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High Performance Hydrogen Engine Applications Using Westport Fuel Systems' Commercially Available HPDI Technology

Verwendung der kommerziell erhältlichen Westport Fuel Systems HPDI-Technologie in Hochleistungs-Wasserstoffmotoren

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Abstract

Driven by need to address the challenges posed by climate change, the transportation sector is currently undergoing rapid transformation. Improvements in fuel cells technology has rejuvenated interest in potential of hydrogen as a source of clean energy. Engine manufacturers have also responded by re-evaluating the potential of ICEs utilizing hydrogen fuel. Combustion characteristics of hydrogen (such as fast burning speed, rapid mixing, and tolerance to wide range of fuel-air equivalence ratios) if utilized properly can deliver very high performance (torque/power) and efficiency. Internal combustion engines (ICEs) power almost all vehicles globally and have attained a high degree of maturity over the last 100+ years through sustained technological and manufacturing improvements and breakthroughs. There is still room for further improvements and breakthroughs to the incumbent ICE technology. The medium and heavy-duty sectors have been typically dominated by the diesel engine due to its superior attributes in terms of power output, efficiency, reliability, and total cost of ownership. Westport Fuel Systems initiated a study starting with engine combustion modeling analysis followed by multi-cylinder engine testing that indicated that high pressure direct injection (HPDI) of hydrogen with pilot ignition is the most promising combustion approach and has the potential to deliver highest engine performance (torque/power) and efficiency. H_2 HPDI is eminently suitable for high load factor duty cycles such as on-road heavy duty commercial vehicles. A preliminary system level impact of adapting the HPDI fuel system and engine architecture to run on hydrogen was carried out including estimation of energy consumption for compressing hydrogen to pressure levels required for HPDI operation. Cost of ownership analysis was also carried out. Issues such as compatibility of fuel system materials with hydrogen operation were also considered. The paper will also discuss future steps to accelerate the commercialization of the H_2 HPDI technology such as development and deployment of a heavy duty hydrogen vehicle demonstrator.

Kurzfassung

Angetrieben von der Notwendigkeit, sich den Herausforderungen des Klimawandels zu stellen, durchläuft der Transportsektor derzeit einen raschen Wandel. Verbesserungen in der Brennstoffzellentechnologie haben das Interesse am Potenzial von Wasserstoff als Quelle sauberer Energie wiederbelebt. Motorenhersteller haben ebenfalls darauf reagiert, indem sie das Potenzial von Wasserstoff-Verbrennungsmotoren neu bewertet haben.

Die Verbrennungseigenschaften von Wasserstoff (wie z.B. hohe Verbrennungsgeschwindigkeit, schnelle Mischbarkeit und Entzündbarkeit innerhalb eines breiten Konzentrationsspektrums in Luft) können bei korrekter Nutzung zu sehr hoher Leistung (Drehmoment/Leistung) und Effizienz führen.

Verbrennungsmotoren (ICEs) treiben zur Zeit nahezu alle Fahrzeuge weltweit an. Durch kontinuierliche Verbesserungen der Technologie und der Fertigungstechniken wurde über viele Jahrzehnte hinweg ein sehr hoher Reifegrad erreicht. Es bestehen jedoch weiterhin Möglichkeiten für Verbesserungen und sogar Quantensprünge dieser etablierten Technologie.

Im Mittel- und Schwerlastbereich sind Motoren, die auf dem Dieselprinzip beruhen, bis heute die einzig sinnvolle Antriebslösung. Westport Fuel Systems initiierte eine Studie, die mit einer Modellanalyse der Wasserstoff-Verbrennung begann, gefolgt von Mehrzylinder-Motortests, die darauf hindeuteten, dass die Hochdruck-Direkteinspritzung (HPDI) von Wasserstoff mit Pilotzündung der vielversprechendste Verbrennungsansatz ist und das Potenzial für sehr hohe Motorleistung und Wirkungsgrad besitzt. HPDI mit Wasserstoff als

Hauptbrennstoff eignet sich hervorragend für Anwendungen mit hoher Last, wie z. B. schwere Nutzfahrzeuge.

Eine vorläufige Systemebenenstudie zur Anpassung des existierenden HPDI-Kraftstoffsystems und der Motorarchitektur an den Betrieb mit Wasserstoff wurde durchgeführt, einschließlich einer Abschätzung des Energieverbrauchs für das Komprimieren von Wasserstoff auf ein Druckniveau, das für den HPDI-Betrieb erforderlich ist. Auch eine Cost-of-Ownership-Analyse wurde durchgeführt. Fragen wie die Verträglichkeit von Materialien, die im Kraftstoffsystem verwendet werden, mit Wasserstoff wurden berücksichtigt. Die Studie behandelt ebenso zukünftige Schritte zur Beschleunigung der Kommerzialisierung der Wasserstoff-HPDI-Technologie, wie z. B. die Entwicklung und baldige Vorstellung eines Wasserstoff-Demolastfahrzeugs.

1. Introduction

Westport Fuel Systems' (WFS) HPDI^{TM} fuel system technology has been commercially available in Europe on Original Equipment Manufacturer (OEM) Heavy Duty natural gas trucks since 2018, during which time it has gained a significant foothold. HPDI^{TM} is used in association with a line of WFS products and systems for use with compression ignition engines whereby an alternative gaseous fuel to diesel is substituted as the main fuel and is directly injected at high pressure into the combustion chamber where it is ignited by a small amount of pilot fuel, thereby retaining the advantages of the diesel engine (torque, transient response, efficiency and durability) while maximizing the CO_2 reduction relative to diesel. While natural gas, and in particular biomethane, continues to offer significant CO_2 benefits approaching or even exceeding 100% reduction on a Well-To-Wheels (WTW) basis, there is a strong push in the European market towards Tank-to-Wheels (TTW) carbon-free solutions such as Fuel Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs). As previous studies have shown [1, 2], the Heavy Duty (HD) long haul market application is challenging for many of these technologies, with size and weight for BEVs significantly impacting the ability to haul goods, while hydrogen systems like those on FCEVs and H_2 ICEs are challenged for storage space and hence driving range. FCEVs are also still in their infancy for Heavy Duty applications, with high initial costs and significant changes required to manufacturing and supply chain systems, along with stringent fuel quality requirements. Many OEMs have continued to explore approaches using the Internal Combustion Engine (ICE), primarily Spark Ignited systems. As reported in Vienna and in Linz in 2021 [3, 4], WFS explored the various hydrogen approaches for ICEs, concluding that the HPDI technology offers a path to the most efficient hydrogen engine approach. More recent studies have shown that HPDI fuel system equipped engines can in fact exceed diesel engine efficiencies, while providing increased power and torque within the same engine limits. This paper will focus on the latest results, including the ability to exceed 50% Brake Thermal Efficiency while reducing CO_2 by up to 97%, via early-stage testing using existing commercially available natural gas hardware. The paper will also look at how to further improve the CO_2 reduction as well as an assessment of the steps needed for commercialization, including a cost comparison across multiple approaches.

2. Overview of WFS's HPDI^{TM} Fuel System

WFS's HPDI fuel system technology uses late cycle, direct injection, compression ignition combustion with the vast majority of the energy derived from the combustion of a gaseous fuel. Combustion is initiated via late cycle direct injection of a small quantity of diesel pilot fuel, with injection of both fuels via WFS's proprietary dual concentric needle injector design. By utilizing Diesel Cycle thermodynamics, the HPDI fuel system retains the thermal efficiency, power, torque and engine braking of the base diesel ICE.

By consuming low-carbon fuel (such as natural gas), or net-zero carbon fuel (such as biomethane), in conjunction with the well-established high thermal efficiency of Diesel Cycle combustion, WFS's HPDI technology offers significant greenhouse gas emission reductions. Based on full fuel-cycle accounting (WTW), an HPDI fuel system equipped ICE with conventionally-sourced natural gas provides meaningful CO_2 reduction compared to diesel ICEs consuming conventional diesel fuel, and potentially more than 100% CO_2 reduction when consuming renewable fuels, such as biomethane. HPDI technology is fully compatible with, and is commonly used with, renewable fuels in blends up to and including 100%.

Early-generation HPDI fuel system product (HPDI 1.0) was commercially available in North America and Australia on a 15L HD truck engine platform (MY 2001 through 2013). The HPDI 2.0 fuel system (see Figure 1) is currently commercially available in HD trucks in Europe on a 13L platform, and will launch soon in China on a 12L platform. The HPDI 2.0 fuel system uses natural gas as the primary fuel, with Liquid Natural Gas (LNG) as the onboard fuel storage medium. High pressure natural gas is supplied to the engine via WFS's proprietary onboard, in-tank LNG pump.

