Westport INNOVATIONS INC.

Advancing the shift of global commercial transportation to natural gas and hydrogen.

HCNG Engine Technology for Medium/Heavy Duty Applications

20th March, 2007

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Westport Innovations Inc.

Hydrogen Engines

- Internal Combustion Engines are very well developed and increasingly sophisticated.
  - Engine power and efficiency are improving
  - Engines are getting much cleaner to meet emissions targets
- Adapting high efficiency engines to operate on a mixture of hydrogen and natural gas (HCNG) could result in cost effective power plants. Some questions:
  - Can HCNG powered engines meet customer requirements on power density, efficiency and emissions?
  - How can one benefit from current progress in engine/emissions control technologies?
- The overall goals of the current project are to develop HCNG powered commercial vehicles that would be part of a long term hydrogen roadmap while providing emissions benefits.

IWHUP Demonstration Overview

- Integrated Waste Hydrogen Utilization Project (IWHUP).
- IWHUP is an $18,000,000 initiative to harness waste hydrogen and promote its use as a fuel by demonstrating emerging clean fuel cell and transportation technologies.
- Comprised of eight (8) Sub-Projects:
  - SP1. Waste Hydrogen Supply
  - SP2. Compressed Hydrogen Distribution
  - SP3. Light-duty Hydrogen Vehicle Fuelling Station
  - SP4. Heavy-duty HCNG Vehicle Fuelling Station
  - SP5. Light-duty H_2-ICE Powered Vehicle Demonstration
  - SP6. Heavy-duty HCNG Powered Transit Bus Demonstration
  - SP7. Combined Heat & Power Fuel Cell Demonstration
  - SP8. PM, Communications & Public Outreach

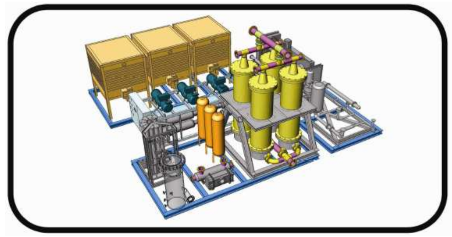
IWHUP: Specific Project Goals

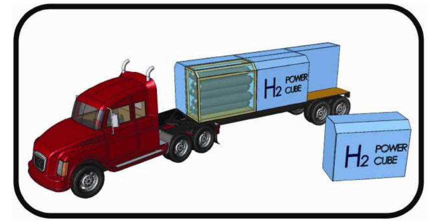
- An integrated approach to promoting:
  - the use of vented by-product hydrogen, and,
  - the necessary infrastructure, end use applications, regulatory framework and education
- Stimulate greenhouse gas (GHG) emission reduction.
- Further hydrogen usage from by-product streams.
- Explore economic performance of sub-project applications.
- Evolve current codes, standards and regulations of distribution and use of hydrogen fuel.
- Provide education on hydrogen fuels, applications and safety issues.
- North Vancouver "*NODE*" of the BC Hydrogen Highway™.

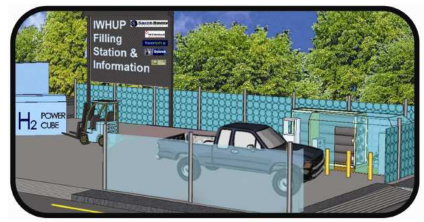
IWHUP Partners and Funding Programs

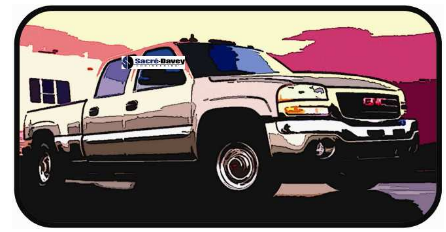
Industry/Other Partners

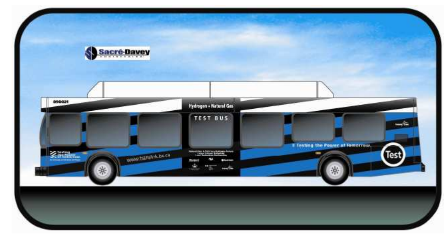
- Sacré-Davey Innovations (Lead)
- Sacré-Davey Engineering
- Westport Innovations
- Clean Energy Fuels
- Dynetek Industries
- Easywash
- HTEC H2 Energy & Tech. Corp.
- Newalta
- Nuvera Fuel Cells
- Powertech Labs & BC Hydro
- QuestAir Technologies
- TransLink (GVTA)











