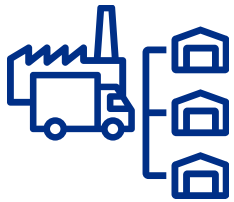
High Performance Hydrogen Engine Applications

Application of Westport's H_2 HPDI™ Fuel System to a Demonstration Truck

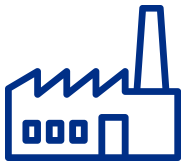
David Mumford, Stephen Ptucha, Scott Baker, Sandeep Munshi - **Westport Fuel Systems** Inc

Anders Palmkvist, Eric Olofsson – **Scania** Powertrain Pre-Development

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


Hydrogen Station
Changing the way w
HPDi
Hydrogen Mobility
Westport

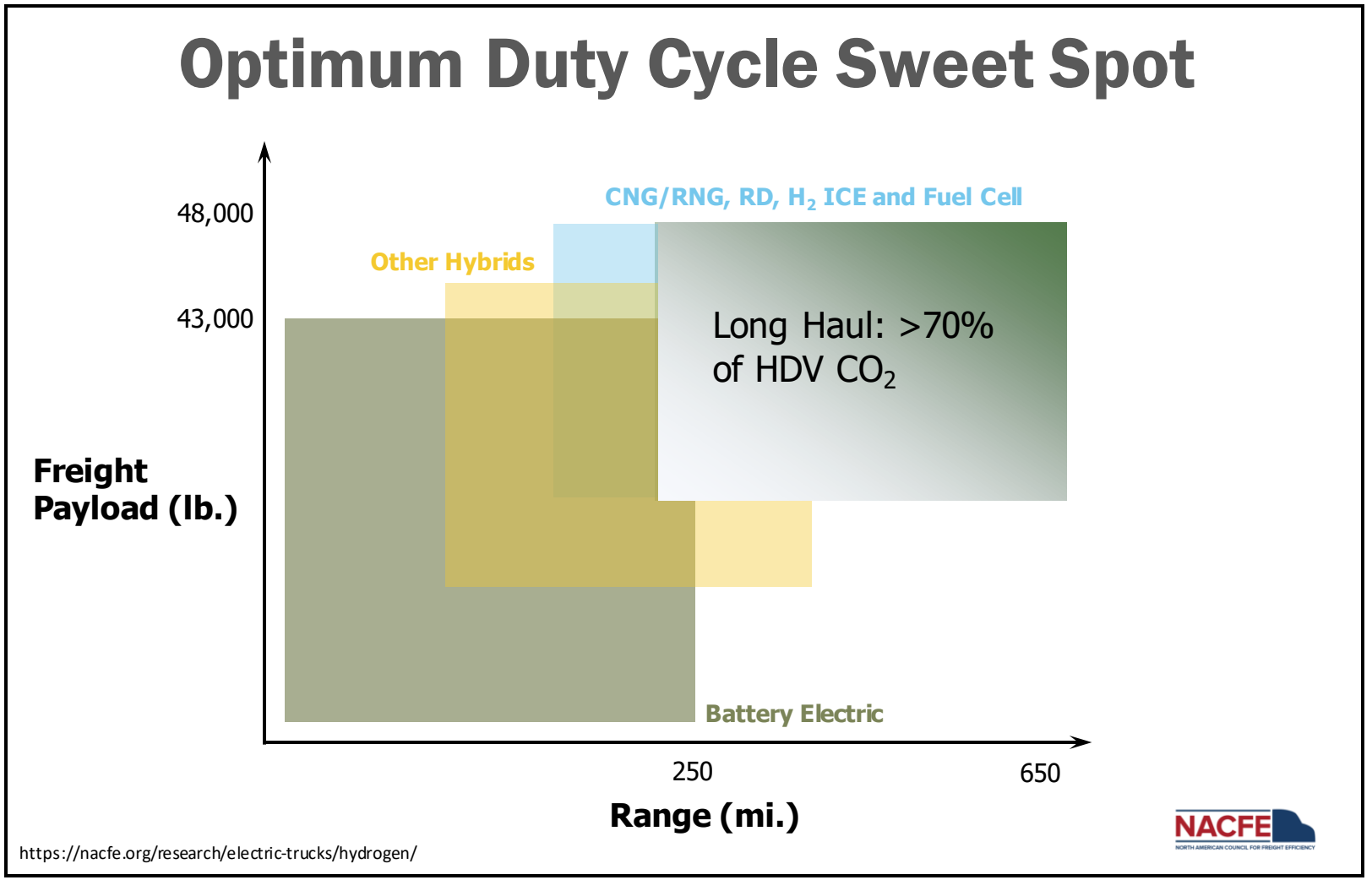
GHG Reduction: The Role for H_2 ICEs

Multiple solutions for decarbonizing transportation:

