HCNG Engine Technology for Medium/Heavy Duty Applications

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ABSTRACT
Adapting high efficiency internal combustion engines to operate on a mixture of hydrogen and natural gas (HCNG) could result in cost effective power plants to assist with the transition to hydrogen based transportation. Previous studies have shown that HCNG fuel can reduce emissions of NOx (oxides of nitrogen) of a lean burn engine. If the hydrogen is obtained from a renewable source it can help reduce greenhouse gas emissions. This paper presents knowledge gained from engine combustion and emissions testing with three different fuels. A turbocharged lean burn spark ignition engine was operated on natural gas as well as mixtures of hydrogen and natural gas (20/80 and 30/70 H2/NG by vol%). The engine performance and emissions were recorded at several speed and load conditions. Test parameters included air/fuel ratio and the combustion timing. A response surface model was developed from the experimental data and used for predictive purposes. Results indicate that addition of hydrogen to natural gas fuel improves combustion at lean air/fuel ratios and extends the lean limit resulting in lower NOx and hydrocarbon emissions without sacrifice in engine torque or fuel economy. A full engine calibration was also developed for the 20/80 mixture, and was verified over the steady-state test cycle. In general, the chosen HCNG calibration included operation at higher air-fuel ratios and retarded spark timings. The results indicated that the emissions of NOx+NMHC and unburned methane were reduced substantially. The HCNG engine torque, power and fuel consumption were maintained the same as for the natural gas fuel. Field testing verified that the HCNG bus acceleration and drivability were on par with that of CNG bus.

Keywords: hydrogen, natural gas, HCNG, lean burn engine

1. INTRODUCTION

Internal Combustion Engines are very well developed and becoming increasingly sophisticated. Engine power density 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 capable of using hydrogen as a transportation fuel. Some questions that are generally raised are:

- 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.

This test program aimed at improving the understanding of the operation of medium/heavy duty lean burn spark ignition natural gas engines fuelled by a mixture of hydrogen and natural gas (HCNG). The overall project goals were to develop HCNG powered vehicles that serve as a commercially viable bridge for utilizing hydrogen in the transportation sector while demonstrating significant emissions benefits. Most HCNG studies in the past have been conducted typically with a low level of hydrogen enrichment (up to 30 % by volume or 10% by mass in the fuel mix). Experience gained from these studies has indicated that natural gas vehicle fuel system is compatible with HCNG and that the engine can be recalibrated with only few modifications to the hardware.

Benefits of HCNG fuel is that it allows early adopters of the hydrogen engine technology with a nearly commercial technology while delivering significant emissions reductions. HCNG also promotes the use of hydrogen fuel to greater number of people with a lower cost premium. HCNG can effectively utilize the existing investment in natural gas fueling and vehicle infrastructure.

2. IWHUP Demonstration

In North Vancouver, BC Sacre-Davey Innovations (SDI) is leading an initiative titled the "Integrated Waste Hydrogen Utilization Project" (IWHUP). IWHUP is an initiative to harness waste hydrogen generated from the production of sodium chlorate and promote its use as a fuel by demonstrating emerging hydrogen technologies and applications for transportation.

It is 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 H2-ICE Powered Vehicle Demonstration
SP6. Heavy-duty HCNG Powered Transit Bus Demonstration
SP7. Combined Heat & Power Fuel Cell Demonstration
SP8. Project Management, Communications & Public Outreach

It is an integrated approach:

- Promote the use of vented by-product hydrogen, and,
- Develop the necessary infrastructure, end use applications, regulatory framework and education for by-product hydrogen
- Stimulate greenhouse gas (GHG) emission reduction.
- 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.
- Develop the North Vancouver "NODE" of the BC Hydrogen Highway

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 and TransLink (GVTA).

Funding Programs

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

BC's Hydrogen Highway

The IWHUP project is part of the British Columbia Hydrogen Highway. The Hydrogen Highway is a coordinated demonstration, deployment and market development program framed around the 2010 Winter Olympics in the Greater Vancouver region. There are seven nodes from cities of Victoria through Surrey, Vancouver, North Vancouver and Whistler.

Hydrogen Supply

The hydrogen source for IWHUP is an electro-chemical plant (Sodium Chlorate & Chlor-alkali) situated in North Vancouver. The plant uses industrial electrolyzers to convert brine and electricity into sodium chlorate and by-product hydrogen. The facility has 62 MW of installed electrical power on site available to this industrial process. Up to 1000 kg/hr of by-product hydrogen is vented. This is enough hydrogen to power a fleet of over 20,000 pure hydrogen powered cars. For comparison, in Canada, over 50,000,000 kg hydrogen is vented annually (enough to power about 200,000 pure hydrogen cars). Approximately 750 wind turbines (1 MW each) would be required to produce this amount of hydrogen from electrolysis of water. There are over 1000 such sources of by-product hydrogen around the world.

The hydrogen captured from the by-product stream is purified and compressed by the HTEC's pilot plant. The pilot plant is designed to supply 20 kg/hr of pure hydrogen (99.999% purity level) at 450 bar (6500psig).

The purified, compressed hydrogen is stored in high-pressure storage cylinders for transport. Each PowerCube module stores about 89 kg of pure hydrogen at 450 bar pressure in ten high-pressure cylinders manifolded together in a rigid steel frame construction. The cylinders are aluminum lined with carbon-fiber body. A tractor-trailer can carry up to 6 PowerCubes (534kg of H2) and a self load/unload forklift. The system has been approved by Transport Canada.

Figure 2. Hydrogen capture, purification and compression plant.