Funding Programs

- Sustainable Development Technology Canada (SDTC)
- Hydrogen Early Adaptors (h2EA)
- Canadian Transportation Fuel Cell Alliance (CTFCA)
- US Department of Defense (USDoD)

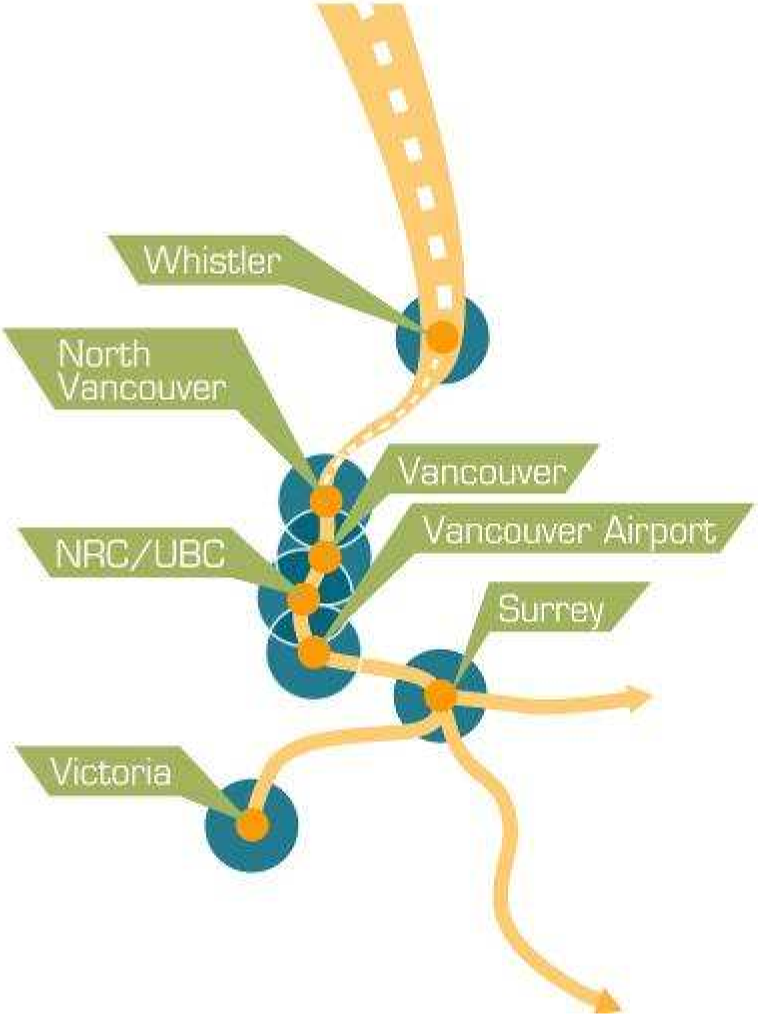
By-product Hydrogen

- IWHUP Source – North Vancouver electro-chemical plants (Sodium Chlorate & Chlor-alkali)
  - ~ enough by-product hydrogen to power a fleet of over 20,000 vehicles
- Over 50,000,000 kg vented annually in Canada
  - ~ enough to power almost 200,000 vehicles
  - ~ approximately 750 wind turbines (1MW) would be required to produce this amount of hydrogen with electrolysers
- Over 1000 sources of by-product hydrogen around the world

