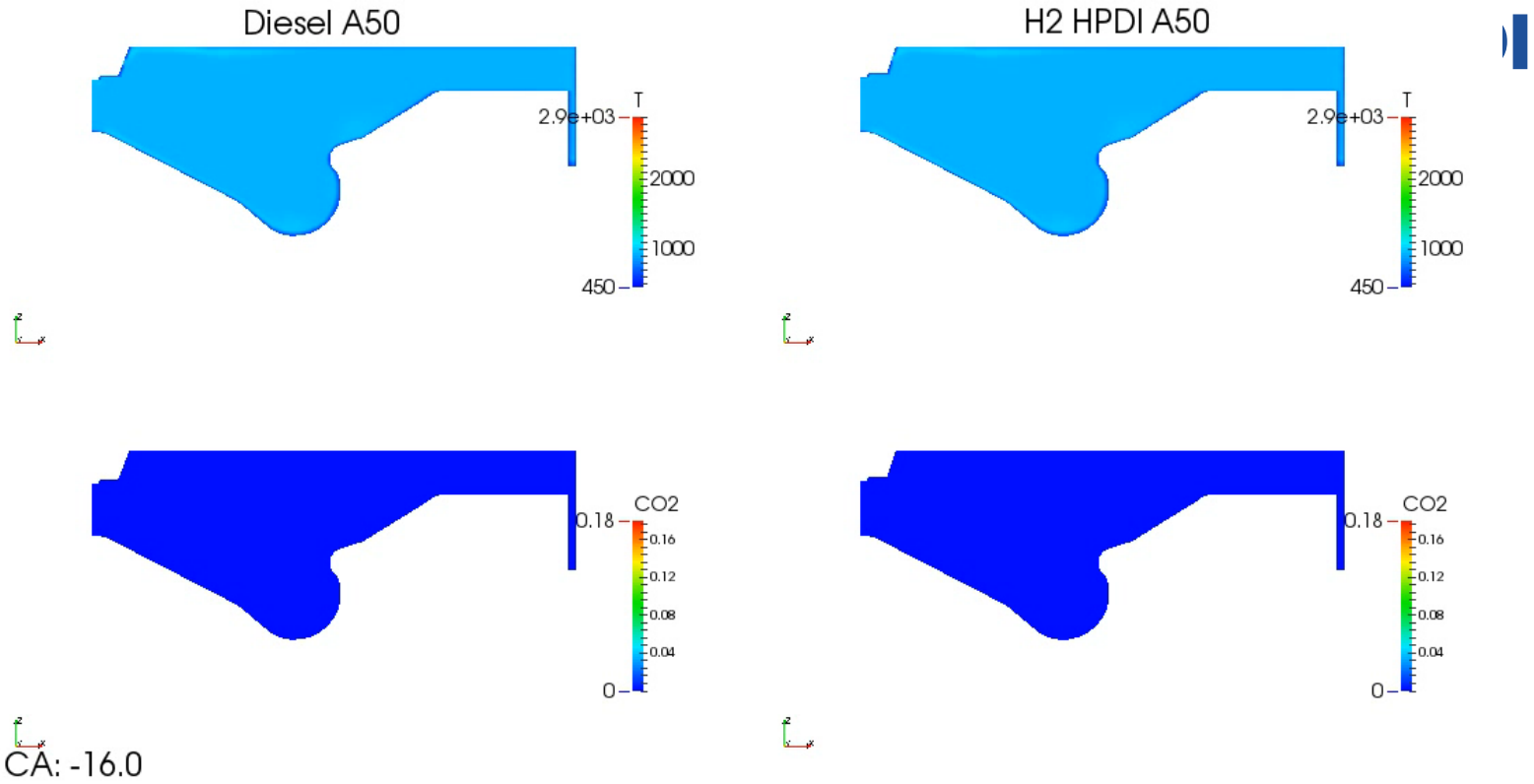
- Renewable, zero carbon fuel
- Lower investment path to reduce CO_2 in heavy-duty, long-haul trucking