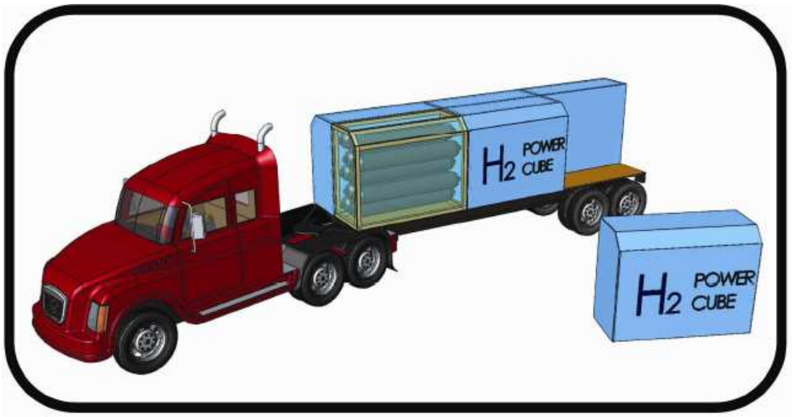

Figure 3. Hydrogen distribution trailer with PowerCubes.

HCNG Refueling Station

The CNG station in Port Coquitlam that refuels a fleet of CNG buses was upgraded by Clean Energy Fuels to provide hydrogen and HCNG refueling capability. The upgraded included ability to receive hydrogen from a PowerCube, blending of hydrogen and CNG mixture, high pressure dispensing as well as ground storage. A H2/HCNG dispenser can provide quick filling of vehicles up to 3,000 psi.

Heavy Duty HCNG Bus Demonstration

Westport together with GVTA/TransLink is participating in sub-project-6 involving heavy-duty HCNG powered transit bus demonstration. Four existing low floor 40-foot CNG buses owned by the GVTA have been converted to HCNG for the following purposes:

- Demonstrate the feasibility of using purified waste hydrogen mixed with natural gas as a transportation fuel,

- Evaluate and collect operational, performance and emissions data from buses fueled with a mixture of waste hydrogen and natural gas;
- Compare the operational, performance and emissions data with 2 CNG buses using the same engine and bus configuration;

The total project duration will be three years with the first half for engineering to be followed by vehicle testing and demonstrations in the second half.

A transit vehicle demonstration will allow for the evaluation of HCNG (Hydrogen enriched, compressed natural gas) technology, which is based on today's commercially available spark ignited compressed natural gas (SI CNG) engine technology. The HCNG technology has been demonstrated successfully on the commercially available Cummins Westport Inc. (CWI) 5.9 Liter B Gas Plus SI CNG engines as part of the recently completed field demonstrations at the SunLine Transit Agency in California, USA. The current project involves further refinements in HCNG calibration and exploration of the robustness to HCNG operation using the larger 8.3 Liter CWI C Gas Plus SI CNG engine. The HCNG transit bus offers the potential to reduce oxides of nitrogen (NOx), particulate matter (PM) and GHG (green house gas, i.e. CO_2) emissions in the Greater Vancouver Region. If the project is successful, the technology has the potential to be showcased during the 2010 Olympics.

The HCNG buses are part of TransLink's Bus Technology and Alternative Fuels Program. As part of this initiative TransLink is evaluating a variety of different buses that involve innovative propulsion technologies and alternative fuels.

3. HCNG COMBUSTION

Nitric Oxide (NO) emission from the combustion of fuel and air mixture is strongly dependent on the flame temperature. One of the methods used to reduce NO, which is the main constituent of NOx emissions, is to lower flame temperature during combustion by diluting the mixture with excess air also known as lean fuel-air combustion. Many spark ignited natural gas engines available commercially utilize lean burn combustion to reduce NOx emissions. As the emissions target become more stringent there is further need to reduce NOx emissions compared to what is achievable today. In addition, there is growing concern regarding impact of CO_2 emissions on long term climate of the earth due to its action as a greenhouse gas. Methane is also known to be a very potent greenhouse gas. Hence reduction of CO_2 and unburned methane emissions from an internal combustion engine are of considerable interest.

Natural gas, which mainly consists of methane, has a low burning speed. This is further aggravated as the relative air-fuel ratio is increased for lean combustion applications. This imposes a practical limitation on how lean a premixed charge spark-ignition natural gas engine can be operated without excessive HC emissions and sacrificing the engine efficiency. Compared to natural gas (i.e. methane) hydrogen has a very high burning speed, very wide flammability limits, higher diffusivity and low ignition energy. These characteristics make hydrogen an excellent fuel additive. Adding hydrogen to

natural gas can be used to improve the combustion characteristics of the resulting fuel mixture. A comparison of the fuel properties of hydrogen, methane and HCNG are shown in Table 1.
Over the years a number of engine studies and vehicle projects utilizing various blends of hydrogen and methane/natural gas have been reported [1-5]. In a lean burn internal combustion engine fuelled by hydrogen natural gas mixture allows the fuel-air mixture to burn leaner as well as retard the spark timing (due to improved heat release rate), both of which help reduce NOx. The overall effect is net NOx reduction. Between 15-30 volume% hydrogen in the fuel mix extends the lean operating limit and promotes complete combustion of a leaner mixture (reduced NOx, CO and HC emissions) and improves torque and thermal efficiency near the lean combustion limit.

Table 1. Comparison of physical properties of some gaseous fuels (values generally reported in the literature).