BC’s Hydrogen Highway

HydrogenHighway

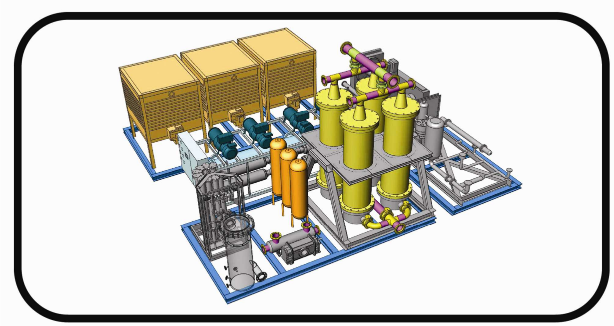
- Coordinated demonstration, deployment and market development program
- Framed around the 2010 Winter Games
- Seven highly visible locations
- Not *just* vehicles!
- Multi-party effort
- www.hydrogenhighway.ca



Sub-project 1 - Hydrogen Supply

- Hydrogen captured from a by-product streams
- HTEC's pilot plant will purify & compress 20 kg/hr to 450 bar (6500psig) at 99.999% purity levels

HTEC
Hydrogen Technology & Energy Corporation



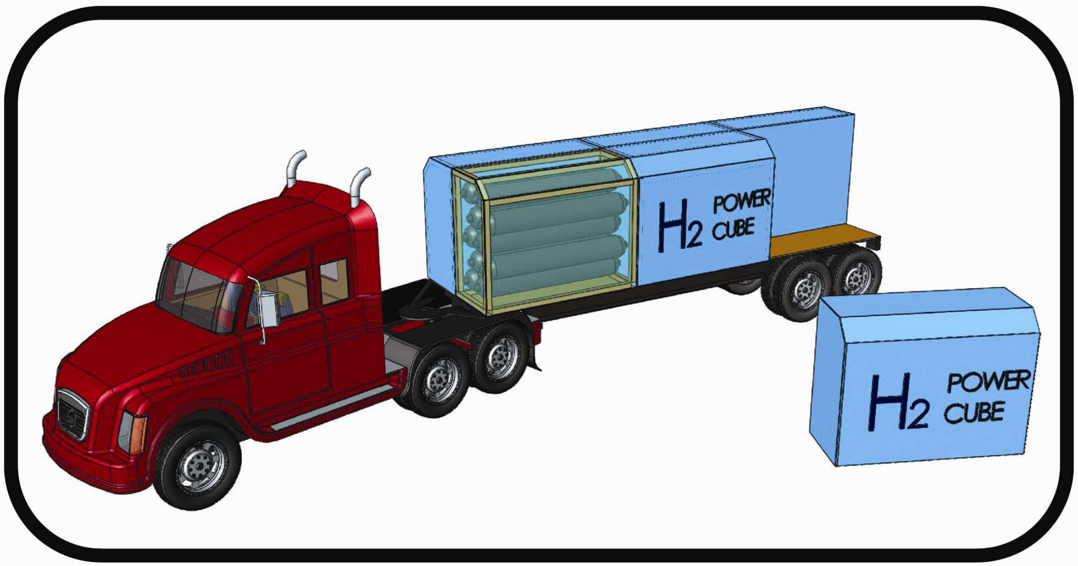
Natural Resources Canada | Ressources naturelles Canada
Hydrogen Early Adopters Program (h2EA)

Sustainable Development Technology Canada
Partnering for real results.

US-DoD/ERDC-CERL
Climate Change Fuel Cell Program

Sub-project 2 - Hydrogen Distribution

- Self Load/Unload compressed hydrogen distribution system
- TC approved aluminum - carbon-fiber cylinders – 450Bar
- 89 kg of hydrogen per PowerCube (6 total on trailer)



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Hydrogen Early Adopters Program (h2EA)

SUSTAINABLE DEVELOPMENT TECHNOLOGY CANADA

Partnering for real results.

