

Impacts and Mitigation of Varying Fuel Composition in a Natural Gas Heavy-Duty Engine

Gordon McTaggart-Cowan, Jian Huang, and Sandeep Munshi
 Westport Fuel Systems

ABSTRACT

Natural gas offers the potential to reduce greenhouse gas emissions from heavy-duty on-road transportation. One of the challenges facing natural gas as a fuel is that its composition can vary significantly between different fuel suppliers and geographical regions. In this work, the impact of fuel composition variations on a heavy-duty, direct injection of natural gas engine with diesel pilot ignition is evaluated. This combustion process results in a predominantly non-premixed gaseous fuel combustion event; as a result, end-gas autoignition (knock) is not a concern. Changes in the fuel composition do still impact the combustion, both through the changes in the chemical kinetics of the reactions and due to changes in the density of the fuel. Increasing concentrations of heavier hydrocarbons, such as ethane or propane, in the fuel lead to higher fuel densities and hence greater fuel mass being injected for a given injection duration. This results in a combustion that has similar peak heat-release rates but longer combustion duration. There is little impact on peak cylinder pressures or the timing of the start of the combustion. The main effect on engine emissions is a substantial increase in PM emissions, due to the greater concentrations of C₂-and higher species in the fuel. Various on-board sensors can be used to monitor the engine and correct fueling to avoid engine damage. In this work, a sensing system including bearing-cap mounted accelerometers is used to detect changes in the combustion event and adjust the fueling as needed to maintain engine torque over significant fuel composition variations. These results demonstrate a potential technique for engine protection and control that can accommodate wide variations in natural gas composition.

CITATION: McTaggart-Cowan, G., Huang, J., and Munshi, S., "Impacts and Mitigation of Varying Fuel Composition in a Natural Gas Heavy-Duty Engine," *SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-01-0777.

INTRODUCTION

Low carbon to energy ratio, wide availability and the potential to be generated from renewable sources make natural gas a promising alternative fuel for transportation applications. Its use can be particularly attractive for heavy-duty on-road applications, with high mileage and fixed routes to reduce fueling infrastructure requirements. One challenge for natural gas remains that its composition and performance characteristics are not as tightly controlled as for liquid fuels. Changes in the chemical composition of the natural gas can impact engine performance. This paper assesses the implications of fuel composition variations on a late-cycle direct injection of natural gas engine and presents a combustion sensing strategy that enables a controller to compensate for changes in fuel composition.

Diesel engines dominate heavy-duty on-road applications, due to their high efficiency and high torque. To meet regulatory requirements and customer demands, diesel engine technology has advanced in the direction of improved efficiency and lower emissions. These have been achieved through increases in engine power density, improvements in fuel system architecture, and advances in exhaust aftertreatment. To keep pace with the advances in diesel engines, natural gas technologies are also evolving

towards higher power densities. Higher performance natural gas engines are potentially more susceptible to variations in fuel composition. Premixed charge technologies are particularly sensitive to end-gas autoignition (engine knock); many modern premixed NG engines have fuel quality specifications to avoid engine damage due to knock, as well as on-board sensors to detect knock onset and respond appropriately, including through derating the engine if necessary.

One technology that can match diesel engine performance while replacing more than 90% of the diesel fuel with natural gas is high pressure direct injection (HPDI) [1]. HPDI retains a non-premixed, diesel-like combustion process, and hence is not sensitive to knock due to changes in fuel composition. Even so, changes in fuel composition impact the energy content, stoichiometric fuel-air ratio, and density of the fuel, which can impact the performance of an HPDI engine. Changes in concentrations of specific species will also impact engine-out emissions, although the robustness of modern exhaust aftertreatment systems should reduce the impact on tailpipe emissions.

The overall aim of the work reported here was to investigate the impacts of NG composition variation on an HPDI engine. The specific objectives were:



1. Evaluate performance and emissions impacts of natural gas that is representative of the lowest quality that might be delivered to an engine.
2. Demonstrate the ability of a combustion sensing strategy to detect changes in engine performance attributed to natural gas composition variations.
3. Identify whether the combustion sensing strategy could be used as feedback to help to compensate engine performance for very low quality natural gas.
4. Quantify the changes in engine-out and tailpipe emissions after the compensation strategy was implemented.

High Pressure Direct Injection of Natural Gas

HPDI is a pilot-ignited non-premixed natural gas combustion strategy. It is in service in commercial heavy-truck applications in North America and Australia. Results show that maximum torque and efficiency are very close to those of equivalent diesel engines, while more than 90% of the fuel used (on an energy basis) is natural gas [1]. Tank-to-wheel GHG emissions as much as 20% lower than an equivalent diesel engine have been demonstrated, when the HPDI system is optimized for efficiency [2].

