Opportunities and Challenges in Green House Gases Reduction using High Pressure Direct Injection of Natural Gas

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Introduction

Westport has been developing a high-pressure direct injection (HPDI) technology for gaseous fuels. This technology is an effort to adapt the diesel cycle for gaseous fuels. The diesel cycle is desirable since it provides high efficiency, high low-speed torque, fast transient capabilities, and reliability. Because of their high efficiency, diesels are very favorable from a green house gas (GHG) point of view, however they remain challenged by high nitrogen oxides (NOx) and particulate matter (PM) emissions. When directly injecting natural gas, NOx and PM emissions can be reduced by approximately 50% while maintaining the performance of the diesel engine. This allows the use of abundant and historically cheaper natural gas. Because of its lower carbon content per unit energy, natural gas also offers further GHG reduction over the diesel if the efficiency is preserved and if methane emissions are low.

Westport is adapting and building on its direct injection of gaseous fuel technology for several applications:

- On-highway trucks: HPDI with pilot-ignition and LNG on-board fuel system,
- Light-duty delivery truck: HPDI with glow-plug ignition and CNG on-board fuel system,
- Power generation: HPDI with pilot-ignition and partial fumigation,

Each of the application offers a particular GHG opportunity.

On-Highway Trucks: HPDI with Pilot Ignition and LNG On-Board Fuel System

This is the initial implementation of HPDI technology. As illustrated in Figure 1, a small amount of pilot diesel fuel is injected prior to the injection of the natural gas to provide ignition. The Cummins ISX engine fitted with Westport's HPDI system recently received optional low-NOx certification in California, reaching NOx emissions below 2.5 g/bhp-hr. It also resulted in PM emissions of 0.03 g/bhp-hr, a 62% reduction over diesel operation. ISX HPDI engines are now being demonstrated at 2 customer sites in British Columbia and California. 14 new trucks will be delivered in the fall of 2001 to Norcal for waste transportation.

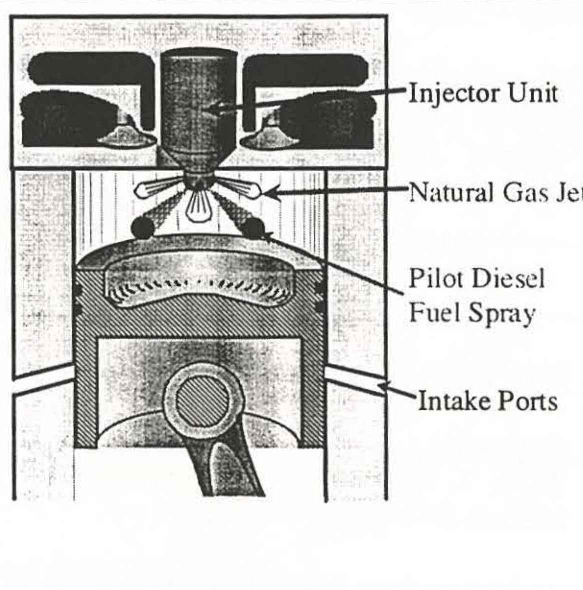

Figure 1. Schematic representation of the natural gas HPDI injection.

The GHG emissions of the engine are

dependent on the efficiency of the engine, the amount of pilot diesel fuel used, the composition of the natural gas and the methane emissions. In this application, the efficiency of the engine is the same as that of diesel. The amount of pilot fuel varies depending on the application between 5% and perhaps 15%.

LNG composition may vary depending on the source. Gas chromatograph analysis of the LNG delivered at our site in Vancouver shows a typical methane fraction of 99.5%. The hydrogen to carbon ratio is 3.99, and the molecular weight 16.1 kg/kmol.

The methane emissions achieved over an AVL 8 mode steady-state cycle are approximately 1 g/bhp-hr, compared to CO_2 emissions of approximately 450 g/bhp-hr. It is important to realize that methane emissions are cycle dependent and the values provide here are approximation.

	Diesel Fuel	B.C. LNG	B.C. CNG	Low methane Natural Gas
Ratio of Hydrogen to Carbon atoms	1.795	3.99	3.93	3.83
Molecular Weight (kg/kmol)	166	16.1	16.7	17.6
Mass of CO_2 formed per mass of fuel burned (kg)	3.17	2.74	2.72	2.66
LHV (kJ/kg)	42,800	50,000	49,500	48,600

Table 1. Diesel and LNG properties and natural gas property considered in this study.

Based on the above figures, the GHG emissions from the engine are reduced by between 18 and 21% for the range of pilot fuel given. Reducing methane emissions by half would allow the range to move to 20 to 23% reduction.