Property	Hydrogen	Methane	20/80 Hydrogen/Methane
Molecular weight	2.016	16.043	13.238
C/H atom ratio	0	0.25	0.222
Diffusivity in air, cm^2/s	0.63	0.2	Not Available
Lower Heating Value,	119.93	50.02	52.15
Lower limit of flammability in air,	4.0	5.3	Between 4.0 and 5.3
Upper limit of flammability in air,	75.0	15.0	Not Available
Stoichiometric composition in air,	29.5	9.5	11.0
Stoichiometric air/fuel	34.3	17.2	17.8
Autoignition temperature,	580	540	Between 540 and 580
Ignition Energy in air for a stoichiometric mixture	0.02	0.29	Not Available
Laminar burning velocity* in air for a stoichiometric	275	40	46
Laminar burning velocity* in air for a lean mixture	165	8	15

* Measured data from Kido et al. [6].
λ is the relative air-fuel mass ratio (air-fuel ratio / stoichiometric air-fuel ratio).

4. SCOPE OF THE WORK
The objectives of the engine combustion study were the following:

- Determine the effectiveness of hydrogen in improving the combustion properties of lean natural gas air mixtures for a heavy duty engine;
- Determine whether there are additional benefits in increasing the hydrogen content from 20% to 30% by volume.

Subsequent to the combustion study a detailed re-calibration of the engine on HCNG mixture was carried out. HCNG with 20 mol% H2 was selected based on vehicle range considerations and commonality with previous work. The current work builds on an earlier project carried out for SunLine Transit Agency [7]. Experience gained from the SunLine project was taken into consideration in the planning of engine calibration and vehicle field trials. Re-calibration objectives were following:

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

5. EXPERIMENTAL SET-UP

Composition of the British Columbia natural gas used in the present study was measured using a calibrated gas chromatograph on-site. The natural gas contains about 96% methane, 2% ethane, 0.5% propane, small quantities of butane and other higher hydrocarbons as well as <1% of nitrogen and carbon dioxide combined. The fuel has a lower heating value of 48.7 MJ/kg and a density of 0.71 kg/m^3(at 15 ^{o}C and 1 atm. pressure).

A commercially available Cummins Westport Inc. C Gas Plus lean burn natural gas fueled spark ignition engine was selected for the HCNG testing. The engine has a bore and stroke of 102 and 120 mm respectively. It is a four stroke in-line six cylinder engine having a compression ratio of 10:1 and a displacement of 8.3 Liters. The engine has a rating of 280HP at 2,800 RPM. The engine is in widespread use in North American market and has number of advanced features. The engine is equipped with a water-cooled turbocharger and wastegate control. The air intake system is provided with charge air cooling to reduce emissions and improve power density by lowering intake manifold temperature. The engine does not require a catalyst to meet CARB/EPA heavy-duty emissions standards but is commercially fitted with an exhaust oxidation catalyst to achieve very low emissions (CO, NMHC, PM, HCHO). The engine has a closed loop electronic air/fuel regulation system. A wideband oxygen sensor in the exhaust is used for closed loop air/fuel control. The engine has improved combustion chamber design, a knock detection sensor and electronic controls to enable reliable operation over a wide range of natural gas fuel quality (natural gas fuels having methane number as low as 65).

A fueling system (Figure 4) was designed and assembled to allow mixing and storage of hydrogen-natural gas mixtures in a high-pressure sphere. Pure hydrogen is supplied from a mobile tube trailer. High-pressure natural gas was supplied from an on-site compressor. A method of partial pressure was used to prepare known mixtures of hydrogen and natural gas in the storage sphere. The method accounts for real gas effects of pressure on the density of the gas. A calibrated thermal conductivity meter was used to check the hydrogen content of the mixture in the sphere in real time during engine testing. Hydrogen content in the HCNG mixture was also verified using the on-site gas chromatograph.

Figure 4. HCNG fuel mixing and storage.

Figure 5. Engine as installed in the test cell for HCNG testing

The engine was connected to a dynamometer (Figure 5). The engine and test cell were fully instrumented to record performance and emissions data. The emissions analyzer can measure real time levels for CO, CO_2, NOx, THC, CH_4 and O_2. Baseline data with natural gas was also taken to use as a direct comparison to the HCNG performance of the engine. The engine was fitted with an instrumented cylinder head with water-cooled flush-mounted piezoelectric pressure transducers in cylinders 1 and 6 to measure in-cylinder pressure during the engine cycle. The in-cylinder pressure was acquired in real time using a high speed data acquisition system. Typically up to 100 consecutive engine cycles were recorded for each individual test point. The in-cylinder pressure data was also analyzed thermodynamically to obtain heat release during combustion.

6. TEST MATRIX

Engine testing was carried out to determine impact of hydrogen in extending the lean air/fuel mixture operating limit of the engine and effect on exhaust emissions. Engine controls were reconfigured for operation on the HCNG mixtures. The test constraints at each operating condition included, 1) maintaining engine torque same as baseline natural gas operation, 2) maintaining engine operation close to current hardware limits (i.e. air-handling, in-cylinder and ignition systems limits).

The engine performance and emissions were recorded at several speed and load conditions. The operating points tested are shown in Table 2. Tests fuels used in the study are shown in Table 3. Test parameters included air-fuel ratio and the combustion timing. At each speed load condition, the baseline performance was measured with no overrides applied to the engine controller. Then spark timing and λ were adjusted to generate a surface of varying '50% Mass Fraction Burned (50%MFB)' and 'Air Fuel Ratio'. The results were then processed, compiled and organized such that they could be used as inputs to a response surface modeling software. The software was then used to generate basic regressions that could be used to mathematically calculate performance at any given condition within the boundaries tested. Typical R^2 values for the regressions were ~90% for NOx and ~99% for BSFC and HC.

Table 2. Operating conditions used in the study.

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

Table 3. Fuels tested.