WFS has extensive product development and product industrialization experience with a range of gaseous fuels (CNG, LNG, propane, H_2), including a dedicated H_2 fuel supply and fuel pressure management components business, under the GFI™ brand. WFS recognized an opportunity to adapt the HPDI fuel system technology for operation with H_2, by fully leveraging the existing natural gas HPDI fuel system architecture and component designs, albeit requiring H_2-specific upgrades including material selection, certain validation activities, and H_2-specific component certifications. The unique aspect of an H_2 HPDI fuel system product will be the off-engine fuel storage and supply system to provide a continuous supply of high pressure H_2 to the engine throughout the fuel depletion cycle. WFS's current R&D work is focused on developing a prototype onboard high pressure gaseous fuel compressor, integrated with 700 bar compressed H_2 fuel storage tanks using GFI-branded fuel pressure management components. The need for a compressor (and its capacity) will be determined by application requirements. WFS has previous experience with the design of onboard high pressure gaseous fuel compressors, providing the basis for the current compressor development. This next phase of work is in anticipation of 700 bar H_2 becoming the predominant fuel supply and storage medium for H_2 on-road vehicles. If the H_2 fuel supply infrastructure develops in favour of liquefied H_2, then WFS is very well equipped to leverage its extensive cryogenic fuels expertise and quickly adapt the current LNG tank and pump architecture for liquefied H_2 fuel storage and supply. WFS has already successfully evaluated the current LNG pump approach with liquid hydrogen.

Figure 1: HPDI 2.0 fully integrated system for Heavy Duty applications

H_2 HPDI: Next Steps

WFS' next generation HPDI 3.0 fuel system technology will be the basis for both natural gas (and biomethane) and hydrogen systems (Figure 2). This third-generation evolution of the proven HPDI system will provide significant efficiency, emissions, and fuel control improvements, enabling the HPDI fuel system to maintain and expand its best-in-class performance, emissions and efficiency advantages with advanced, next-generation diesel engine platforms. WFS' HPDI 3.0 system will be commercially available coinciding with the implementation of the EU VII emission regulations.

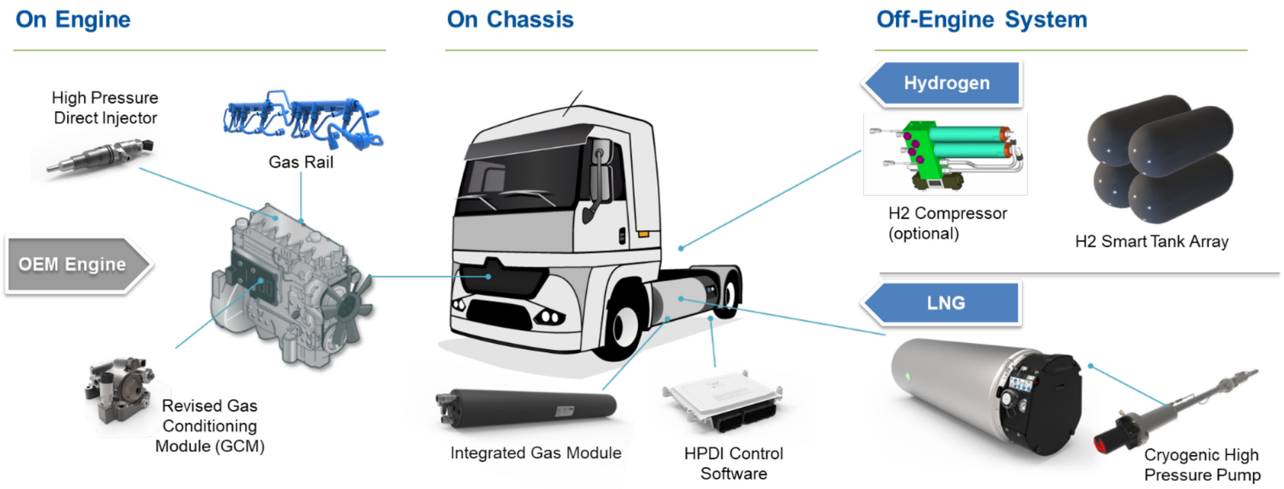


Figure 2: Overview of HPDI 3.0 showing natural gas & CH_2 options. Compressor selection depends on application requirements

The technology advancements that will be introduced with the HPDI 3.0 system will be equally applicable for natural gas and H_2 applications.

Looking beyond HPDI 3.0, WFS anticipates ongoing development and technological innovation of the HPDI fuel system, to further optimize and ultimately eliminate all CO_2 emissions.

3. H_2 HPDI Technology: Overview of Results

CFD Model for HPDI Fuel System Combustion Simulation

The details for the combustion CFD model used in the current study have been provided in our previous publication [5, 6]. A brief description of the model follows. The engine combustion solver was built on the platform of OpenFOAM [7] (version 2.3.1). A modified Conditional Moment Closure (CMC) method was implemented to model the interaction between the combustion chemistry and the turbulence in the flow field. Detailed chemical kinetic mechanisms were used to compute the conditional reaction rates for the pilot fuel and the gaseous fuels. For pilot combustion, a reduced n-heptane mechanism (159 species, 770 reactions) [8] from Lawrence Livermore National Laboratory (LLNL) was used; and for natural gas combustion, a modified Gas Research Institute (GRI) mechanism developed in our previous work (55 species, 278 reactions) [7, 10] was used. For hydrogen, the LLNL mechanism [5] (10 species, 40 reactions) discussed earlier was used. The combustion model described above has been validated over various HPDI engine platforms in the past.

Results and Discussion

HPDI fuel system combustion simulations were carried out for two gaseous fuels - natural gas and pure hydrogen focusing on a heavy-duty engine application, typically used for long-haul trucks. The rated power for the base engine is around 330kW, with the peak torque at around 2400 N.m and 1200 rpm.

HPDI Fuel System Combustion

In an ICE equipped with the HPDI fuel system,the gaseous fuel is injected late in the cycle directly into the combustion chamber at high pressure (~300 bar). A small quantity of pilot fuel injection at similarly high pressures precedes the injection of the gaseous fuel and acts as a source of ignition. Using the combustion CFD model introduced above a total of four operating conditions were simulated, which represent typical peak power (C100 - 1600 RPM/100% load), peak torque (A100 - 1200RPM/100% load), cruise (A50 - 1200 RPM/ 50% load), and light load (A25 - 1200 RPM/25% load) operating conditions for a typical heavy-duty truck application. The maximum fuel injection pressure is 290 bar for gas and 300 bar for pilot. At medium-to-low load conditions the fuel injection pressure is lower than 290bar. For each operating point, simulations (including pilot ignition) were conducted for natural gas and then repeated for hydrogen, adjusting the hydrogen fuelling quantity to produce equivalent torque to the natural gas scenario. The quantity of pilot fuel varies typically from 2% to 8% of the total energy input depending on engine load, with the high load points having the higher substitution rate (low pilot quantity). After taking into account the relative density and fuel energy per unit mass for hydrogen (as compared to natural gas) it was found that current gas hole size was more than adequate to meet the required maximum energy flow demand; the injector nozzle configuration (number of gas injection holes and total flow area) was kept identical between natural gas and hydrogen cases.

To validate the H_2 combustion CFD modelling and to get experimental confirmation, engine testing of a multi-cylinder heavy duty engine was carried out in the first half of CY2021. WFS's engine testing facility was upgraded to allow for the direct injection of hydrogen at high pressure (300 bar). A comprehensive safety review of the engine and test cell systems was carried out and additional H_2 specific safety measures (e.g. hydrogen leak detection, protection against exhaust backfire, etc.) were implemented.

The heavy-duty engine used for testing was an unmodified version of a natural gas HPDI fuel system equipped development engine. After installation in the test cell, the engine was first operated on natural gas and a fresh baseline was created. Then the fuelling was switched to hydrogen and the engine was successfully transitioned, starting with very low load operation and then gradually increasing the load (Figure 3). Once sufficient experience was gained in the operation of the engine with H_2, it was operated over a wide range of the torque vs speed map from idle to full load as well as intermediate load conditions at various engine speeds. The engine operation with H_2 was smooth and repeatable with similar torque response to its natural gas operation. Engine test results fully confirmed the modelling predictions, i.e., engine performance and efficiency are higher for H_2 as compared to natural gas.