The upstream emissions must obviously be considered. The Transportation Issue Table for the National Climate Change Process "Alternative and Future Fuels and Energy Sources for Road Vehicles"[1] provides a Canadian context for the upstream emissions. The table below shows the upstream emissions of selected fuels according to this study.

	Diesel Canada	**CNG Canada**	**LNG Canada**	**Diesel GREET**	**CNG GREET**	**LNG GREET**
Incl. Dispensing	17,116	12,359	27,590	17,125	19,870	19,965
W/o dispensing	16,988	10,812	n/a	n/a	10,885	n/a

Table 2. Upstream GHG emissions for different fuels in grams of CO2 equivalent per Million BTU delivered.

As may be seen, Canadian specific LNG has relatively high upstream GHG emissions compared

[1] Prepared by W. Edwards, R. Dunlop, W. Duo of Levelton Engineering Ltd., D. O'Connor, N. Fitzpatrick, and S. Constable. July 1999.

to CNG and diesel. This is due to 2 main factors. For one the study estimated at 2% the loss of fuel during transfers. Secondly, GHG emissions are produced during the energy generation required to liquefy the natural gas. The table also shows the upstream emissions reported in GREET[2], the green house gases spreadsheet analysis produced by Argonne National Laboratory (version 1.5, with revisions dated April 21 2001). The results from GREET do not show such a difference between CNG and LNG, and both are in an intermediate position when compared to the Canadian study.

The various upstream estimates were applied to an on-highway truck application operating HPDI and a LNG fuel system, with the assumption that the truck used 5% pilot diesel fuel. For the estimate of the actual number of GHG reductions, the assumptions were that the truck drove 100,000 miles per year and had a fuel consumption of 7.5 miles per gallon. The following GHG emissions reduction are obtained:

	Upstream GHG emissions [grams of CO2eq / MBTU]	GHG reduction with HPDI	Typical GHG reduction per year per truck [metric tons]
Canada Study LNG	27,500	6.9%	11
GREET LNG	20,000	14.3%	24
GREET Flared Gas LNG	-50,000	85%	138

Table 3. GHG emissions reduction for on-highway trucks using HPDI with pilot fuel and LNG on-board fuel system.

It is interesting to note that according to GREET, more than 20% of the upstream emissions of GHG are actually leaks of methane during processing and transportation of the fuel. The additional case of producing LNG from flared gas was added. Here the reduction is so large because there is a credit associated with the capture and utilization of flared gas. A similar result would be obtained from using landfill gas.

Light-Duty Trucks: HPDI with Glow-Plug Ignition and CNG On-Board Fuel System

In this implementation of HPDI, a hot surface is used to ignite the directly injected natural gas, as illustrated in Figure 2. This technology is being applied to light-duty diesel engines ranging from 2 to 4.5 liters, as part of technology demonstration programs with Ford and Isuzu. These engines are used for urban and interurban delivery trucks in Europe and Japan.

In this case, no diesel pilot is being used. The GHG emissions of the engine are dependent on the efficiency of the engine, the composition of the natural gas and the methane emissions.

In this application, the efficiency of the engine is the same as that of diesel, but there is a parasitic load associated with the needed on-board compressor. At refueling time and for some

[2] Michael Wang, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Copyright University of Chicago

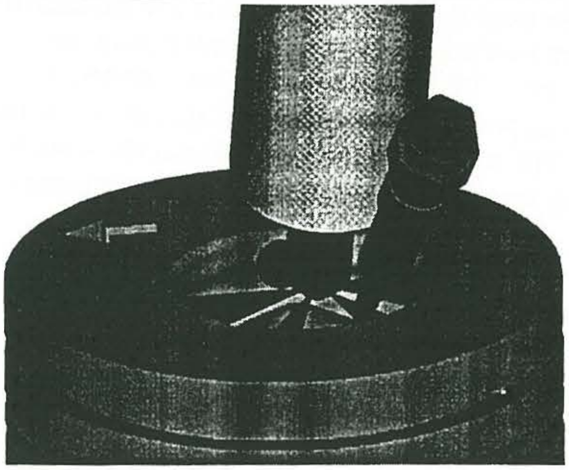

Figure 2. Schematic representation of the natural gas HPDI injection with glow plug.

time after, the pressure in the storage cylinder is above the injection pressure. As the gas in the storage cylinder is consumed, the pressure drops and the fuel must be recompressed. The on-board compressor, or intensifier, takes the CNG in the storage cylinder and re-compresses it to the desired injection pressure. The fuel cycle average is estimated to require about 3% of the engine output.

CNG composition varies significantly depending on the source. Table 1 contains a typical B.C. natural gas as well as a lower methane content natural gas.