Fuel Mixture	Hydrogen			Natural Gas			Lower Heating Value
	vol%	mass%	energy%	vol	mass%	energy%	MJ/kg
NG	0	0	0	100	0	100	48.7
20/80	20	2.9	6.9	80	97.1	93.1	50.8
30/70	30	4.9	11.2	70	95.1	88.8	52.2

7. Results - Combustion Study

7.1 Measured Data - Heat Release

Figure 6 shows the heat release rate for both natural gas and the 20/80 HCNG fuels at two different air/fuel ratios (λ = 1.17 and 1.3). The results clearly indicate that adding hydrogen to the fuel speeds up the combustion. The combustion starts earlier and the maximum rate of heat release is slightly higher for the 20/80 HCNG mixture. Similarly, effect of combustion timing on the heat release rate is shown in Figures 7. Again, one can notice faster earlier combustion for the 20/80 HCNG mixture.

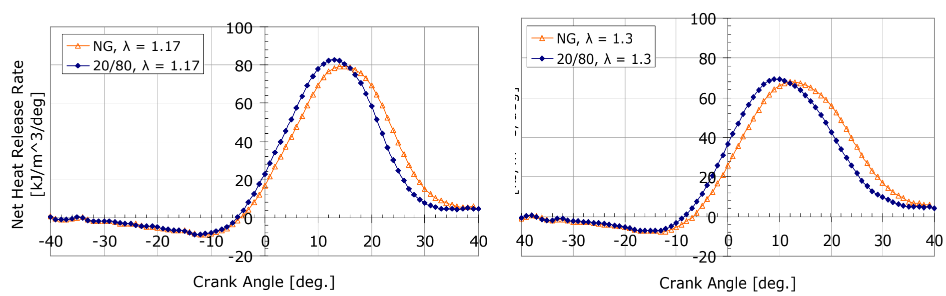

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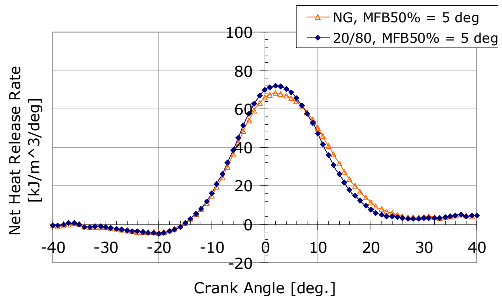
Figure 6. Effect of λ on the heat release rate for natural gas and 20/80 HCNG fuels. Test point-Pt1, speed-1061 RPM, load-8.4 bar BMEP, timing-MFB50% = 15^{o}CA after TDC.



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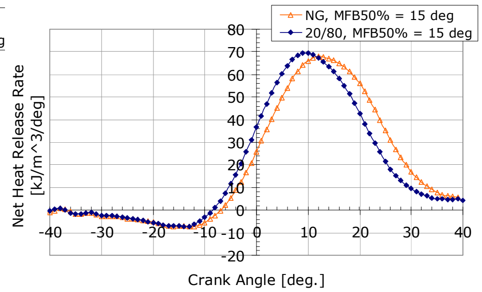


7-b

Figure 7. Effect of combustion timing on the heat release rate for natural gas and 20/80 HCNG fuels. Test point-Pt1, speed-1061 RPM, load-8.4 bar BMEP, λ=1.3.

7.2 Measured Data - Emissions

Figure 8 shows the effect of relative air/fuel ratio (λ) on the NOx and THC (total hydrocarbon) emissions, fuel economy and maximum in-cylinder pressure at combustion timings of 15 ^{o}CA (degrees crank angle) after top dead center (TDC). The NOx emissions were found to be higher and THC emissions lower for the 20/80 HCNG mixture as compared to pure NG fueling. As λ was increased the rise in THC emissions for NG fueling increased much more rapidly compared to the 20/80 HCNG mixture. This indicates the improvement in combustion at lean conditions due to presence of the hydrogen fuel. Hydrogen promotes a more complete burning of the fuel-air mixture. The diesel equivalent brake specific fuel consumption (BSFC) was found to be slightly lower for the 20/80 HCNG mixture. A small increase in maximum in-cylinder pressure was also noticed for the 20/80 HCNG mixture, which would be consistent with a faster heat release rate in presence of hydrogen.