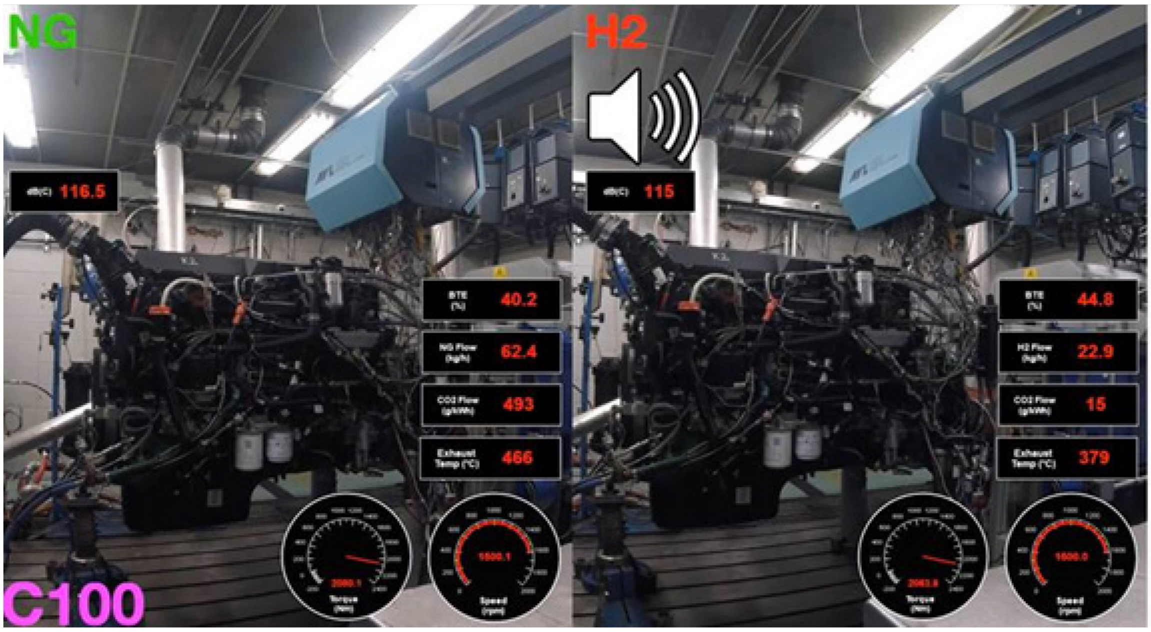
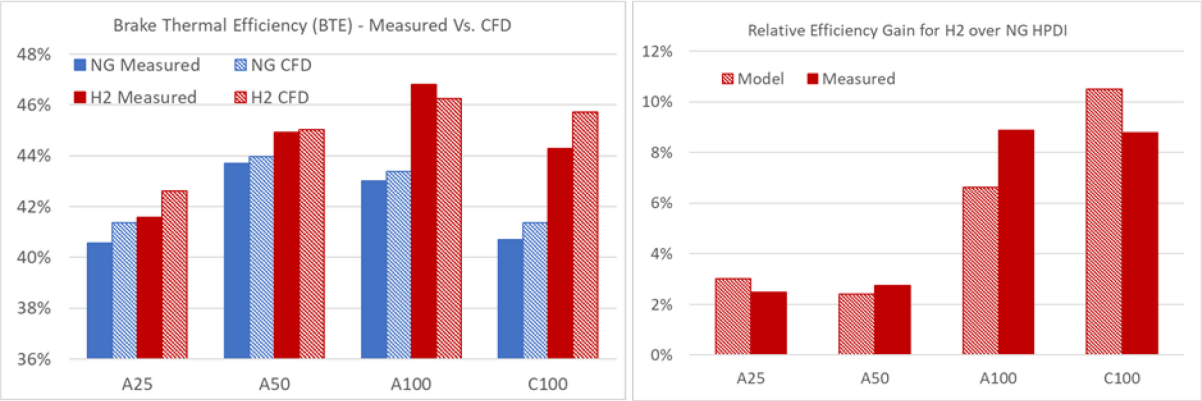


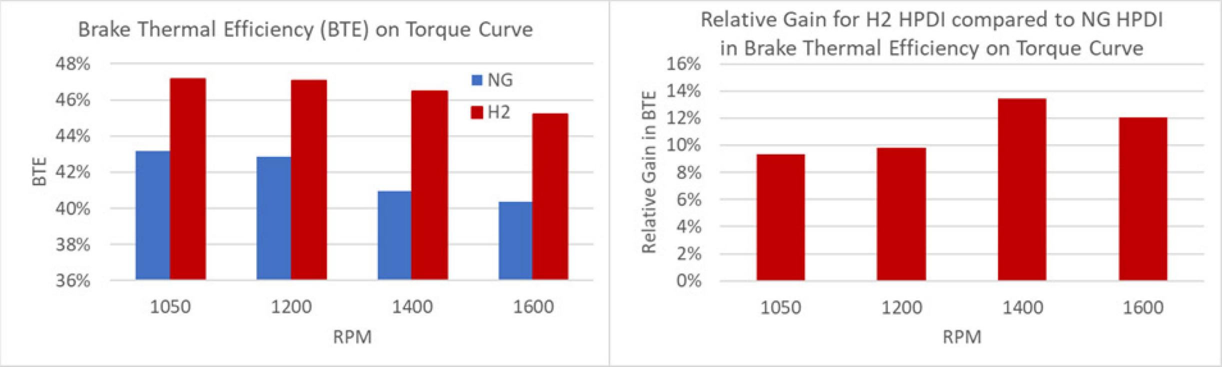
Figure 3: Test engine in WFS Cell

Figure 4-a shows the comparison of Brake Thermal Efficiency (BTE, modelled and measured) between hydrogen and natural gas combustion at the four operating points listed above. Comparison between modelled and measured efficiency indicates good agreement. For each engine operating point, thermal efficiency of hydrogen is higher than for natural gas . At full load (A100 & C100) the H_2 engine had 46-47% measured BTE versus 41-43% for natural gas. In general, the natural gas torque and efficiency are typically very closely matched to the base diesel engine torque and efficiency. The relative gain in thermal efficiency for H_2 is larger for the high load points than those for the lower load points. For instance, the relative efficiency gain for H_2 (as compared to natural gas) at the full load (A100 & C100) points is around 6-10% versus 2-3% at the 25 to 50% load points. Improvement in fuel-air mixing at high load conditions is one of the key reasons for this gain in efficiency. Depending on the operating conditions, H_2 has a BTE 3 to 9% higher than the base diesel engine BTE.



(a) (b)

Figure 4: BTE at various engine operating conditions for natural gas and H_2 HPDI, a) Measured vs Predicted %BTE , b) Relative BTE gain for H_2 HPDI over natural gas HPDI.



(a) *(b)*

Figure 5: Improvement in BTE for H_2 HPDI combustion as compared to natural gas HPDI

Figure 5 shows the comparison of measured brake thermal efficiency between hydrogen and natural gas combustion at full load conditions on the torque curve. As seen from the results H_2 combustion with the HPDI fuel system consistently achieves BTE in the range of about 45-47% (Figure 5-a) for the specific 13L engine platform used in this testing. Compared to natural gas, and therefore to the base diesel engine, the relative improvement in BTE (Figure 5-b) for H_2 ranges from about 9.5% to 13.5% on the torque curve.

The improvement in H_2 efficiency is also indicated by the drop in exhaust temperature (Figure 6) compared to natural gas, as the piston extracts more work out of the expanding gases. The drop in the exhaust temperature ranges from about 55°C to 127°C depending on the operating conditions. The relatively low exhaust temperature also allows the maximum torque and power of the H_2 engine to be raised beyond the base calibration without exceeding the mechanical or thermal limits of the engine (please refer to Figure 8 for further details).

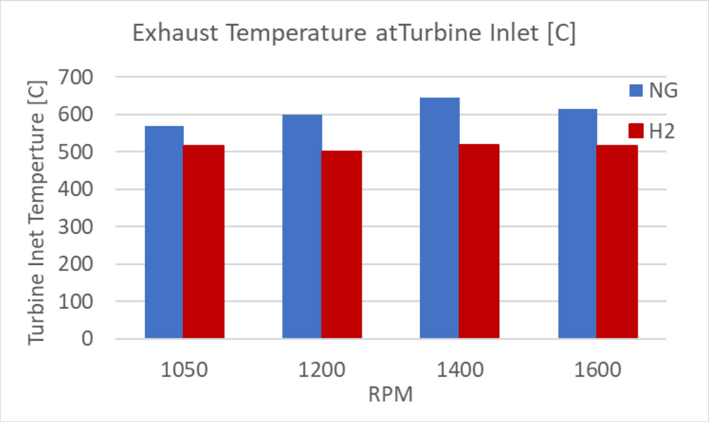


Figure 6: Engine exhaust temperature at turbine inlet (°C).

