HCNG Engine Powered Transit Buses Operating on Waste Hydrogen

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ABSTRACT
The British Columbia Hydrogen Highway's^{TM}, Integrated Waste Hydrogen Utilization Project (IWHUP) is a multi-partner collaboration demonstrating capture of hydrogen from a vented waste stream in North Vancouver and promotion as a clean fuel alternative through the development and demonstration of infrastructure and end use applications. Westport Innovations, together with The South Coast British Columbia Transportation Authority (TransLink) is demonstrating four hydrogen enriched compressed natural gas (HCNG) fuelled transit buses in regular passenger service and two compressed natural gas (CNG) buses for baseline comparisons. The HCNG bus program targeted development and field testing of a new calibration for a commercially available spark ignition natural gas engine for transit applications. An 8.3 Liter, turbocharged, lean burn engine was recalibrated to operate on a mixture of 20 volume% hydrogen and 80 volume% CNG. Substantial reductions in exhaust NO_x, unburned hydrocarbons and CO_2 emissions were observed in the engine test cell. On-the-road vehicle testing also verified that the HCNG bus acceleration and drivability were on par with that of the CNG bus. Currently all four HCNG buses are undergoing extended field trials in regular passenger service. Emissions testing of HCNG and CNG buses under transient operation indicated 38% lower NO_x, 20% lower hydrocarbons and about 9% lower CO_2 emissions for HCNG as compared to CNG operation.

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

1. INTRODUCTION

Adapting high efficiency internal combustion 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.

This project is aimed at developing commercial HCNG engine technology and gaining real world experience with heavy duty transit buses operating on a mixture of hydrogen and natural gas. Most HCNG engine projects in the past have been conducted typically with a low level of hydrogen enrichment (up to 30 % by volume or 10% by energy 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.

Operation with HCNG allows early adopters of the hydrogen with a nearly commercial engine technology while delivering significant emissions reductions at a considerably lower cost premium. HCNG can effectively leverage the growing investment in natural gas fueling and vehicle infrastructure around the world.

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2. IWHUP Demonstration

Led by Sacre-Davey Innovations located in North Vancouver, 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.

IWHUP is comprised of following suite of sub-projects: 1. Waste Hydrogen Supply, 2. Compressed Hydrogen Distribution, 3. Light-duty Hydrogen Vehicle Fuelling Station, 4. Heavy-duty HCNG Vehicle Fuelling Station, 5. Light-duty Hydrogen Vehicles, 6. Heavy-duty HCNG Transit Buses, 7. Combined Heat & Power Fuel Cell Demonstration, 8. Education and Outreach Initiative, and 9. Project Management Initiative.

IWHUP is an integrated approach with following objectives:

- Promote the use of vented by-product hydrogen
- 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
- Develop the North Vancouver "NODE" of the BC Hydrogen Highway

The project has following industrial partners: Sacré-Davey Group (North Vancouver, BC), Westport Innovations (Vancouver, BC), Powertech Labs, (Surrey, BC), Hydrogen Technology & Energy Corporation – HTEC (North Vancouver, BC), Clean Energy Fuels (Burnaby, BC), Dynetek Industries (Calgary, Alberta), Nuvera Fuel Cells (Billerica, MA), QuestAir Technologies (Burnaby, BC), Easywash (North Vancouver, BC), Newalta (North Vancouver, BC), The South Coast British Columbia Transportation Authority – TransLink, Ford Motor Company of Canada.

In addition to the investment of the industry partners above, IWHUP is being jointly funded by the following government programs: Industry Canada (IC), Sustainable Development Technology Canada (SDTC), Natural Resources Canada (NRCan), US-DoD Climate Change Fuel Cell Program.

Hydrogen Capture and Purification

The supply of purified and compressed hydrogen is derived from by-product streams of electro-chemical plants in North Vancouver.

Figure 1. Hydrogen capture, purification and compression plant.

Hydrogen Technology & Energy Corporation (HTEC) has designed and built a hydrogen capture and processing facility at Newalta's oil recycling plant. The site is ideal due to its proximity to ERCO WorldWide's sodium chlorate plant and Canexus' chlor-alkali facility both of which produce by-product hydrogen streams. The total by-product hydrogen generated by the two operations exceeds 1000kg/hr with over 600 kg/hr presently being vented. HTEC's plant is designed to provide 20kg/hr of purified hydrogen at Grade 5 (99.999%) purity and at pressures of 6550psig. For reference, the total site production level of 1000 kg/hr is enough hydrogen to power a fleet of over 20,000 pure hydrogen powered passenger cars. There are over hundreds of such sources of by-product hydrogen around the world.

Hydrogen Transport and Distribution

Sacré-Davey Engineering and Dynetek Industries have developed a Transport Canada approved system that transports hydrogen compressed to 450bar (6550psig) via roadways from HTEC's processing facilities to the vehicle fuelling stations and stationary fuel cell demonstrations of IWHUP. Dynetek Type 3 aluminum-lined, carbon fiber cylinders are racked together in banks of ten cylinders. These racks of cylinders have been named PowerCubes and are transported inter-modal style on a specially designed trailer that will hold up to six PowerCubes. Each PowerCube has a capacity of 89kg hydrogen at 450bar.

Figure 2. Hydrogen distribution trailer with PowerCubes.

Heavy Duty Vehicle HCNG Refueling Station

The fast fill CNG station in the city of Port Coquitlam that refuels a fleet of TransLink buses was upgraded by Clean Energy Fuels to provide refueling for the HCNG buses. The upgrade included ability to receive pure hydrogen from a PowerCube, blending and dispensing of hydrogen and CNG mixture as well as ground storage. The final mixture contains 20% hydrogen and 80% CNG by volume and is dispensed at pressures up to 3600psig.

Figure 3. Refueling of a HCNG bus at the Port Coquitlam HCNG station.

Heavy Duty HCNG Bus Demonstration

Westport together with TransLink is responsible for the heavy-duty HCNG powered transit bus demonstration. Four existing low floor 40-foot CNG buses owned by TransLink 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;

Figure 4. Heavy Duty HCNG Passenger Bus.

