Hydrogen’s Role in Internal Combustion Engines for Heavy Duty Applications

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We are Driving Cleaner Performance and Changing the Way the World Moves

- 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 & manufacture gaseous fuel systems & components to enable cleaner, affordable transportation.
Gaseous Fuel Component, Combustion & Systems Expertise

- Deep experience with combustion system & engine management systems for gaseous fuels (CNG, LNG, LPG, H2)
  - Dual Fuel
    - Heavy Duty trucks - Aftermarket
  - Spark Ignition
    - Light, Medium & Heavy Commercial Vehicles - OEM
    - Passenger cars – Aftermarket, Delayed OEM & OEM
  - High Pressure Direct Injection (HPDI)
    - Heavy Duty trucks – OEM
    - Potential application for High Horsepower / Off-Road – OEM & Aftermarket
Westport – Volvo JV Announcement

Westport and Volvo have signed a LOI and are partnering to provide solutions to decarbonize the long-haul and offroad transport sector.

The joint venture’s purpose:

- Accelerate global adoption of both HPDI (High Pressure Direct Injection) fuel system and lower carbon fuels, including biomethane and hydrogen

- Focus on further development of HPDI fuel systems for the next generation of highly efficient compression ignition internal combustion engines

- Attract new customers globally, primarily in long-haul transportation and off-road applications including marine, rail, mining, power generation, construction, and agriculture
GHG Reduction: The Role for H2 Internal Combustion Engines

- Multiple solutions for decarbonizing transportation:
  - BEVs
  - FCEVs
  - H2 ICEs
  - Hybrids

- NACFE Study:
  - BEVs & hybrids - short haul
  - FCEVs & H2 ICEs - long haul

NACFE: North American Council for Freight Efficiency

https://nacfe.org/research/electric-trucks/hydrogen/
Energy Efficiency by Technology

- **FCEVs:**
  - Max efficiency at lower loads

- **H₂ Spark Ignition:**
  - Can be a cost-effective solution for certain commercial vehicle applications
  - Larger engines required to achieve power & torque levels required for heavy duty trucks

- **H₂ HPDI:**
  - Same base diesel engine
  - Diesel-equivalent (or better) performance
  - Higher efficiency

Westport analysis of:
- Published Keyou engine data
Westport H2 Engine Technologies

- **WFS is actively developing & demonstrating all of our established engine management systems for hydrogen applications**
  - Leveraging gaseous fuel combustion expertise & established H2 component development expertise (GFI brand)

**Dual Fuel**
- Convert existing vehicles = Cost-effective carbon reductions
- Up to 30% diesel substitution
- Create refueling demand & promote refueling infrastructure development
- **Status** – demonstration truck built in Netherlands and independently tested (TNO) for performance, fuel economy and emissions.

**Spark Ignition (SI)**
- Can be a cost-effective solution for certain commercial vehicle applications
- Very low NOx emissions due to ultra-lean combustion
- Power & torque density, and brake thermal efficiency, are lower than diesel engines
- Transient response and uncontrolled combustion considerations
- **Status** – SI H2 OEM engine development projects underway in Asia

**HPDI**
- Best-in-class power, torque and efficiency combination, leveraging the fundamental properties of H2 in diffusion flame combustion
- Near-zero CO2 emissions, and highly cost-effective CO2 reductions
- Lower TCO than FCEVs in high load factor applications
- Diesel-like NOx emissions, with similar NOx control levers as diesel engines (EGR, SCR, fuel injection timing, etc.)
- Requires continuous high-pressure fuel supply to engine
- **Status** – multiple engine demonstration projects underway and demonstration trucks available
An Overview of Westport’s HPDI™ Fuel System

- Westport’s HPDI™ fuel system enables Diesel engines to retain all their benefits (efficiency, high power & torque, reliability, durability) while using primarily a clean gaseous fuel (~95% substitution ratio) and reducing emissions and Total Cost of Ownership significantly.

- The “heart” of the system is a unique fuel injector which features a small pilot injection and a larger primary injection of the main fuel – commercially available today with natural gas.