Evaluation & Simulation of H_2 Combustion

H_2 HPDI Investigation on a State-of-the-Art HD Diesel Engine

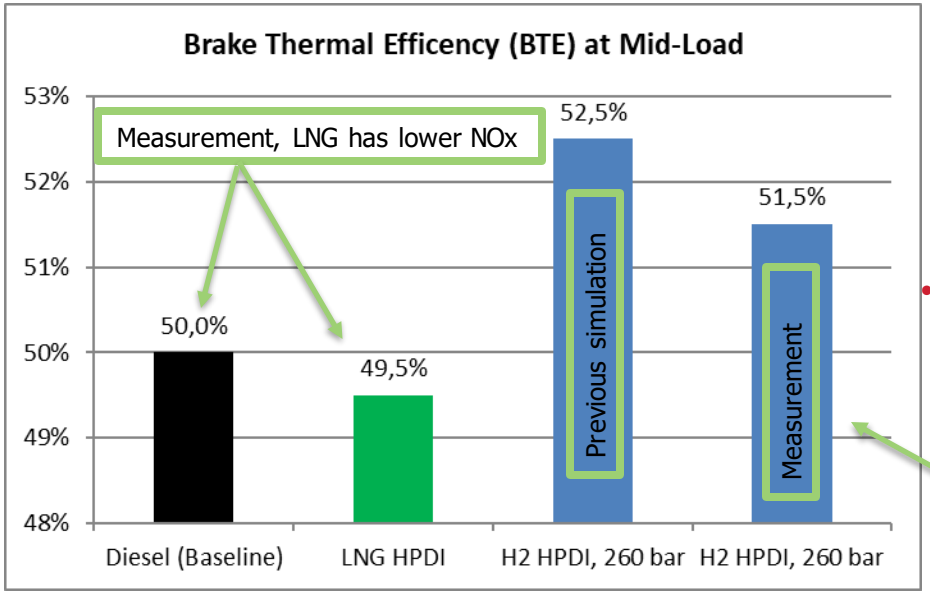


- Westport Fuel Systems carried out a simulation study on a heavy-duty diesel engine utilizing the WFS in-house state-of-the-art engine combustion CFD solver
- The model predictions have been validated against experimental engine test data over a wide range of operating conditions on multiple engine platforms for pilot-ignited gaseous fuel combustion over the last 15+ years including H_2
- Figure 1 shows the CFD visualization of the fully ignited hydrogen jet as the HPDI combustion is unfolding in the engine cylinder at mid-load condition (50% load at 1200 RPM). The CFD tool has been critical in investigating and optimizing HPDI combustion for H_2 fuel.



Flow Visualization for Temperature and CO2 Field During Diesel and H2 HPDI Combustion (Mid-load Point)

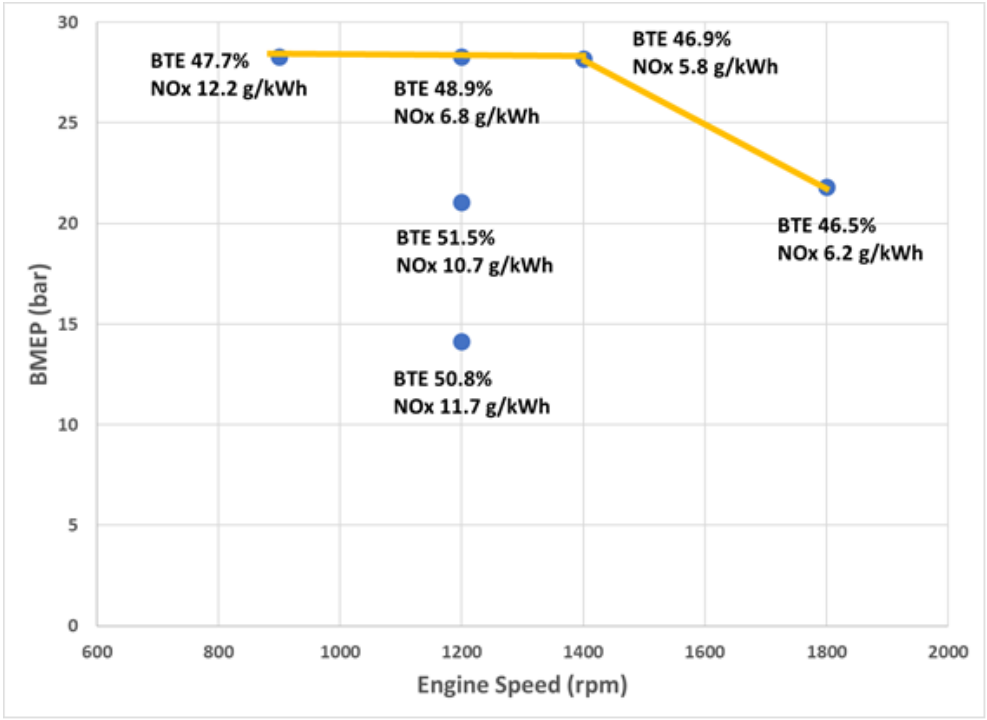
H_2 HPDI Investigation on a State-of-the-Art HD Diesel Engine