The HCNG bus project was initiated in August 2005. The first phase of the project was engineering activity concerned with retrofitting of existing CNG buses with a new CNG engine, development of HCNG engine calibration and followed by the upgrade of the CNG buses for HCNG operation. In the next phase of the project the HCNG buses were field tested to verify their performance and emissions. Necessary regulatory permits to allow HCNG bus operation on the road were also obtained. Currently all four HCNG buses and two CNG control buses are being operated in regular passenger service as part of the extended field demonstration and test verification program.

A transit vehicle demonstration will allow for the evaluation of the HCNG technology, which is based on today's commercially available spark ignited compressed natural gas engine technology. Westport's HCNG technology was initially developed on the commercially available Cummins Westport Inc. (CWI) 5.9 Liter B Gas Plus SI CNG engine platform as part of the field demonstrations at the SunLine Transit Agency in Thousand Palms, CA [1]. The current project involves further refinements to the 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 (NO_x), particulate matter (PM) and GHG (green house gas) emissions in the Greater Vancouver Region. 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 bus technologies that involve newer propulsion technologies and alternative fuels.

3. HCNG (20/80) Calibration Development

Before undertaking HCNG recalibration of the CNG engine an engine combustion study was carried out to determine the effectiveness of hydrogen in improving the combustion properties of lean natural gas-air mixtures. The results of combustion study indicated that the addition of 20-30 volume% hydrogen to natural gas fuel improved combustion at lean air/fuel ratios while reducing NO_x and THC emissions without sacrificing engine torque or fuel economy. The heat release rate was found to begin earlier during the combustion cycle and the maximum of the rate of heat release curve was slightly higher for the HCNG mixture compared to CNG. Further details of the combustion study were reported last year at the National Hydrogen Conference in 2007 [2].

Subsequent to the combustion study a detailed re-calibration of the engine on was carried out on HCNG. A commercially available Cummins Westport Inc. C Gas Plus lean burn natural gas spark ignition engine was selected for the HCNG testing. The 8.3 Liter engine is a four stroke, in-line, six cylinder with a bore (102 mm) and stroke of (120 mm) and a compression ratio of 10:1. The engine has a rating of 280HP at 2,800 RPM. 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 is also has an exhaust oxidation catalyst to achieve very low emissions (CO, NMHC, PM, HCHO). The engine employs closed loop electronic air/fuel regulation system with a wideband oxygen sensor in the exhaust. 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 (methane number $\geq$ 65).

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

The engine installed in a dynamometer test cell is shown in Figure 5. A new calibration for HCNG operation (20 volume% H_2 and 80 volume% NG) was developed after a series of tests to optimize the HCNG performance and emissions while ensuring that the vehicle drivability is unaffected. 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. AVL 8-Mode steady-state test cycle was used to compare engine performance and emissions between CNG and HCNG.

Test Cell Steady State Torque Curve and Exhaust Emissions

The engine torque on HCNG (Figure 6) was kept equal or slightly above the CNG torque. This ensured that the vehicle performance remained identical under CNG and HCNG fueling.

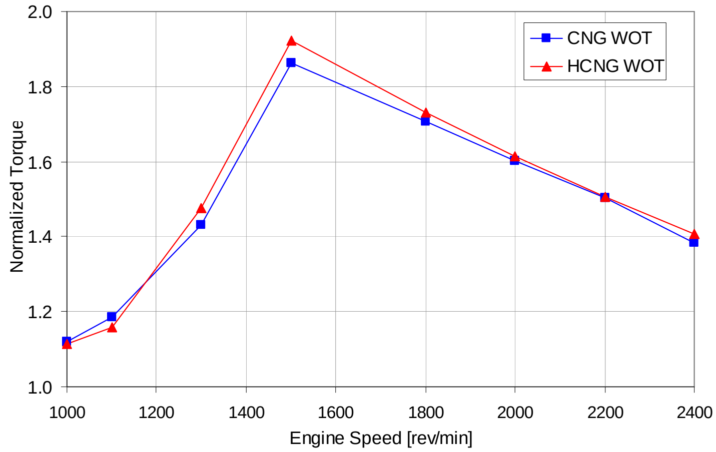

Figure 6. Engine torque curve comparison. The torque values are normalized against CNG torque at the lowest engine speed.

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. Post catalyst emissions for the 8-mode AVL steady-state test cycles under HCNG operation are shown in Table 1. The diesel equivalent brake specific fuel consumption was reduced by 2%.

Table 1. 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%

Test Cell 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 NO_x and CH_4 emissions were 44% and 18% lower respectively compared to CNG and the exhaust CO_2 emissions about 8% lower.

HCNG Bus Upgrade and Performance Verification

As part of the HCNG engine calibration verification on-road vehicle tests were also carried out by converting a CNG bus to HCNG operation. In order to record the bus performance instrumentation was added to the bus for data logging. An experienced professional bus driver was hired to drive the bus. Driver feedback was also recorded as part of the bus performance tests.

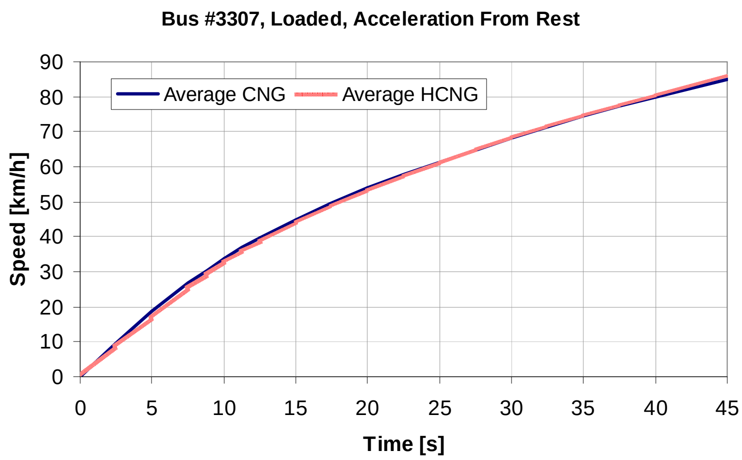

Figure 7. Bus#3307 CNG vs. HCNG acceleration comparison. Each curve represents the average of five runs.