Analysis of modelling and test results have helped identify some of the key reasons that contribute to the higher thermal efficiency for hydrogen combustion. First, at a given air mass and fuelling quantity, the global fuel-air equivalence ratio for hydrogen is lower than that for natural gas (i.e., leaner combustion because hydrogen has a higher air specific heating value than natural gas). The leaner condition leads to higher combustion efficiency in diffusion combustion mode, reduced exhaust energy (as indicated by significantly lower exhaust gas temperature compared to natural gas operation) and reduced wall heat loss. Secondly, at a given fuel injection pressure-to-cylinder pressure ratio, hydrogen jets contain higher kinetic energy due to the high flow velocity, which increases the mixing rate and benefits the combustion efficiency. Finally, the mechanical work done by the expansion of the compressed hydrogen on the piston is substantially higher than that of natural gas due to hydrogen's low density.

Figure 7-a shows the reduction in tailpipe CO_2 emissions as compared to the diesel engine. Due to lower carbon content of the fuel, natural gas typically provides about 18-20% reduction in tailpipe CO_2 compared to diesel operation. Switching to H_2, the CO_2 reductions are greatly increased to 88-97% (the residual CO_2 is attributed to the small quantity of pilot fuel used for the ignition process). These results were obtained with the same pilot fuelling quantity for natural gas and H_2. With no hardware changes or changes to pilot quantity, the H_2 HPDI fuel system offers significant CO_2 reductions, with further CO_2 reductions possible by leveraging the low ignition energy of hydrogen.

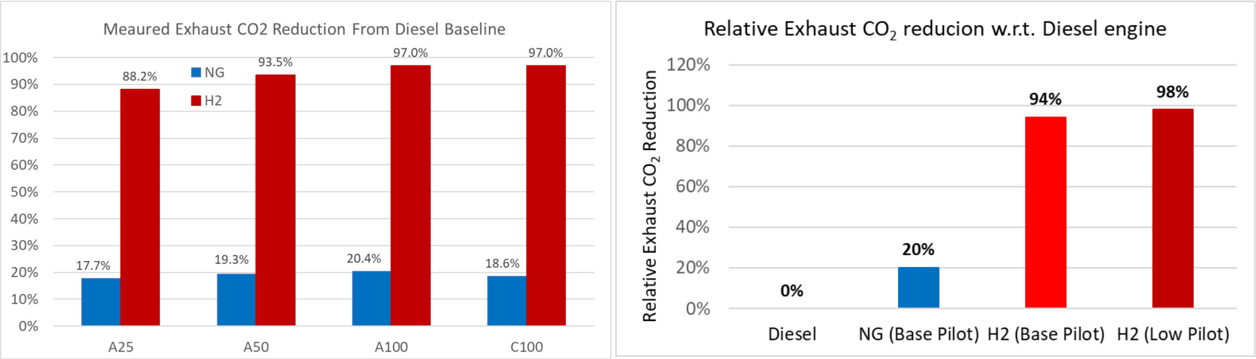
As noted, the above testing was conducted on the existing natural gas engine platform. Recent work has shown that the improvement in BTE is consistent across platforms. CFD has shown that a BTE greater than 52% should be achievable on the latest diesel engines; this is expected to be demonstrated through further engine testing [11].

CO_2 Reduction for H_2 HPDI Fuel System

To explore the potential for further reduction in pilot fuel and hence a further reduction in CO_2 emissions, a series of CFD simulations were first conducted with reduced pilot quantity to examine its effect on gas jet ignition at peak power. Table 1 summarizes the pilot quantities and observed results from the simulation study specifically for the peak power condition (C100). At minimum pilot quantities below ~0.7 mg/stroke, an increase in ignition delay time and a spike in the rate of heat release (due to a larger fraction of premixed charge at the time of ignition) was observed. The minimum pilot quantity at rated power corresponds to around 1.5g of CO_2 emission per kilowatt-hour of energy generated.

Table 1: CFD Model Results with Pilot Quantity Sweep at C100 point

Pilot Qty	Pilot Energy%	Main Fuel	Brake Specific CO_2	% CO_2 Reduction	Ignition Stability
mg/Str			g/kW.h		
	NA	Diesel	597	0.0%	Baseline Diesel
5.34	2.09%	NG	482	19.3%	Baseline NG HPDI
5.34	2.09%	H_2	13.2	97.8%	Baseline H2 HPDI
2.67	1.04%	H_2	6.6	98.9%	Little Impact
1.34	0.52%	H_2	3.3	99.4%	Little Impact
0.67	0.26%	H_2	1.7	99.7%	Longer Delay, HRR Spike
0.33	0.13%	H_2	0.8	99.9%	Longer Delay, HRR Spike

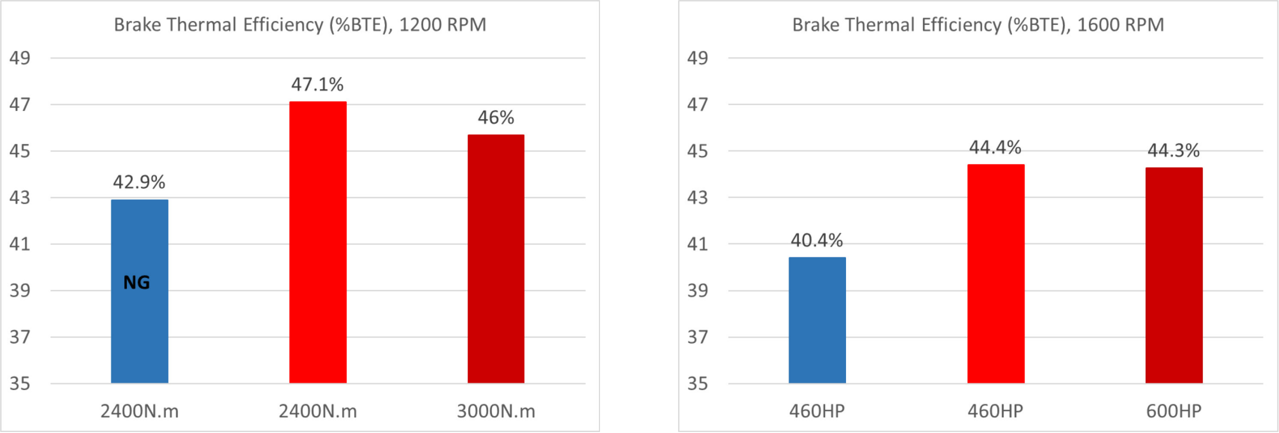


a) *(b)*

Figure 7: CO_2 emissions at various engine operating conditions,
a) Measured reduction in CO_2 for natural gas and H_2 HPDI relative to diesel combustion,
b) Impact of pilot quantity on reduction in CO_2 for H_2 HPDI

To confirm the CFD predictions engine testing was carried out at the mid load condition (A50 point). During the engine test pilot quantity was gradually reduced from the baseline value for H_2 with no hardware changes. A reduction of ~75% in pilot quantity could be achieved without any significant impact on the engine combustion. As shown in Figure 7-b the CO_2 emissions reduction was further improved from 94% to 98% due to this reduction in pilot quantity. Further reductions in pilot quantity were most likely restricted due to the limitations imposed by the stock natural gas concentric needle injector used for this initial testing, which was designed originally to operate at higher pilot quantity levels. For H_2 further minimization of pilot quantity through modification of the injector design is likely achievable and is part of the future development of the fuel system.

Earlier modelling and analytical estimates had indicated that combustion with H_2 has significant potential to further improve the power density of the engine by as much as 20-25%. Further engine testing was carried out to raise the maximum torque rating of this engine at the A-speed starting with A100 point (2400 Nm brake torque). The brake torque was systematically increased above the baseline value while ensuring the critical parameters (e.g. maximum cylinder pressure, exhaust temperature, etc.) were maintained within the safe mechanical limits for the engine. The maximum gas injection pressure needed was about 320 bar to achieve the torque and power increases. As shown in Figure 8-a, the torque was increased from 2400 Nm to about 3000 Nm (25% higher, 30 bar BMEP). Similarly, the maximum engine power (at C-speed) was increased from a baseline value of about 460 BHP to 600 BHP (~ 30% higher, Figure 8-b). This comparison is with the current natural gas base calibration, but these baseline values for natural gas should not be interpreted as an upper limit for torque and power. Nonetheless, H_2 potentially offers approximately 20-25% higher torque and power than with natural gas using the HPDI fuel system.