US-DoD/ERDC-CERL

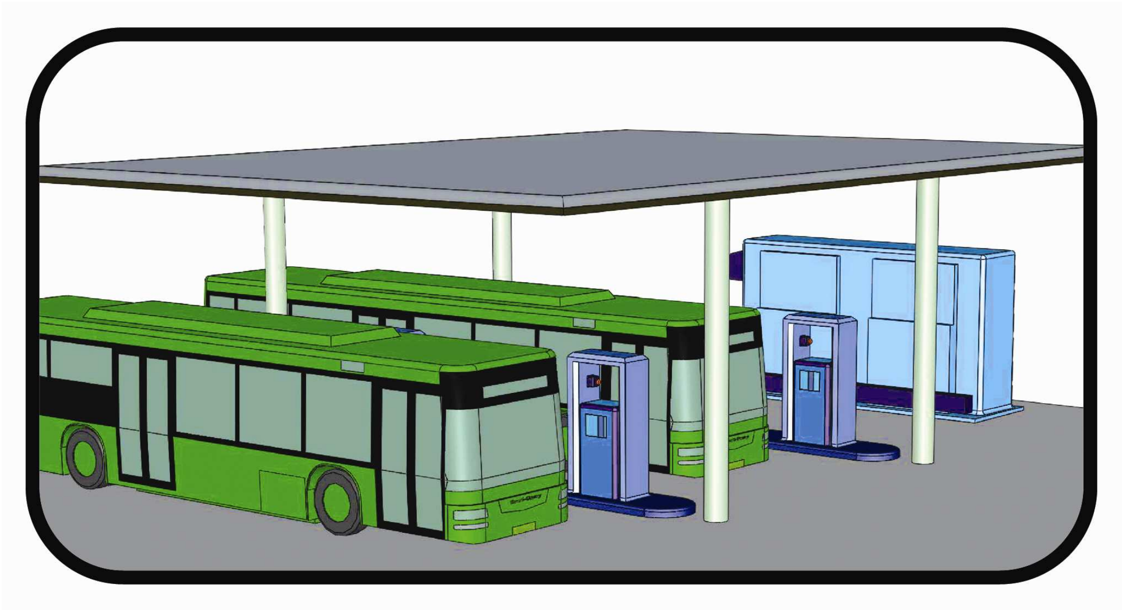
Climate Change Fuel Cell Program

Dynetek®

Sacré-Davey ENGINEERING

Sub-project 4 - Heavy-Duty HCNG Fuelling Station

- Added to existing CNG Station
- New H2, HCNG, CNG Capability High Volume Dispenser
- Located at Translink's Port Coquitlam Transit Facility



Clean Energy

Natural Resources Canada | Ressources naturelles Canada

Hydrogen Early Adopters Program (h2EA)

Sustainable Development Technology Canada
Partnering for real results.

US-DoD/ERDC-CERL
Climate Change Fuel Cell Program

Sub-project 6: HCNG Buses for Greater Vancouver

- By-product hydrogen from a local sodium chlorate plant.

  $NaCl + H_2O + 6e^- \longrightarrow NaClO_3 + H_2 \uparrow$
- $NaClO_3$ is used to generate Chlorine Dioxide (ClO_2).
- HCNG with 20 mol% H_2 was selected based on vehicle range considerations and commonality with previous work.
- Builds on the technology developed on the 5.9L BG+.
- Upgrade the 280HP 8.3L CG+ engine.

Re-calibration objectives:

- Maintain engine torque, power and fuel economy
- Reduce NOx while keeping other emissions same or better
- No detrimental impact on drivability

Cummins Westport – SI NG Engine Products

B GAS PLUS	C GAS PLUS	L GAS PLUS	ISL G
			

HCNG Calibrations Available

5.9 Liter	**8.3 Liter**	**8.9 Liter**	**8.9 Liter**
195–230 hp	**250-280 hp**	**320 hp**	**250-320 hp**
420–500 lb-ft	**750 – 850 lb-ft**	**1000 lb-ft**	**660-1000 lb-ft**
1.8 NOx+NMHC	**1.8 NOx+NMHC**	**1.4 NOx+NMHC**	**0.1 NOx**
0.01 PM	**0.01 PM**	**0.01 PM**	**0.01 PM**
← **Lean Burn SI** →			**Stochiometric +EGR+TWC**