The HCNG bus acceleration from zero to 80 km/h was at par with that of CNG bus (Figure 7). During a steep hill climb test the HCNG bus reached the top of the hill 5 seconds (2.3%) faster than CNG bus (Figure 8.). 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 identical to that of the CNG buses.

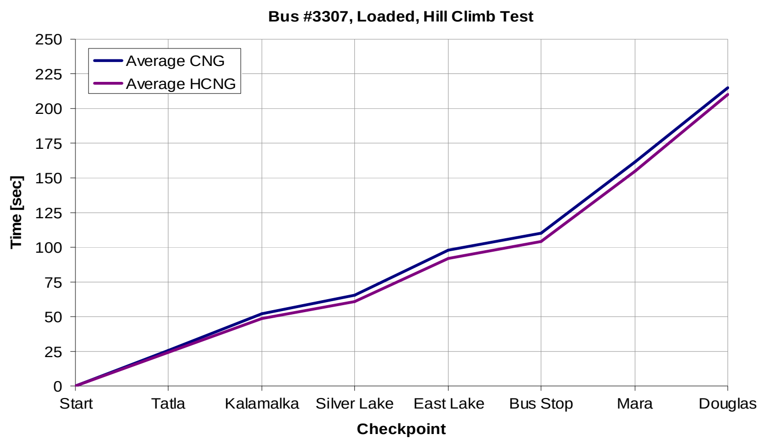

Figure 8. BUs#3307 CNG vs. HCNG hill climb comparison. Each curve represents the average of four runs.

4. HCNG Compliance and Regulatory Approval of HCNG Buses

One of the requirements of the project was that every effort should be made to ensure that the HCNG buses met or exceeded all possible safety-related regulations and requirements, prior to placing them into regular passenger service. In particular, Coast Mountain Bus Company (an operating subsidiary of TransLink) wished to obtain explicit approvals from the requisite government agencies to perform regular safety inspections of the HCNG buses and to apply the necessary Commercial Vehicle Inspection Program (CVIP) decal to those buses, despite the fact that they would be operating on a unique fuel blend. It was agreed that approval from the BC Safety Authority (BCSA) would be needed for the compressed gas storage system and that, once such approval was obtained, the Commercial Vehicle Safety and Enforcement (CVSE) branch of the Ministry of Transportation would be asked to give their approval to inspect and operate the buses according to the same rules governing existing CNG buses.

HCNG Component Compatibility

Westport undertook following steps to assess the compatibility of engine and bus components for HCNG service. The component compatibility review was meant to identify and mitigate potential effects of HCNG on the engine and vehicle components. A review of available literature on codes & standards, materials interaction with hydrogen and past operational experience with HCNG vehicles was conducted. Review of past experience with HCNG engine testing as well as vehicle demonstrations at various places did not reveal any adverse impact of using HCNG fuel in a CNG engine. Documentation related to engine fuel system and bus fuel system components including drawings and parts lists were obtained and reviewed. A matrix of fuel system components was prepared and reviewed for compatibility with HCNG operation. Suppliers of CNG fuel storage tank and the gas leak detection/fire suppression system were contacted. The suppliers confirmed compatibility of these systems for HCNG operation. Engine fuel supply system components (both metallic and non-metallic) coming into contact with HCNG mixture were also assessed for their compatibility with hydrogen operation. This information then was submitted to the regulatory agencies as part of the approval process.

Regulatory Approval of the HCNG Buses

The Commercial Vehicle Safety and Enforcement (CVSE) branch of the BC Ministry of Transportation and the BC Safety Authority (BCSA) were contacted in August of 2006. BCSA provided a list of requirements to be satisfied before they could issue an approval of the HCNG fuel system. An independent consulting firm (Powertech Labs, Surrey, BC) having experience with gaseous fuels and pressure vessels was hired to perform a thorough inspection of the HCNG bus fuel system. One HCNG bus (#3288) was delivered to Powertech December of 2006 for inspection. After inspection, Powertech recommended that the type of pressure relief device installed in each end of the gas storage cylinders and at junction points in the system plumbing needed to be replaced due to potential for hydrogen embrittlement. The potential for hydrogen embrittlement existed due to presence of nickel in the rupture disks used in the pressure relief device. Although potential for such a failure was only expected when exposed to pure hydrogen, in order to eliminate any uncertainty regarding safety with HCNG fuel, it was decided to replace all of the pressure relief devices on the HCNG buses. After replacement of the pressure relief devices on the bus the fuel system was repressurized with HCNG and a leak check was performed on the system. Once all the requirements were met, the BCSA issued their approval.

Subsequent to BCSA approval, in February of 2007, CVSE personnel also carried out inspection of the HCNG buses and the refueling facility. Shortly after the visit, CVSE provided a list of requirements to be met, the most significant being that each HCNG bus was required to be inspected by an independent designated inspection facility qualified to perform CVIP inspections of gaseous-fueled buses. In April of 2007, Bus # 3308 and #3288 were sent for inspection to the designated independent inspection facility and received a passing result. In addition, CVSE requested that Clean Energy Fuels investigate methods of providing a secondary verification of the blend ratio for the HCNG so as to provide a virtual guarantee that the hydrogen content in the HCNG would never exceed 20%. The HCNG dispenser is designed to continuously monitor the amount of hydrogen and CNG that is being mixed and dispensed and has the necessary safety logic built into it as a primary means of blend quality verification. Despite a general belief that the dispenser unit already represented the state of the art in terms of accuracy of blending and safety monitoring, CVSE insisted on developing an action plan to implement a secondary blend check. As a result it was agreed in principle to at least investigate potential strategies for secondary verification of the HCNG blend. Approval from CVSE to operate the first two HCNG buses in regular service was obtained in May of 2007.

Implementation of Safety Procedures at the Bus Operating Facility

In order to meet Coast Mountain Bus Company's standards for workplace safety, it was agreed from the beginning that the project would adopt a policy of the highest possible standards for monitoring of critical parameters and providing clear warnings to employees in the event of a problem. Clean Energy Fuels had been particularly proactive in this regard and undertook a number of site improvements initiatives to increase visual and audible warnings for the staff working at or in the vicinity of the HCNG refueling facility.