(a) (b)

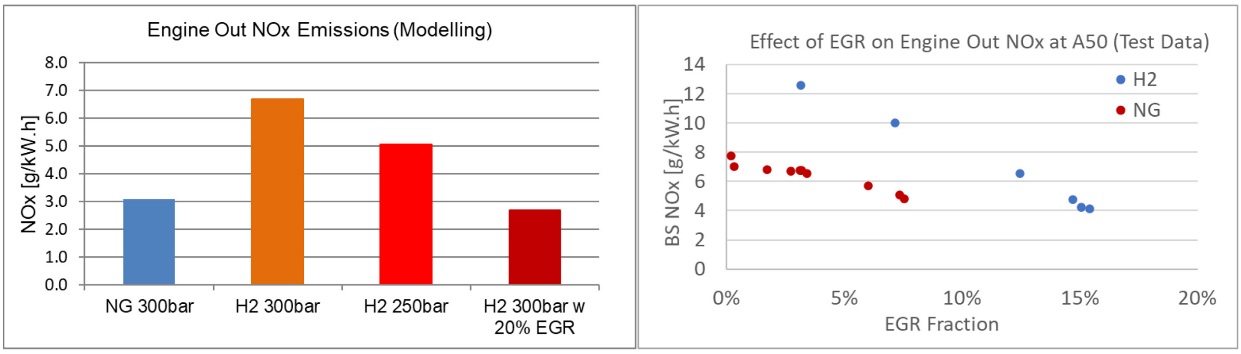
Figure 8: Improvement in H_2 HPDI torque, power and efficiency, a) H_2 HPDI - measured maximum torque, b) H_2 HPDI - measured maximum power

In summary, the current 13L natural gas HPDI fuel system equipped engine has a peak torque of about 2400 Nm (24 bar BMEP @ 43% BTE) and rated power of 460 HP @ BTE of 40%. In comparison, using H_2 the 13L performance demonstrated a peak torque of 3000 Nm (30 bar BMEP @ 46% BTE), and a maximum power output of 600 BHP @ BTE of 44.3%. These improvements were achieved while keeping the operation of the H_2 engine within the mechanical limits of the base engine (i.e., turbine inlet temperature ≤ 680°C and maximum cylinder pressure ≤ 220 bar). WFS believes that the combination of power density, thermal efficiency and near-zero emissions offered by the H_2 HPDI fuel system, without exceeding the mechanical and thermal limits of the base engine, is unprecedented amongst internal combustion engines. The key significance of these results is that downsizing the engine is possible; for example, a smaller engine equipped with the H_2 HPDI fuel system (for example a 10 or 11L engine) could provide the same power & torque as a 13L diesel or natural gas engine equipped with the HPDI fuel system.

NOx Levels for H_2 HPDI Fuel System

A common concern for Internal Combustion Engines is the NOx levels. EU VI legislation requires engines meet a cycle average of 0.46 g/kW.hr, and this is expected to be reduced further within the future EU VII legislation. It is anticipated that NOx will be reduced by a combination of aftertreatment and in-cylinder strategies; WFS's initial H_2 HPDI fuel system testing focused on in-cylinder reduction to identify the key levers allowing NOx levels similar to EU VI to be met.

For H_2, the rate of NOx formation is increased due to the higher flame temperature of the jet (i.e., a jet produced by mixing of high pressure injected fuel and cylinder air) as well as availability of more abundant excess air for H_2 combustion. Figure 9 shows that the CFD model predicted NOx emissions for hydrogen significantly higher than for natural gas. There are several in-cylinder options available to reduce NOx, such as reduction in fuel injection pressure and retardation of combustion timing as well as introduction of exhaust gas recirculation (EGR), and optimization of the Urea-SCR NOx exhaust aftertreatment system. Modeling results (Figure 9) showed that using 20% EGR at peak power (C100 point) with hydrogen combustion could reduce the engine out NOx to a level below that of the baseline natural gas combustion with a 3% impact on the thermal efficiency. Engine tests confirmed the benefits of EGR in reducing NOx to lower levels (Figure 9-b). Adjusting the fuel injection pressure and timing were also found to be very beneficial in bringing NOx to baseline diesel levels.



(a) *(b)*

Figure 9: Effect of EGR on engine out NOx (before the exhaust aftertreatment system) from modelling and test data, a) CFD modelling prediction, b) Effect of EGR on engine out NOx at A50 point from engine test data.

Transient Operation

From the test data generated from steady state engine testing, a preliminary transient engine calibration was developed, and the engine was run over the WHTC cycle (both cold and hot operation). The H_2 fueled engine operated well in transient operation similar to the natural gas fueled engine (i.e. in terms of engine response, ability to follow the commanded torque, etc.). Compared to natural gas, the H_2 fueled engine showed a cycle average 94% reduction in tailpipe CO_2 emissions (both for cold and hot WHTC), and the H_2 engine-out NOx was within about 10% of the natural gas engine. Since the natural gas calibration with the exhaust aftertreatment is certified to meet the current Euro VI NOx regulation it is expected that the H_2 fueled engine should be able to do the same. For H_2 the engine out CO_2 emissions were reduced by about 97% compared to natural gas (results were quite similar for both cold and warm WHTC). The H_2 fuel consumption over the WHTC cycle (warm portion) was 5% lower compared to natural gas. The H_2 calibration is still very preliminary and there exists considerable room for further optimization as part of the ongoing development of this technology. For clarity, the natural gas engine performance and efficiency are closely matched to the base diesel engine and the improvements for H_2 reported above can also be directly compared to a Heavy Duty diesel engine.

Materials Compatibility

The engine testing regime also provided an opportunity to study the effect of H_2 on engine fuel system components. Internal preliminary assessment of the existing natural gas concentric needle injector nozzle tip (which is made from high strength tool steel) indicated that it may not meet long-term durability requirements when operating with hydrogen. External third party materials experts were consulted as part of a comprehensive review before engine testing was initiated on hydrogen. In total the fuel system hardware was subjected to engine operation with hydrogen fuel over a period of about three months. Throughout the engine testing the performance of the injectors was monitored by using repeat check test points that were run periodically. No changes in injector or engine behavior at these conditions could be detected. At the end of the test program injectors were taken out and visually examined; no discernible changes were detected. One of the injectors exposed to hydrogen has been sent for further materials testing.

Fuel Quality Considerations

An important consideration for differentiating between different hydrogen technology options is fuel quality sensitivity. Because of the highly sensitive catalysts used in FCEVs, the hydrogen they use must be extremely pure or they risk permanently damaging/disabling the vehicle. FCEVs require hydrogen of purity 99.97% as per ISO 14687, and furthermore contaminants at volumes as low as <0.00000004% sulphur or <0.0002% CH_4 can destroy the catalyst.

Conversely, H_2 ICEs are far more robust to hydrogen impurity. This not only decreases risks for fleet operators, and potentially leads to lower costs, it also eases the expansion of refuelling infrastructure. This is especially true for Europe, where the European Commission is working to enable the development of interconnected hydrogen networks. As such, H_2 ICEs would be able to offtake hydrogen from diverse sources, including through repurposed natural gas infrastructure, which FCEVs would not.

4. Abatement Costs for Emissions Reduction

In Heavy Duty trucking the global focus on reducing CO_2 has led to a policy framework focusing on two key areas: tailpipe CO_2 (i.e. TTW) and tailpipe air pollutants. As a result, key elements of the CO_2 picture are not easily considered, such as manufacturing and lifecycle emissions. The actual cost of implementing solutions is also easily forgotten in the rush to implement new ideas.

The following analysis assesses the cost of reducing emissions on a WTW basis; this assessment is based on methodologies and assumptions used by Frontier Economics in their study: "CO_2 Emission Abatement Costs of Gas Mobility and Other Road Transport Options" [12].

The Frontier study considered a 2030 timeframe, and examined ICEs using LNG and liquefied biomethane (LBM), and FCEVs (Table 2). The target vehicle segment is Heavy Duty vehicles, with 40 tonne gross vehicle weight capability, for use in long haul operation. The following analysis extends the Frontier work to consider the relative merits of three different technologies for use in the most demanding long-haul sector.