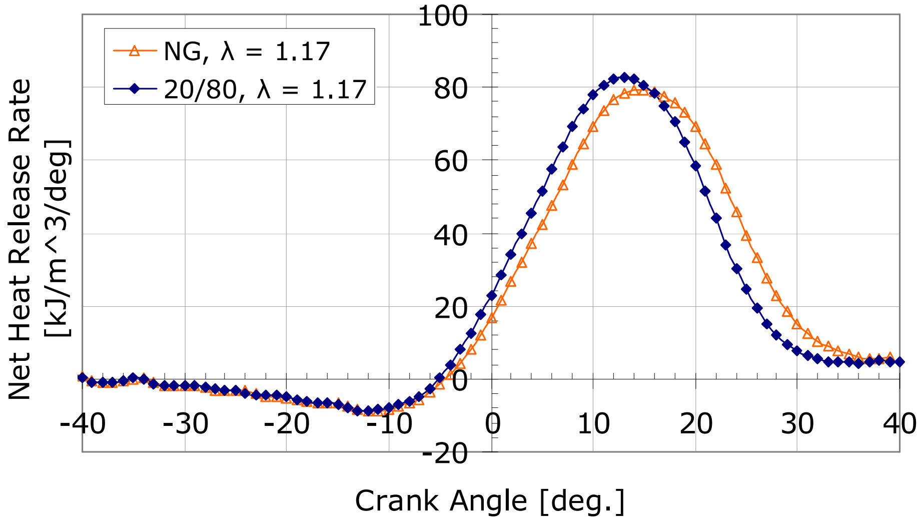
(emissions are in g/bhp-hr)

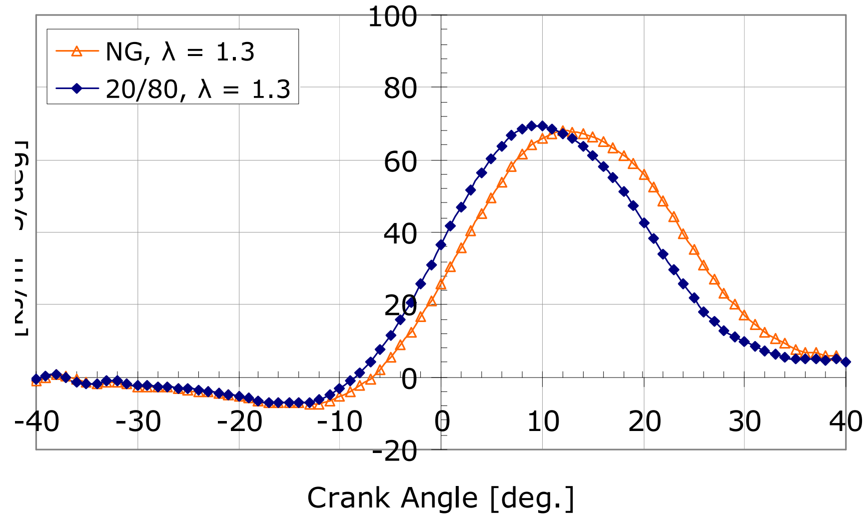
Combustion Study with Various H2 Blends

- Determine the effectiveness of hydrogen in improving the combustion properties of lean natural gas air mixtures in a heavy duty engine;
- Determine if there are additional benefits in increasing the hydrogen content from 20 to 30 mol%.
- Fuels tested: NG, HCNG with 20 and 30 mol% H2.
- Test parameters included A/F ratio and the combustion timing.