In April of 2007, a small fire occurred inside an electrical building situated adjacent to the hydrogen storage area. The fire was not related to the HCNG project and was apparently caused by old wiring in a circuit breaker. The fire was extinguished with minimal damage. Power was interrupted to the entire refueling facility for number of hours and also resulted in disabling of the warning systems installed by Clean Energy for the HCNG project. In order to prevent recurrence of such an incident, steps were taken to isolate the area with the electrical switches and breakers from the rest of the building. The back-up power supply (UPS) was upgraded to ensure operation of all audible alarms and warning lamps in the event of a power outage. The Autodialer system was re-programmed to alert the staff when an alarm was tripped in the refueling area. Further improvements were also made to the emergency response plan to reflect the changes made to the safety systems. Manually-operated evacuation siren and warning lamp installed at the bus refueling facility were also connected into the UPS to provide for the system operation in the event of a power loss. Additional procedures including both visible and audible alarms for various levels of contingencies, for notification and evacuation of the staff members working around the fueling facility were also developed and implemented. Once all the safety upgrades were completed, the operating staff was provided with necessary training to handle HCNG and decision was made to go ahead with the HCNG bus demonstrations.

HCNG Buses on the Road

With all of the necessary approvals completed, the first two HCNG buses were put into regular passenger service in June of 2007. Final conversions and approvals of the remaining two HCNG buses were completed at the beginning of November. All four HCNG buses have been in service since November of 2007.

5. HCNG Bus Emissions Testing

Emissions from heavy-duty diesel engines have been regulated for approximately 30 years, although it is only within the past decade that the limits have become sufficiently stringent to require sophisticated electronic fuel injection controls, engine emission control devices and exhaust gas after treatment.

Due to the diversity of possible truck chassis configurations, compliance testing of heavy-duty gasoline and diesel vehicles on chassis dynamometers is usually not practical. Instead, engine manufacturers are required to test their various engine models in a test cell with the load provided by an engine brake. When the first emission test procedures and standards were developed in the 1970's, the engines were operated in a number of steady-state operating modes. In the early 1980's the test cycle was changed to include transient operation and a period in which the engine is motored by the dynamometer.

Emissions are measured using a constant volume sampler. Second-by-second concentration measurements of HC, CO, NO_x and CO_2 are combined with dilute exhaust volume data to calculate cumulative mass emissions. Particulate matter emissions are calculated gravimetrically by massively diluting the exhaust gas in a dilution tunnel in order to minimize entrained moisture and passing a proportional sample of the dilute exhaust through a filter in order to capture any suspended PM. The filters are weighed before and after the test with the increase in weight representing the amount of PM accumulated through the test. Recently, portable emission measure systems (PEMS) have become available to make on-road emission measurement a practical possibility. Although emission compliance tests continue to be performed on engine dynamometers, the use of PEMS allows for supplemental compliance testing and for research into the real-world emission rates of heavy duty vehicles and off-road equipment.

In 2005, TransLink initiated a testing program to collect information on the relative performance of various bus engine/transmission/fuel combinations for emissions output, operational characteristics and life cycle cost. To measure emissions output, controlled tests were performed on a test track set up on a closed airport runway in Delta, British Columbia. TransLink has continued this testing program since 2005, with Phase 3 scheduled to commence in mid-2008.

<u>Emission Testing Cycle</u>
In order to achieve representative and repeatable results, it was necessary to develop a driving cycle that would simulate typical in-service operation. Transit bus operation is highly stop-and-go in nature with fairly low cruising and average speeds. Analysis of various routes within the Vancouver region revealed that a typical bus route has an average speed of about 20 km/hr. Although some routes involve sections where buses may reach speeds higher than 60 km/hr, such operation is rare and cruise speeds are generally 50km/hr or less.

The layout of the testing location limited operation in any one direction to less than 700 meters. A rectangular track layout was selected, with two straights of approximately 500 meters running down each edge of the runway and a short chute at either end spanning the width of the runway. Figure 9 shows the layout of the test track with 3 stops per lap.

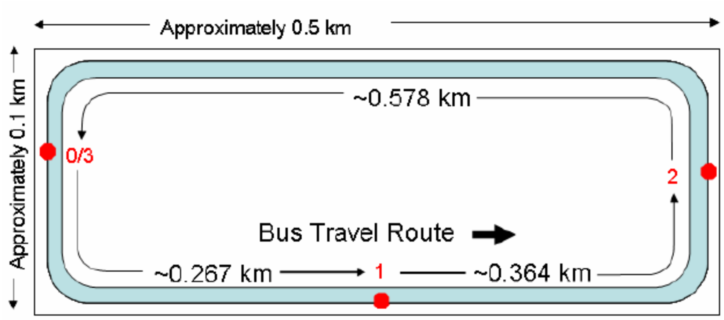

Figure 9. Bus emissions test track (2006).

The 2006 cycle is designed to represent actual transit service. This test cycle is shown in Figure 10 as a speed vs. time plot.

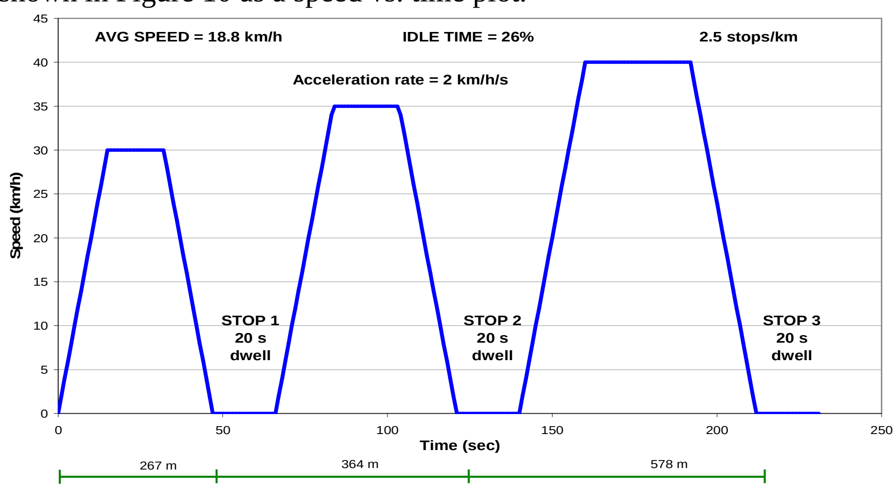

Figure 10. 2006 Emission Test Cycle.

