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ABSTRACT

A turbocharged lean burn natural gas engine was upgraded to operate on a blend of hydrogen and natural gas (HCNG). Tests were carried out to determine the most suitable H_2/NG blend for H_2 fractions between 20 and 32 vol%. A 20 vol% H_2 content was found to provide the desired benefits when taking into consideration the engine and vehicle performance attributes. A full engine map was developed for the chosen mixture, and was verified over the steady-state AVL8 cycle. In general, the HCNG calibration included operation at higher air-fuel ratios and retarded spark timings. The results indicated that the NOx and NMHC emissions were reduced by 50% and 58% respectively, while the CO and CH_4 emissions were slightly reduced. The HCNG engine torque, power and fuel consumption were maintained the same as for the natural gas fuel. The chassis dynamometer transient testing confirmed large NOx reduction of about 56% for HCNG operation. The buses have successfully completed the 24,000 miles field trials and their performance was found very satisfactory.

INTRODUCTION

This program targeted development and testing of a new engine calibration for a lean burn natural gas engine to operate on HCNG (hydrogen blended natural gas mixture) fuel. The overall project goals were to develop HCNG powered vehicles that serve as a commercially viable bridge for utilizing hydrogen in the heavy-duty transit vehicle market as well as demonstrate emissions benefits and commercial viability of HCNG fuel in state of the art internal combustion engines available today.

HCNG COMBUSTION IN NATURAL GAS VEHICLES

A typical blend ratio for HCNG fuel mixture is about 20% hydrogen (H_2) by volume (3% by mass or 7% by energy). A natural gas vehicle fuel system is generally compatible with HCNG and natural gas engine can be recalibrated to operate with HCNG with small modifications to the engine.

HCNG BENEFITS

HCNG allows customers early hydrogen deployment with nearly commercial technology. Engines can be calibrated for lower oxides of nitrogen (NOx) emissions or lower greenhouse gas (GHG) emissions. It also allows governments and agencies to promote the use of hydrogen to greater number of people at lower cost. HCNG can help the hydrogen industry to develop volume and transportation solutions while reducing costs. HCNG can take advantage of existing investment in natural gas infrastructure and HCNG has a much higher volumetric energy storage density than pure hydrogen.

MAIN SECTION

SCOPE OF WORK

The project involved adapting a commercially available heavy-duty lean burn spark ignited natural gas engine to operate on the most suitable HCNG fuel blend. The project involved the following:

- Determination of the most suitable HCNG fuel blend.
- A review of the engine components capability for HCNG operation.
- Engine dynamometer testing to recalibrate the engine for operation on the selected HCNG mixture.
- Verification of the engine performance and estimation of the emissions benefit for the selected HCNG mixture.
- 24,000 miles field-testing demonstration of two buses equipped with the HCNG fueled Cummins Westport B Gas Plus engines and two B Gas Plus NG (natural gas) control buses to gain operating experience.
- Chassis dynamometer testing of the four (2 HCNG and 2 NG) buses to verify emissions over a selected transient operating cycle.

HCNG COMBUSTION

In a lean burn internal combustion engine a hydrogen blended natural gas fuel allows the mixture to burn more lean (Figure 1) as well as allows retarding of the spark timing, both of which help reduce the NOx formation. The overall effect is net NOx reduction. Between 15-30% hydrogen (by volume) extends the lean operating limit, promotes complete combustion of a leaner mixture (reduced NOx, CO and HC emissions) and improves torque and thermal efficiency near the lean combustion limit. It is also possible to calibrate the engine on HCNG to operate with higher thermal efficiency while sacrificing some of the gains in NOx reduction. Addition of hydrogen increases the H/C ratio of the fuel. A higher H/C ratio results in less CO_2 per unit of energy produced and thereby reduce GHG emissions. Improvements in thermal efficiency could also help reduce GHG emissions.

Hydrogen also has a very low energy density per unit volume and as a result the HCNG mixture volumetric heating value decreases as the proportion of hydrogen is increased in the mixture. But, at the same time it should also be noted that hydrogen addition improves the heating value per unit volume of the air-fuel mixture by a small amount at very lean conditions. As shown in Figure 2 the theoretical improvement in BMEP at very lean conditions is about 1% but the actual improvement is considerably more because of improvement in the combustion efficiency due to hydrogen addition.

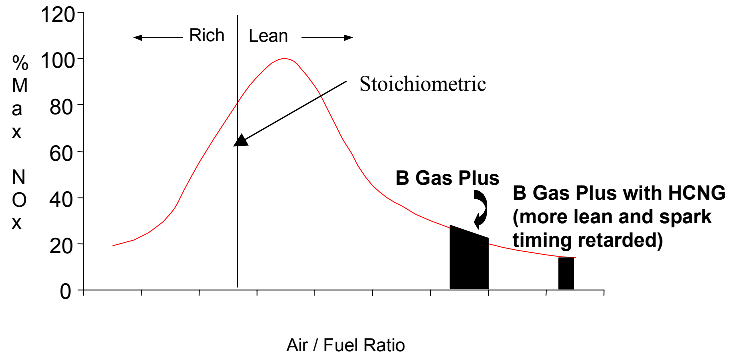


Figure 1. Effect of air/fuel ratio on percentage maximum NOx emissions.

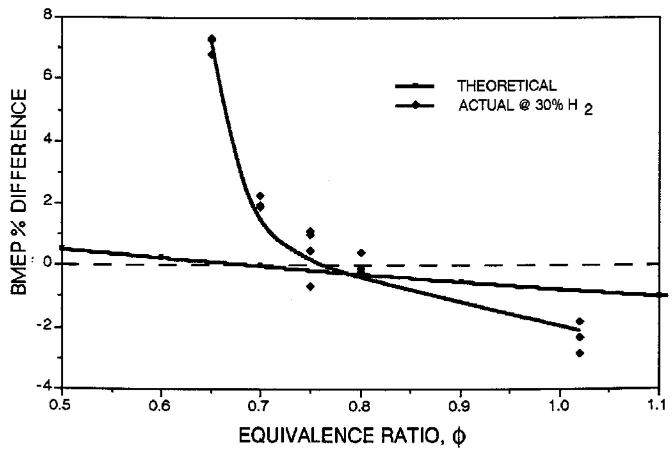


Figure 2. Comparison between theoretical and actual BMEP change with 30 vol% hydrogen in methane [5].

PREVIOUS WORK AND EVIDENCE FOR MOST SUITABLE HCNG BLEND

To achieve desired performance versus emissions trade-off for the engine it was necessary to determine the relative proportion of the hydrogen and natural gas in the fuel mixture. A literature review was undertaken to understand the effect of hydrogen enrichment of hydrocarbon fuels on the performance and emissions of engines as well as to review the effect of hydrogen content.

Early research on hydrogen enrichment of hydrocarbon fuels focused on fuels such as gasoline and isooctane [1-2]. Hydrogen addition up to 10% by mass was investigated. Experiments conducted established the effectiveness of hydrogen in extending the lean operating limit as well as reduction in NOx accompanied by improvement in the thermal efficiency of the engine. One of the earlier studies of using hydrogen supplemented natural gas as an engine fuel was by Nagalingam et al. [3] in an AVL single cylinder engine. Tests were carried out with pure NG, 80:20, 50:50 and 100 vol% hydrogen. Results indicated that loss in the engine power and indicated thermal efficiency was proportional to the amount of hydrogen supplemented. With a higher concentration of hydrogen the methane number of the fuel (an index of anti-knocking property) decreases which translates into a reduction in spark advance at a given operating condition. Emissions results were not reported for the hydrogen-supplemented cases.

In the Denver Hythane® (a registered trademark of Hydrogen Components Inc) project [4], comparative testing of three identical vehicles (1991 Chevrolet 5.7 liter pick-up trucks) with Hythane (15% hydrogen by volume, 85% NG) indicated that the Hythane fueled vehicle was able to meet ULEV (ultra low emissions vehicle) standards at sea level for NOx, CO (carbon monoxide) and NMHC (non-methane hydrocarbons).