Test Point	Engine Speed [RPM]	Torque [N-m]	BMEP [bar]
Pt1	1061	552	8.4
Pt2	1566	261	3.9
Pt3	2000	696	10.6
Pt-A	2130	852	13.0
Pt-B	2130	655	10.0

Effect of λ on HCNG combustion

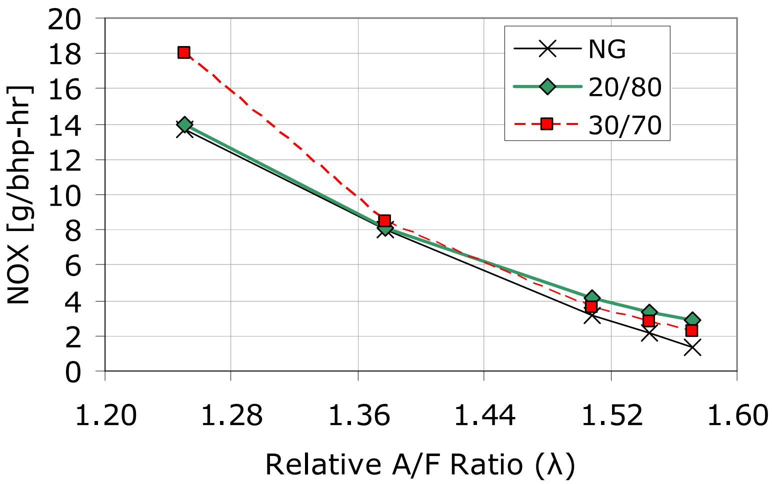


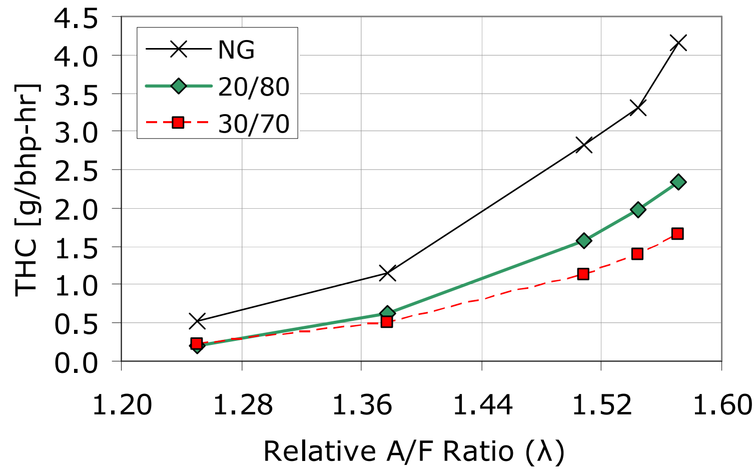


- Combustion timing was measured in terms of '50% Mass Fraction Burned (50%MFB)' by adjusting the spark timing.
- Effect of λ on the heat release rate for natural gas and 20/80 HCNG fuels. Test point-Pt1, speed-1061 RPM, load-8.4 bar BMEP, timing-MFB50% = 15^{o}CA after TDC.
- The results indicate that hydrogen speeds up the combustion. The combustion starts earlier and the maximum rate of heat release is slightly higher for the 20 mol% HCNG mixture.

Model Predictions – Emissions

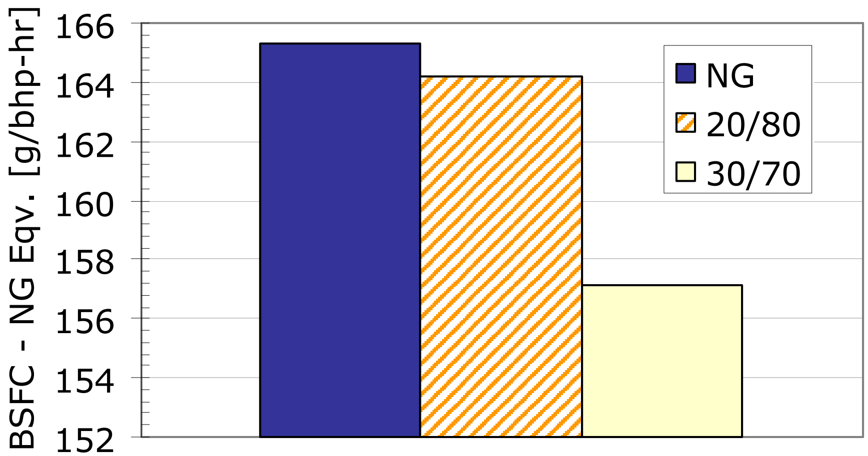
- A response surface model was generated from the test data.
- The model input parameters were the relative air/fuel ratio, λ and combustion timing - MFB50%.