HPDI COMBUSTION

As in a conventional diesel engine, in HPDI the inducted charge consists of fresh air externally mixed with some recirculated exhaust. The charge is then compressed; just before the end of the compression stroke, a small amount of diesel is injected. This is followed by an injection of natural gas through separate nozzle holes. The diesel pilot auto-ignites, providing multiple ignition sources that ignite the natural gas jets. Assessment of key aspects of the HPDI combustion process has been reported previously (e.g. [3,4]).

In an HPDI engine, end-gas autoignition (knock) is not a concern as the fuel and air are not premixed; this allows the engine to retain the diesel engine's high compression ratio. The global air-fuel ratio remains similar to that of an equivalent diesel engine, with similar sensitivity to EGR and combustion phasing. Load control is achieved by simply reducing the amount of natural gas injected; part-load throttling is not required. Emissions of unburned methane are controlled, even at low load, by adjusting the injection process to avoid over-mixing of the natural gas. Crevice and end-gas regions see virtually no fuel, improving fuel conversion efficiency and reducing tailpipe methane emissions. As the combustion is non-premixed, some particulate is formed from the natural gas; this process is particularly sensitive to equivalence ratio [5].

HPDI FUEL SYSTEM

Liquefied natural gas (LNG) offers benefits of increased volumetric and gravimetric energy density compared to other alternatives for heavy-duty natural gas engines [6]. For HPDI, this state has the added benefit of being substantially less compressible than gaseous natural gas (whether stored at high pressure as compressed natural gas, or in more exotic systems such as absorbed storage), reducing the

compression work needed to achieve the fuel pressures needed for direct injection into a high compression ratio engine. A schematic of the key components for an LNG-based HPDI fuelling system is shown in Figure 1. In this system, cryogenic LNG is first compressed to the desired supply pressure (up to approximately 300 bar in a standard HPDI engine), using a pump immersed in the LNG tank. The natural gas is then passed through a heat exchanger to ensure it is fully vaporized before being supplied to the engine.

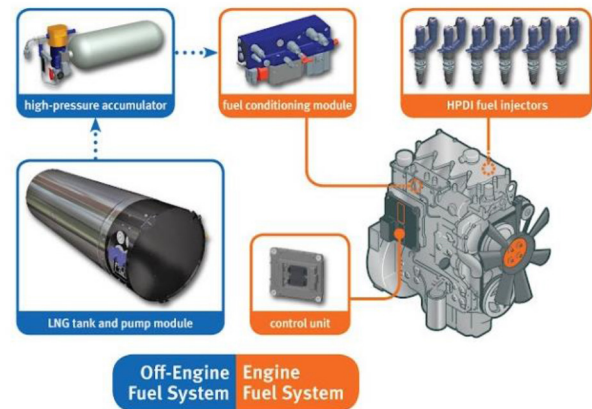


Figure 1. HPDI LNG fuel system

The diesel pilot is supplied separately, and is compressed using a high-pressure common-rail pump. The diesel is supplied to the engine at a pressure slightly above that of the natural gas. The diesel pressure is regulated using an inlet-metering valve on the diesel pump.

Both high pressure gas and diesel are supplied to the on-engine fuel system. The gas pressure is regulated relative to the diesel pressure using a dome-loaded self-relieving regulator. The two fuels are supplied separately to the injectors; in the first generation HPDI technology reported here, these were delivered through internal rails in the cylinder head. In the latest generation of HPDI technology, the gas and diesel are supplied to the injectors through external fuel rails [1]. HPDI injectors are twin-fuel concentric needle injectors, with separate needles for controlling diesel and natural gas injection through different sets of holes. A schematic of the HPDI injector nozzle is shown in Figure 3. The diesel needle is located inside the gas needle. The diesel holes are located in the tip of the gas needle, which protrudes below the bottom of the injector nozzle. Gas and diesel injection are independently controlled, with separate actuators to enable changes in relative timing and injection durations.

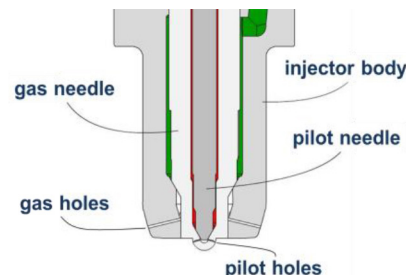


Figure 2. HPDI injector nozzle schematic

Natural Gas Composition Implications

The implications of variations in natural gas composition on an internal-combustion engine depend on the nature of the combustion event. For premixed-charge spark-ignition engines, higher concentration of species such as ethane and propane in the fuel increases the propensity for end-gas autoignition (knock) [7]. For natural gas engines, this is represented as the 'methane number' (MN) of the fuel, which is roughly analogous to the octane number in gasoline engines [8]. In this scale, pure methane is given a value of 100 and pure hydrogen a value of 0. Any gaseous fuel can be assessed on this scale through testing on a CFR engine running a specific test protocol. To avoid the expense and complexity of testing every fuel blend, calculations are available that provide a reasonable estimate of MN based on measured compositions of gaseous hydrocarbons [8]. Many spark-ignition engines will have a fuel specification, typically around 70-80 MN. Below this level, knock is likely to occur, resulting in significant damage to the engine. Unlike gasoline, the NG available in the commercial distribution network is not typically controlled to a specific methane number; so the risk of providing a sub-optimal or even hazardous fuel to the engine increases.