Previous testing (in 2005) had indicated that the buses were accelerated at full throttle every time, in the belief that many bus drivers accelerate in this manner. However, after studying the behavior of bus drivers operating their vehicles in regular passenger service, it was determined that maximum throttle accelerations were not always possible and that an acceleration rate of 2 km/hr/sec. was fairly typical. In order to achieve the desired acceleration rate for the 2006 tests, signposts were placed at strategic points along the test track, giving the driver a goal speed at that position. Once the bus reached the desired cruising speed, the driver simply maintained that speed until the braking point, stopping the bus at the simulated bus stop and then idling for 20 seconds. Each test cycle consisted of 5 laps around the track. On the 5th lap, all accelerations were done at wide-open throttle to the desired cruising speed.

Figure 11. HCNG bus# 3302 undergoing emissions testing at the test track. The photograph also shows a simulated bus stop and blue marker barrels used to provide the driver with guidance on the point where a particular speed should be reached in order to adhere to the desired acceleration rate.

In practice, the test track layout and cycle design worked quite well. The repeatability of the test cycle was quite good as indicated by consistent lap times and total distance traveled. The target distance for 5 laps of the track was 6 km with an average speed of 18.8 km/hr meaning that the 5 laps would take about 19 minutes to complete. Each emission test consisted of 3 sets of 5-lap cycles with separate emission measurements performed for each. In practice, the total test cycle distance averaged 5.79 km with an average cycle time of 1108 seconds (18.81 km/hr average speed). The percentage of time at idle was consistently 29%. Although some variation was evident bus-to-bus, the standard deviation and coefficient of variation (CoV) for test distance and time was very low with CoV's of 2.55% and 0.40%, respectively.

In addition to the transient tests, the test consultant recommended that the emissions from each test bus also be measured under "steady state" conditions. This cycle was performed using the same track layout as the transient test, except that the bus did not stop at any of the bus stops and slowed only to negotiate the corners at either end of the test loop. The steady state test consisted of 5 laps, with speeds of 40 km/hr on the straights and 20 km/hr around the corners. The steady state cycle allowed for evaluation of emissions characteristics of various bus types under stable engine operating conditions.

Emission Measurement System

Two separate emissions sampling systems were used for the testing program. One was a commercially-available PEMs unit manufactured by SEMTECH and the other was a custom-fabricated unit built by Environment Canada called DOES2. The DOES2 system incorporates the ability to collect sample of particulate matter, a feature that the PEMs lacks. In the DOES2 system the exhaust samples are collected in a bag that are later on analyzed by a portable gas analyzer. The PEMS uses a venturi type exhaust flow meter to measure the volume of exhaust gas exiting the engine. A sample probe in the exhaust allows for continuous measurement of HC, CO, NO_x and CO_2 concentrations.
The DOES2 system differs from the PEMS in that the exhaust gas volume is calculated from the volume of air being drawn into the engine (measured with a laminar flow element). Due to the formation of water vapor during the combustion process and the addition of the fuel constituents to the exhaust mass, corrections must be applied to the intake air data to calculate the dry exhaust flow. The degree of correction is proportional to the air-fuel ratio (lambda), with greater corrections necessary as lambda approaches 1. For a diesel engine with significant excess air, the calculated exhaust flow is about 99% of the intake air. In a lean burn natural gas engine, the dry exhaust gas volume is closer to 92% of the intake air.

In addition to the measurements of exhaust volume and intake air volume, it was possible to calculate the exhaust flow using engine data from the engine's ECM. Using assumptions of engine volumetric efficiency, it was possible to calculate the exhaust flow from the engine rpm. Comparison of the calculated exhaust flow from ECM data with corrected intake air flow measurements from a natural gas powered bus indicated good absolute agreement between the two methods as well as excellent correlation of the dynamic response through the test cycle. For the testing described in this paper, the exhaust flow meter measurements had to be discarded because the thermocouple in the unit malfunctioned. As a result, all of the PEMS emissions calculations rely on exhaust volume measurements calculated from engine data.

In order to accurately represent in-use service during testing each bus was loaded with water barrels and bladders to simulate passenger weight. The two buses used in testing had following weights, loaded and unloaded. Differences in actual loads are due to difference in the amount of water added to the bladders, which proved to be more difficult to fill consistently than the water barrels. Each vehicle was weighed with full emissions measuring equipment and personnel on board.

Table 2. Bus Weight.

Emissions Test Bus Weight (kg)			
Bus#	Curb Weight	Tested Weight	Load Weight
3302	13,190	15,570	2,380
3308	13,265	16,555	3,290

For every test run, duplicate readings for HC, CO, NO_x and CO_2 were provided by the PEMS and DOES2. Although the two values did not agree precisely, they were fairly close and relative differences between buses were consistent with either method of analysis.

Figure 13. Inside of the HCNG test bus showing emissions measuring equipment at the back end and simulated passenger weight in terms of bags filled with water at the front end.

Emission Results

The emission testing was carried out in November 2006 and involved two HCNG test buses, designated #3308 and #3302. In order to identify the effect of the HCNG recalibration, Bus #3308 was operated in back-to-back tests running on 100% CNG and later on HCNG. The change of engine calibration (from CNG to HCNG) was conducted on site between test runs and was performed by Westport engineering team. For operation on the transient emission test cycle the following results were obtained:

Table 3. PEMS System Emission Results from Transient Operation. Fuel consumption in L/km is in terms of diesel equivalent liters.