A comprehensive investigation of HCNG fueling of lean burn SI engines was carried out by Lynch et al. [4-8]. Methane-Hydrogen mixtures with 0, 5, 15 and 30 vol% hydrogen were tested using a GM 5.7 liter, V8 engine. HCNG mixtures with 15 and 30 vol% hydrogen enabled very lean operation with a large reduction in NOx emissions with some penalty in THC emissions. It was also found that below an equivalence ratio of 0.7, adding hydrogen increased BMEP due to improvement in combustion at lean conditions. This advantage was sacrificed by retarding spark timing until the torque with 30 vol% hydrogen was the same as with pure methane. The results clearly indicated that hydrogen addition up to 30 vol% can reduce NOx considerably while maintaining THC (total hydrocarbon) emissions close to original levels and enable significant extension of the lean limit without sacrificing engine torque or fuel efficiency.

Similar results were also obtained for a Cummins L-10 240G engine with HCNG fueling [8]. Impact of hydrogen addition on NOx and NMHC emissions for 5, 7 and 10% hydrogen by energy content (i.e. 15, 20 and 30 vol%) are shown in Figure 3. The results indicate NOx reduction of 43% with 7% hydrogen by energy content (20 vol%). Increasing hydrogen content to 10% by energy content (30 vol%) increased NOx slightly compared to 20 vol% case. This can be explained by the following argument. There are two opposing effects at higher hydrogen concentrations. At a given air/fuel ratio, hydrogen makes natural gas combustion hotter (more NOx) but at the same time it is possible to burn leaner and cooler (less NOx) with added hydrogen as long as NMHC does not become excessive. In the present case oxidation catalyst efficiency decreased rapidly below 300 deg. C causing NMHC to increase rapidly, forbidding leaner operation. Engine torque and efficiency were maintained at the same level as the baseline natural gas operation.

Two NG urban buses fitted with the L-10 240G engine were evaluated in the city of Montreal fuelled by HCNG (H_2/NG - 20/80 by volume). The results indicated that NOx was reduced by 44% on a CBD (Central Business District) cycle and about 16% on a NYC (New York Composite) cycle without a large penalty in emissions of NMHC and CO [9]. The minimal 16% NOx reduction on the NYC cycle was due to the transmission hanging in 2nd gear, causing the engine to over speed [10].

Hydrogen supplementation of natural gas up to 50 vol% using a 4.6L spark ignited V8 engine was studied at the Florida Solar Energy Center [11-12]. With 20-30 vol% hydrogen the brake specific NOx emissions were reduced below 0.5 g/kW-h. Increasing hydrogen content to 50 vol% reduced the NOx to a very small value. Increasing hydrogen beyond 30 vol% resulted in diminished additional NOx benefit. A similar trend for THC emissions was also observed.

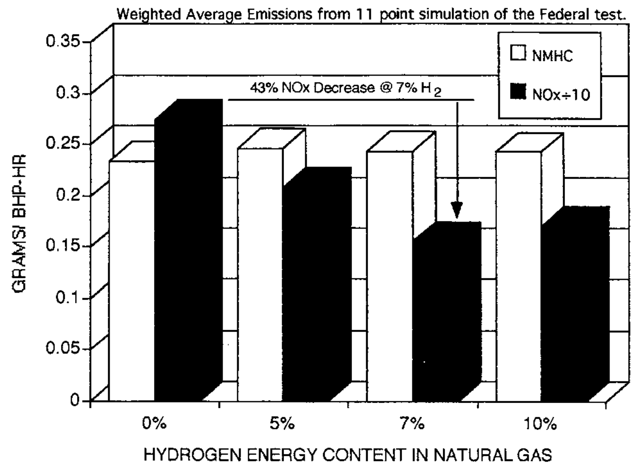


Figure 3. Weighted average emissions of a Cummins L-10 240G lean burn engine fuelled with HCNG with various levels of hydrogen supplementation [8].

Recommendation for best HCNG blend

Analysis of HCNG fuel properties, as a function of hydrogen content as discussed above, and the available literature on previous test results, with hydrogen supplemented natural gas fuel, indicate that 20 to 30 vol% hydrogen in a HCNG mixture provides desired benefits in terms of NOx reduction without unduly affecting engine performance (torque, power) and efficiency, as well as maintaining hydrocarbons within original limits. Increasing hydrogen content beyond 30 vol% can provide diminishing returns in terms of NOx reduction but with associated penalty in terms of engine performance, existing hardware limitations as well as fuel storage and cost.

IMPACT OF HCNG ON ENGINE COMPONENTS

Due to the small proportion of the hydrogen in the mixture (up to 5% hydrogen by mass) the physical properties of the fuel mixture are close to those of natural gas fuel and do not have significant impact on fuel system components designed for natural gas service. Potential impact of hydrogen on the seals used in the fuel system over extended periods will be determined through inspection at regular intervals. The wide range exhaust oxygen sensor worked well under both NG and HCNG operation. The fuel mass flow rate sensor is of hot-wire type that uses thermal conductivity of the gaseous fuel to measure the fuel flow rate. At similar conditions hydrogen has over six times higher thermal conductivity compared to natural gas. The HCNG mixture saturated the output of the current fuel flow rate sensor near maximum flow conditions. The existing fuel flow rate sensor was replaced with one with a higher capacity. No other modifications were needed on the original engine hardware.

EXPERIMENTAL SET-UP

The composition of the British Columbia natural gas used in the present study was measured using a calibrated gas chromatograph on-site.

Table 1. Natural gas properties.

Gas component	Mol%		
n-Butane	0.061	NG Molar Mass	16.78
i-Butane	0.105	NG Higher Heating Value (MJ/kg)	53.95
i-Pentane	0.028	NG Lower Heating Value (MJ/kg)	48.67
n-Pentane	0.023	NG Lower Heating Value (MJ/m^3)	34.57
Hexane	0.004	Relative Density w.r.t. air at NTP*	0.580
Nitrogen	0.449	NG Density at NTP (kg/m^3)*	0.710
Methane	96.255	H/C ratio	3.905
Carbon Dioxide	0.600	Wobbe Index, MJ/m^3	45.41
Ethane	1.950	Methane number	94
Propane	0.524	* NTP (1 atm and 288K)	

HCNG fueling supply system

A fueling system was designed and assembled to allow mixing and storage of hydrogen-natural gas mixtures in a high-pressure sphere. Pure hydrogen was supplied from a mobile tube trailer shown in Figure 4 The trailer was about 40 feet long and had 12 tubes with each tube storing hydrogen at 16.7 MPa with a total capacity of 4280 Nm^3 (385 kg). High-pressure natural gas (supply pressure, 33 MPa) was supplied from an on-site compressor. Hydrogen-natural gas blends were prepared using the mixing panel and stored in the large high-pressure (up to 23 MPa) storage sphere (Figure 4). All fuel system components (piping, fittings and valves) were of commercially specification and were checked for suitability for hydrogen and natural gas service at high pressure. A safety review including FMEA (Failure Modes Effects Analysis) of the fuel system was carried out to address safety issues. HCNG mixture from the sphere was supplied to the engine test cell fuel panel through over the ground fuel lines covered by a metal bridge (Figure 4 and 5).

HCNG mixture preparation

A method of partial pressure was used to prepare known mixtures of hydrogen and natural gas in the storage sphere. The method accounted 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. The thermal conductivity meter was calibrated using accurately prepared mixtures of hydrogen and natural gas.

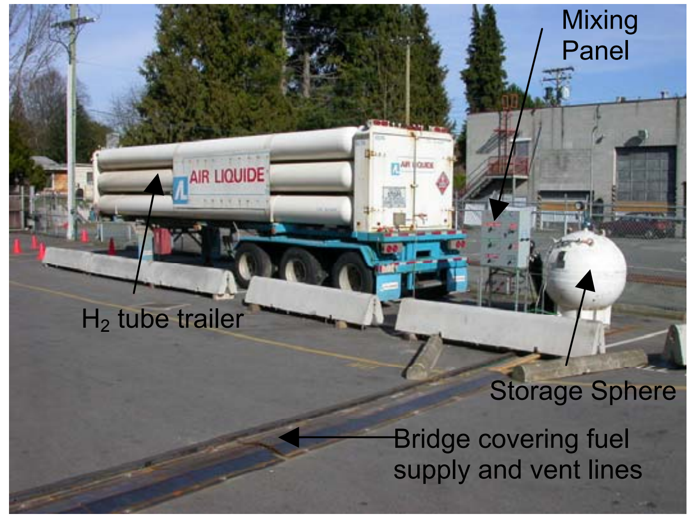


Figure 4. Hydrogen tube trailer, HCNG fuel mixing and storage facility.