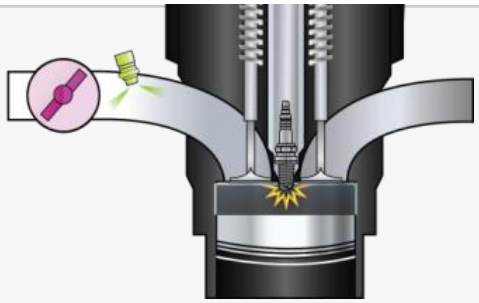
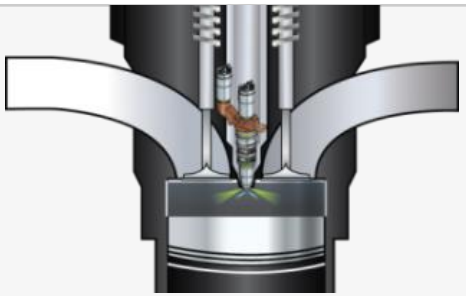
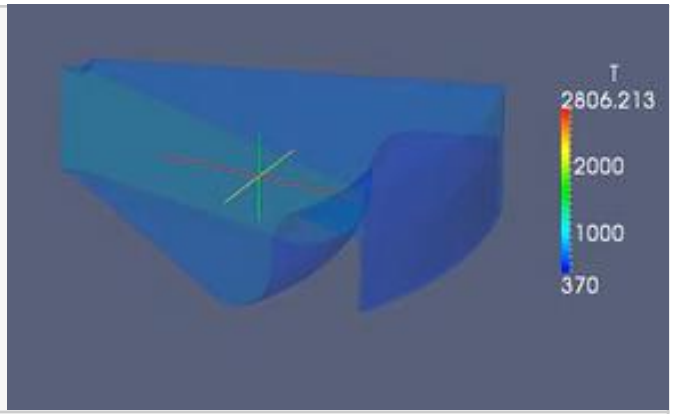
- BEVs
- FCEVs
- H_2 ICEs
- Hybrids

NACFE Study:

- BEVs & hybrids - short haul
- FCEVs & H_2 ICEs - long haul



NG / H_2 ICE Technologies

	 **Spark Ignited**	 **Compression Ignition** 
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) • **Power / torque / efficiency typically lower than base diesel engine**	• Direct injection of high pressure gas into combustion chamber • **Same base diesel engine can be used equipped with Westport's HPDI fuel system** • Compression Ignition from diesel pilot • Same piston / compression ratio as diesel to retain high efficiency • SCR & DPF (same as diesel) • Diesel cycle - high substitution (~94% on typical road cycle) • **Power / torque / efficiency can exceed base diesel engine on Hydrogen**