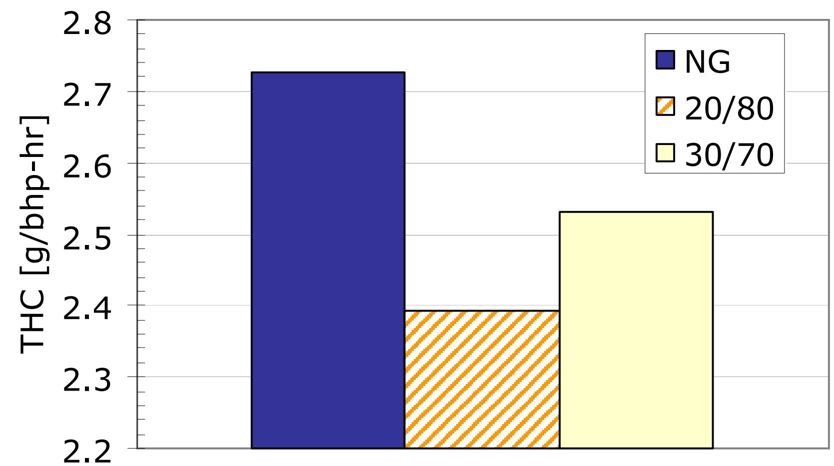




- Effect of λ on emissions for HCNG mixtures (20 and 30 mol% H_2). Test point-Pt3, speed-2000 RPM, load-10.6 bar BMEP. Timing (MFB50%) was held constant at 11° CA after TDC.
- At very lean conditions NOx is not affected significantly. THC emissions were reduced as hydrogen content in the fuel was increased.

Response Surface Model Predictions – NG Equivalent BSFC and THC





- Response surface model prediction of NG equivalent BSFC and THC emissions for test point-Pt3. NOx and engine torque were held constant and equal to that produced by the baseline NG fueling at this operating condition.
- The results indicate that increasing hydrogen content in the fuel from 20 to 30 mol% reduced the brake specific fuel consumption by approximately 1% and 5% respectively. The THC emissions dropped as well for both HCNG mixtures.

Engine Hardware Modification

- Minimal changes to the engine hardware.
- The hot-wire type mass flow meter unit on the engine measures the fuel flow rate.
- Higher thermal conductivity of hydrogen in HCNG has a stronger cooling effect on the hot wire sensor. The output voltage of the original unit built for CNG service saturates when the engine is operated on HCNG.
- Modifications to the mass flow meter were carried out to enable operation on the HCNG fuel. The process was:
  - Identification of a design solution
  - System modeling to simulate the mass flow meter
  - Mass flow meter bench tests and model validation
  - Machining of modified parts based on model prediction
  - Engine testing of the modified mass flow meter with HCNG

HCNG Compliance

- Compliance of the demonstration vehicles for HCNG operation consisted of the following:
  - Bus fuel system: Fuel tanks, Piping, Gas leak detection and Fire Suppression system
  - Engine fuel system components
- Bus fuel system was assessed for HCNG service and its compatibility with B-109 code requirements by an independent laboratory (Powertech Labs/BC Hydro).
- Letter of approval from fuel tank and gas leak detection system suppliers were obtained for HCNG service.
- Engine fuel supply components (metallic and non-metallic) coming into contact with HCNG mixture were also assessed for compatibility with hydrogen.
- Regulatory approval from local authorities in final stages.

HCNG Bus Project – Activities

- Engine fuel mass flow meter modified is able to successfully handle 20 mol% HCNG fuel.
- Engine calibration completed. Calibration refinement was carried out in conjunction with bus performance testing.
- Engine performance and emissions were verified on steady-state and transient test cycles in the test cell.
- HCNG Bus field trials completed and on-road transient performance verified against CNG.
- Bus emissions testing completed in Nov-06 in collaboration with TransLink and Environment Canada.
- Upgrade of all four buses to HCNG completed.
- Phase-I bus demonstration to start very shortly (Mar-07).
- Bus demonstration to continue in 2008.