- CFD simulation shows comparison between diesel and hydrogen (H_2) HPDI. Baseline simulation is made on a diesel combustion system designed to achieve 50% BTE. As seen from Figure 2, the H_2 HPDI at mid-load (50% load) condition demonstrates a brake thermal efficiency (BTE) of 52.5% with 260 bar gas injection pressure.
- When compared with **measurements** it can be seen that:
  - High efficiency is achieved with LNG with lower engine out NOx.
  - 51,5% BTE with H2 HPDI with same engine out NOx as baseline diesel.

Measurement, SOI adjusted to same engine out NOx as diesel baseline

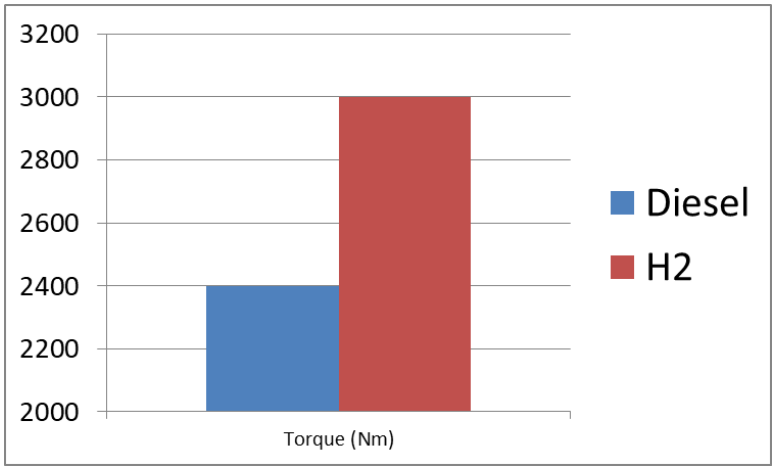
H_2 HPDI Investigation on a State-of-the-Art HD Diesel Engine



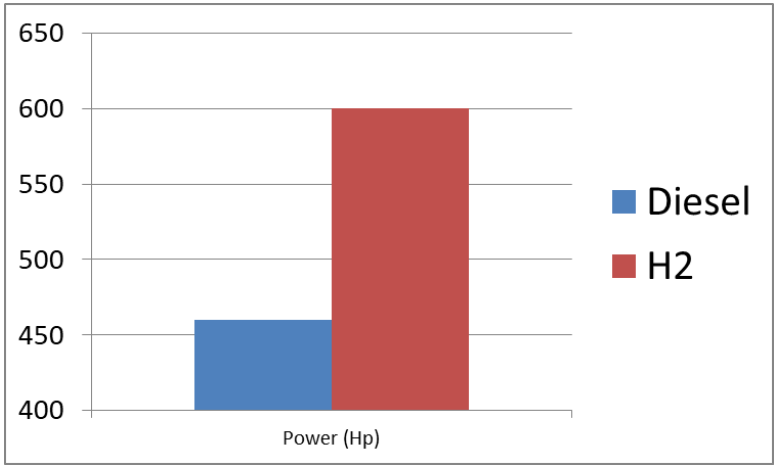
- Brief test results on the latest Scania engine
- Engine calibration is far from final. Further refinement is expected to further improve performance.
- No change to the engine except the fuel system. Same injector and nozzle specification as the LNG engine.

H_2 HPDI Initial Testing of Performance Potential

Torque



Power



Torque and power comparison of 13-liter engine with diesel and with H_2 HPDI (engine limitations like PCP, exhaust temp, and boost pressure kept below limit)

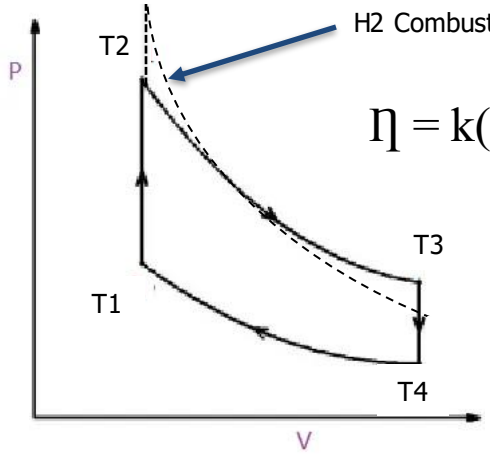
Why do H_2 HPDI enable higher power & Torque

$O_2 + 2H_2 = 2H_2O$ => 3.5 MJ/kg air

$O_2 + 0{,}41CH_{1,8} = 0{,}41CO_2 + 0{,}37H_2O$ => 2.9 MJ/kg Air

For a given airflow thru the engine H2 can release more energy than combustion of diesel.