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

www.westport.com

ON ENGINE

OFF ENGINE

Fuel Rail

HPDI
Fuel Injector

Gas Conditioning
Module

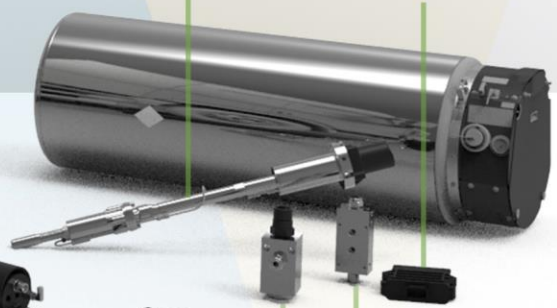
Tank
Selection
Control
Manifold

Integrated Gas
Module

HPDI
Control Software

Cryogenic High
Pressure Pump

Fuel Level
Signal
CANditioner

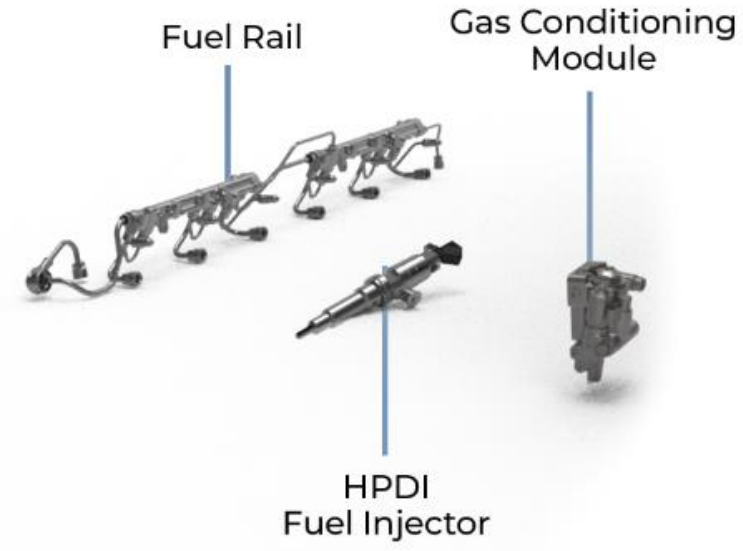


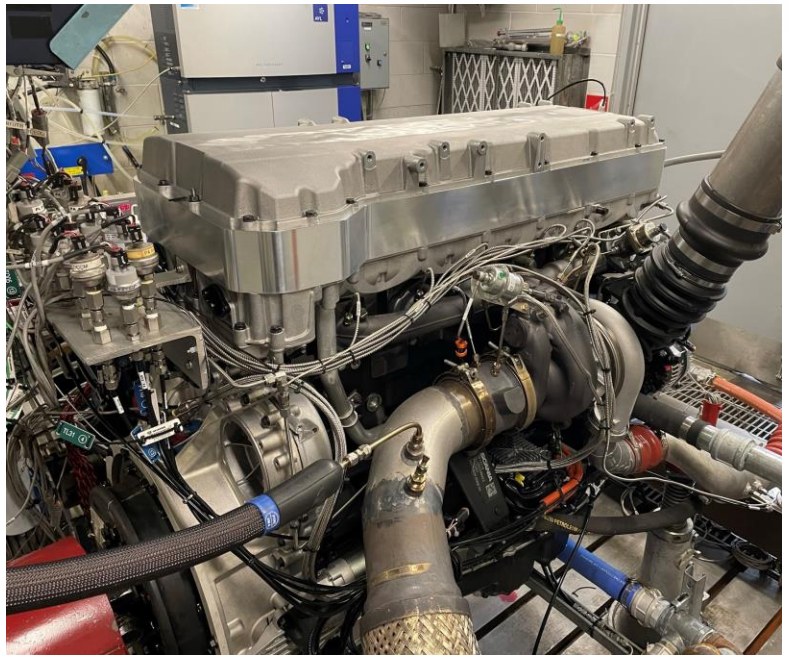
Gas
Temperature
Sensor

Pump
Control Manifold

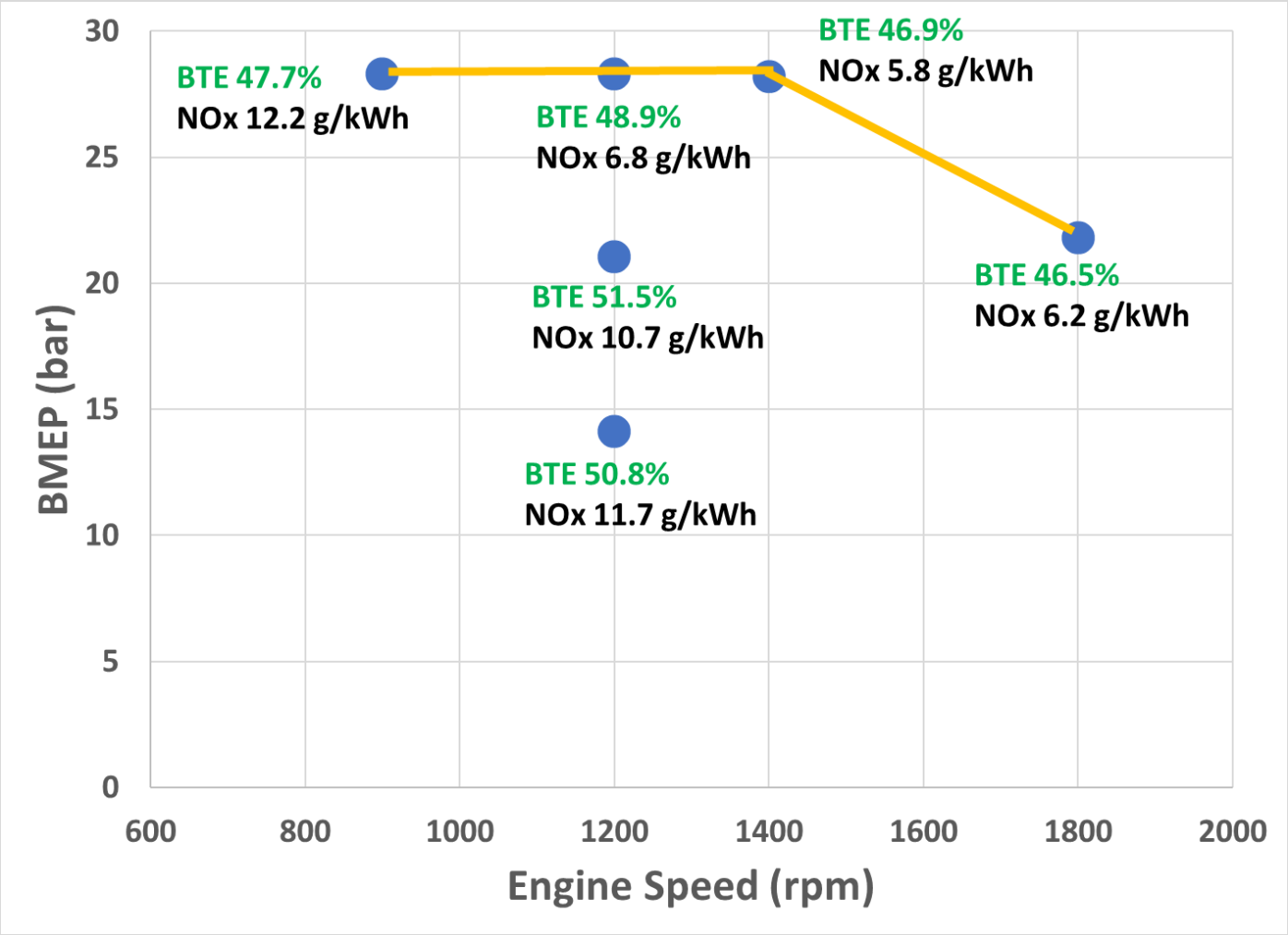
H_2 HPDI Combustion Overview

- 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.