Bus 3302 - HCNG

Test	Total Time (seconds)	Total Distance (km)	Avg Speed (kph)	Idle Time (seconds)	Percent Idle	Average Fuel Cons. (L/km)	Average Emission Rates CO2 (g/s)	CO (g/s)	HC (g/s)	NO (g/s)	NO2 (g/s)	NOx (g/s)
T1	1105	5.87	11.88	311	28.1%	0.705	6.27	0.0031	0.0329	0.0295	0.0041	0.0336
T2	1103	5.88	11.92	306	27.7%	0.688	6.14	0.0029	0.0339	0.0291	0.0037	0.0329
T3	1103	5.86	11.89	305	27.7%	0.679	6.04	0.0026	0.0339	0.0264	0.0035	0.0300
T Average	1104	5.87	11.9	307	28%	0.691	6.15	0.0028	0.0335	0.0284	0.0038	0.0321
St. Dev	1	0.01	0.02	3	0.3%	0.013	0.12	0.0003	0.0006	0.0017	0.0003	0.0019
COV	0%	0%	0%	1%	1%	2%	2%	10%	2%	6%	7%	6%

Bus 3308 - HCNG

Test	Total Time (seconds)	Total Distance (km)	Avg Speed (kph)	Idle Time (seconds)	Percent Idle	Average Fuel Cons. (L/km)	Average Emission Rates CO2 (g/s)	CO (g/s)	HC (g/s)	NO (g/s)	NO2 (g/s)	NOx (g/s)
T1	1108	5.91	11.92	301	27.2%	0.739	6.59	0.0035	0.0265	0.0318	0.0044	0.0363
T2	1110	5.90	11.87	324	29.2%	0.721	6.40	0.0037	0.0271	0.0355	0.0052	0.0407
T3	1103	5.90	11.96	320	29.0%	0.723	6.47	0.0032	0.0277	0.0361	0.0051	0.0412
T Average	1107	5.90	11.9	315	28%	0.727	6.49	0.0035	0.0271	0.0345	0.0049	0.0394
St. Dev	4	0.01	0.04	12	1.1%	0.010	0.09	0.0003	0.0006	0.0023	0.0004	0.0027
COV	0%	0%	0%	4%	4%	1%	1%	8%	2%	7%	8%	7%

Bus 3308 - CNG

Test	Total Time (seconds)	Total Distance (km)	Avg Speed (kph)	Idle Time (seconds)	Percent Idle	Average Fuel Cons. (L/km)	Average Emission Rates CO2 (g/s)	CO (g/s)	HC (g/s)	NO (g/s)	NO2 (g/s)	NOx (g/s)
T1	1093	5.89	12.04	319	29.2%	0.758	7.38	0.0048	0.0398	0.0570	0.0078	0.0648
T2	1111	5.88	11.84	323	29.1%	0.728	6.96	0.0037	0.0399	0.0532	0.0079	0.0611
T3	1113	5.87	11.78	315	28.3%	0.729	6.94	0.0038	0.0392	0.0553	0.0085	0.0638
T Average	1106	5.88	11.9	319	29%	0.738	7.10	0.0041	0.0396	0.0552	0.0081	0.0632
St. Dev	11	0.01	0.14	4	0.5%	0.017	0.25	0.0006	0.0004	0.0019	0.0004	0.0019
COV	1%	0%	1%	1%	2%	2%	3%	14%	1%	3%	4%	3%

Inspection of the relative performance of Bus #3308 on CNG and HCNG indicates that NO_x emission rates are significantly lower on HCNG as expected. Note that the tables show the emission rates expressed in terms of average grams per second for each of the three individual test runs (5 laps per test run). As mentioned previously, there were simultaneous readings obtained from DOES2 for all of the exhaust emissions measured by the PEMS as well as particulate matter. These DOES2 results are shown in Table 4 below.

Table 4. DOES2 System Emission Results from Transient Operation. Fuel consumption in L/km is in terms of diesel equivalent liters.

Bus 3302 - HCNG

Test	Total Time (seconds)	Total Distance (km)	Average Fuel Cons. (L/km)	Average Emission Rates CO2 (g/s)	CO (g/s)	HC (g/s)	NO (g/s)	NO2 (g/s)	NOx (g/s)	CH4 (g/s)	NMHC (g/s)	GHG (g/s)	TPM (g/s)
T1	1104	5.87	0.605	5.39	0.0005	0.0436	0.0153	0.0053	0.0206	0.0289	0.0147	6.05	NA
T2	1101	5.87	0.629	5.62	0.0002	0.0491	0.0178	0.0047	0.0224	0.0325	0.0165	6.37	0.000005
T3	1103	5.87	0.584	5.20	0.0006	0.0419	0.0145	0.0038	0.0183	0.0277	0.0142	5.84	0.000002
T Average	1103	5.87	0.606	5.40	0.0004	0.0449	0.0159	0.0046	0.0205	0.0297	0.0151	6.0841	0.000003
St. Dev	2	0.00	0.023	0.21	0.0002	0.0038	0.0017	0.0008	0.0021	0.0025	0.0012	0.2663	0.000002
COV	0%	0%	4%	4%	39%	8%	11%	16%	10%	8%	8%	4%	56%

Bus 3308 - HCNG

Test	Total Time (seconds)	Total Distance (km)	Average Fuel Cons. (L/km)	Average Emission Rates CO2 (g/s)	CO (g/s)	HC (g/s)	NO (g/s)	NO2 (g/s)	NOx (g/s)	CH4 (g/s)	NMHC (g/s)	GHG (g/s)	TPM (g/s)
T1	1107	5.91	0.632	5.64	0.0004	0.0364	0.0193	0.0052	0.0245	0.0241	0.0123	6.20	0.000029
T2	1108	5.90	0.613	5.46	0.0014	0.0351	0.0220	0.0064	0.0283	0.0229	0.0121	5.98	0.000032
T3	1102	5.90	0.628	5.63	0.0010	0.0390	0.0221	0.0069	0.0291	0.0257	0.0133	6.22	0.000045
T Average	1106	5.90	0.625	5.58	0.0009	0.0368	0.0211	0.0062	0.0273	0.0242	0.0126	6.1340	0.000035
St. Dev	3	0.01	0.010	0.10	0.0005	0.0020	0.0016	0.0009	0.0025	0.0014	0.0006	0.1310	0.000008
COV	0%	0%	2%	2%	59%	5%	8%	14%	9%	6%	5%	2%	24%

