High Performance Hydrogen Engine Applications

Application of Westport’s H₂ HPDI™ Fuel System to a Demonstration Truck

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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
GHG Reduction: The Role for H₂ ICEs

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

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

Optimum Duty Cycle Sweet Spot

https://nacfe.org/research/electric-trucks/hydrogen/
# NG / H₂ ICE Technologies

<table>
<thead>
<tr>
<th>How it works</th>
<th>Spark Ignited</th>
<th>Compression Ignition</th>
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</thead>
<tbody>
<tr>
<td>Fuel &amp; air pre-mixed at low pressure</td>
<td>• Direct injection of high pressure gas into combustion chamber</td>
<td></td>
</tr>
<tr>
<td>Dedicated natural gas (100%)</td>
<td>• Same base diesel engine can be used equipped with Westport's HPDI fuel system</td>
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<tr>
<td>Ignition from spark plug</td>
<td>• Compression Ignition from diesel pilot</td>
<td></td>
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<tr>
<td>Reduced compression ratio to avoid knock</td>
<td>• Same piston / compression ratio as diesel to retain high efficiency</td>
<td></td>
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<tr>
<td>Simple 3-way catalyst</td>
<td>• SCR &amp; DPF (same as diesel)</td>
<td></td>
</tr>
<tr>
<td>Otto cycle (Stoichiometric)</td>
<td>• Diesel cycle - high substitution (~94% on typical road cycle)</td>
<td></td>
</tr>
<tr>
<td><strong>Power / torque / efficiency typically lower than base diesel engine</strong></td>
<td>• <strong>Power / torque / efficiency can exceed base diesel engine on Hydrogen</strong></td>
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An Overview of Westport’s HPDI™ Fuel System

- Westport’s HPDI™ fuel system was conceptualized ~30 years ago with the goal of creating a more efficient natural gas engine.

- 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 – initially 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 to combust on the Diesel cycle
CURRENT HPDI FUEL SYSTEM

ON ENGINE

Fuel Rail
Gas Conditioning Module
HPDI Fuel Injector

OFF ENGINE

Cryogenic High Pressure Pump
Fuel Level Signal CANditioner
Gas Temperature Sensor
Pump Control Manifold

Tank Selection Control Manifold
Integrated Gas Module
HPDI Control Software
H₂ HPDI Combustion Overview

- The following results will focus on the initial calibration of Scania’s state-of-the-art 13-litre CBE1 platform
  - Commercially available HPDI fuel system hardware was used for the initial calibration and demonstration of the H₂ HPDI fuel system
- In parallel, hydrogen work continues on several other HPDI fuel system-equipped engine platforms – both Single and Multi-Cylinder.
**H₂ Combustion on Scania CBE1 Engine**

- BTE on torque curve of ~47-49%
- **Peak BTE at 51.5%**
- Engine-out NOx levels calibrated to ~6-12 g/kW.h to reflect EATs strategy
- Note: EGR can be used to reduce NOx further to ~3g/kW.hr
- Pilot quantities as low as 2-3mg have been tested, equating to near-zero CO₂ emissions
Minimal \( H_2 \) Slip

- \( H_2 \) combustion is almost fully complete
- \( \eta_{\text{Combustion}(H_2)} \) is > 99.97\% at the measured A-speed points
- No measurable slip infers a low risk of \( H_2 \) interaction with combustion chamber
Next Generation Fuel System Architecture (LNG Shown)

- Revised approach to gas pressure control
- Eliminates dynamic venting
- Facilitates higher pressures (eliminates non-metallic seals)
- Capable of OBFCM for EU VII
H₂ Fuel System: Off-Engine Approach

- Target for onboard fuel is 80kg – equates to ~2050-litres of storage
  - Note: H₂ does not follow ideal gas law at higher pressures: 40% over-estimate for ideal gas calculation
- Range without compressor is less than 600km
H₂ Smart Tank System

- Compressor required for ranges greater than 500km
- Smart Tank strategy evolved to maximize efficiency and minimize compressor flow
  - Able to reduce size, weight and power requirement.
Smart Tank Simulation Results (Södertälje - Norrköping route)

- Average power draw over the entire cycle is 2%
- Fuel Rail pressure relatively constant at 300-bar
- Full power available throughout operating range
- Average power draw over the entire cycle is 2%

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### General Simulation Results

<table>
<thead>
<tr>
<th>Routes</th>
<th>Load (Tonnes)</th>
<th>Predicted H\textsubscript{2} Consumption (kg/100km)</th>
<th>Average Speed (km/h)</th>
<th>Range with 80kg of H\textsubscript{2} (Tonnes-Km) with 80 kg of H\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Södertälje – Norrköping Highway, moderately hilly</td>
<td>20</td>
<td>7.4</td>
<td>84</td>
<td>970</td>
</tr>
<tr>
<td>München, Trucker magazine testrunde Highway and rural, moderately hilly</td>
<td>40</td>
<td>11.3</td>
<td>85</td>
<td>590</td>
</tr>
<tr>
<td>Koblenz - Trier Highway, hilly and Scandinavian vehicle load</td>
<td>60</td>
<td>16.3</td>
<td>81</td>
<td>370</td>
</tr>
</tbody>
</table>

- A typical truck cycle will allow approximately 800-km of range.
- Cycles which require significant power (i.e., high loads or steep climbs) will clearly impact total range for fixed fuel storage.
Demonstration trucks use current hardware.
**H₂ Demonstration Trucks**

- Westport has built two H₂ HPDI demonstration trucks
  - Both trucks are converted from commercially available NG European models
  - Truck #1 is US-based
  - Truck #2 is European based

- Onboard storage is currently 16kg in a four-tank array with no compressor
**H₂ Demonstration Trucks – Challenges & Next Steps**

- **Challenges:**
  - Permitting
  - Fueling

- **Next steps:**
  - Increase fuel storage:
    - 80kg of fuel with no compressor will allow up to ~600km range* with Smart Tank strategies
  - Add compressor:
    - 80kg of fuel w/ compressor will allow up to ~900km range*

* Cycle/load dependent
Summary

- Westport’s HPDI fuel system can be used with the same base diesel engine – same engine architecture for Biomethane or Hydrogen.

- Interest in Westport’s H₂ HPDI fuel system is growing from OEMs, with multiple development projects recently announced and underway.

- The SCANIA CBE1 engine equipped with Westport’s H₂ HPDI fuel system reached a peak BTE of 51.5%.

- H₂ HPDI fuel system equipped engines have demonstrated near-zero CO₂ emissions.

- The next generation HPDI fuel system will provide improved fueling accuracy, reduced emissions, and higher performance capability while meeting the new EU VII regulations.

- The Smart Tank off-engine system is predicted to allow up to ~900km range with 80kg of H₂ storage and a small compressor.

- Demonstration vehicles with H₂ HPDI fuel system equipped engines are running in both Europe and the US.
Thank you