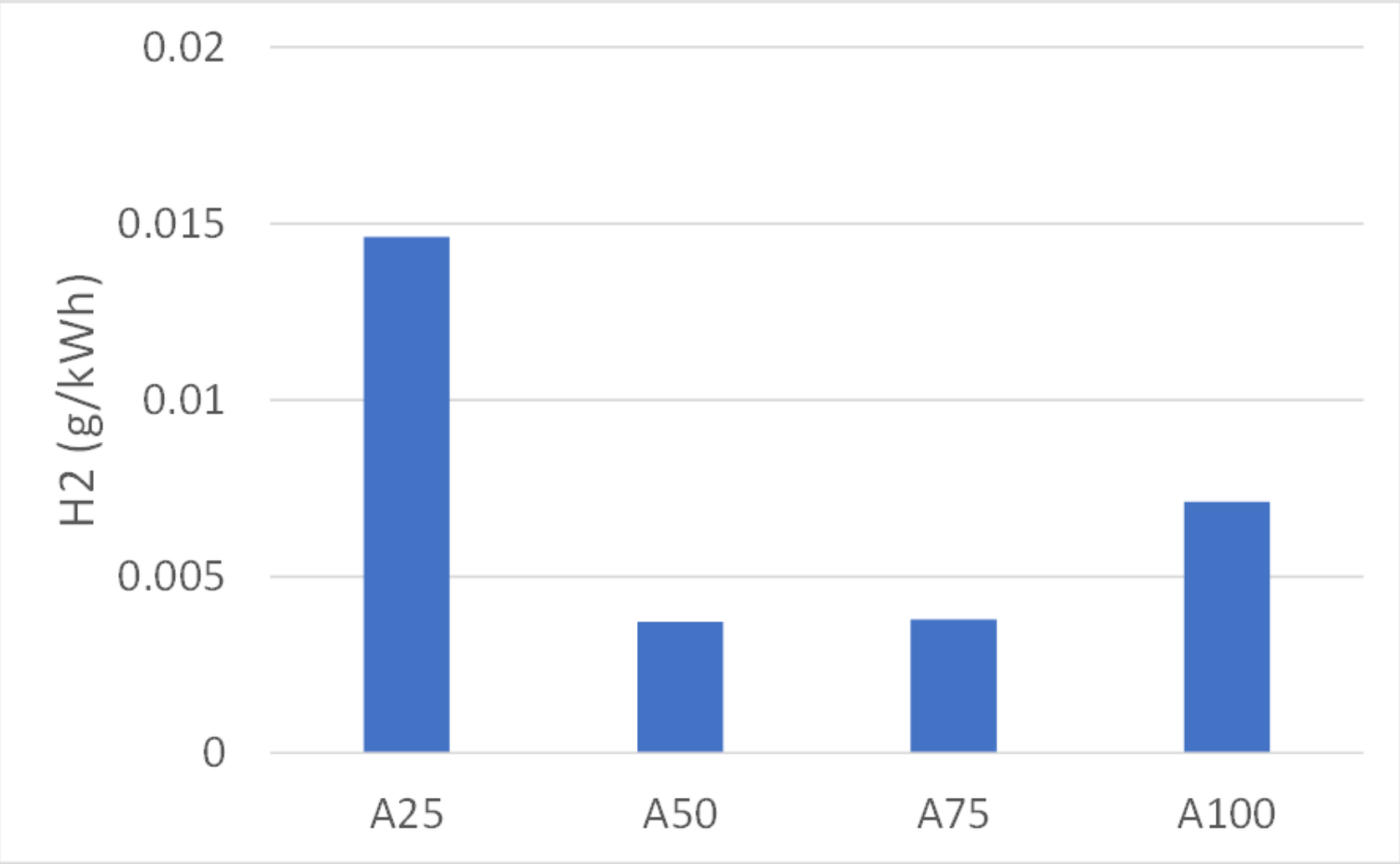


H_2 Combustion on Scania CBE1 Engine



- 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 CO_2 emissions**

Minimal H_2 Slip



- H_2 combustion is almost fully complete
- $\eta_{Combustion(H2)}$ is **> 99.97%** at the measured A-speed points
- No measurable slip infers a **low risk of H_2 interaction with combustion chamber**