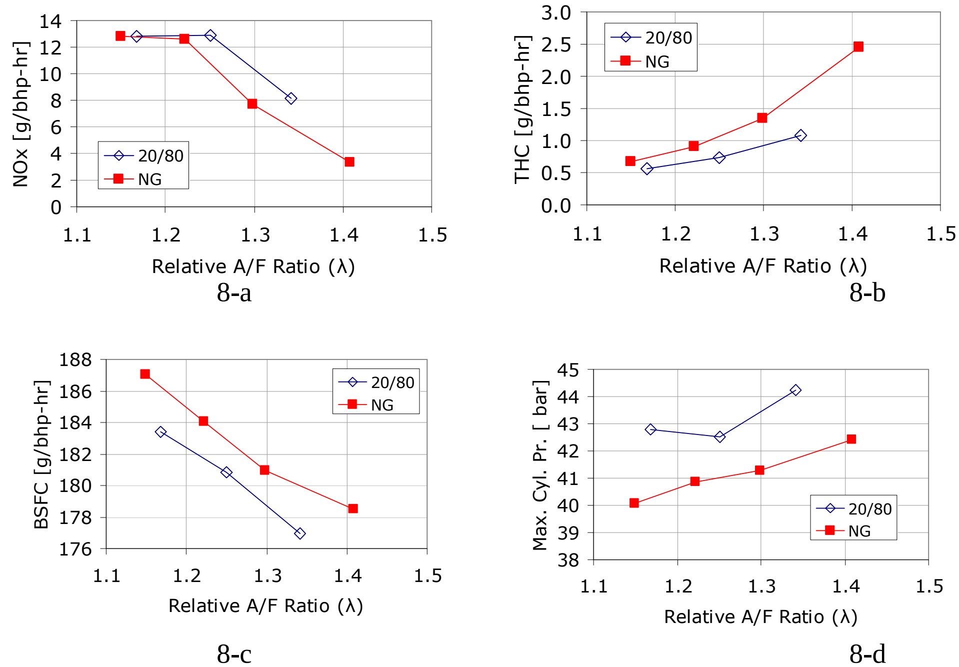
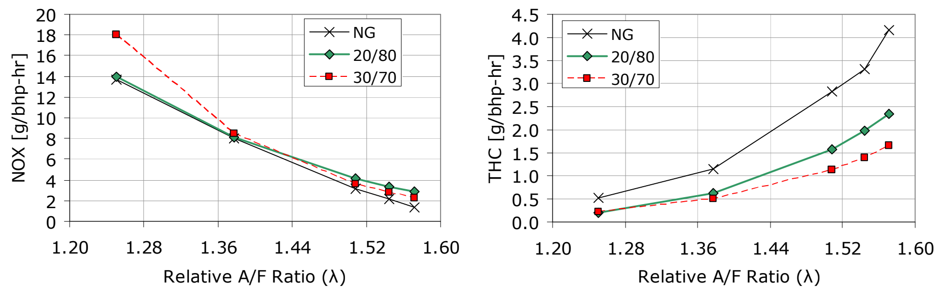


Figure 8. Comparison between natural gas fueling and 20% hydrogen in natural gas showing effect of relative air/fuel ratio (λ) on brake specific emissions and fuel economy. Test point-Pt1, speed-1061 RPM, load-8.4 bar BMEP, timing-MFB50% = 15^{o}CA after TDC.

<u>7.3 Response Surface Model Predictions</u>

The response surface model that was generated from the test data was used for prediction of emissions at various engine operating conditions for the 20/80 and 30/70 HCNG mixtures. The model input parameters were the relative air/fuel ratio, λ and combustion timing - MFB50%. For natural gas actual test data were used. The model for 20/80 and 30/70 HCNG mixtures was run at the same λ and combustion timing as natural gas fueling. Model predictions are shown for test point - Pt3 (Figure 9). The model predicts that NOx is reduced as λ is increased for all three fuels. At low values of λ only the 30/70 HCNG mixture showed higher NOx emissions, other wise there was little difference between all three fuels. This indicates that the combustion is already quite lean and the combustion temperature was sufficiently low such that the NOx was not significantly affected by the presence of hydrogen. On the other hand, THC emissions were significantly reduced as the hydrogen content of the fuel was increased. The main contributor to the THC emissions is unburned methane from the fuel. The reduction in THC emissions also improved as λ was increased. This confirms that hydrogen in the fuel makes it possible to operate at leaner air/fuel ratios (compared to natural gas) in order to achieve reduction in NOx emissions while keeping the THC emissions within acceptable limits. Except small differences fuel consumption for all three fuels was quite close to each other.



9-a 9-b

Figure 9. Effect of relative air/fuel (λ) on emissions for 20% and 30% hydrogen in natural gas as predicted by the response surface model. The predictions are compared to actual test data for natural gas. Test point-Pt3, speed-2000 RPM, load-10.6 bar BMEP, timing-MFB50%=11^o CA after TDC.

The model was also run at test condition - Pt3 for the 20/80 and 30/70 HCNG mixtures such that the NOx was maintained same as baseline natural gas fueling. Both λ and combustion timing were adjusted for the HCNG mixtures such that the NOx remained the same as NG. The model predictions for BSFC and THC emissions are shown in Figure 10. The results indicate that increasing hydrogen content in the fuel from 20 to 30 % by volume reduced the brake specific fuel consumption by approximately 1% and 5% respectively. The THC emissions dropped as well for both HCNG mixtures, the 20/80 mixture showing the largest decrease of about 12%. The results indicate effectiveness of hydrogen in improving combustion at very lean conditions.

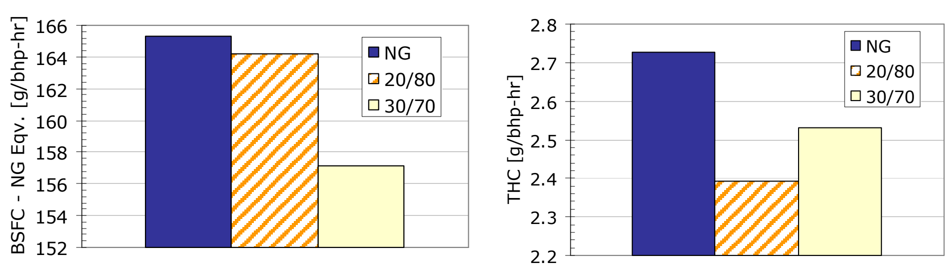


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Figure 10. Response surface model prediction of NG equivalent BSFC and THC emissions for test points-Pt3. NOx and engine torque were held constant and equal to that produced by the baseline natural gas fueling at this operating condition.

