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Hydrogen Admixture Impact on NGVs

Potential Impacts on Natural Gas Vehicles from Introducing Hydrogen in Natural Gas Vehicle Fuel Supplies

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Gas Quality Working Group

Introduction

Hydrogen fueled transportation promises significant future benefits in terms of addressing air pollution and reducing greenhouse gas emissions. Unlike existing battery-electric zero-emission vehicle technologies, hydrogen offers extended range, higher payload capacity, and fast refueling, making it ideal for heavy-duty, long-haul trucking and other hard-to-electrify applications like mining equipment, ships, and aircraft. It also promotes energy security and fuel diversification and can integrate with renewable energy sources to balance high demands on the power grid and energy distribution systems.

While key challenges remain in terms of the cost and energy-intensive nature of hydrogen production and the limited infrastructure for its transportation and storage, efforts to blend hydrogen into the existing natural gas distribution system are underway as a means to reduce carbon emissions by leveraging current infrastructure. This promising transmission solution, however, poses unique challenges for the established natural gas vehicle (NGV) industry.

Intentionally increasing the concentration of hydrogen above trace amounts that occur naturally in natural gas may negatively impact the performance, reliability, and durability of natural gas engines that have not been designed or developed to operate with hydrogen-in-compressed-natural-gas admixtures (HCNG). Engine maintenance components such as spark plugs—designed with specific fuel specifications in mind—are among the most vulnerable engine components to potential HCNG negative impacts. In general, there has been limited assessment on how HCNG will affect engine durability, maintenance, and total cost of ownership (TCO). Assessments that have been conducted[1,2] indicate potential impacts to NGV engines and fuel systems, but the long-term durability and reliability impacts are not yet fully understood. While there are many blending demonstration projects that have been conducted in the past, some that are currently underway, and some that are planned for the future, most are focused on industrial and residential natural gas use and generally do not consider transportation end use applications.

Until additional NGV testing and demonstration projects are completed, the real impact of HCNG on automotive engines and transportation end use customers will not be fully understood. In addition, the timeline for determining when and at what concentrations hydrogen will be added to natural gas for vehicle fuel remains uncertain.

This technical bulletin serves to inform natural gas providers and utility companies of the potential HCNG negative impacts on NGVs and on the end users that use natural gas as a transportation fuel.

Codes, Standards, and Regulatory Overview

Within the natural gas industry, there are many gas quality codes, standards, and regulations that specify volume percentage limits of hydrogen as a constituent of natural gas. Many of the limits are specific to natural gas pipelines and the infrastructure for distributing natural gas as a source of energy. The following list of standards serves to identify the lack of harmonization and consistency that exists between the various codes and standards and the associated regulatory requirements to limit hydrogen percentage concentrations in natural gas distribution systems.

- The **SAE J1616** recommended practice specifies a **0.1%** limit.
- The **ASTM D8080** standard specifies a **0.3%** limit.
- The **ASTM D8487** standard specifies a **10%** limit.

[1] Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150; U.S. Department of Energy FreedomCAR & Vehicle Technologies Program Advanced Vehicle Testing Activity; November 2003
[2] Development and validation of a quasi-dimensional combustion model for SI engines fueled by HCNG with variable hydrogen fractions; International Journal of Hydrogen Energy; Volume 33, Issue 18; 2008

- The **UN ECE R110** regulation specifies a **0.1%** limit for wet gas and **2%** limit for dry gas.
- The first edition of the **Worldwide Fuel Charter for Methane-based Transportation Fuels** specifies a **2%** limit for dry gas.
- Typical **pipeline tariff structures** and **contract constituent limits** for hydrogen range from **0.01 to 0.05%**.