ON ENGINE

OFF ENGINE

Gas Rail Inlet Injector & Gas Rail Vent Valve

Fuel Rail

HPDI Fuel Injector

Diesel Rail Pressure Regulator & Diesel Minimum Pressure Regulator

H_2

LNG

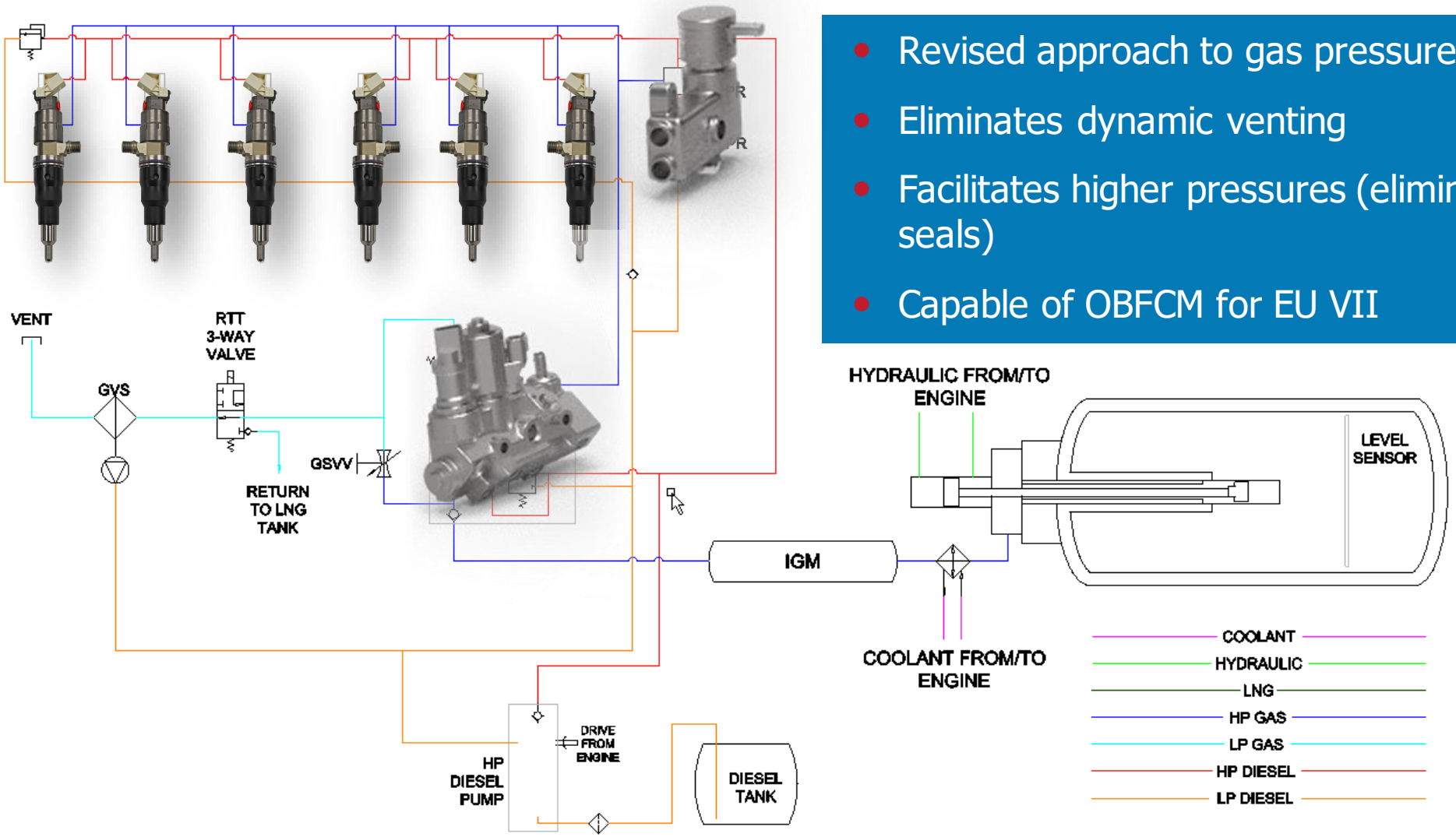