Blue hydrogen refers to steam methane reforming of natural gas coupled with Carbon. Capture, Utilization and Storage (CCUS). Green hydrogen is defined as production via electrolysis using renewable electricity. Grey hydrogen (Steam Methane Reforming (SMR) of natural gas with no abatement) is not included as a fuel/energy option, since it offers no WTW CO_2 reductions compared to diesel.

Table 2: Powertrain and Fuel Technologies

ICE	Compression Ignition - HPDI	Biomethane (LBM)	• 40% LBM blend • 100% LBM
ICE	Compression Ignition - HPDI	Hydrogen	• 100% Blue • 80% Blue/20% Green • 100% Green
FCEV	Proton Exchange Membrane Fuel cell, hybrid electric	Hydrogen	• 100% Blue • 80% Blue/20% Green • 100% Green

CO_2 Emissions and Abatement Costs

Figure 10 shows the TTW CO_2 reduction for HPDI fuel system equipped ICEs vs FCEVs. Biomethane blends are included to illustrate the importance of the full WTW picture.

Analysis of purely tailpipe CO_2 (TTW) yields the expected 100% reduction for FCEVs. The H_2 HPDI fuel system ICE exhibits very high tailpipe CO_2 reductions (97%) but falls short of the zero tailpipe CO_2 metric used in the majority of EU policy due to the use of small quantities of pilot for ignition. On a TTW basis the HPDI LBM options produce ~20% CO_2 reductions since the fuel contains elemental carbon; the large benefits of biomethane are derived from the WTT portion.

On a WTW basis, including vehicle manufacturing emissions, it is evident that there is a far greater range of CO_2 reductions, and clearly the relationship between tailpipe CO_2 and total CO_2 reductions is not directly correlated to a simple tailpipe only perspective.

Due to the high efficiency of an ICE equipped with the HPDI fuel system (per Section 3), fueling with H_2 can deliver equivalent CO_2 reductions to fuel cell vehicles, though even with green hydrogen neither technology results in zero CO_2. Indeed, the 40% biomethane option delivers similar CO_2 reductions to the hydrogen pathways. Only the 100% biomethane pathway achieves zero WTW CO_2.

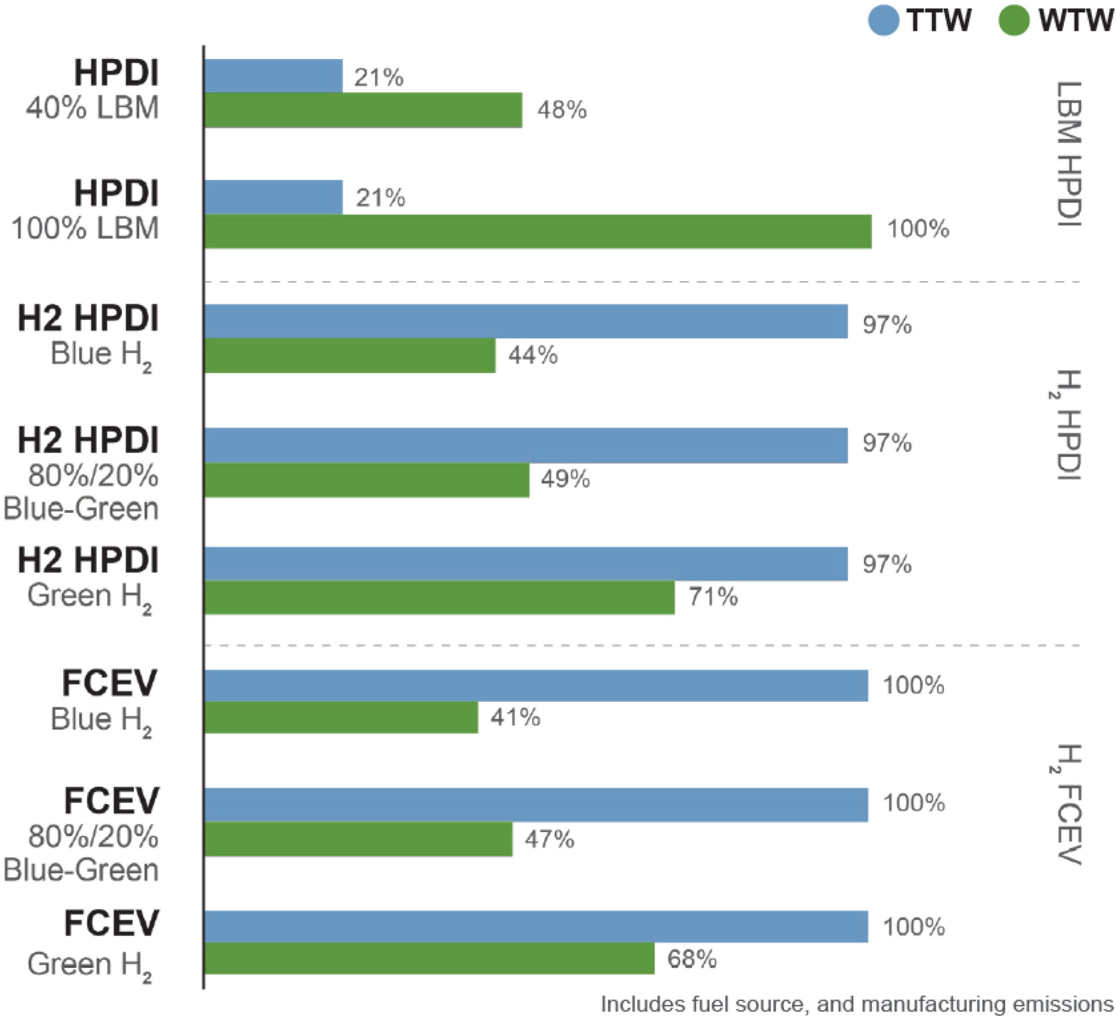


Figure 10: Total CO_2 Reductions relative to Diesel (including Fuel & Manufacturing)

Acknowledging that most, if not all, decarbonization strategies represent added cost, the cost of CO_2 abatement is a critical differentiating factor between technologies and should be carefully considered in policy development, especially where there is broad parity in environmental performance.

A key advantage of both biomethane and hydrogen ICEs is their commonality with high volume diesel powertrains, resulting in lower capital cost estimates. Consequently, including ICEs leads to far more cost-effective abatement strategies than fuel cell only approaches. WFS's HPDI fuel system's economic advantage is significant enough that it is more cost effective to deploy an H_2 HPDI fuel system ICE with 100% green hydrogen than it is to deploy fuel cells with the lower cost option of blue hydrogen.

Figure 11 illustrates the cost of CO_2 abatement for FCEVs as well as hydrogen and biomethane fuelled vehicles equipped with HPDI fuel systems, while Figure 12 shows the reduction in CO_2 for every €1,000 invested. It is clear from both figures that an HPDI fuel system equipped ICE fuelled with biomethane is the most cost-effective pathway, offering the greatest overall CO_2 reductions. This technology approach should be strongly supported in any balanced road freight decarbonization strategy.