For non-premixed natural gas combustion, as in the pilot-ignited HPDI technology, there is no premixed charge so end-gas autoignition is not a significant concern. Instead, natural gas composition tends to impact the combustion event through the ignition delay and combustion of the fuel, and the corresponding generation of pollutants. The changes in the energy density of the fuel will also affect the amount of chemical energy available from each injection event. In commercial (non-vehicle) applications, this is evaluated on the basis of the Wobbe Index (WI). The wobbe index is calculated as:

$$WI = \frac{HHV}{\sqrt{\text{specific gravity}}}$$

Where HHV is the volumetric higher heating value of the fuel and specific gravity is the density relative to air at standard temperature and pressure (STP). As the fuel pressures in the HPDI system are much higher than STP, the WI does not fully capture the impacts of changes in fuel composition on HPDI engine performance [9].

A previous study, conducted on a single-cylinder research engine, indicated that increases in either ethane or propane composition could lead to increases in PM and CO emissions [10]. That work was conducted under conditions where all other parameters were artificially controlled, including equivalence ratio. The fuel supply was adjusted to maintain the target IMEP based on in-cylinder pressure transducer feedback. The prior work did not quantify the impacts of changes in fuel composition on brake torque or on the response of the turbocharger system. In particular, the impacts of changing exhaust enthalpy on in-cylinder EQR were not evaluated, although it would be expected to significantly impact emissions.

Combustion Sensing

Ideally, the performance of an HPDI engine would be controlled such that engine hardware was protected and torque was constant independent of the composition of the natural gas fuel.

Measurement of fuel composition would be the most direct way to provide feedback to the engine control (ECU) but at present there are no commercially-viable sensors that would provide reliable readings while meeting the size, durability, and cost requirements for on-road transportation applications.

Indirect assessment of fuel composition can be conducted based on changes in the combustion process, determined from the cylinder pressure trace or from exhaust emissions. Finally, impacts on air-handling system performance can be an indicator of the engine performance. From this, the changes in engine performance caused by variations in fuel composition can be diagnosed and corrected.

In-cylinder pressure transducers can be used to measure cylinder pressure, and from those results the combustion phasing can be calculated. However, the cost and complexity of the sensors and measurement train have limited their application in production environments. An alternative method that has seen significant research is to reconstruct the pressure trace based on indirect measurements. These have included crank kinematics and block or head vibration measurements. Crankshaft speed measurements have been evaluated by a number of researchers (e.g. [11,12,13]); peak cylinder pressure accuracy within 5% has been demonstrated through the use of neural network-based control strategies. Engine vibration measurements, using accelerometers attached to the engine block or head, have also been shown to be able to predict peak pressure magnitude and phasing (e.g. [14,15]). However, this work has not demonstrated the ability to extract more complex information, such as the cumulative heat release.

The work reported here uses a vibration measurement technique, but with the accelerometers mounted on the bearing caps of the engine. This location maximizes the strength of the pressure signal, as the displacement of the bearing cap responds directly to the force exerted by the piston on the crankshaft. It also minimizes engine-to-engine variability, as tighter manufacturing controls mean that vibration transmission through the piston - crank assembly is less susceptible to part-to-part variations than through the cast block or cylinder head. The accelerometer signal can then be combined with crankshaft position sensing to reconstruct the cylinder pressure trace, which can then be used to estimate the apparent heat-release rate (HRR). The knock-sensor based combustion control strategy has been under development for some time [16,17,18,19].

It should be noted that, while the combustion sensing concept is demonstrated here on an HPDI engine with the objective of accommodating variations in fuel composition, it can be equally applied to other combustion strategies. In particular, it could enable advanced combustion strategies where near real-time feedback on cylinder pressure would be beneficial. Part of the work that led to the development of the combustion sensor was as a tool to adjust the diesel injection quantity to control the combustion phasing in a mixed-mode combustion strategy using partially-premixed autoignition [20]. As it is measuring combustion progression directly, it is not sensitive to the fuel or even combustion type.