HPDI Control Software

Integrated Gas Module

NEXT GENERATION HPDI FUEL SYSTEM

www.westport.com

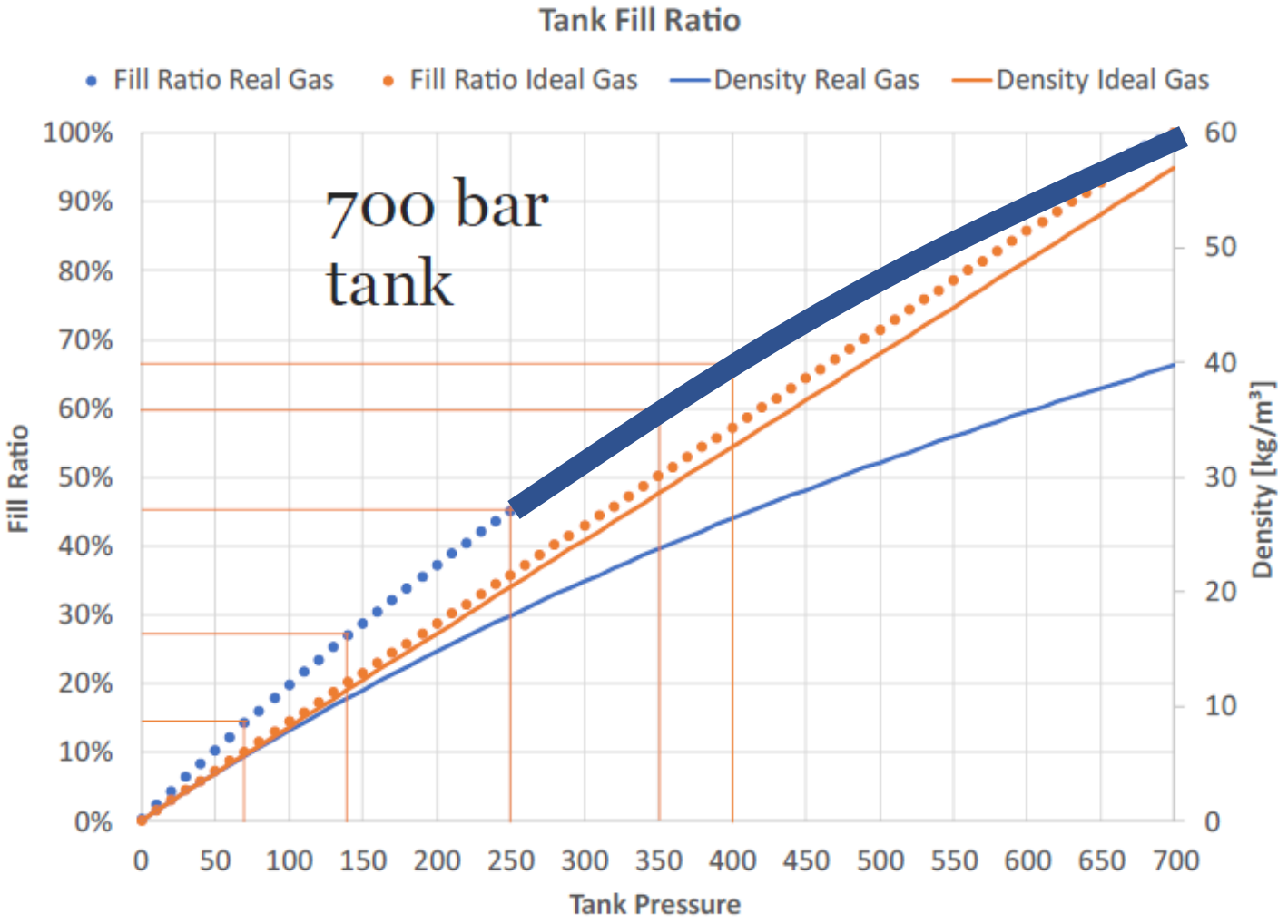
Next Generation Fuel System Architecture (LNG Shown)