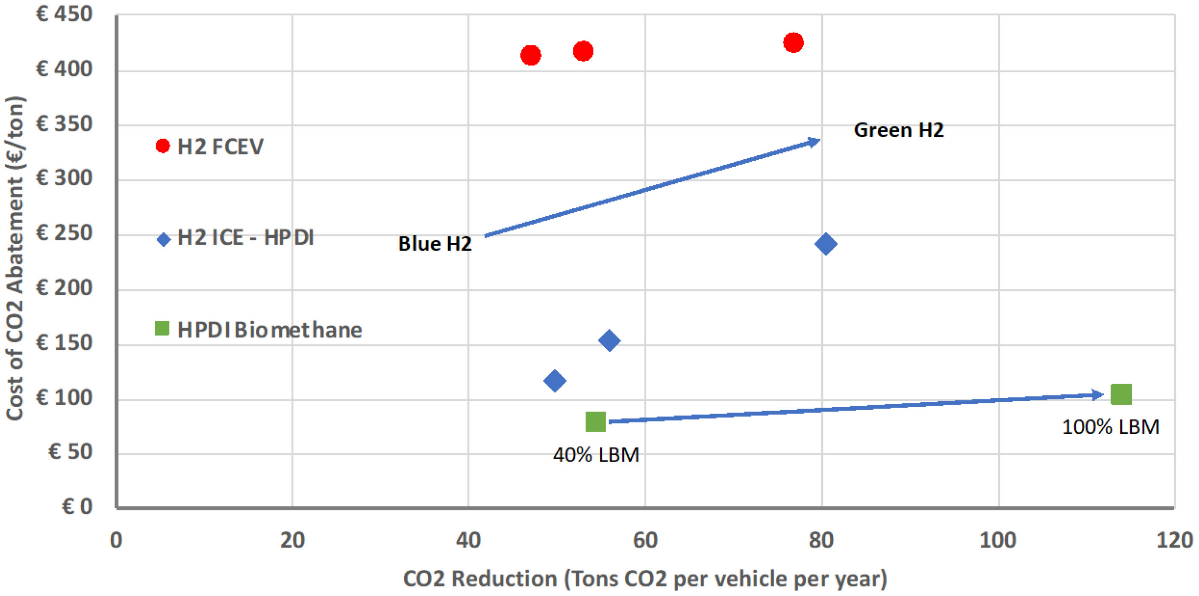


Figure 11: Cost of Total CO_2 Abatement for FCEV and H_2 ICEs

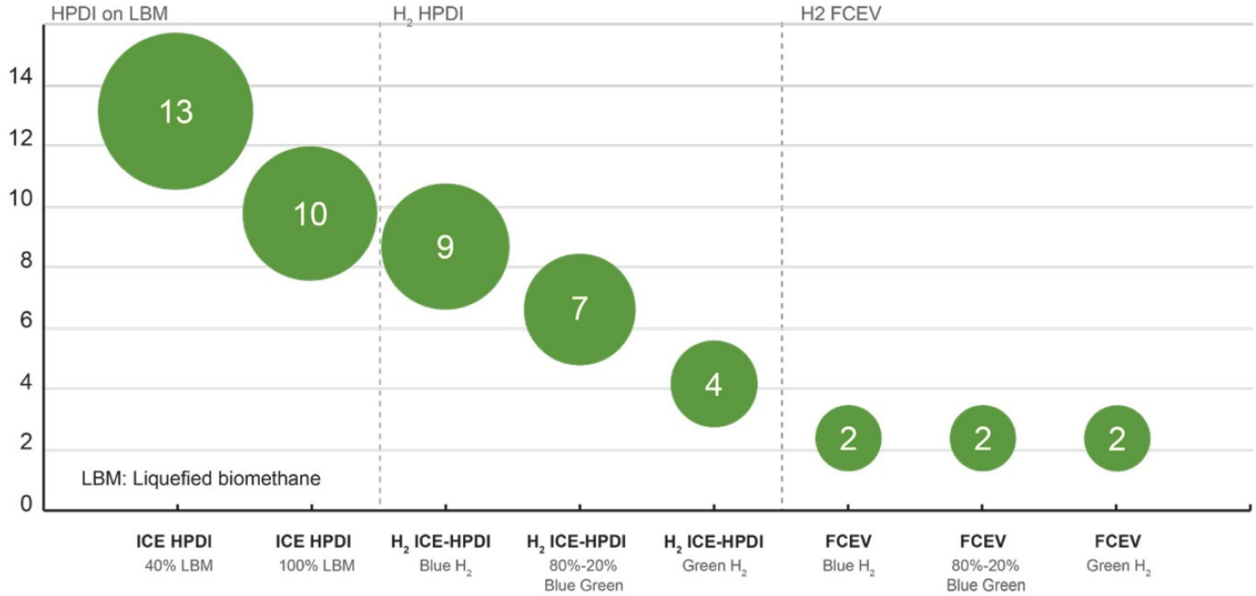


Figure 12: Cost Abatement in Tons of CO_2 reduced per €1,000 Invested

The analysis demonstrates that while fuel cell solutions for heavy-duty trucks do provide 100% reduction in tailpipe CO_2, on a WTW basis fuel cells produce no incremental CO_2 reductions, no discernible increase in energy efficiency, and are a far more cost intensive approach to decarbonization compared with hydrogen internal combustion engines.

NOx Emissions and Abatement Costs

FCEVs do offer one advantage over combustion engines – the absence of tailpipe sources of air pollutants (disregarding water vapour, and other vehicle pollutant sources such as tire and brake wear). However, recognizing that on-road emission standards are already very stringent with respect to regulated pollutants such as NOx, and are projected to become more stringent with the pending introduction of EU VII standards, it is important to understand the marginal cost of transitioning from current near-zero emission levels to true zero tailpipe emissions.

To illustrate, a marginal cost-benefit analysis was performed to show the cost of NO_x abatement of FCEVs compared to hydrogen ICEs with the HPDI fuel system. For simplicity, NO_x emissions of Euro VI trucks are used as the baseline [13], recognizing that future Euro VII NO_x levels are likely to be lower.

Table 3: NOx Abatement – Fuel Cells vs H_2 ICE - HPDI

Euro VI NO_x emissions	mg/km	<500
	kg/year	<58
Annualised cost premium of fuel cell vs H_2 ICE - HPDI	€/year	€13,500
Cost of NO_x abatement – Fuel Cell	**€/ton NO_x**	**> €233,000**
Order of magnitude societal cost of NO_x emissions [14]	€/ton NO_x	€21,300 Urban €12,600 Rural

As Table 3 shows, the marginal cost of NOx abatement delivered by FCEVs vs. ICEs is extremely high and will only be further exacerbated by the future Euro VII emissions standards.

In summary, the cost of CO_2 and NOx abatement for hydrogen HPDI fuel system engines is considerably lower than the cost of implementing FCEVs in long haul applications. Natural gas HPDI fuel system combustion engines are already in the market and biomethane is increasingly available, allowing an immediate path to reduced emissions for substantially lower cost per ton of CO_2 and NOx. Hydrogen HPDI fuel system engines are already in development, and offer an alternate path to reduced emissions, achieving similar reductions to Fuel Cell vehicles but at considerably lower cost.

5. Total Cost of Ownership (TCO) Analysis

WFS and AVL previously conducted a comparison of TCO for trucks with the following powertrains: (1) Conventional diesel powertrain with 12-speed automated manual transmissions and EURO VI compliant exhaust aftertreatment system, (2) H_2 fuel cell (PEM) trucks with 700bar H_2 storage and (3) H_2 HPDI fuel system trucks with same transmission and aftertreatment system as conventional diesel powertrain, 700 bar H_2 storage and a booster compressor [2, 15].

The major boundaries for the initial investigations are summarized here, plus changes for the revised analysis based on WFS's recent data:

1. Vehicle prices: Vehicle prices started with €110.000 EUR for a conventional diesel truck. Fuel cell trucks were varied between 2.6 and 3.4 times more expensive than the diesel reference truck, and H_2 HPDI fuel system trucks between 1.3 and 1.4 times versus the reference diesel (mainly due to the H2 storage tanks).
2. For the energy consumption a typical highway operation in Germany was taken as reference. The energy consumption was simulated by AVL for different powertrain configurations, including diesel, diesel pilot, H_2 and AdBlue consumption.
    a. The HPDI fuel system was updated to include a 5% efficiency improvement per Section 2.
3. Prices for energy carriers were set to €1.5/litre diesel, €6/kg H_2. AdBlue price was set to €0.33/litre
4. The service and maintenance costs were varied as a function of the powertrain.
5. Trucks were assumed to operate over a 5-year period with an annual mileage of 116.000 km.
6. Driver costs were assumed as €60,000/year and kept the same for all truck variants.
7. Residual value was set to zero for all trucks.
8. No subsidies and/or road tolls and exemptions considered.
9. Tire costs were considered w/ approx. €3,600 each ~150,000 km.

Figure 13 shows the updated assessment values: the TCO for HPDI fuel system equipped trucks was improved slightly relative to the initial assessment, with a reduction from €851k to €835k. The lighter parts of the bars represent the variance in TCO based on the range in the original assumptions.