<u>7.4 NOx Reduction Study</u>

Further engine testing to investigate NOx reduction at two operating conditions was carried out in the test cell. The test conditions were Pt-A (ESC mode-10) and Pt-B (ESC mode-12) as described in Table 2. These operating points were selected from the ESC 13-mode cycle (European Stationary Cycle), which is one of the test cycle used for emissions certification of heavy duty diesel engines. At each test condition for the 20/80 HCNG mixture the combustion timing was retarded and the relative air/fuel ratio - λ was increased compared the natural gas fueling, while maintaining the fuel consumption and torque unchanged . For Pt-A and Pt-B the combustion timing for the 20/80 HCNG mixture was retarded by 3.5 and 3.0 ^{o}CA respectively over that for natural gas. The λ for Pt-A and Pt-B was increased by 0.01 and 0.03 respectively over that for natural gas. The combined retarding of the combustion timing and leaning of the air-fuel mixture resulted in substantial emissions reduction (both NOx and THC emissions) while the fuel consumption remain essentially unchanged (less than ± 1%). The results are shown in Figure 11. For Pt-A and Pt-B the NOx was reduced for the 20/80 HCNG mixture by 35% and 30% respectively as compared to natural gas fueling. Similarly, the THC emissions were reduced for Pt-A and Pt-B by about 44% and 35% respectively.

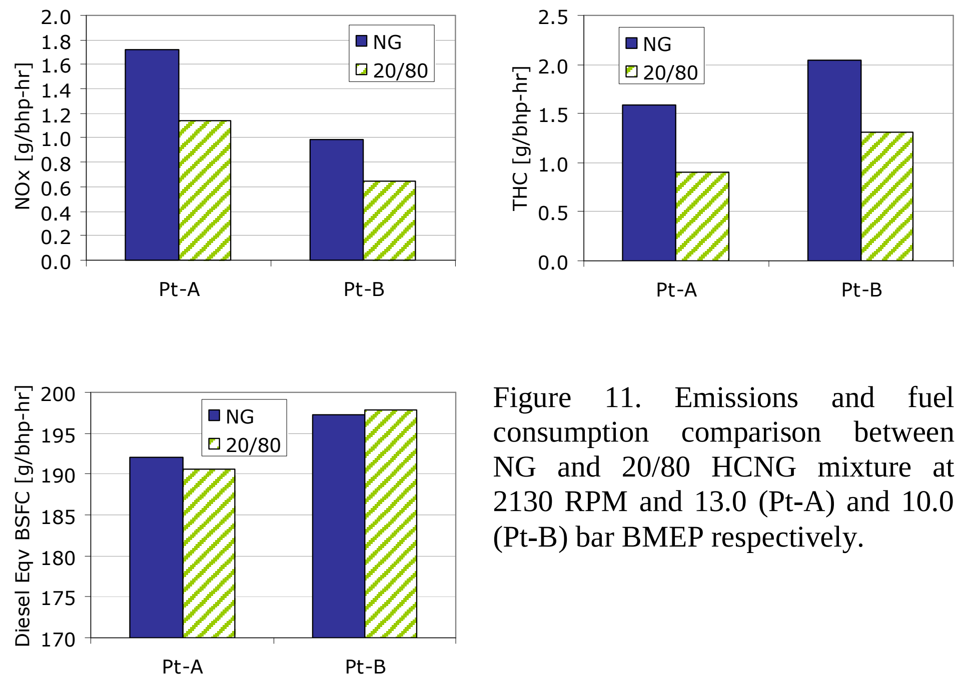

Figure 11. Emissions and fuel consumption comparison between NG and 20/80 HCNG mixture at 2130 RPM and 13.0 (Pt-A) and 10.0 (Pt-B) bar BMEP respectively.

8. HCNG (20/80) Calibration Development

Once the engine baseline on CNG and the investigation of HCNG combustion was completed a process of steady state calibration on 20 vol% HCNG was initiated. The HCNG calibration was issued after a series of tests to optimize the HCNG performance and emissions while ensuring that the vehicle drivability is not affected. The operating parameters that were altered are the ignition timing, the mixture Lambda (relative air/fuel ratio), and to a lesser extent, the intake boost pressure. The test cell engine calibration work was done in conjunction with on road bus performance testing.

8.1 AVL8 test cycle

The AVL 8-Mode test (Figure 12) is a steady-state engine test procedure, designed to closely correlate with the exhaust emission results over the US FTP heavy-duty engine transient cycle. The test involves 8 steady state modes. The composite value is calculated by applying weighing factors on the modal results.

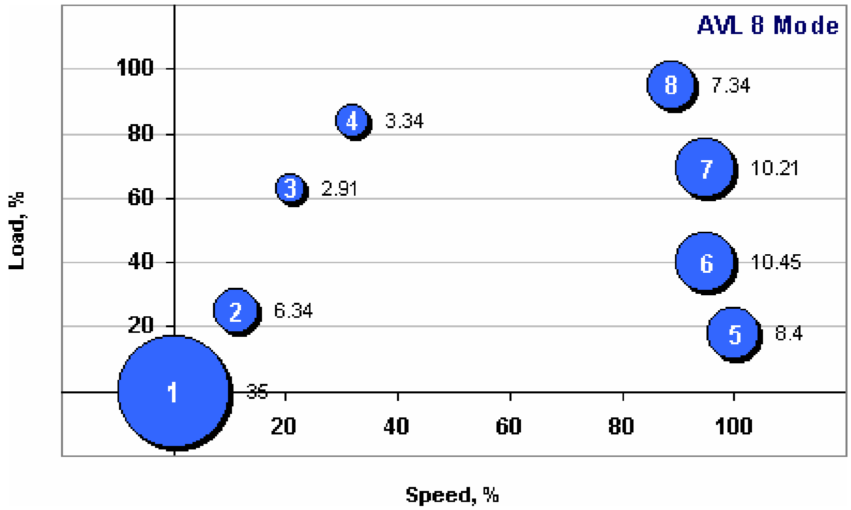

Figure 12. AVL 8-mode steady state test cycle points with weighting factors.