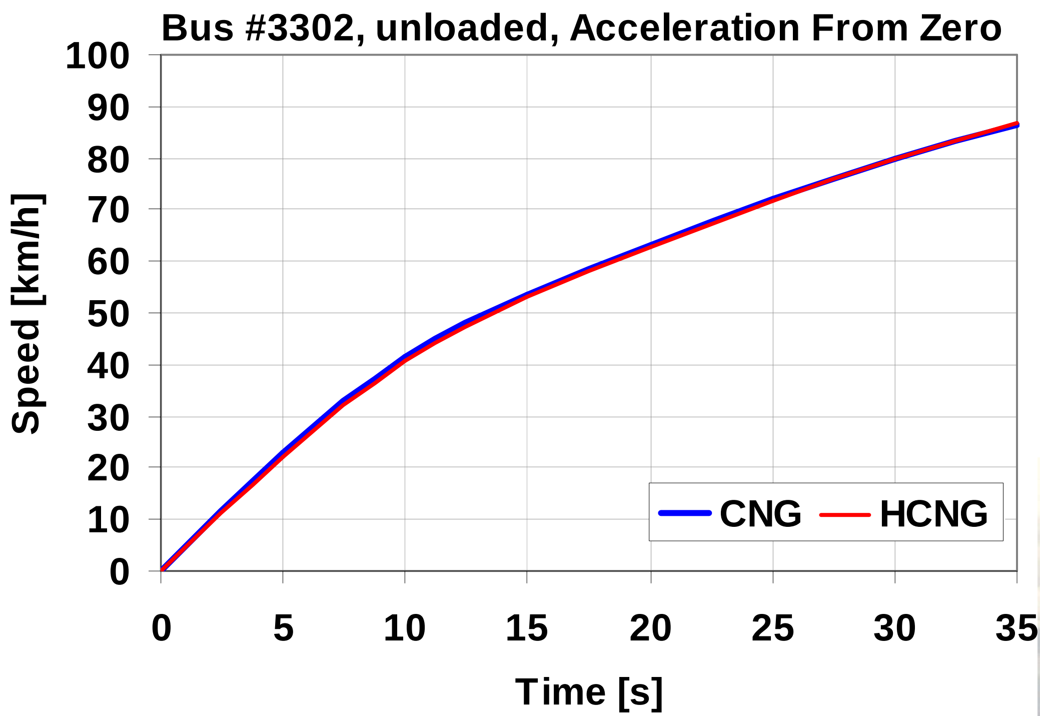
HCNG Engine Emissions

Post-catalyst test cell emissions from the CG+ engine were following:

AVL 8-mode Cycle Composite		
Emission	**HCNG emissions relative to CNG**	**% Change**
NOx+nmHC	0.70	-30%
CH_4	0.71	-29%
CO_2	0.92	-8%
BSFC	0.98	-2%

- Engine torque/power on HCNG same as CNG.
- Test cell transient NOx reduced by over 40% (School Bus Cycle).

HCNG Bus Testing



Two buses with on-board instrumentation were emissions tested in Nov-2006. Bus emissions testing has confirmed these large (>40%) NOx reduction.

- HCNG bus drivability and acceleration at par with CNG.
- Driver feedback very satisfactory.

Summary

- A coordinated approach to promoting and developing hydrogen ICEs and by-product hydrogen streams is a logical strategy.
- Westport has developed key engine technologies for natural gas that are building blocks for hydrogen.
- The results confirm findings from earlier studies and demonstrates that it is indeed possible to operate modern medium/heavy duty engines on HCNG mixtures with accompanying emissions benefits.
- HCNG engine technology based on commercially available NG engines (CWI 5.9L BG+, 8.3L CG+) is available for fleet deployment of following types of vehicles: Buses, Refuse haulers, Delivery Vans.
- Advantages of the HCNG technology need to be better leveraged to nurture the growth of the hydrogen based economy.