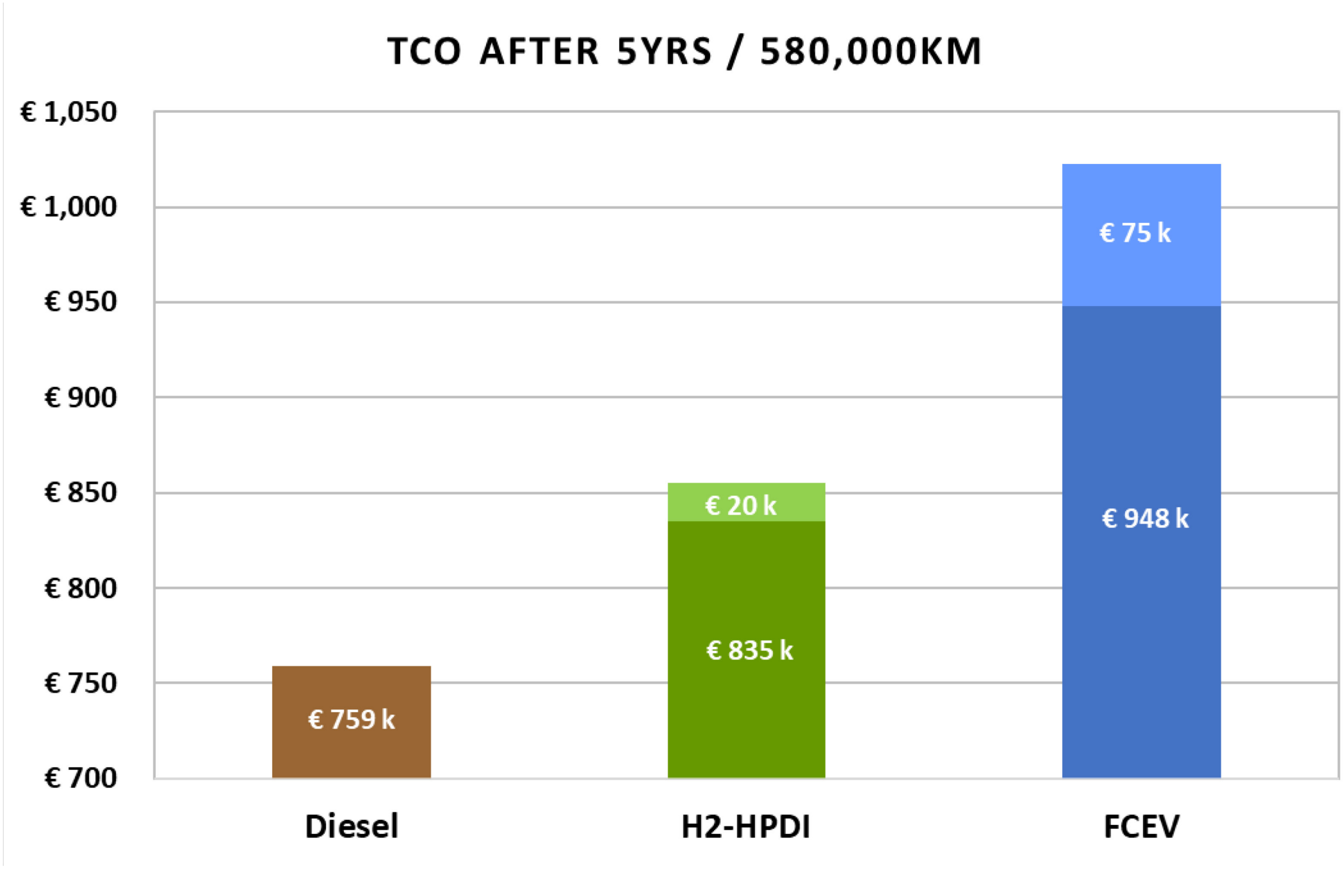


Figure 13: Total Cost of Ownership After 5 Years of Operation

6. Regulatory Approach

Transitioning heavy road freight to a sustainable, decarbonized, future is a clear societal need, but is well understood to be a very challenging prospect. A number of potential powertrain / fuel / energy solutions exist, including battery electric, fuel cell electric, hydrogen ICEs and biomethane fueled ICEs. There is a large array of attributes that defines sustainable freight, and there are equally numerous trade-offs between different solutions; trade-offs that in all likelihood have different optima when seen from the differing perspectives of policy and end user.

WFS believes that an optimal pathway to sustainable road freight requires keeping all these options available, recognising that different technical pathways are at different stages of technical and commercial viability, and that there will be segments of the road freight sector where, for example, battery electric may prove to be an ideal solution, but for heavier vehicles, in long haul operation, hydrogen and biomethane ICEs have a stronger set of attributes.

European Union policy and regulation should not be framed in such a way that it limits the spectrum of options available to transition to a sustainable, decarbonized freight system.

- Vehicle CO_2 regulation should take account of carbon intensity of fuel/energy production.
- The extremely strict definition of Zero Emissions Vehicles (ZEVs) from a CO_2 perspective as laid out in the HDV CO_2 Regulations should:
    - Be restated to encompass ICE options that are near-zero tailpipe CO_2 and deliver equivalent or greater WTW CO_2 reductions;

    - Be revised in other pieces of legislation, such as the Taxonomy, in order to encourage investment in all options that deliver urgently needed CO_2 reductions while moving away from fossil fuels.
- Regulatory instruments used in the certification and type approval of vehicles should be revised to accommodate hydrogen ICEs:
    - R49 to include “mono-fuel” and “dual-fuel” hydrogen ICE;
    - Euro VI and Euro VII;
    - VECTO to include “mono-fuel” and “dual-fuel” hydrogen ICE in the next planned release.
- Hydrogen fuel approved for use in transport should not be restricted to the same, extremely high purity, grades required for fuel cells. Hydrogen ICEs are much more tolerant to lower specification hydrogen, making them more robust in the market place, increasing compatibility with distribution systems, and eliminating some of the cost components of fuel cell grade hydrogen.
- EU investment and R&D funds should consider the highly competitive, cost-effective option of hydrogen and biomethane fueled ICEs.

7. Summary & Conclusions:

This paper has shown that WFS’s HPDI^{TM} gaseous fuel system applied to current combustion engines is a cost-effective and emissions-effective solution for Heavy Duty long haul trucks relative to Fuel Cell options. When considered from a WTW perspective, the HPDI solution can offer the same CO_2 reduction as a Fuel Cell vehicle while using readily available fuels like biomethane. The same solution can also be easily adapted to hydrogen, allowing a TTW reduction of up to 97% for CO_2.

The latest engine results have also highlighted that the HPDI fuel system technology, already capable of matching diesel efficiency with natural gas, is able to exceed this same efficiency when fueled by hydrogen using the same base engine: depending on the operating conditions, the BTE of H_2 HPDI fuel system engines is 3 to 9% higher than the base diesel engine BTE, with recent studies predicting more than 52% BTE on the latest engines. The study also showed that power and torque could be increased by approximately 20-25%, potentially enabling engines to be downsized for some applications. Paths for NOx and for CO_2 reduction were covered, with NOx controllable through a combination of EGR, fuel pressure tuning and aftertreatment systems, while further CO_2 reduction will be focused on pilot reduction in the near term. WFS is already working on its next generation HPDI^{TM} system (HPDI 3.0^{TM}), which will be the platform for the natural gas and hydrogen variants for the latest state of the art combustion engines.

One critical aspect often overlooked is the cost to consumers and the OEMs to actually achieve the CO_2 reductions. This paper presents a further look into the recently released Frontier Economics study, extending the same methodology to look at the CO_2 abatement cost for HPDI vehicles versus Fuel Cell vehicles. This study showed that the lowest CO_2 abatement cost (tons of CO_2 reduced per €1000 invested) was actually achieved using a biomethane blend – for every €1000, between 10 and 13 tons of CO_2 would be reduced. Blue or green hydrogen as a fuel was more cost-effective with the HPDI vehicle (4 to 9 tons of CO_2) than the Fuel Cell vehicle, which achieved a reduction of ~2 tons of CO_2 for the same investment.

Finally, a previous assessment of the Total Cost of Ownership by AVL was updated with the latest HPDI fuel system efficiencies. This TCO assessment illustrated that the HPDI fuel system equipped vehicle was a more cost-effective solution by ~14% over a five-year ownership cycle, which represents a savings of ~€140,000.

Another way to consider this savings is from the perspective that the Fuel Cell vehicle is expected to be at least two times as expensive as an HPDI fuel system equipped truck, which in real world terms would mean that customers could purchase at least twice as many HPDI fuel system equipped trucks as Fuel Cell trucks for the same initial outlay. From a fleet-wide CO_2 reduction approach, this would mean that for the same initial investment, twice as many HPDI fuel system equipped trucks could be purchased (vs Fuel Cell trucks) with almost double the resultant reduction in total CO_2 emissions.

In summary, fuel efficient biomethane and hydrogen engines still have a powerful role to play in long haul trucking, with a more cost effective approach that leverages known technology. Biomethane is widely available, while hydrogen infrastructure is still evolving. WFS's HPDI fuel system solution allows a broad approach with up to 100% reduction in WTW CO_2, both now and into the future.

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