8.2 Steady State Torque Curve

First a CNG baseline was carried out in the test cell. Once the HCNG calibration was completed a torque curve was also recorded for HCNG. The torque curves as obtained in the test cell are shown in Figure 13. The engine performance on HCNG was kept at or slightly above the CNG baseline level. This would ensure that the vehicle performance remain identical under both the CNG and HCNG fueling.

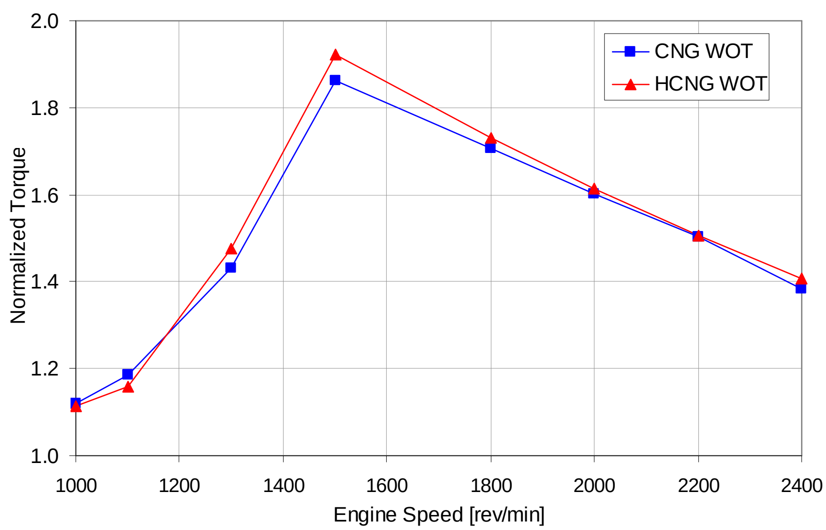

Figure 13. Engine torque curve comparison. The torque values are normalized against CNG torque at the lowest engine speed.

8.3 Steady State Emissions

The engine calibration was modified to take advantage of the HCNG capabilities to lower emissions while keeping the engine performance and the vehicle drivability at the same level as the baseline case. Results post catalyst emissions for AVL steady-state test cycles are shown in Table 4. Under HCNG operation the NOx+NMHC and methane emissions were reduced by about 30%. CO2 emissions were reduced by 8%. This is expected as about 7% of the energy in the fuel is coming from hydrogen. The diesel equivalent brake specific fuel consumption (DE BSFC) was reduced by 2%.

Table 4. CNG and HCNG Post Catalyst Emissions

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%

Transient Performance and Emissions

The HCNG engine operation was also verified on a transient school bus test cycle. No significant differences were detected between CNG and HCNG operation. The HCNG transient NOx and CH4 emissions were 44% and 18% lower respectively compared to CNG and the exhaust CO2 emissions about 8% lower.

8.4 HCNG Bus Performance

Once the test cell calibration of the engine reached a certain state of development the next step was to evaluate the calibration in actual road service by converting a CNG bus to HCNG operation. The operation of the bus provided real life transient conditions and was used to refine and validate the HCNG calibration.

As a first step the bus performance was recorded on CNG, which would serve as a basis for comparison with HCNG. Next, the bus is converted to operate on HCNG fuel and tests were repeated on the HCNG operation. In order to record the bus performance instrumentation was added to the bus for data logging. Care was exercised in ensuring that actual service conditions can be reproduced accurately. An experienced professional bus driver was hired to drive the bus. Driver feedback was also recorded as part of the bus performance tests. Some of the important tests used to evaluate bus performance and operation are described below.

- Acceleration from zero - The bus is accelerated from rest to 80 km/h maintaining the pedal position fully pressed at all times during the test.
- Hill Climb Test - The test is performed while climbing a steep hill and consists of measuring the time bus takes to cross certain landmarks. The test starts with the bus stopped at the bottom of the hill and then the bus is accelerated away from the stop with the pedal fully pressed to the floor. Time and Vehicle speed were measured at pre-selected checkpoints.
- Urban drive test - The route was selected to assess bus operation in a stop and go traffic on a busy street during daytime.

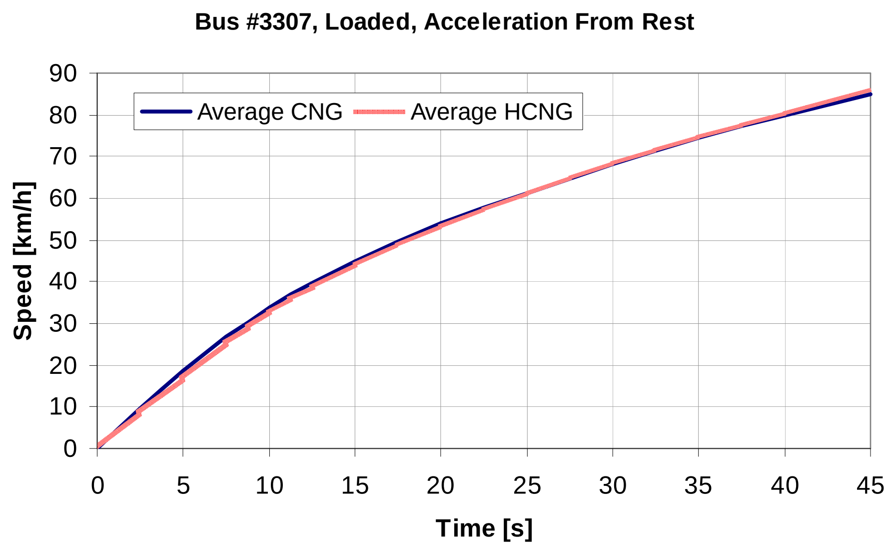

Figure 14. Bus#3307 CNG vs. HCNG acceleration comparison. Each curve represents the average of five runs.