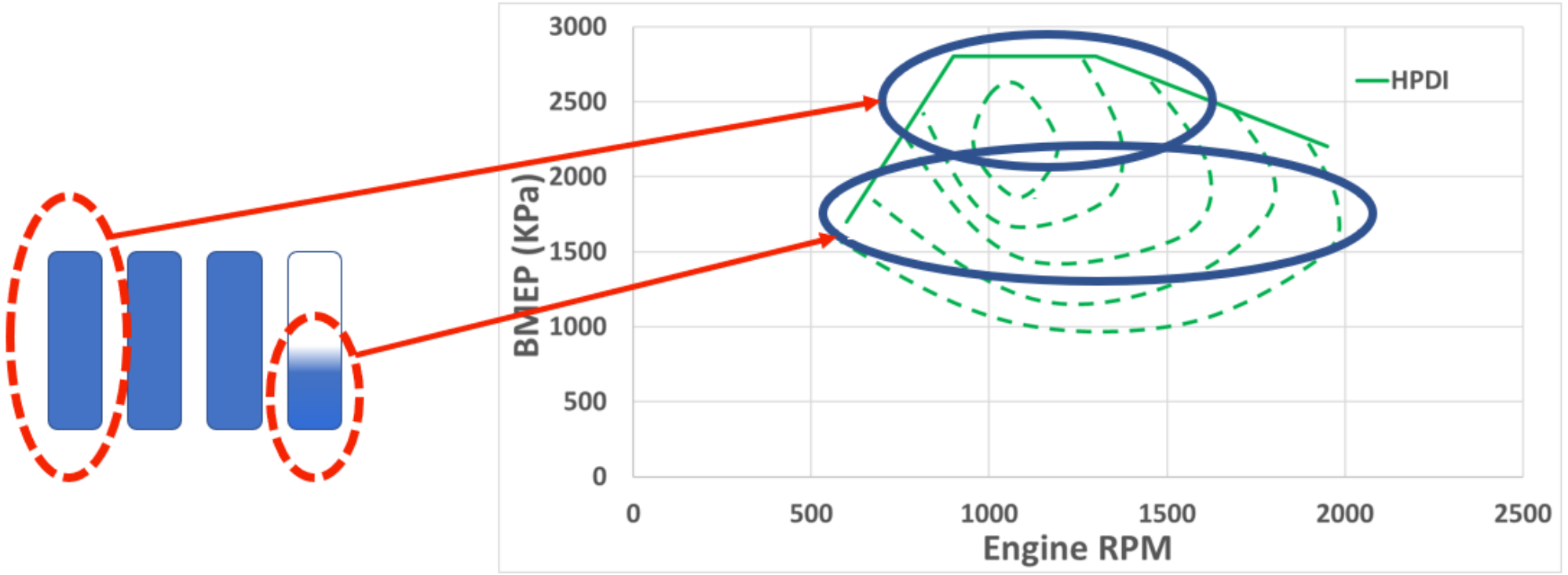
- Revised approach to gas pressure control
- Eliminates dynamic venting
- Facilitates higher pressures (eliminates non-metallic seals)
- Capable of OBFCM for EU VII

H_2 Fuel System: Off-Engine Approach

- Target for onboard fuel is 80kg – equates to ~2050-litres of storage
  - Note: H_2 does not follow ideal gas law at higher pressures: 40% over-estimate for ideal gas calculation
- Range without compressor is less than 600km