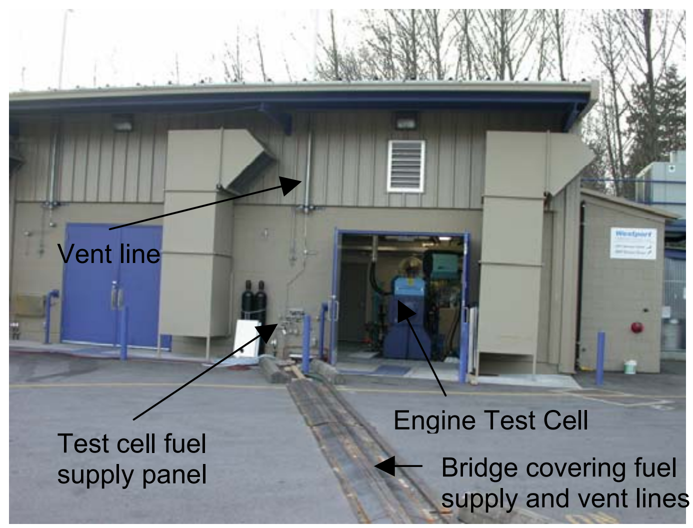


Figure 5. HCNG supply to the engine test cell.

Lean burn spark ignition engine

A commercially available Cummins Westport Inc. B Gas Plus lean burn natural gas fueled spark ignition engine was selected for the HCNG upgrade (Table 2). The engine was selected due to its widespread use in both North American and European markets as well as its advance features. The engine was equipped with a waste-gated water-cooled turbocharger. The air intake system was provided with charge air-cooling to reduce emissions and extend BMEP by lowering the intake manifold temperature. The engine was fitted with an exhaust oxidation catalyst to achieve very low emissions (CO, NMHC, PM, HCHO).

Table 2. Specifications of the Lean Burn Spark-ignited B Gas Plus Engine.

Bore, Stroke, Compression Ratio	102mm, 120 mm, 10.5:1
Operating Cycles, Number Of Cylinders	4, 6
Engine Displacement	5.9 Liter
Rated Power	230 BHP (172 KW) @ 2800 RPM
Peak Torque	677 N-m @ 1600 RPM

The engine had a closed loop electronic air/fuel regulation system, using a wideband oxygen sensor in the exhaust. Some of the key features and capabilities are listed below (see also Figure 6).

- State-of-the-art full-authority closed-loop electronic engine management.
- Drive-by-wire electronic throttle.
- Electronically controlled high-energy ignition system.
- Improved combustion chamber design, engine knock sensor and electronic controls enable reliable operation over a wide range of fuel quality (natural gas fuels having methane number as low as 65).
- Advanced high-speed engine diagnostics and adaptive learn capabilities.

Engine test cell

The engine was connected to an AVL AC dynamometer (Figure 7). The engine and test cell were fully instrumented to record performance and emissions data using the AVL PUMA test bed control system. This system controlled the data acquisition and the engine operating conditions. Capabilities included on-line calculations and automated testing. Emissions analysis was achieved using a Horiba 7500 analyzer. This gave real time levels for CO, CO_2, NOx, THC, CH_4 and O_2. Combustion air was handled by an air conditioning unit that supplied air with controlled humidity and temperature. This is essential for a spark-ignited engine in order to achieve repeatable results day to day. A laminar flow element measured the air mass flow into the engine. Measurement of the gas mass flow to the engine was handled with a Micromotion meter. The engine was started and put through a 6 hour "break-in" using NG. Baseline data with NG was also taken to use as a direct comparison to the HCNG performance of the engine.

TEST DEVELOPMENT MATRIX

The scope of the engine testing and program targets as well as constrains were defined before undertaking the engine test cell development. The overall strategy used for the HCNG engine development was also developed.

Scope of the engine testing

- Establish a natural gas performance and emissions baseline.
- Determine if significant NOx reductions could still be achieved on modern engines operating close to the lean air/fuel combustion limit.
- Determine most suitable hydrogen supplementation of natural gas based on program targets and constraints.
- Configure engine controls for operation on the chosen HCNG mixture.
- Verify engine performance and calculate overall emissions benefits.

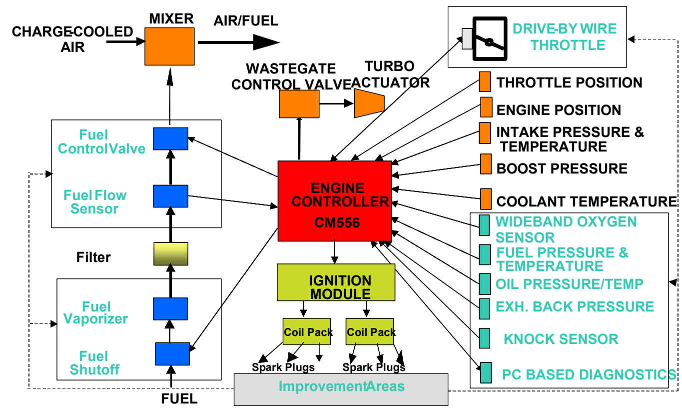


Figure 6. Schematic showing architecture of the B Gas Plus engine.

Figure 7. Engine test cell with B Gas Plus engine installed and connected to the dynamometer.

Program targets and constraints

- Maintain original engine performance (power/torque the same as the baseline NG).
- Maintain pre-catalyst THC emissions the same as the baseline NG.
- Maximize the benefit in terms of NOx reductions over the baseline NG while staying within current hardware (e.g. maximum allowable turbine inlet temperature, turbocharger speed, ignition system excitation).
- Maintain or improve thermal efficiency of the engine compared to baseline NG while staying within current hardware specifications.

Strategy for HCNG testing

Increase the relative air/fuel ratio (leaner mixture) at baseline spark timing to keep the pre-catalyst THC emissions the same as the NG baseline. Hydrogen in the HCNG fuel contributes to faster burning of the air/fuel mixture and has been known to improve combustion efficiency, increase torque and thermal efficiency under lean conditions. This can help in retarding the spark timing to get further NOx reduction until there is no efficiency advantage over baseline NG while maintaining THC emissions the same as the baseline NG mode. This also helps in maintaining cyclic combustion variation under very lean operating conditions similar to baseline NG mode.

HCNG BLEND INVESTIGATION

Tests were carried out at four engine operating conditions (Table 3) in order to get a good representation of the engine map. At each of the engine operating condition a matrix of six points (Figure 8) was tested for each of the fuel blend. HCNG fuel blends with hydrogen content between 20 to 32 vol% were tested. HCNG blends with more than 32% hydrogen were not tested based on the recommendations from previous studies. The desired operating point was found using a combination of spark timing retardation and leaning the mixture while keeping the torque, the fuel consumption and the THC (total hydrocarbon) emissions the same as the NG baseline. The engine map with test points is shown in Figure 9.

Table 3. Test Conditions used for HCNG Blend Investigation

Test Point	Engine Speed [RPM]	Torque [N-m]	Torque [Ft-lb]
WOT3	1600	700	516
WOT4	2800	587	433
SET7	1769	301	222
SET13	2534	172	127

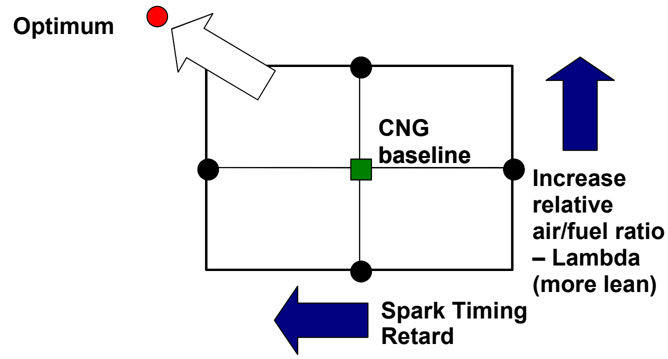


Figure 8. Test matrix used for HCNG blend investigation.