At light load, this technology yields higher methane emissions than the pilot ignited technology. Although combustion optimization has only recently started and is not completed, engine-out methane emissions of 3 g/bhp-hr are expected. This is very load dependent however, with low load operation providing for more methane emissions. For the purpose of this study, and based on experimental results, methane emissions ranging from 1 to 2% of CO2 emissions are considered. These will have to be treated by catalysis for application in some markets, with a target of approximately 0.4 g/bhp-hr. The GHG estimates are quite sensitive to the methane emissions and so the results should be considered approximate.

Based on the above figures for efficiency, methane emissions and gas quality, the GHG emissions from the engine are changed by approximately –8% to 7.5%. Reducing methane emissions to 0.4 g/bhp-hr would allow the range to move to approximately 20%, so methane emissions are very significant in this application.

The upstream estimates of Table 2 were applied to a light duty diesel vehicle performing 30000 miles per year at an average mileage of 19 mpg. The fuel life-cycle GHG reductions are indicated in the following table:

	Upstream GHG emissions grams of CO2eq / mBTU	GHG reduction with HPDI
Canada Study w/o Catalyst	12,359	-8% to 8%
Canada Study CNG, w/ Catalyst	12,359	22%
GREEET CNG, w/o Catalyst	19,870	-10% to 2.4%
GREET CNG, w/Catalyst	19,870	14%

Power Generation: HPDI with Pilot ignition and Partial Fumigation

In this implementation of HPDI, a fraction of the natural gas is fumigated rather than directly injected. This is done for two main reasons. First, in stationary applications the natural gas must be constantly compressed from pipeline pressure to injection pressure. Because pipeline pressure at a given site is usually rather low, the power requirement to compress the natural gas is very significant. For example, with a pipeline pressure of 3 bar, the efficiency penalty is as much as 8%. By fumigating approximately 50% of the natural gas, the parasitic loss is cut to 4%. A second reason to use partial fumigation is to reduce NOx emissions by forming a very lean yet flammable homogeneous mixture that burns before the subsequent direct injection phase.

This technology is being installed on a Cummins QSK 60 engine and is being packaged as a power generation station at the Anaheim convention center. A second demonstration is being prepared at Grande-Prairie, Alberta. This technology has demonstrated in the laboratory a net efficiency of 40% and NOx emissions of 1.0 g/bhp-hr, at relatively high power density. In this market segment, the competing alternatives are a diesel engine or a spark ignited natural gas engine. Although the diesel is capable of 44% thermal efficiency, it is assumed here to be reduced to 42% to enable low NOx emissions of 1 g/bhp-hr. Although several options exist, it is assumed here that the spark ignited engine has an efficiency of 36%, a typical figure in the field.

The GHG emissions of this engine are dependent on the efficiency of the engine, the amount of pilot fuel used, the composition of the natural gas and the methane emissions. This system uses about 4% pilot fuel as it operates mostly at high loads.

The combustion of the lean mixture results in higher methane emissions than the above described pilot ignited technology. Although combustion optimization has only recently started and is not completed, engine-out methane emissions of 3 g/kW-hr are expected. These will have to be treated by catalysis for application in some markets, with a target of approximately 1 g/kW-hr. CO2 emissions over duty cycle typical of these applications is approximately 450 g/kW-hr. Methane emissions from the spark-ignited engine were considered the same as that of HPDI, and the same treatment was applied.

The upstream emissions of Table 2 without dispensing were used to produce life cycle emissions for different options as indicated in the following table.

	Upstream GHG emissions grams of CO2eq / mBTU	GHG reduction with HPDI over Diesel	GHG reduction with HPDI over spark-ignited engines
Without Methane Catalysis	10,812	15% (1630 tons)	8% (800 tons)
With Methane Catalysis	10,812	20% (2230 tons)	8% (800 tons)

Conclusions

The direct injection of natural gas offers good potential to reduce GHG emissions over diesel fueling. With LNG fueling, upstream emissions impact significantly the fuel cycle emissions of GHG, the various estimate indicating savings in the range of 7 to 15% when pilot ignition of the directly-injected gas is used on a highway truck. For other implementations of HPDI, me thane emissions resulting from incomplete fuel combustion have a significant impact on the life-cycle GHG emissions. In these cases, catalysis of the methane emissions is necessary to maximize the GHG emissions reduction. For light duty delivery trucks, non-catalyzed systems may result in savings of 8% or less, while catalyzed system could yield GHG emissions reduction of up to 22%. For power generation, the HPDI technology yields savings in GHG of 15 to 22% over diesel fueling and of approximately 8% over spark-ignited engines.