In addition to the inconsistency surrounding published limits for hydrogen in natural gas distribution systems, varying admixture concentrations within HCNG may affect engine exhaust emissions from NGVs, which are strictly regulated.[3] Specifications for natural gas as a fuel during engine emissions testing and certification reference standards such as ASTM D1945, which may vary from actual constituent levels in natural gas pipelines. Until further scientific analysis and industry emissions testing is conducted, the impact of increasing hydrogen percentage concentrations to natural gas engine exhaust emissions remains uncertain at this time.

Engine Durability Concerns with Increasing Hydrogen Concentrations

I. Spark Plug Beading

Even at trace amounts in natural gas as a vehicle fuel, hydrogen may be linked to spark plug beading in natural gas engines. The bead formations on the electrode of the spark plug can occur throughout the life of the spark plug, reduce the spark plug gap, and lead to cylinder misfire. This beading effect is the main driver for a 0.03% hydrogen limit in fuel for Cummins natural gas engines, which is identified in proprietary research performed by Cummins.

[3] Admissible hydrogen concentrations in natural gas systems | Altfeld, K., & Pinchbeck, D. | 2013 | Retrieved from https://www.gerg.eu/wp-content/uploads/2019/10/HIPS_Final-Report.pdf

Figure 1 – Image of beading effect on the electrode of an internal combustion engine spark plug

II. Spark Plug Erosion

Increased hydrogen concentration in natural gas as a vehicle fuel may increase in-cylinder flame speed and temperature, potentially resulting in increased erosion and reduced life of natural gas engine spark plugs.

III. Engine Knock and Preignition

As percentages of hydrogen concentration increase in natural gas as a vehicle fuel, the propensity for engine knock and preignition increases.[4] This adverse behavior is attributed to the reduction in the methane number characteristic of the fuel, which is affected by the many constituents and impurities that may contaminate CNG fuel supplies and lower the overall methane percentage concentrations. The propensity for engine knock and preignition increases as the methane number of the fuel decreases; this has been demonstrated by all reputable analytical methods for engine behaviors; and it has been proven by real world data as well.

Studies analyzing the effects of knock and preignition have identified long-term durability impacts to an internal combustion engine. For examples of engine damage resulting from severe engine knock and preignition conditions, refer to Figure 2 below.

[4] Admissible hydrogen concentrations in natural gas systems | Altfeld, K., & Pinchbeck, D. | 2013 | Retrieved from https://www.gerg.eu/wp-content/uploads/2019/10/HIPS_Final-Report.pdf

Figure 2 – Piston damage resulting from 300-600 consecutive cycles of engine knock

It is also important to note that the combustion characteristics of hydrogen are different than methane, and the combustion characteristics of the two fuels blended together can compound the uncertainty of combustion behavior. This uncertainty, coupled with the impacts of decreased methane number, creates further susceptibility for engine knock and preignition and diminished combustion behavior predictability, which underscores the need for more analytical research and testing before HCNG is considered an acceptable fuel for natural gas engines. For more information on the impacts of HCNG on engine combustion behavior, refer to the Performance Impacts section below.

NOTE: *The combustion characteristics for natural gas and hydrogen are well understood as individual fuels within the engine industry and the scientific community, but there is a deficiency of scientific study and analysis that exists today to fully understand the combustion characteristics when the fuels are blended together in an internal combustion engine.*

IV. Advanced Engine Electronics, Tuning, and Diagnostics

Even with the most advanced onboard diagnostic (OBD) technology commercially available today, engines cannot reliably and efficiently accommodate inconsistent fuel quality caused by varying hydrogen percentage concentrations in natural gas as a vehicle fuel. Reliable and consistent hydrogen blending concentrations at the point of injection into a natural gas engine cannot be expected based on current plans to introduce hydrogen admixtures for general natural gas supply use, current natural gas distribution infrastructure, storage systems, refueling equipment, or vehicle fuel systems. Inconsistency in fuel quality, hydrogen percentage concentration, and combustion characteristics will impact the accuracy of fuel volume required for the lower energy density HCNG fuels, the fuel trims required for efficient engine performance, and engine diagnostics.