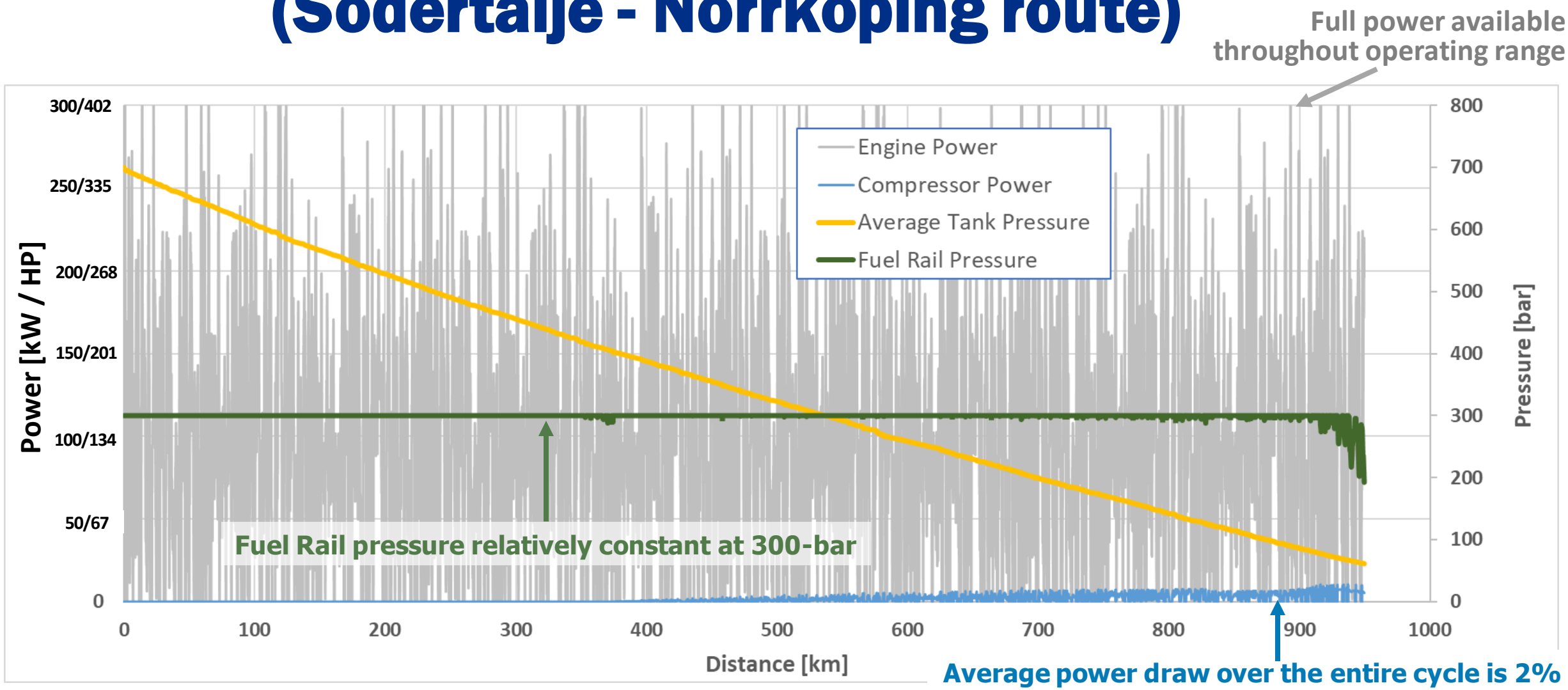


H_2 Smart Tank System



- 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)



General Simulation Results

Routes	Load (Tonnes)	Predicted H_2 Consumption (kg/100km)	Average Speed (km/h)	Range with 80kg of H_2	Tonnes-Km with 80 kg of H_2
Södertälje – Norrköping Highway, moderately hilly	**20**	**7.4**	**84**	**970**	**19,400**
München, Trucker magazine testrunde Highway and rural, moderately hilly	**40**	**11.3**	**85**	**590**	**23,600**
Koblenz - Trier Highway, hilly and Scandinavian vehicle load	**60**	**16.3**	**81**	**370**	**22,200**

- 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

DEMONSTRATION TRUCKS

H_2 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

H_2 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 H_2 HPDI fuel system is growing from OEMs, with **multiple development projects** recently announced and underway.
- The SCANIA CBE1 engine equipped with Westport's H_2 HPDI fuel system reached a **peak BTE of 51.5%.**
- H_2 HPDI fuel system equipped engines have demonstrated **near-zero CO_2** 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 H_2 storage and a small compressor.
- Demonstration vehicles with H_2 HPDI fuel system equipped engines are running in both Europe and the US.

Thank you