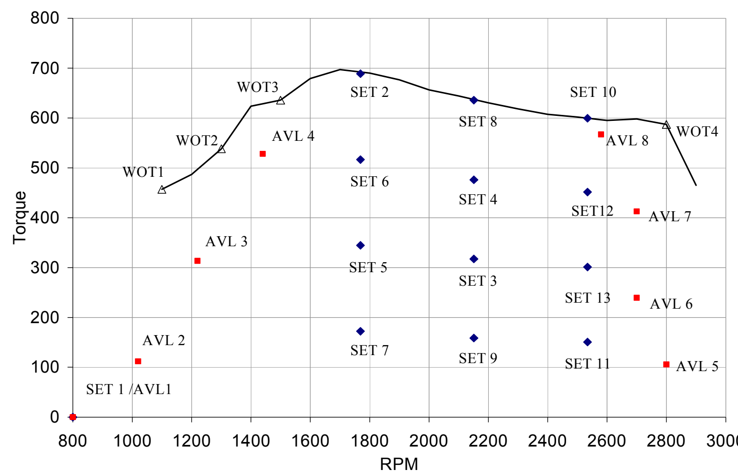


Figure 9. Test conditions for HCNG investigation

HCNG blend testing results are summarized in Table 4. The data is an average of the four points (Table 3) in the test matrix. The table indicates that 25 vol% H_2 blend has the highest average NOx reduction. But this should be considered in conjunction with THC emissions, which were higher for the 25 vol% H_2 blend. This can be explained as following. The optimization was carried out in real-time with the engine running at constant torque while varying spark timing and lambda (relative air-fuel ratio) were varied. It was found difficult to maintain the pre-catalyst THC emissions exactly the same as the baseline level. Similarly an attempt was made to maintain the fuel consumption (BSFC) at the baseline level. The NOx leverage factor (% NOx reduction / % of hydrogen energy in the fuel) was found to be highest for the 20 vol% blend.

It should be noted that the engine has closed loop air-fuel ratio control and is equipped with a waste-gated turbocharger and an electronically controlled intake throttle. These features allowed the engine to maintain torque under HCNG operation at higher air-fuel ratios and retarded spark timings by increasing the intake airflow while keeping the fuel energy flow rate the same as the NG operation.

Table 4. HCNG Blend Test Results Summary.

H_2 Volume Fraction (%)	H_2 Energy Fraction (%)	% Emissions Level Relative to NG*			Leverage (%NOx reduction/ H_2 Energy)
		NOx	THC	BSFC	
20	6.9	40.3	107.8	102.3	8.7
23	7.7	37.3	103.0	101.5	8.2
25	9.0	25.8	112.8	101.0	8.3
32	12.2	32.3	102.8	101.5	5.5

* Average of the four points in the test matrix (Table 3)

An example of change in spark timing and relative air/fuel ratio (lambda) for WOT4 test point are shown in Table 5. Similar results were obtained for other operating conditions.

Table 5. Spark timing and Lambda Offset for various H_2/NG blends at WOT4 engine operation condition. The offset is defined with respect to NG baseline.

WOT 4	NG	20/80	23/77	25/75	32/68
Spark Timing Offset	0.0	-3.6	-3.6	-3.6	-3.6
Lambda Offset	0.00	0.06	0.08	0.13	0.14

H2/NG blends are in % vol/vol

Spark timing offset is in degrees crank angle (-ve implies retarded timing)

Lambda = Relative air/fuel ratio = (air/fuel ratio)/(stoichiometric air/fuel ratio)

(a +ve lambda offset implies more lean operation)

In order to determine the best HCNG blend for the engine calibration a weighting factor based comparison was carried out in addition to the actual blend testing. Each blend was rated for its ability to reduce NOx as well as factors such as ability to maintain engine performance, operating risk for this project, ease of conversion for this project and economic considerations. As shown in Table 6, shows a tie between 20 and 23 vol% H_2 blends.

Table 6. HCNG Blend Comparison using Weighting Factor Analysis.

	Ability to reduce NOx	Ability to maintain engine perform ance	Ability to reduce operating risk for this project	Ease of conversion to HCNG for this project	Economics (fuel cost, fuel storage penalty)	Total
Weight factor	10	5	5	10	10	
20 vol% H2	2*	4	4	5	5	160
23 vol% H2	3	4	4	5	4	160
25 vol% H2	4	3	3	3	3	130
32 vol% H2	5	2	1	1	2	95

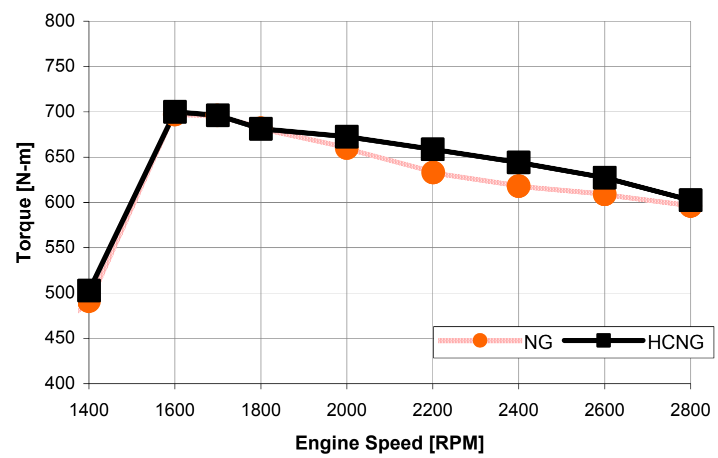
A scale factor of 1 to 5 has been used to rate each point, with 1= lowest/least and 5 = highest/best.

It should be noted that the NOx reduction at individual points may be high but the cycle composite NOx reduction (e.g. AVL8 steady-state cycle representing the US FTP transient test) could be lower. In addition there is likely some penalty when moving from a manual optimization at cycle points to a controller-based operation on a real engine. Based on the above information, either a 20 or 23 vol% H_2 blend seems to offer the best advantage in terms of ability to reduce NOx, ease of conversion/operation and economics of fuel storage/cost. A subsequent discussion with the customer (SunLine) confirmed that they would use a 20 vol% H_2 blend provided that the engine retains original performance and has lower emissions within the constraints of existing hardware.

HCNG ENGINE PERFORMANCE AND EMISSIONS VERIFICATION

Engine torque curve and maximum power comparison

Engine performance was verified by comparing the torque curve. The torque curve demonstrates the capability of the engine to maintain full load under HCNG fueling. Results are shown in Figure 10 comparing full torque achieved under NG and HCNG fueling. As seen from the results the HCNG torque is either equal to or slightly higher than the NG torque. The engine achieves a peak torque of 697 Nm at 1600 rpm and a rated torque of 596 Nm at 2800 rpm. Corresponding results for the engine power at full torque are also shown in Figure 10. The engine achieves a rated power of 237 HP at 2800 rpm under HCNG fueling.



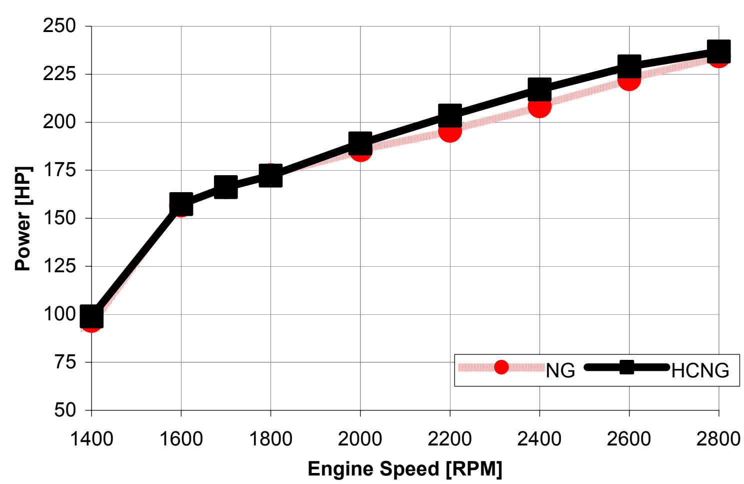


Figure 10. Comparison between NG and HCNG full torque and power curves.

AVL8 test cycle results

The AVL8 steady state test cycle (Table 7) has been used in the past as an indicator of heavy duty engine performance and emissions over an actual FTP transient cycle. The AVL8 cycle results are used in the present study to demonstrate benefits to engine emissions under HCNG operation.