Bus 3308 - CNG

Test	Total Time (seconds)	Total Distance (km)	Average Fuel Cons. (L/km)	Average Emission Rates CO2 (g/s)	CO (g/s)	HC (g/s)	NO (g/s)	NO2 (g/s)	NOx (g/s)	CH4 (g/s)	NMHC (g/s)	GHG (g/s)	TPM (g/s)
T1	1092	5.89	0.641	6.25	0.0002	0.0491	0.0322	0.0131	0.0453	0.0411	0.0081	7.19	0.000069
T2	1110	5.89	0.595	5.70	0.0001	0.0384	0.0290	0.0121	0.0411	0.0321	0.0063	6.44	0.000043
T3	1113	5.89	0.602	5.75	0.0009	0.0393	0.0295	0.0125	0.0421	0.0327	0.0066	6.50	0.000042
T Average	1105	5.89	0.613	5.90	0.0004	0.0423	0.0302	0.0126	0.0428	0.0353	0.0070	6.7113	0.000051
St. Dev	11	0.00	0.025	0.30	0.0005	0.0059	0.0017	0.0005	0.0022	0.0050	0.0009	0.4175	0.000016
COV	1%	0%	4%	5%	112%	14%	6%	4%	5%	14%	13%	6%	31%

The DOES2 data confirm the results of the PEMS measurements, even if the absolute readings are somewhat different. In every case, the data are consistent from run to run. The DOES2 data includes PM emissions, which, as expected, were very low. The use of HCNG appears to lower PM emission output compared to CNG operation, although the measurements in all cases are at or below the limits of detection for the analytical equipment.

In addition to the gram/sec. data, the emission results were also calculated in units of grams/kilometer by dividing the cumulative mass of each pollutant by the distance driven

Tables 5 shows the emission results calculated from PEMS data for Bus #3302 and #3308 under both transient and steady state operation test cycles. Bus #3302 was operated only on HCNG while Bus #3308 was operated on both CNG and HCNG. The test performed while running on CNG are shown under the designation 3308-CNG. The results show that the HCNG buses had NO_x emissions of 6.04 g/km and 7.39 g/km, respectively. When Bus #3308 was operated on CNG, its NO_x emissions increased to 11.90 g/km. Its hydrocarbon emissions were also increased substantially. These effects are consistent with the expected effects of the added hydrogen, which is to enhance the combustion of the CNG charge, even at leaner air-fuel ratios. Reduced CO_2 emissions are also evident, consistent with the displacement of 7% of the CNG energy with a non-carbon fuel.

Table 5. Transient and Steady State Emissions (PEMS).

Transient Cycle	**Time (seconds)**	**Distance (km)**	**Fuel Cons. (L/km)**	**Emission Rates (gram/kilometer)**					
				CO_2	**CO**	**HC**	**NO**	**NO_2**	**NO_x**
3302	1104	5.87	0.69	1156	0.53	6.31	5.33	0.71	6.04
3308	1107	5.90	0.73	1217	0.65	5.08	6.47	0.92	7.39
3308-CNG	1106	5.88	0.74	1335	0.77	7.45	10.38	1.52	11.90

Steady State	**Time (seconds)**	**Distance (km)**	**Fuel Cons. (L/km)**	**Emission Rates (gram/kilometer)**					
				CO_2	**CO**	**HC**	**NO**	**NO_2**	**NO_x**
3302	992	9.37	0.48	801	0.37	4.69	2.35	0.23	2.58
3308	1011	9.45	0.51	858	0.50	4.51	2.40	0.28	2.68
3308-CNG	1020	9.42	0.52	939	0.44	5.42	4.82	0.59	5.40

Tables 6 show similar data taken from DOES2 data for both transient and steady state operation. Of greatest interest here is the result for PM emissions, which shows a significant range of results. Bus #3302 had much lower PM emissions than Bus #3308 although it must be said that both are well below the limit of accuracy of the measurement equipment.

Tables 6. Transient and Steady State Emissions (DOES2).

Transient Cycle	**Time (seconds)**	**Distance (km)**	**Fuel Cons. (L/km)**	**Emission Rates (gram/kilometer)**									
				CO_2	**CO**	**HC**	**NO**	**NO_2**	**NO_x**	**CH_4**	**NMHC**	**GHG**	**TPM**
3302	1103	5.87	0.61	1014	0.08	8.42	2.98	0.86	3.84	5.58	2.84	1142	0.0006
3308	1106	5.90	0.62	1045	0.17	6.90	3.96	1.16	5.12	4.54	2.36	1149	0.0066
3308-CNG	1105	5.89	0.61	1108	0.08	7.94	5.67	2.36	8.03	6.62	1.31	1260	0.0096

Steady State	**Time (seconds)**	**Distance (km)**	**Fuel Cons. (L/km)**	**Emission Rates (gram/kilometer)**									
				CO_2	**CO**	**HC**	**NO**	**NO_2**	**NO_x**	**CH_4**	**NMHC**	**GHG**	**TPM**
3302	990	9.37	0.40	677	0.01	4.80	1.70	0.46	2.16	3.89	0.90	737	0.0004
3308	1010	9.45	0.44	730	0.10	5.88	2.06	0.55	2.61	4.78	1.10	840	0.006
3308-CNG	1019	9.42	0.43	782	0.15	5.82	3.18	1.32	4.50	4.74	1.49	891	0.0225

As would be expected, the emissions for the steady state test cycle were generally lower than for transient operation, especially for NO_x, The relative difference between CNG and HCNG was quite pronounced in steady state operation, in the order of 50% lower.

Figures 14 and 15 show the comparative emission results for CNG vs. HCNG for Bus #3308 on both the steady state and transient emission cycles. Significantly lower NO_x and PM emissions are evident in either case.