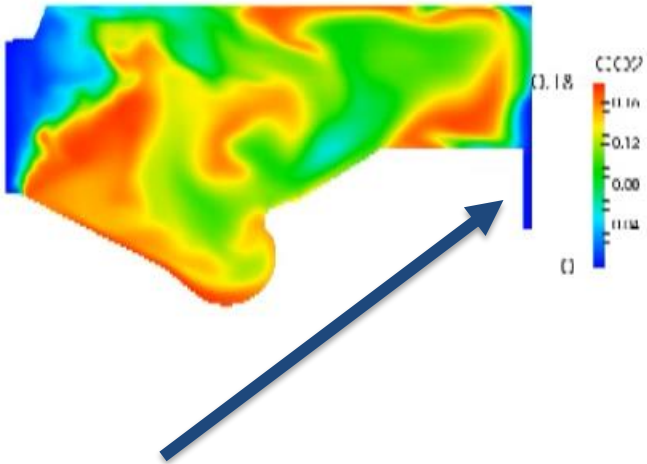
Why do H_2 HPDI enable higher efficiency



$$\eta = k(T2-T1)/(T3-T4)$$

1. **The low density H2 that is injected at TDC contribute to work when expanded during the expansion stroke.**
2. **The higher flame temp gives directly a better cycle efficiency.**
3. **The higher combustion speed enables a more favourable heat release close to TDC**
4. **As the H2 is injected a low pressure compared to diesel less turbulence is induced and therefore lower heat flux thru the combustion chamber walls.**

With H2 HPDI no special measures to crank case ventilation is required



Top-land is only filled with air.

For visibility, a diesel combustion is taken as an example. CO2 not traceable with H2 combustion. It is evident that with a diffusion flame combustion the top-land is only filled with air. Therefore, blowby gases will only consist of air.

In the case of homogeneous combustion (Spark ignited) the blowby will consist of both unburnt H2 and water vapor. Special measures for crankcase ventilation and avoidance of sludge required

Engine platform commonality

Fuel agnostic?

Engine platform commonality

One of the beauties with the HPDI technology is the great commonality with engine suitable for other fuels

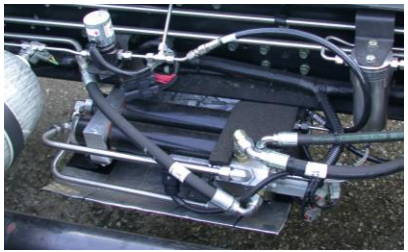
Item	Diesel	LNG HPDI	H2 HPDI	LNG SI	H2 SI
Base engine	Baseline	->	->	->	Displacement increse
Cylinderhead	Baseline	Injector fit	Injector fit	Sparkplug cooling	Access for DI
Piston	Baseline	->	->	New ring pack	New ring pack
Piston bowl	Baseline	->	->	New	New
Camshaft	Baseline	->	->	New?	New?
Charging system	Baseline	->	->	New	New (2 stage)
Exhaust manifold	Baseline	->	->	New?	->
Aftertreatment system	Baseline	->	->	New	Stoich => New
Fuel storage system	Baseline	LNG - cryopump	700 bar (LH2)	LNG	700 bar (LH2)