Table 7. AVL8 Steady-State Test Cycle Points

AVL mode#	Weighting Factor	Engine rpm	Torque Nm	Torque lbft
1	35.00%	800	0	0
2	6.34%	1020	111	82
3	2.91%	1220	314	231
4	3.34%	1440	517	382
5	8.40%	2800	106	78
6	10.45%	2700	238	176
7	10.21%	2700	414	305
8	7.34%	2580	569	419

Results for AVL modes 1 to 8 are shown in Figure 11 for the NOx and BSFC. The data is normalized against NG baseline at each mode, i.e. NG NOx and BSFC at each mode is assumed 1. Depending on the mode, NOx was reduced by 35% to as much as 65% under HCNG fueling. At the same time the engine fuel efficiency was maintained close to the NG baseline. Engine fuel efficiency calculations are corrected for HCNG to account for the change in fuel heating value. As shown in Figure 12, CO emissions under HCNG operation increased by between 5-12% for AVL modes 1 to 3 and were reduced by between 9-22% for modes 4 to 8. The non-methane hydrocarbon (NMHC) emissions were reduced by between 49-72% for AVL modes 1 to 8 under HCNG operation. The total hydrocarbon (THC) and methane emissions were reduced by between 10-25% for all the modes except mode 2 and 3 where an increase of about 10-15% was observed (Figure 12).

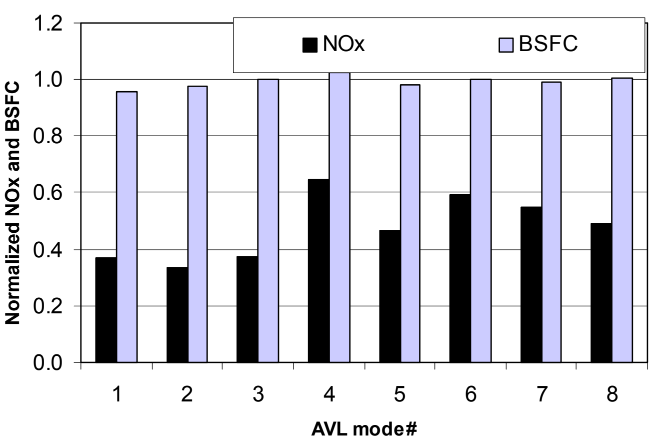


Figure 11. Relative NOx emission and BSFC at each of the AVL modes under HCNG operation.

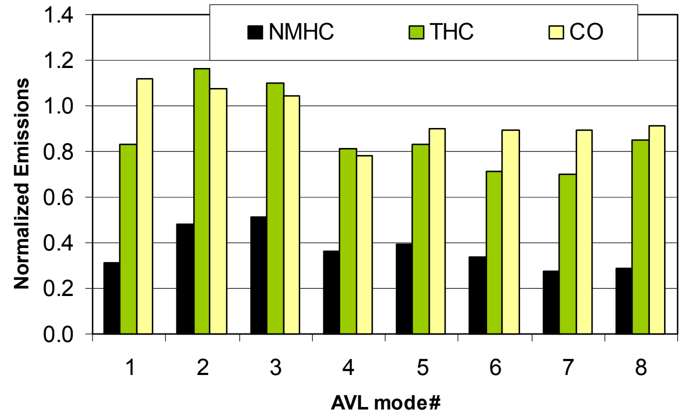


Figure 12. Relative NMHC, THC and CO emissions at each of the AVL modes under HCNG operation.

Figure 13 shows relative comparison of the normalized turbocharger speed at each of the AVL modes under NG and HCNG operation. As seen from the figure there is a small increase between 2-8% in the speed depending of the mode under HCNG operation.

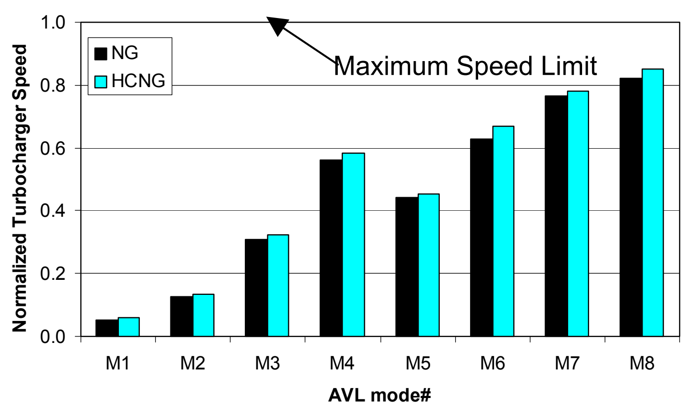


Figure 13. Normalized turbocharger speed at each of the AVL modes under NG and HCNG operation.

AVL cycle composite emissions

The AVL cycle weighted composite emissions are shown in Figure 14. The results are also compiled in Table 8 for ease of comparison. It should be noted that these are engine out (pre-catalyst) emissions over a steady-state cycle and not actual FTP transient test emissions. Under HCNG operation cycle NOx was reduced by 50% and cycle non-methane hydrocarbon emissions were reduced by 58%. Cycle methane and total hydrocarbon emissions were reduced by 16 and 23% respectively. A small reduction in cycle CO emissions was also observed. Particulate matter emissions were not measured but are not expected to increase under HCNG operation. As shown in Figure 14, the cycle averaged fuel consumption under HCNG operation was identical to that of NG baseline.

Table 8. Engine out (pre-catalyst) AVL Cycle Composite Emissions.

Emission g/bhp-hr	NG	HCNG	% change w.r.t NG
NOx	2.0	1.0	-50%
NMHC	0.24	0.1	-58%
NOx+NMHC	2.24	1.1	-51%
CH4	3.0	2.5	-16%
THC	3.4	2.6	-23%
CO	2.3	2.1	-9%

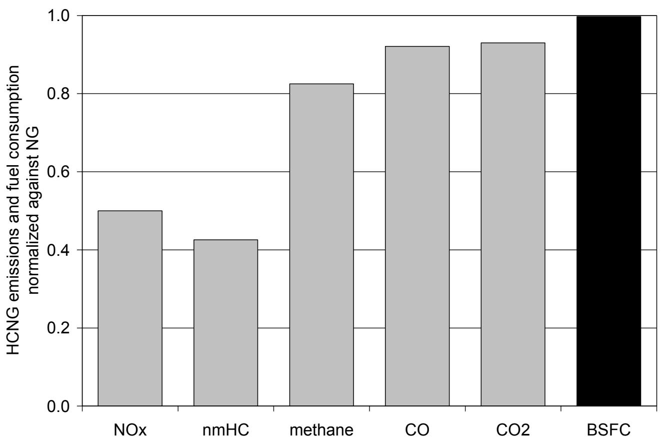


Figure 14. Comparison between NG and HCNG AVL cycle composite engine out (pre-catalyst) emissions and fuel economy.

Engine transient performance verification for drivability

The engine test cell was equipped with an AC dynamometer that permitted transient drivability verification of the B Gas Plus engine under both NG and HCNG operation. The school bus cycle (Figure 15) selected is a transient test representing several gear-shifts, cruise and operation at the rated condition. As seen from Figure 16, the engine under HCNG fueling is able to follow the speed and torque changes very closely as compared to the NG. These results demonstrate the capability of the HCNG fueled B Gas Plus engine to maintain original torque and speed under transient conditions. In addition exhaust emissions were recorded. As seen in Figure 16, NOx emissions were consistently much lower under HCNG operation as compared to NG. Both THC and CO emissions under HCNG were found to be close to NG.

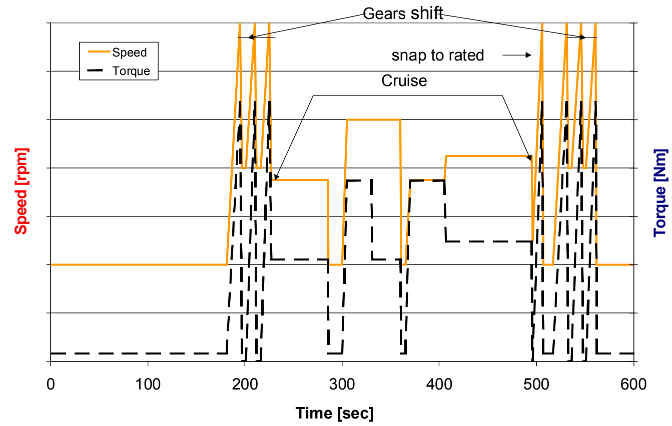


Figure 15. School bus cycle for transient drivability verification.