- The rest of the system falls broadly into two categories:
  - Fuel conditioning – accurate control of the fuel
  - Fuel supply – storage and supply of the appropriate fuel

- Two important takeaways:
  - The base diesel engine remains the same – just switch out the fuel system
  - While Westport’s HPDI fuel system was first developed with natural gas, the system allows a number of primary fuels (including hydrogen) using Diesel cycle combustion
LH2: Existing LNG architecture can be adapted for LH2.

700 bar H2: Onboard compressor required for H2 HPDI.

Supplies high pressure gaseous fuel (~300 bar) to engine from LNG fuel storage tank.

No major design changes required for H2 HPDI.

Potential material selection changes.

H2 HPDI

LH2: Existing LNG architecture can be adapted for LH2.

700 bar H2: Onboard compressor required for H2 HPDI.
H₂ HPDI Benefits

Higher thermal efficiency than best-in-class diesel engines, leveraging combustion fundamentals of H₂

Up to 98% CO₂ reduction vs. diesel engine

Up to 15% higher power & torque than NG HPDI engine, leveraging combustion fundamentals of H₂

Demonstrated 51.5% Brake Thermal Efficiency!
**TCO & Abatement Cost of CO₂**

**HPDI-equipped trucks provide cost-effective CO₂ reductions**

**Abatement Cost:**
Tons of WTW CO₂ Reduced per $1,000 Invested

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Abatement Cost</th>
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<tr>
<td>H₂ HPDI</td>
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<tr>
<td>H₂ FCEV</td>
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*Analysis based on Frontier Economics: “CO₂ Emission Abatement Costs of Gas Mobility and Other Road Transport Options”*
H₂ Demonstration Trucks

• Westport has built two H₂ HPDI demonstration trucks
  – Both trucks are converted from commercially available LNG HPDI European models
  – Truck #1 is North America based
  – Truck #2 is European based

• Onboard storage is currently 16 kg in a four-tank array
  – Suitable for proof of concept using the existing truck wheelbase
  – Not production-representative

• Challenges:
  – Permitting
  – Fueling
H₂ Demonstration Trucks – Next Steps

• Increase fuel storage:
  – 80 kg of fuel @ 700 bar w/ no compressor < 600km (375 mile) range* with Smart Tank fuel utilization strategies

• Add a compressor:
  – 80 kg of fuel @ 700 bar w/ compressor would allow up to ~900 km (560 mile) range*

* Cycle/load dependent
H₂ HPDI Partnerships

• In addition to the recently-announced Westport / Volvo HPDI JV, multiple OEM engine demonstration projects are underway, both announced and unannounced. A third HD global OEM demonstration project was announced in March 2023
  – Announced projects include Scania, AVL/Tupy and TNO.
  – Preliminary results have been shared from these projects at the 2023 Vienna Motor Symposium and the 2023 SAE Gothenburg conference by Westport, TNO and AVL
  – Tests include both single and multi-cylinder engines
Summary & Next Steps

• **WFS is actively developing & demonstrating all of our established engine management systems for hydrogen applications (Dual Fuel conversion systems, H2 SI, H2 HPDI)**
  
  • H2 HPDI combustion allows the highest power density and the highest efficiency using hydrogen in an internal combustion engine for heavy duty applications
  
  • H2 SI combustion offers an alternate balance of cost, power and efficiency that can be well-suited for certain commercial vehicle applications
  
  • H2 Dual Fuel conversions can provide near-term carbon-reductions utilizing existing equipment, and quickly establishing end-user fuel demand to support refueling infrastructure development

• Interest in Westport’s H₂ fuel systems is growing from OEMs and aftermarket conversion customers, with multiple development projects recently announced and underway

• Westport anticipates commercial availability of H2 Dual Fuel retrofit systems first (~1 year), followed by H2 SI OEM trucks in India (~2 years), followed by H2 HPDI OEM trucks (~5 years, preceded by customer demonstrations and field trials in the next few years)
Thank You