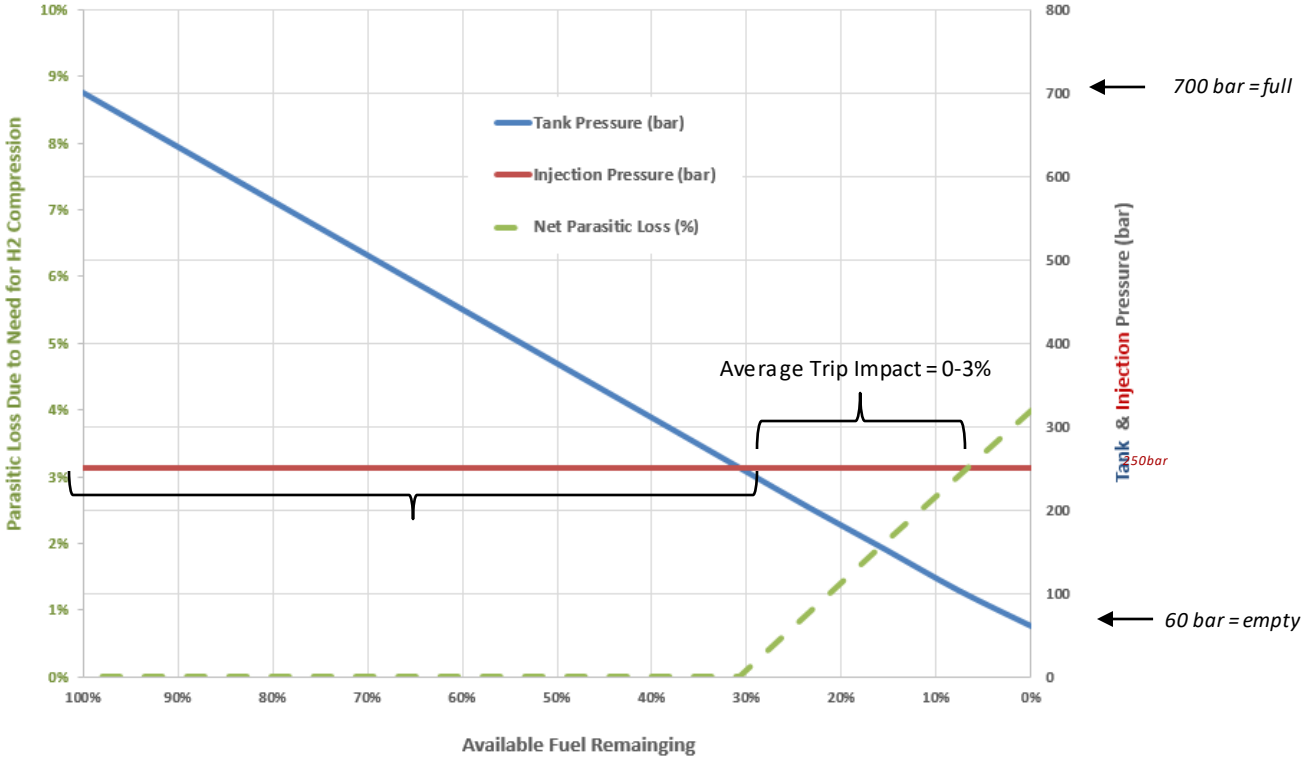
What Makes WFS and H_2 HPDI Uniquely Positioned

- 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 vales, regulators, PRVs for FCEVs today
  - WFS has a booster compressor at TRL 3-4
- Hydrogen market is moving toward 700 bar for automotive applications, and this benefits H_2 HPDI significantly
  - Injection pressure will be <300 bar so booster compressor only needed for 30-40% of the trip

Example of Booster Compressor During Drive Cycle

- Compressor only runs when needed tank pressure < injection pressure
- Hydraulic drive will be same as for HPDI 2.0 LNG product





Prototype H_2 HPDI Trucks are Already Running on the Road

The world's first compression ignition HD H_2 Truck

Back-Up Material

H_2 HPDI Conclusions and Statements

The fact that H_2 HPDI solves at lot of issues operating a combustion engine with H_2 while delivering excellent performance and efficiency makes it a promising path forward and enables a short time to market.

- H_2 HPDI offers the most efficient solution for an HD combustion engine. At high load, it is even more efficient than a fuel cell
- With the introduction of H_2 HPDI, HPDI is no longer a methane "bridge" technology and will be competitive with FCEV near and long term
- HPDI requires minimal changes to the base engine. Only fuel system is replaced and major changes to the aftertreatment system are avoided, which translate into short time to market.
- Existing production lines can be used and value creation kept within the OEM company
- Potential to utilize same injector hardware for both LNG and H_2. Unsensitive to fuel quality and purity.
- Ignition initiator fluid (pilot) can be significantly reduced. Westport is aiming for a Zero CO_2 engine.
- Higher torque and power density than diesel due to the absence of knock
- Even higher efficiency than the excellent efficiency of a diesel engine
- No difference in thermal and mechanical load to combustion chamber, crank train, and exhaust train compared to diesel operation
- Lubricity and safety: No combustible H_2/Air mixture and water vapor passing the ring pack into the crankcase


Thank you