HCNG BUS FIELD TRIALS

Two 40-foot buses equipped with the upgraded CWI 5.9L B Gas Plus HCNG engines (Figure 17) were deployed on the road in regular service as part of the field trials at SunLine Transit Agency in California. SunLine's hydrogen facilities are described in [13]. Two NG control buses (equipped with NG CWI B Gas Plus engines) were also deployed on the same routes and were monitored for comparison. All four buses originally had 1994 Cummins B Gas engines in them. They were modified to 2003 B Gas Plus specifications. For the HCNG buses a new calibration specific to HCNG operation was installed in the engine ECM (engine control module). Operation of each bus was verified in a road trial before putting them into regular service. Further details of the engine and buses are shown in Appendix B. The upgraded buses have an exhaust oxidation catalyst fitted to them. For a given tank size and pressure HCNG fuel occupies more volume (density of hydrogen is much lower) compared to NG. For a 20/80 by volume H_2/NG blend there is about 15% reduction in fuel storage capacity (assuming there is no change in engine efficiency between NG and HCNG). In order to compensate, tanks with larger capacity were installed on the HCNG buses.

The HCNG buses were fuelled by a dispenser provided by FTI (Fueling Technologies Inc). The dispenser was supplied with high pressure NG and hydrogen. The FTI hydrogen/NG blend dispenser was configured to provide an accurate blend of hydrogen and NG on one hose and pure hydrogen on a second hose. Both fuels are measured using Coriolis type mass flow meters; the dispenser monitors the mass of each and injects hydrogen into the NG flow as required to meet an accuracy of ± 2.0%. A dispenser control system monitors mass flow of hydrogen and NG. Blend control valves on hydrogen and NG lines are operated by the control system assuring accurate blending of fuels. It also controls temperature compensated filling pressure into the vehicles. Hydrogen and natural gas are blended to a programmable ratio in terms of volume, mass or gasoline gallon equivalent basis.

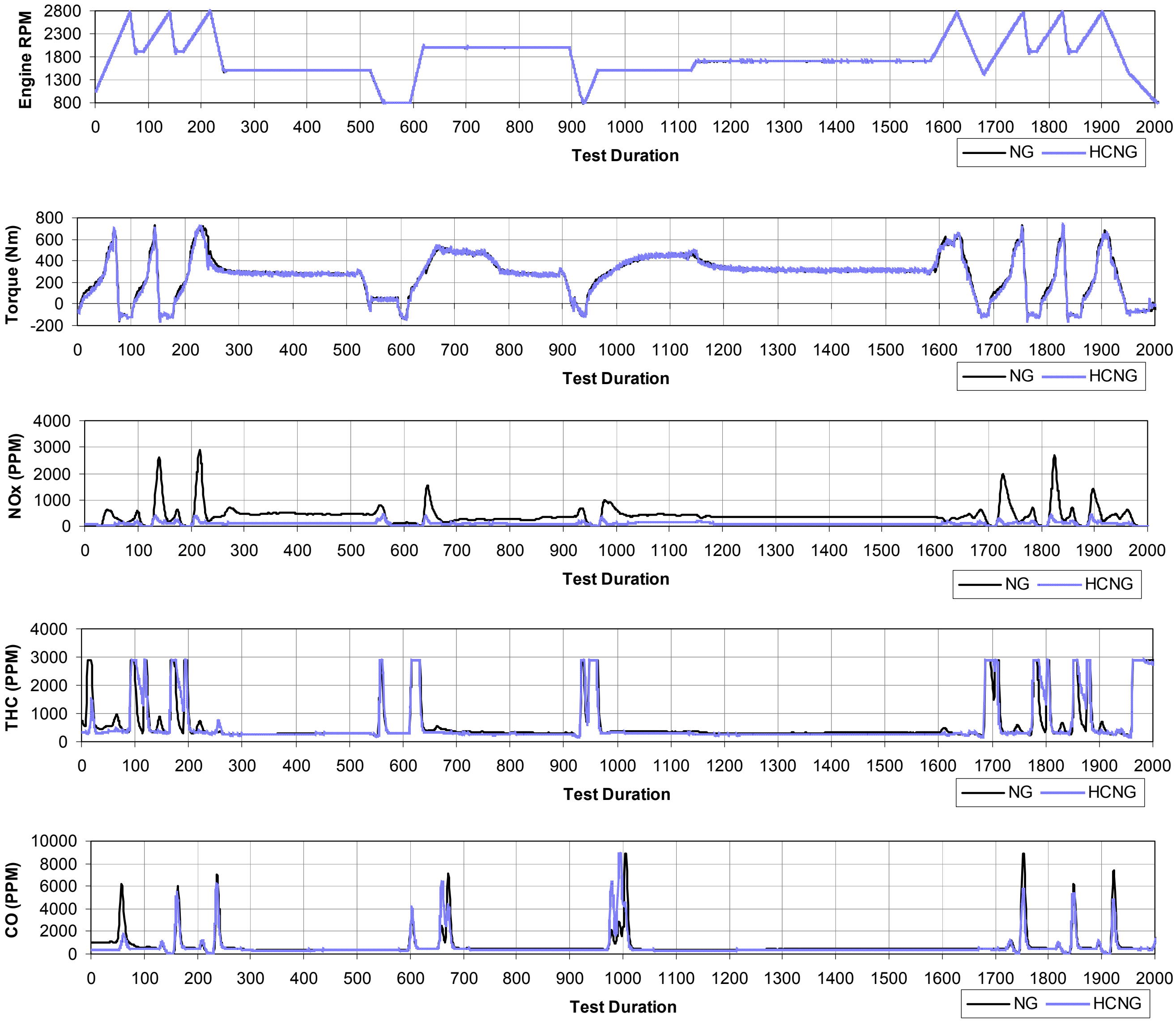


Figure 16. Engine performance and emissions comparison between NG and HCNG operation for the transient school bus cycle. The test duration is in terms of sample points taken over 600 seconds.

Figure 17. A 40-foot transit bus fitted with the upgraded B Gas Plus HCNG engine used in the field trials at SunLine Transit Agency. Also shown is a HCNG dispenser.

A gas detector/alarm system disables the dispenser under certain potentially hazardous conditions. The dispenser was configured to provide 20/80 by volume H_2/NG blend ratio. The accuracy of the HCNG blend was verified from gas composition analysis of the samples taken from the gas supplied by the dispenser. The hydrogen content was found to be within 20 ± 1%.

The buses have now completed the planned 24,000 miles field trials on regular routes. Routine inspection and maintenance including oil changes was carried out during this period and any problems were recorded. Used oil samples were also sent for analysis. The oil analysis from HCNG and NG buses did not indicate any difference between them. The drivers did not notice any difference between the drivability of the HCNG and NG buses and no problems specific to HCNG engine operation were reported. Overall the two HCNG buses performed equally as well as the two NG control buses.

CHARACTERIZATION OF EMISSIONS FROM TRANSIT BUSES

Chassis dynamometer transient emissions testing of the four buses (two HCNG and two NG control buses) were carried out by NREL at the West Virginia University (WVU) Transportable Heavy-Duty Vehicle Emissions Testing Laboratory. EPA regulated emissions of NO_X, PM, HC and CO were measured as well as CO_2 emissions and fuel economy. Testing was completed in February 2004. Vehicle descriptions are shown in Table-9. Fuel properties are listed in Appendix A.

Test methodology

In seeking to assess the contribution of a heavy-duty truck or bus exhaust to the atmospheric inventory it is prudent to exercise the vehicle on a chassis dynamometer through a test schedule that is reasonably representative of its real world use, while measuring the tailpipe emissions. A chassis dynamometer is a device capable of providing realistic load to the drive wheels of a test vehicle as it is operated through a driving schedule that mimics real-world use. A recent paper by Traver *et al*. [14] reviewed the performance of chassis dynamometers comparatively. Detailed information pertaining to the design and operation of the WVU emissions testing laboratories can be found in technical papers [15-17].

Dynamometer test cycles

Emissions are known to be dependent on the duty cycle of the vehicle and thus the dynamometer test schedule used [18-20]. The test cycles were selected to best represent the in-use duty cycle of the SunLine Transit Agency buses. In this program each bus was tested over the Orange County Transit Authority Cycle and the City-Suburban Heavy Vehicle Route.

