# Topic Paper #25

# Hydrogen-Compressed Natural Gas (HCNG) Transport Fuel

On August 1, 2012, The National Petroleum Council (NPC) in approving its report, *Advancing Technology for America's Transportation Future*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

#### Hydrogen-Compressed Natural Gas (HCNG) Transport Fuel

#### What is HCNG?

HCNG is a vehicle fuel which is a blend of compressed natural gas and hydrogen, typically 8-50% hydrogen by volume. Global HCNG testing to date has demonstrated the fuel's potential to reduce nitrous oxide ( $NO_x$ ), carbon dioxide ( $NO_x$ ), and carbon monoxide ( $NO_x$ ) vehicle emissions compared to traditional CNG. Existing natural gas engines can be used with HCNG, although higher hydrogen blends require re-tuning of the engines for optimal performance. Studies indicate that HCNG mixtures with 20-30% hydrogen by volume are optimal for vehicle performance and emissions reduction [3].

HCNG refueling sites require sources of hydrogen and natural gas, which are blended and pressurized on-site for vehicle fueling. Gas is supplied through the existing natural gas infrastructure while hydrogen is provided though electrolysis or natural gas reformation. Electrolysis is generally performed on-site using electricity from the local grid. Hydrogen from reformation of natural gas is supplied to sites by truck or produced on-site using small-scale reformers. All these options have been tested in field trials.

#### State of the Industry

HCNG is a developing technology. The primary technical challenge to HCNG deployment is improving CNG engine tuning for HCNG blends. As can be seen in the research below, engine tuning is a critical and sensitive step in optimizing the positive effects of introducing HCNG. This is a particular challenge in converting existing CNG vehicles where each engine requires individual adjustment.

Hydrogen and vehicle production costs are key economic challenges. Hydrogen is currently produced using large-scale steam methane reforming (SMR) of natural gas. To avoid hydrogen transportation costs, smaller, site-scale models are being developed and their production costs are falling; however  $CO_2$  is produced in this process. Production costs for electrolysis are currently above target levels and hydrogen research is tackling these cost challenges independent of HCNG activities.

Vehicle costs for HCNG are tightly linked to CNG vehicles costs. OEM-manufactured CNG vehicles remain more expensive than gasoline and diesel vehicles in the US, with incremental costs ranging from \$6,000 for a car [13], up to \$60,000 for a heavy-duty truck [14]. No OEM-manufactured HCNG vehicles are currently in production. For CNG vehicle conversions, only small additional retuning costs would be required. Economies of scale in equipment manufacturing are likely to have a significant effect on improving costs for both hydrogen production equipment and vehicle manufacture.

#### **HCNG Research**

Since the early 1990's, a number of government, academic and professional groups have performed HCNG research and field trials in the US, Europe and Asia. A summary of the major trials can be found in the appendix. These include laboratory bench tests of different HCNG fuel mixes and engine designs as well as field trials of buses and light-duty HCNG vehicles. The main objective of the research has been to:

- Determine the optimum mix of hydrogen and CNG in the HCNG fuel
- Identify optimum engine tuning for HCNG fuel mixes
- Measure emissions and performance of HCNG vehicles against CNG equivalents
- Assess the ability of existing CNG components to work with HCNG blends

Due to the variety of HCNG fuel mixes, vehicle types, engines, engine adjustments, operating activities, and testing methods, a range of analysis results have been produced for HCNG fuels. The consensus for each of the research objectives is as follows:

The majority of research sought to identify the hydrogen mix which optimized reduction of  $NO_x$ , CO,  $CO_2$  and unburned hydrocarbon emissions while limiting engine redesign and maintenance. The broad consensus is that 20% is the optimum blend for meeting these purposes. Laboratory bench trials by NREL [3] in early 2000 indicated that a 25% blend minimized  $NO_x$  emissions but at the expense of a 12.8% increase in total hydrocarbon emissions (vs. +3% at 23% blend). NREL therefore used an optimization strategy assessing all emissions and adjusting HCNG and engine calibration to achieve a reduction in  $NO_x$  by 50%, with reductions of non-methane hydrocarbons by 58%, and total hydrocarbons by 23%. Using a balanced scorecard of emissions, engine performance and total costs, it judged 20-23% hydrogen by volume to be the optimum blend range. A research trial in India [11] led by the Society of Indian Automobile Manufacturers identified 18% hydrogen as providing the greatest  $NO_x$  reduction with the lowest engine power loss for their vehicle and fuel standards, reflecting a similar hydrogen blend optimum range.

Adjustments to the engine must be performed during trials to optimize emissions reduction and engine efficiency. Tests performed using unadjusted CNG engines reported an increase in emissions with direct use of HCNG [9]. In order to optimize the value of HCNG's higher flame speed and leaner combustion ability, engines were most commonly adjusted to a leaner air/fuel mix and delayed spark timing. These adjustments to CNG engines are straightforward, requiring 4 hours in a Swedish trial, and do not change the ongoing maintenance requirements. As will be noted in the next paragraph, these adjustments are critical to HCNG analysis.