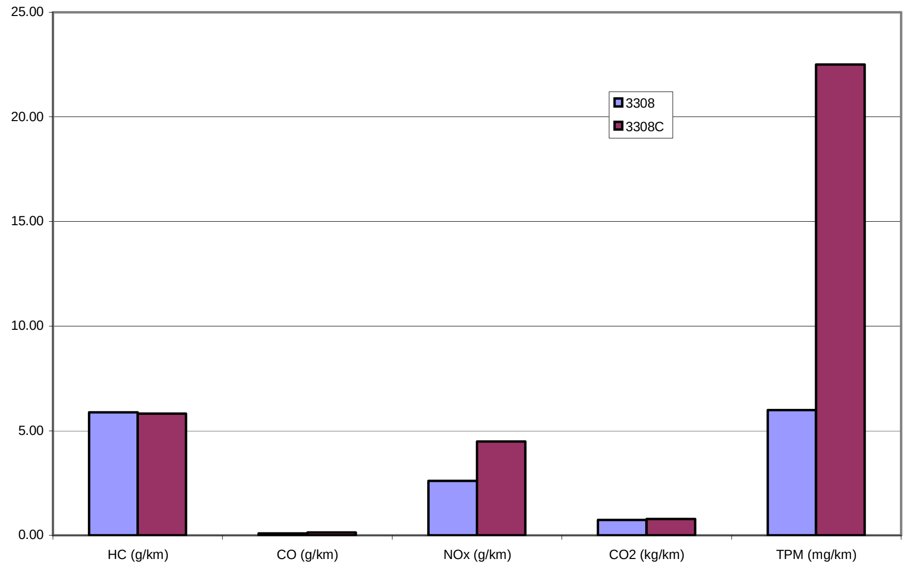

Figure 14. HCNG vs. CNG Bus Emissions in Steady State Operation. 3308C designates the CNG operation of the bus.

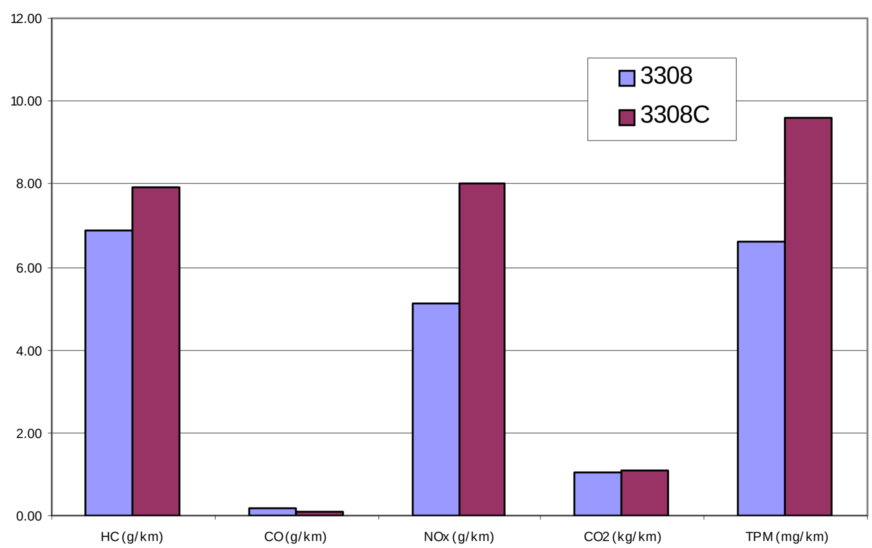

Figure 15. HCNG vs. CNG Bus Emissions in Transient Operation. 3308C designates the CNG operation of the bus

6. Regular passenger service Testing

In order to evaluate the feasibility of operating a fleet of natural gas buses on HCNG, a regular passenger service test was proposed.

The test was designed such that 4 HCNG buses and 2 CNG buses would operate for a six-month period under relatively controlled conditions. Daily mileage, fuel use and all maintenance actions would be carefully logged for each of the test buses during the evaluation. The buses would be limited to weekday use only and would rotate through 10 designated test routes, switching on a weekly basis. The test routes were selected from routes operating out of the Port Coquitlam Transit Center with the goal of including the full range of normally-encountered duty cycles, ranging from low-speed, and frequent stop urban use to higher speed express routes. A terrain index was also applied in order to include a mixture of hilly and flat routes. By assigning the test buses to the full spectrum of possible operating conditions within Coast Mountain Bus Company's operating region, it would be possible to identify any limitations imposed by the HCNG calibration as well as to determine the expected operating cost and reliability of HCNG-powered buses.

The regular passenger service test commenced on November 12, 2007 and is expected to complete in mid-May of 2008. To date, the HCNG buses have exhibited no problems in operation beyond those that normally crop up during transit service delivery. Drivers have not commented or complained about the HCNG buses in any way, which is a good sign that their performance is at least equivalent to a normal CNG bus. Table 7 below shows the distance driven and fuel use for each of the test buses from November 12, 2007 to February 15, 2008

Table 7. Bus Mileage Accumulated and Fuel Usage In Regular Service.

Bus #	Fuel Type	Km Driven	CNG Used (kg)	H_2 Used (kg)	Fuel Consumption in Diesel Equivalent Liters (L/km)
3288	HCNG	16,477	8060	242	0.689
3302	HCNG	16,518	7687	234	0.680
3307	HCNG	15,910	7919	241	0.727
3308	HCNG	16,076	8106	243	0.735
3292	CNG	14,275	8809	0	0.798
3306	CNG	13,524	7371	0	0.670
Total		72,780	47,952	960	

The data show that the HCNG buses are have similar fuel consumption on average. There is a range of 0.05 L/km from lowest to highest (about 8%) but this falls into the range of normal variability for buses. The two baseline CNG buses have accumulated less mileage during the test period and exhibit a more significant disparity in fuel consumption from one to the other. The reason for this was not known at the time of writing this paper but will be monitored as the test progresses.

Based on experience to date, there appears to be no reason that conversion of all lean-burn CNG buses to HCNG operation could not take place. At this point, the main barrier to this is the availability of sufficient hydrogen and refueling capacity to operate a larger fleet.

7. SUMMARY

1. Test cell steady-state tests over an engine cycle revealed 30% reduction in NO_x+NMHC without sacrificing engine torque or fuel economy. Transient

tests in the test cell over the School Bus cycle indicated about 44% reduction in NO_x emissions. Emission of unburned methane was also significantly reduced.

2. Field testing verified that the HCNG bus acceleration and drivability were at par with that of CNG bus.
3. Emissions testing of HCNG and CNG buses under transient operation on a test track indicated following emissions benefits:
    a. NO_x emissions on HCNG were 38% lower compared to CNG.
    b. THC emissions on HCNG were about 20% lower compared to CNG.
    c. CO2 emissions were about 9% lower on HCNG.
    d. Fuel consumption expressed in terms of diesel-equivalent-liters/km was similar on either fuel.
4. To date the HCNG buses have operated very similar to the CNG control buses in regular passenger service.

8. ACKNOWLEDGEMENT

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9. REFERENCES

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