V. Component and Material Compatibility

Materials used in the construction of various components of a vehicle fuel system may not be compatible or suitable for use with hydrogen or HCNG. Embrittlement of different grades and strengths of steels and steel alloys has been analyzed and reported in various scientific research reports, and other guidelines exist within the transportation sector that advise against HCNG due to embrittlement concerns of the high tensile strength steel used widely in CNG vehicle fuel tanks and the methane-based fuel transportation infrastructure.[5]

According to UNECE Regulation 110 for CNG vehicles, the H_2 content in CNG is limited to 2 vol%, if the tank cylinders are manufactured from steel with an ultimate tensile strength exceeding 950 MPa. This limit stems from the risk of hydrogen embrittlement which is known to cause accelerated crack propagation in steel and is, therefore, a critical safety issue. The same 2% limit is [also] echoed in the corresponding ISO standard 11439 and under DIN 51624, the German national standard for natural gas as a motor fuel.[6]

Although vehicle fuel system components constructed with steel materials exhibit HCNG compatibility concerns, the majority of CNG cylinders manufactured today are not subject to this same degree of embrittlement risk. This is because metal is not used to construct Type-4 CNG

[5] Worldwide Fuel Charter | Methane-Based Transportation Fuels | First edition | 28OCT2019
[6] Admissible hydrogen concentrations in natural gas systems | Altfeld, K., & Pinchbeck, D. | 2013 | Retrieved from https://www.gerg.eu/wp-content/uploads/2019/10/HIPS_Final-Report.pdf

cylinder bodies, and therefore, Type-4 cylinders can be safely and reliably used to store CNG, pure compressed hydrogen, or any admixture thereof.[7]

While the negative impacts to a NGV fuel system—including but not limited to the fuel containers or the fuel lines therein—are not yet fully understood, there is significant evidence to support the hypothesis that increasing concentration of hydrogen in natural gas as a vehicle fuel promotes embrittlement and fatigue cracking in steel materials, and it is generally recognized that the greater the purity of the hydrogen, the more pronounced the embrittling effect.[8]

In addition to metallic embrittlement and crack propagation concerns, hydrogen may also affect the reliability and durability of seals and gaskets in the vehicle fuel system due to its higher permeation capability.

Potential Total Cost of Ownership Impacts

I. Reduced Spark Plug Life

The potential for spark plug beading and increased wear may result in shorter maintenance intervals, unplanned vehicle downtime, and more frequent spark plug replacements (see Engine Durability Concerns section above).

II. Increased Downtime

Drivers may submit low power complaints and make repair order requests with increasing percentage concentrations of hydrogen in natural gas as a vehicle fuel. In addition, false positive fault codes are more likely to occur from varying fuel quality and constituent levels.

III. Reduced Energy Density of Fuel

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[7] Hydrogen Blending With Transportation Fuel | Bate, B., & Epp, M. | 2024 | Canadian Standards Association | Retrieved from https://www.csagroup.org/article/research/hydrogen-blending-with-transportation-fuel/
[8] Compatibility of Metallic Materials with Hydrogen | Hervé Barthélémy and Air Liquide

Increasing percentage concentrations of hydrogen in natural gas as a vehicle fuel will result in lower fuel efficiency and reduced range.

IV. Higher Leak Potential

Hydrogen molecules (H_2) are much smaller than methane molecules (CH_4) and therefore may be more prone to leakage from HCNG mixtures, particularly as hydrogen percentages and partial pressures increase. An increase in vehicle downtime may occur if vehicles are taken out of service to troubleshoot the cause of flammable gas detector activation. Public research on this concern for the broad usage of hydrogen admixtures is only now beginning. It is also important to note that leaks from fuel with higher hydrogen concentrations may not be detected with the human nose, as the mercaptan contained in pipeline quality natural gas has a lower leak potential than hydrogen.

V. Unwarrantable Failures

Natural gas engine or fuel system failures that are caused by fuels that do not meet minimum requirement specifications are not warrantable.