The Orange County Transit Authority (OCTA) Cycle was selected to reflect intermediate speed heavy-duty vehicle operation and is one of the test cycles recommended by SAE J2711 [18] for the testing of the transit buses. The OCTA Cycle was developed by West Virginia University from data logged from in-service transit buses on the Orange County California route system based on operating hours, mileage, average speed, and the number of passenger loading events [21]. The OCTA Cycle is a speed versus time schedule. The cycle covers a distance of approximately 6.7 miles with an average speed of 12.3mph. There are 4.6 passenger loading and unloading events per mile and idle operation comprises 27% of total cycle time. The OCTA Cycle was not preceded by a warm-up period. In this project, double length OCTA cycles (OCT2X) were used in order to improve the accuracy of the PM measurements by increasing the mass of particulates collected on the filter media.

The City-Suburban Heavy Vehicle Route (CSHVR) was derived by West Virginia University from vehicle behavior in Richmond, VA and Akron OH. The CSHVR was intended to represent heavy-duty vehicle activity in delivery areas between the four lane beltways and the stop-and-go downtown areas [22-23]. In normal dynamometer testing practice, the test vehicle is driven through a transient test by a human driver who is prompted by a driver's aid, which presents the driver with a target speed versus time trace. In the case of a 'route', which is speed versus distance based, the time axis on the driver's aid is expanded or contracted in real time to account for faster or slower accelerations of the vehicle in practice. In other words, there is feedback from the dynamometer control system to alter the driver's aid according to the cumulative distance traveled. A 'route' allows the full power of the test vehicle to be utilized while accelerating during a portion of a test. A 'cycle' prescribes the speed of the vehicle at all times regardless of the performance capability of the vehicle. The CSHVR (Figures 19 and 20) covers a distance of 6.67 miles with an average speed of 12.87mph and a maximum speed of 44mph. The CSHVR was preceded by a vehicle warm-up period during which emissions data were not collected.

Sampling and analysis of EPA regulated emissions

The exhaust from the vehicle tailpipe was ducted into a dilution tunnel and mixed with HEPA filtered ambient air. The quantity of diluted exhaust was measured precisely by a constant volume sampling system (CVS). The dilution process ensured that the in-use exhaust–air interactions that normally occur when the hot vehicle exhaust mixes with the cool atmospheric air are accounted for in the emissions testing process. The dilution also quenched post-cylinder combustion reactions and lowered the exhaust gas dew point in order to inhibit condensation. Exhaust line quenching was necessary in order to prevent inconsistent emissions measurements. The elimination of condensation was paramount since water droplets can absorb certain gaseous components (for example, NO_2). In addition, the presence of water in the sampling system would affect certain instruments.

The diluted exhaust was analyzed using non-dispersive infrared (NDIR) for carbon monoxide (CO), and carbon dioxide (CO_2). Total hydrocarbons were measured using heated flame ionization detection (HFID) and non-methane hydrocarbons (NMHC) were determined by gas chromatography. Oxides of nitrogen (NO_X) emissions were analyzed using heated chemiluminescent detection. Total particulate matter emissions (PM) were collected on environmentally conditioned fluorocarbon coated glass fiber filter media and analyzed gravimetrically. All analyzers used in the chassis dynamometer emissions testing were laboratory grade and testing procedures generally followed procedures defined in the Code of Federal Regulations Title 40, Part 86, Subparts B and N [19].

For each run, background bags were gathered, analyzed and used to correct gaseous emissions. Dilute gas bags were also collected during a run, but continuous data, integrated over the run, were used for reporting purposes. Separate runs were used to gather background PM levels for PM filter weight correction. Even though the tunnel used HEPA filtered dilution air, PM backgrounds were essential because the tunnel itself may shed PM particles or outgas heavy hydrocarbons that condense onto the PM.

Regulated emissions and fuel economy

The regulated emissions for the CSHVR and OCTA test cycles are shown in Figure 18-21. The details are also documented in Appendix-C. NOx was reduced by about 56% and 57% for HCNG under the CSHVR and OCTA cycles respectively (Figure 18). This is somewhat better than what was observed (about 50% NOx reduction) during the steady state AVL cycle engine testing. The NMHC emissions (Figure 19) were found to be lower for HCNG for the CSHVR test cycle. For the OCTA test cycle the NMHC emissions for Bus#803 were found to be somewhat higher. CH_4 emissions (Figure 20) were found to be somewhat lower for HCNG compared to NG. As expected the CO emissions in most cases were below the detection limit (Appendix-C) due to presence of the oxidation catalyst though small CO emissions were observed for bus#804 (NG) and bust#803 (HCNG). This is most likely due to a variation specific to an individual bus rather than the variation in the type of the fuel. Post oxidation catalyst PM emissions (Figure 21) were quite low but showed significant scatter for individual buses under both NG and HCNG operation. Bus#803 displayed high PM emissions under CSHVR cycle but not under OCTA cycle. This was unexpected and is likely due to the operating condition of the bus rather than the type of fuel. The fuel economy (Figure 22) on a diesel equivalent basis was reduced for HCNG compared to NG. This is also reflected by an slight increase in the CO_2 emissions (Appendix-C) for HCNG. If the fuel economy for HCNG and NG had been identical (as seen in the steady state AVL tests) the CO_2 emissions would have reduced by about 7% for HCNG (7% of fuel energy is contributed by hydrogen). As was expected during engine test cell development it is not possible to fully capture the transient behavior of the buses under specific test cycles using the steady state calibration. The results above indicate improved NOx reduction and somewhat reduced fuel economy for HCNG under transient operation compared to the steady state. One way to address this would be to reduce the leaning of the mixture and retardation of the spark timing. It is also important to point out that individual bus behavior can cause significant variation in specific emission or fuel consumption data. Ideally, the comparison between NG and HCNG should be done on the same bus to eliminate emissions and fuel consumption variation that can be attributed to individual vehicle behavior. In the present case, project constraints did not allow comparison on the same bus.

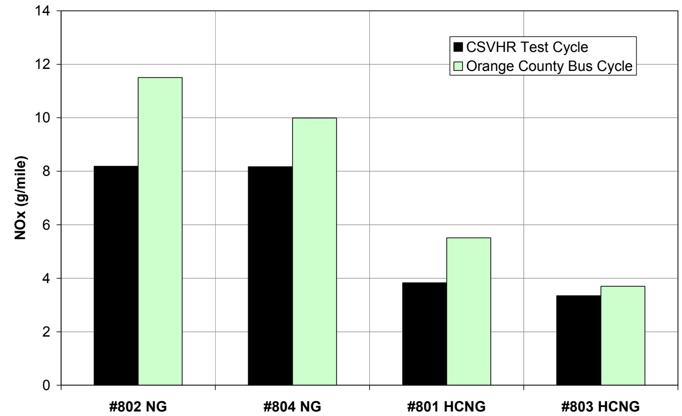


Figure 18. Transient NOx emissions for NG and HCNG operation.

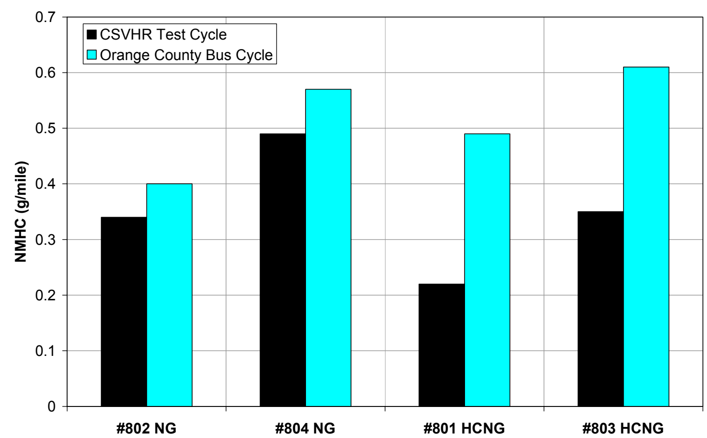


Figure 19: Post oxidation catalyst transient NMHC emissions for NG and HCNG operation.