The research contains a wide range of bench tests and field trials analyzing emissions, engine performance and fuel efficiency across a range of hydrogen fuel mixes and engine designs. NREL's field trials, performed on 20% HCNG and with air/fuel and spark timing engine adjustments to minimize  $NO_X$  emissions, recorded  $NO_X$  emissions reductions of 50% below CNG with CO and total hydrocarbon emissions also falling by 16% and 23%, respectively. Separate bench tests by Cummins Westport Inc, corroborated these  $NO_X$  findings as well as reporting a  $CO_2$  emissions reduction of 7%. In Montreal, field trials on buses operating 20% hydrogen HCNG reported  $NO_X$  emissions reductions of 40% with no increase in unburned hydrocarbons and  $CO_2$  emissions reductions of 7.5%. These tests clearly demonstrate the ability to significantly reduce  $NO_X$  emissions (in the range of 50%) and reduce other emissions (including  $CO_2$  in the range of 7%) while maintaining reasonable performance. Laboratory bench tests in Italy [9] suggested that spark timing adjustments improved all emissions but adjustments to leaner burning air-fuel ratios produced less  $NO_X$  emissions reductions than stoichiometric air-fuel ratios but improved  $CO_2$  emission reductions. It should be noted that these emissions findings are for the tank-to-wheel portion of use and don't consider any additional  $CO_2$  emissions from SMR hydrogen production, non-renewable powered electrolysis or in the hydrogen supply chain.

	Engine emission reduction below CNG level (%)			
Trial	NOx	СО	Total HC	CO <sub>2</sub>
NREL	50%	16%	23%	-
Cummins Westport	50%	-	-	7%
Montreal	40%	-	No increase	7.5%

The final area tested in field trials was the ability of conventional CNG components in the vehicle and refueling infrastructure to operate using hydrogen-blended fuels. All trials to date have reported no

additional maintenance or material failures due to operating with hydrogen blends, with the only adjustments required being initial engine re-tuning to support HCNG fuel optimization.

#### **Ongoing Global Investment**

Trials of HCNG continue to be performed worldwide; companies and governments in countries including India, Korea, and Italy are operating pilots, analyzing engines, and pondering OEM HCNG offerings. As this list suggests, countries with strong CNG industries are most active in the HCNG space. Fiat, a notable player in the CNG vehicle market, is working with a consortium of Italian companies on a public trial of 30% HCNG cars in Italy, and Iveco aims to establish a hydrogen/HCNG highway from Modena to Munich [15]. In India, the Society of Indian Automobile Manufacturers is working with Indian Oil Company on an 18% HCNG trial in New Delhi and has deployed a fleet of fifty vehicles to run for 50,000 km with the intention of then converting all public transport vehicles in the city to HCNG if results are positive [11]. In South Korea, the Ministry of the Environment recently announced plans to deploy more CNG buses immediately and to "promote development and distribution of HCNG hybrid buses in the long-term to improve environmental benefits from CNG buses." [12]

#### **Assessment of HCNG Potential**

As the research shows, the addition of hydrogen to CNG fuel can reduce vehicle emissions [6]. HCNG's ability to reduce  $NO_X$  emissions by up to 50% is particularly significant and would be of most value in urban environments where  $NO_X$  is most harmful. While the level of  $NO_X$  emission reduction delivered by HCNG over CNG in trials is clearly significant, in retrofitted engines these reductions are highly dependent on the adjustment of the engine for HCNG optimization. If the engine is not appropriately retuned, for example if the air-fuel mix is not increased enough, then the higher burning temperature of HCNG can lead to higher  $NO_X$  emissions than CNG. OEM factory-certified HCNG engines would alleviate this issue if an OEM commits to their manufacture.

The required adjustments to retrofitted engines are particularly important when placed in the context of available infrastructure. HCNG re-tuning means the vehicles are now specifically engineered for HCNG use and that fueling with basic CNG will be sub-optimal from a performance and emissions perspective. Given that the public CNG refueling network is currently limited due to challenging economics, adding further limitations to public refueling availability may hinder rather than help widespread NGV deployment. This is a major limitation for widespread public deployment but is mitigated in short-distance fleet applications which use a private, centralized refueling location. Fiat is also researching potential adaptive engines which adjust air intake for CNG or HCNG based on the amount of hydrogen detected in the fuel supply. This technology will however increase vehicle cost.

A second infrastructural challenge is the current cost of deploying hydrogen as a transport fuel. The cost to store hydrogen at CNG refueling sites must be added to existing site development costs which are viewed as restricting growth in public CNG infrastructure at present. If hydrogen is produced centrally, the additional costs of delivering hydrogen must be considered against the emissions reductions delivered. Delivery will almost exclusively be by truck in the medium term as US hydrogen pipeline infrastructure is limited to 800 miles in specific locations [17]. Hydrogen production using decentralized, on-site systems is still above target prices but is falling steadily with research advances on small-scale electrolysis and reformers.