Performance Impacts

I. Lower Power Output

Reduced energy concentration or large swings in energy concentration in natural gas as a vehicle fuel may result in low power complaints from operators and false positive engine fault codes.

II. Diminished Fuel Physical Properties

Increasing percentage concentrations of hydrogen in natural gas affect calculated methane number (MN_c), lower heating value (LHV), and the Wobbe Index of the fuel as shown in the figure below. The red cells indicate where the higher hydrogen concentrations lead to insufficient MN_c and

LHV values to meet the required energy concentration thresholds for each fuel type as defined by the ASTM D8080-21 standard.

	MNc 75 min. or 65 min.				LHV, MJ/m3 33.2 MJ/m3 min.				Wobbe (HHV), (MJ/m3) 46-53 MJ/m3		
H2 (%)	Nat Gas	CNG	Low MNc Nat Gas	H2 (%)	Nat Gas	CNG	Low MNc Nat Gas	H2 (%)	Nat Gas	CNG	Low MNc Nat Gas
0	80	92	71	0	37.66	36.01	38.81	0	51.24	49.83	51.41
1	80	92	71	1	37.39	35.76	38.53	1	51.11	49.71	51.28
2	80	90	71	2	37.12	35.51	38.25	2	50.98	49.59	51.14
5	78	87	70	5	36.32	34.75	37.41	5	50.59	49.23	50.74
10	75	83	68	10	34.97	33.49	36.01	10	49.94	48.63	50.07
15	72	78	65	15	33.63	32.23	34.60	15	49.28	48.02	49.40
20	68	74	62	20	32.29	30.97	33.20	20	48.63	47.42	48.72
25	65	70	59	25	30.94	29.70	31.80	25	47.97	46.82	48.05
30	62	66	56	30	29.60	28.44	30.40	30	47.31	46.22	47.37

Figure 3 – Effect on MN_c, LHV, and the Wobbe Index from increasing hydrogen percentage concentrations in natural gas (Source: ASTM D8221 Standard Practice spreadsheet)

III. Hydrogen Concentration Variance

Mixtures of natural gas and hydrogen can vary in upstream distribution storage containers and should not be assumed as a homogeneous blend when dispensed. Therefore, HCNG at the point of injection into a natural gas engine may not be reliably nor consistently expected based on current natural gas distribution infrastructure, storage systems, refueling equipment, or vehicle fuel systems. Such inconsistency in fuel quality, hydrogen percentage concentration, and combustion characteristics will have an impact on engine performance.

Summary

Natural gas engine durability, total cost of ownership, and performance concerns exist related to the presence of hydrogen above trace levels in compressed natural gas vehicle fuel (HCNG). Engine durability concerns include misfires due to spark plug beading, increased flame speed and temperature leading to spark plug erosion, and a higher propensity for knock and preignition. Increases in total cost of ownership over a vehicle's lifespan may occur due to more frequent spark plug replacements, unplanned downtime, reduced fuel efficiency, and higher chances of fuel leaks. Performance impacts are also

notable, with methane number and lower heating value potentially below the required values with higher percentage blends.

While the negative impacts are not yet fully understood with respect to concentration-related development, the limited analysis and evidence collected by the NGV industry and scientific community to date suggest that low power, diagnostic challenges, and material compatibility problems should all be expected from increasing percentage concentrations of hydrogen in natural gas as a vehicle fuel. Continuing efforts need to be devoted to understanding how hydrogen concentrations may trigger these potential negative impacts. At the same time, gas suppliers need to evaluate natural gas supply approaches and possible fueling site options to minimize hydrogen percentages in HCNG fuel delivery while these concerns remain unresolved. TTP will remain committed to fostering proactive solutions, advocating for ongoing research, and promoting resolution as the impacts of a potential future transition to hydrogen-blended services continues to transpire between upstream production and distribution and the NGV consumers downstream.