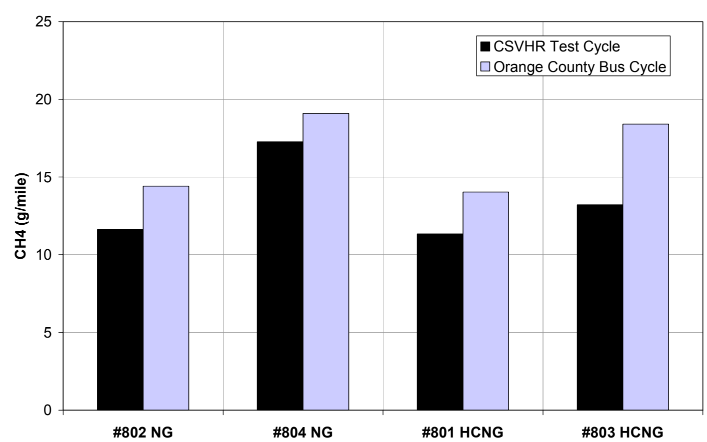


Figure 20: Post oxidation catalyst transient CH_4 emissions for NG and HCNG operation.

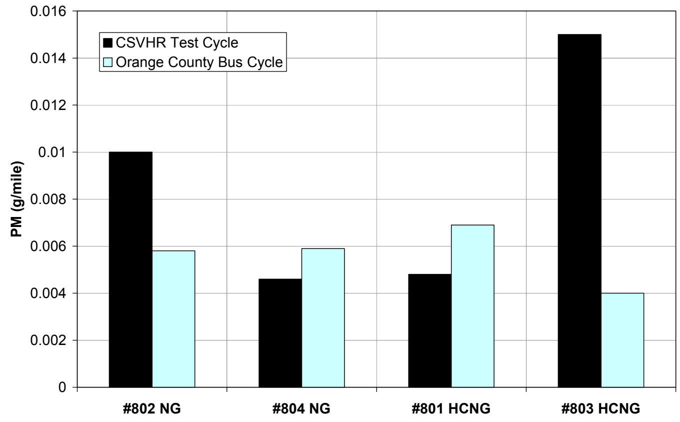


Figure 21: Post oxidation catalyst transient PM emissions for NG and HCNG operation.

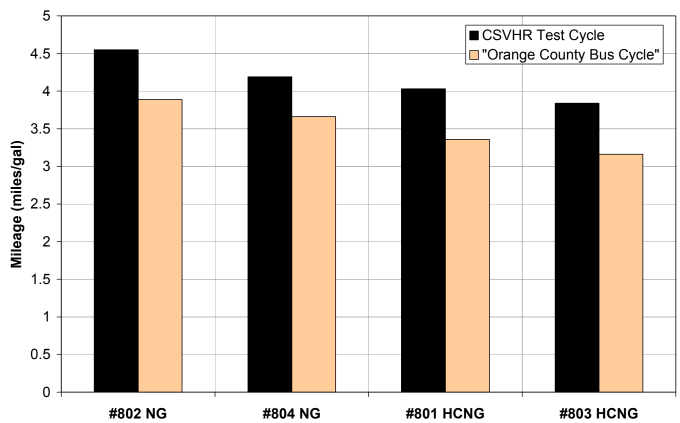


Figure 22: Transient fuel economy for NG and HCNG operation.

CONCLUSION

Based on the blend testing results HCNG blend with 20 vol% hydrogen was selected for engine calibration work. The strategy used during the HCNG calibration was to lean the air-fuel mixture and retard the spark timing (compared to the NG) in order to get best NOx reduction while maintaining torque, fuel efficiency and other emissions similar to the NG baseline. Engine hardware remained unchanged except for replacement of a fuel mass flow sensor. After the calibration the engine was tested over the AVL8 steady state test cycle to predict cycle averaged fuel efficiency and emissions. HCNG fueling reduced engine out (pre-catalyst) NOx and NMHC emissions by 50 and 58 percent respectively. Engine out methane and total hydrocarbon emissions were reduced by 16 and 23 percent respectively. There was no change in fuel efficiency. Engine performance under HCNG was verified by maintaining full load torque and power over the engine speed range. A short drivability study using the school bus cycle verified the ability of the engine to maintain the transient speed and torque capability under HCNG fueling. The chassis dynamometer transient testing confirmed large NOx reduction. NOx was reduced by about 56% and 57% for HCNG under the CSHVR and OCTA cycles respectively. Post oxidation PM emissions were low but showed significant scatter for individual buses under both NG and HCNG operation. Further investigation is necessary to characterize the PM emissions. The fuel economy on a diesel equivalent basis was reduced for HCNG compared to NG. These results indicate better NOx reduction and somewhat reduced fuel economy for HCNG under transient operation compared to the steady state testing. One way to address this would be to refine the HCNG engine calibration by reducing the leaning of the air-fuel mixture and retardation of the spark timing. The buses have completed the 24,000 miles field trials and their performance was found very satisfactory. HCNG technology has been demonstrated successfully on a commercially available heavy-duty engine in a real life application.

ACKNOWLEDGMENTS

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APPENDIX-A: PROPERTIES OF FUELS USED IN THE TRANSIENT TESTING OF THE BUSES.

Components	Sample ID / Units	Bus#802	Bus#804	Bus#803	Bus#801
	Units	Mole %	Mole %	Mole %	Mole %
Methane		97.4	97.4	77.3	77.6
Ethane		0.96	0.91	0.79	0.71
Propane		0.18	0.210	0.16	0.14
C4+		<0.1	<0.1	<0.1	<0.1
CO_2		1.4	1.47	1.1	1.1
N_2		<0.1	<0.1	<0.1	<0.1
H_2		<0.1	<0.1	20.7	20.4
Average Molecular Weight		16.660	16.637	13.604	13.646
Total Wt.% Adjusted Sp. Gravity		0.5746	0.5738	0.4692	0.4707
Net Heating value, BTU/FT^3		907	905	776	777
Gross Heating value, BTU/FT^3		1007	1005	866	866

APPENDIX-B: TEST VEHICLES INFORMATION.

	HCNG		NG	
Chassis	1995 Thomas Transit Liner		1995 Thomas Transit Liner	
Engine	1994 Cummins B5.9L upgraded to 2003 Gas Plus Specifications with modified engine calibration for HCNG fuel		1994 Cummins B5.9L upgraded to 2003 Gas Plus Specifications	
Engine Rating	230hp @ 2800rpm, 500lb-ft @ 1800rpm		230hp @ 2800rpm, 500lb-ft @ 1800rpm	
After-treatment	Fleetguard Nelson Oxidation Catalyst		Fleetguard Nelson Oxidation Catalyst	
Transmission	4-speed Automatic		4-speed Automatic	
GVWR/Curb Weight	36,200lbs / 23,980lbs		36,200lbs / 23,980lbs	
Bus Number	**801**	**803**	**802**	**804**
VIN	1T75T2F2851130061	1T75T2F2951130067	1T75T2F25S1130065	1T75T2F2451130073
Engine Sr. No.	45600871	46277857	45664216	45600870
Odometer Reading (miles)	115809	85207	104,747	88,680

APPENDIX-C: CSHVR AND OCTA TEST CYCLE RESULTS.

CSHVR Test Cycle	Emissions in g/mile						Fuel Economy
Vehicle	CO	NOx	CH4	NMHC	PM	CO2	mile/gal diesel eqv.
#802 NG	**b**	**8.19**	**11.62**	**0.34**	**0.010**	**1679**	**4.55**
#804 NG	**b**	**8.17**	**17.27**	**0.49**	**0.0046**	**1809**	**4.19**
#801 HCNG	**b**	**3.83**	**11.34**	**0.22**	**0.0048**	**1730**	**4.03**
#803 HCNG	**0.076**	**3.35**	**13.21**	**0.35**	**0.015**	**1816**	**3.84**

OCTA Test Cycle	Emissions in g/mile						Fuel Economy
Vehicle	CO	NOx	CH4	NMHC	PM	CO2	mile/gal diesel eqv.
#802 NG	**b**	**11.5**	**14.42**	**0.40**	**0.0058**	**1958**	**3.89**
#804 NG	**0.17**	**9.99**	**19.09**	**0.57**	**0.0059**	**2070**	**3.66**
#801 HCNG	**b**	**5.51**	**14.03**	**0.49**	**0.0069**	**2078**	**3.36**
#803 HCNG	**0.045**	**3.70**	**18.41**	**0.61**	**0.004**	**2194**	**3.16**

b = below detection limit