A more practical concern, which ties to issues with a limited public HCNG network, is HCNG's energy density. HCNG has a lower energy density than pure CNG (906 Btu/scf vs. 777 Btu/scf) meaning that the same volume of compressed fuel will provide a reduced vehicle range. Given existing CNG range

concerns, a technology which reduces range is likely to be limited to bus and other fleet applications that refuel daily rather than long-range medium and heavy duty vehicles. A NREL trial [3] noted a 12.3% fuel economy reduction on its buses using 20% hydrogen while a research report for the World Hydrogen Energy Conference [1] identified energy losses of 28% versus CNG for 20% hydrogen.

#### Requirements to support deployment of HCNG

In the event that widespread HCNG deployment is targeted, the following steps would be critical to supporting deployment.

- Standardize the hydrogen/CNG blend in fuel to allow more consistent deployment, testing and regulations. The primary point requiring standardization is the proportion of hydrogen by volume in HCNG
- Develop OEM factory-certified HCNG engines. Engines for mass transit fleets are a prime starting point
- Given the importance of engine tuning to capturing the potential of HCNG, perform decisive analysis on a standard fuel mix to define the specific engine requirements to optimize the value of using HCNG
- Based on consistent fuel standardization and engine optimization, decisive emissions reduction analysis should be performed to allow more reliable emissions comparisons to identify when HCNG should be considered for use
- More detailed research should be performed to determine the value of lower-hydrogen share HCNG blends (8% HCNG) which do not require re-tuning of CNG engines, and can integrate more synergistically with existing CNG infrastructure

#### Conclusion

There is clear potential for the use HCNG as a method of reducing emissions from CNG vehicles, in particular emissions of nitrous oxides. The role of HCNG will be most limited by a lack of existing CNG deployment in the US, particularly for public users. Given current deployment of CNG vehicles is being hampered by up-front vehicle and infrastructure costs, the additional costs and technical pressures of adding hydrogen to CNG will challenge the ability to successfully deploy to the widespread public.

This concern and the current NGV market focus on heavy-duty vehicles mean that mass transit fleets are prime candidates for HCNG consideration. These fleet vehicles are fueled through their own infrastructure, have less concern over range per tank, and consider  $NO_X$  emissions of particular concern due to their concentration in urban areas. In addition, a large number of city bus fleets already operate on CNG meaning conversion costs would be significantly reduced.

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## **Appendix: Major HCNG Trials**

In California, a Department of Energy supported a study of two HCNG buses compared to two CNG control buses. The study was led by the NREL in partnership with Cummins Westport, Hydrogen Components Inc and Sunline Services Group. The study performed lab bench tests on engines as well as 9-month field trials with the Sunline bus company. Bench tests identified a 20% hydrogen blend as being the optimum blend based on a balanced scorecard approach assessing NO<sub>X</sub> reduction, engine performance, maintenance and repair, equipment modification, and fuel cost. In field trials, the 20% HCNG blend reduced NO<sub>X</sub> emissions by over 50% relative to the CNG control group. There was no discernable difference in PM emissions for the two fuels. Emissions of non-methane HC and CO were similar and near minimum detection limits. A fuel economy penalty was experienced in the operation of the HCNG blend; in-use fuel economy for the HCNG buses was reduced by about 12% relative to the CNG operation on a diesel gallon equivalent basis. [3]

In Montreal, the Euro-Quebec project operated to two buses from NOVABUS in the city for nine months on a HCNG blend (20%  $H_2$  by volume, 7%  $H_2$  by energy). The program reported  $CO_2$  emissions reductions of 7.5% and  $NO_X$  emissions reductions of 40% with no increase in unburned hydrocarbons in the exhaust fumes. [6]

In Vancouver, tests by Cummins-Westport Inc. showed that using HCNG (20%  $H_2$ ) led to reduction in  $NO_X$  and non-methane Hydrocarbons by 50% compared to CNG. These results were achieved while maintaining engine performance and efficiency with a slight reduction of CO and  $CH_4$  emissions. In addition,  $CO_2$  emissions were reduced by 7%. **[6]** 

In France, Gaz de France coordinated the ALT-HY-TUDE project which tested HCNG buses in two cities (Dunkerque and Toulouse) from 2005 to 2008. Bus operation began in 2006 after bench trials to identify the optimum hydrogen-CNG blend and engine tuning, as well as to measure lab emissions reductions. Hydrogen was provided in one city from hydrolysis using electricity from the grid (to simulate renewable production) and by natural gas reformation in the other city (the most cost effective method of  $H_2$  production at present). [2]

In Malmo, Sweden; Sydkraft Gas led a trial in which HCNG (8%  $H_2$  volume and 25%  $H_2$  volume) was added to CNG bus fuel. 8% HCNG was used in a bus with no adjustments while 25% HCNG was tested in a bus with modifications made to the air-fuel mix. Buses were reported to run well however emissions were not positive and indicated that  $NO_X$  emissions results are highly sensitive to vehicle tuning. [8]

In Las Vegas, the Department of Energy sponsored a field trial of nine Ford F-150 converted to run on 30% HCNG using an exhaust gas recycling system to reduce  $NO_X$  emissions. The study focused heavily on whether the units remained operational and how the HCNG conversion kits performed, performing limited emissions analysis and no detailed or rigorous comparisons of pre-conversion emissions or fuel efficiency to those after conversion to HCNG.