As seen from Figure14 the HCNG bus acceleration is at par with that of CNG bus.

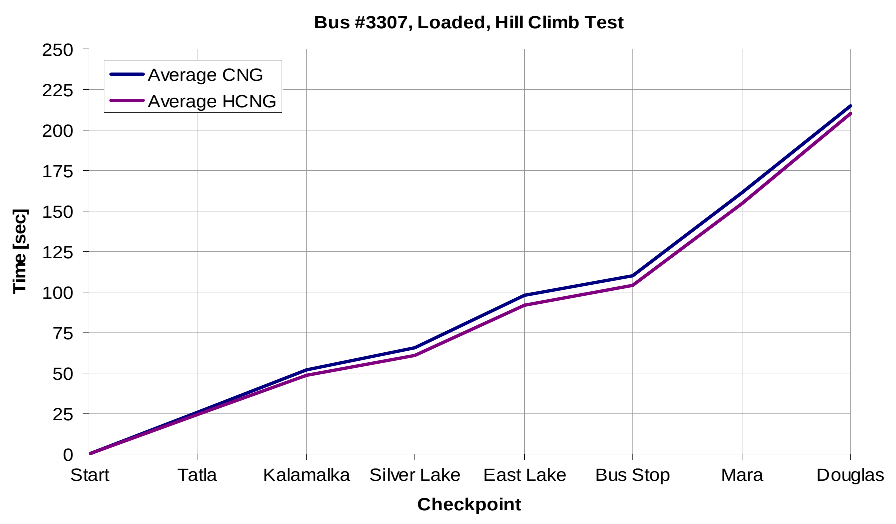

Figure 15. BUs#3307 CNG vs. HCNG hill climb comparison. Each curve represents the average of four runs.

For operation with HCNG fuel the bus reaches the top of the hill 5 seconds (2.3%) faster than CNG (Figure 15.).

The acceleration and hill climb tests verified that the HCNG calibration met the necessary performance requirements laid out at the beginning of the project.
Driver feedback recorded various repeats of the acceleration, hill climb and urban drive tests indicated that HCNG bus performance was nearly identical to that of the CNG buses. This provided additional confidence to the robustness of the HCNG calibration.

9. HCNG Compliance
For this project HCNG composition is 80% Natural Gas and 20% Hydrogen by volume, expressed in mass fraction it is 97% natural gas and 3% hydrogen. The compliance review is meant to identify and mitigate potential effects of HCNG on the engine and vehicle components. The bus fuel system consists of - high pressure fuel storage tanks, piping/valves/pressure relief devices, gas leak detection and fire Suppression system. Compliance of the demonstration vehicles for HCNG operation consisted of the following:

- Literature review of available codes, standards, HCNG materials compatibility and operational experience with HCNG vehicles.
- Collecting and reviewing documentation related to engine fuel system components and bus fuel system components including drawings and parts lists.
- A matrix of fuel system components was prepared and reviewed for compatibility with HCNG operation.
- The bus fuel system was inspected and assessed for HCNG service and its compatibility with B-109 code requirements by an independent laboratory (Powertech Labs/BC Hydro).
- Letter of approval from bus on-board fuel tank and gas leak detection/fire suppression 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.
- The fuel storage and supply system on the bus are rated for 3,000 psi (20.7 MPa) service. The fuel system components were pressure tested as part of the review.
- All the necessary documentation was submitted to the local regulatory authorities for review and approval.

The proportion of hydrogen in HCNG being small it is expected that the HCNG fuel would behave similar to natural gas. Engine testing in the test cell over a period of several months with HCNG during the SunLine project and the current project to date have not indicated any adverse impact of using HCNG fuel in a CNG engine.

Westport’s first project on HCNG buses was with SunLine Transit Agency in California. Two 40 foot buses with CWI 5.9L B Gas Plus engine were converted to operate on HCNG with 20 vol% hydrogen. The buses have accumulated over 100,000 kms in field testing and indicate no HCNG related fuel system component failures to date. This gives some confidence that there are no short term failures associated in using HCNG (20 vol% H2) in a CNG engine.

Potential for failures in the longer term over extended periods of usage remains to be understood. The IWHUP project with four demonstration vehicles to be field tested over next two years will provide some of the necessary information.

10. SUMMARY

1) Addition of hydrogen to natural gas fuel improves combustion at lean air/fuel ratios. It is possible to extend the lean air/fuel combustion limit by adding 20-30 % hydrogen by volume to natural gas and achieve lower NOx and THC emissions without sacrificing engine torque or fuel economy. Employing hydrogen content at 30 volume% may be beneficial under certain operating conditions.

2) The heat release rate was found to begin earlier and the maximum of the rate of heat release curve was slightly higher for the 20/80 HCNG mixture as compared to the natural gas fuel. In general, hydrogen increases the rate of combustion of the air-fuel mixture at lean conditions.

3) A response surface model was generated from the test data. The model predicted that if the NOx emissions for the engine running on the HCNG mixtures were fixed at the same level as natural gas then it would result in lower fuel consumption and THC emissions.

4) Steady-state tests over an engine cycle revealed 30% reduction in NOx+NMHC without sacrificing engine torque or fuel economy. Transient tests over the School Bus cycle indicated about 44% reduction in NOx emissions. Emission of unburned methane was also significantly reduced.

5) Field testing verified that the HCNG bus acceleration and drivability were at par with that of CNG bus.

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