RESEARCH METHODOLOGY

The work conducted here focuses on a Westport 15L HD multi-cylinder heavy duty natural gas engine equipped with a first-generation HPDI fueling system. This engine was produced commercially between 2007 and 2013, and is certified to US EPA/CARB 2010 emissions standards [21].

Research Engine

All the tests were conducted on an instrumented research version of the 15L engine. The base engine configuration and calibration were taken from the 2010 certified, 355 kW (475 hp) production engine. Some of the work reported here was conducted on a prototype, higher-power (390 kW) version of the same engine. The research engine was installed on an engine test bed equipped with an eddy-current dynamometer. The specifics of the research engine are given in Table 1. For the 355 kW engine, the base engine hardware (including pistons and valve timing), air handling system, and exhaust aftertreatment are unmodified from the 2007 Cummins 15L ISX engine that the HD 15L was based upon. For the 390 kW version, the pistons were modified to reduce the compression ratio and the injector flow-rating was increased. No other changes were made to the engine. More details on the research engine are presented elsewhere (see [22,23] for the base engine and [24] for the high power prototype).

Table 1. Research engine specifications

Base Engine	Cummins ISX15	
Bore / Stroke / Con. Rod L.	137 / 169 / 261 mm	
Swept Vol. / Cyl.	2.49 L	
Number of cylinders	6	
Rated power	355 kW	390 kW
CR	17:1	15.3:1
Air handling	VGT, cooled high pressure EGR	
Aftertreatment	DOC, DPF, SCR	
Fuel System		
Injector	Westport J36 HPDI	
Hole number / angle	Diesel: 7 / 18°; Gas 9 / 18°	
Fuel rail pressures	Gas: up to 300 bar	
	Diesel: Gas + 10 bar	

The research engine was fully instrumented, including six flush-mounted water-cooled piezoelectric pressure transducers. This data was collected at a 0.5°CA resolution over 100 consecutive cycles. The in-cylinder pressure from the water-cooled transducers was used to determine the apparent heat release rate (HRR) and to define the combustion phasing. This is defined as the timing at which half of the apparent heat release has occurred, as calculated from the cumulative heat release (CHR). Engine brake torque and speed were determined from sensors on the dynamometer. Intake and exhaust stream pressures and temperatures were recorded at multiple points in the system. Charge air flow was measured using a Meriam laminar flow element and the diesel flow was measured using a gravimetric fuel balance. Emissions of CO, CO₂, NO_x, THC and CH₄ were measured using a Horiba MEXA3100DEGR emissions bench; this was also used to measure intake CO₂ to quantify the EGR rate. Engine-out smoke emissions were measured using an AVL 415 smoke meter. These are reported on the basis of filter smoke number (FSN), and

only represent black-carbon emissions. Previous work [22] has shown that percentage reductions in FSN agree well with the reductions determined from gravimetric filter-based measurements.

Repeatability and reproducibility were assessed by evaluating the long-term variations in measured parameters at a fixed operating condition. For this work, the variation in key parameters was evaluated for a reference condition of 2200 N.m and 1490 RPM. The results are shown in Table 2, in the form of coefficient of variation (COV), defined as the standard deviation divided by the mean. The results shown are for variability over a period of approximately three months during the testing program reported here. This value incorporates measurement errors, random variations in engine condition set-point, and long-term variations in engine performance.

Table 2. Coefficient of variation of key parameters for the 15L research engine at 1490 RPM, 2400 N.m with base fuel composition.

Parameter	Long-term COV
BSFC	±1.2%
FSN	±10%
HC	±11%
CO	±8%
NO _x	±5%
Peak HRR	±5%

Ultra-low sulphur road-grade diesel that met North American fuel specifications was used as the pilot fuel. Natural gas was supplied from a custom fuel supply that allowed various fuel blends to be prepared in advance and then fed to the test cell at the pressures needed for the HPDI engine.

Fuels Tested

Three fuels were used in the work reported here. The base fuel was commercial gas from the distribution network in Vancouver, British Columbia, Canada ("Line Gas"). This fuel is typical of LNG compositions that are expected to be seen in the field and hence is used as the basis for engine calibration development. The two other fuels were selected to be low-quality gas blends with very high concentrations of heavy hydrocarbons: a high propane blend ("MN65"), and a blend with high levels of both ethane and propane ("MN54"). The MN54 in particular was considered to be an extreme case to test the combustion process and compensation strategies. The compositions of the three gas blends are provided in Table 3. The reference baseline tests were run over all modes with 'line gas' (MN90). The results from this baseline were then used as the reference to evaluate the impacts of the different fuel compositions on engine performance and emissions.

The first fuel (MN65) was selected as being representative of the 'worst case' for natural gas that might be provided through a typical distribution network. Most fueling stations provide higher quality fuels, but it is important to assess the ability of the HPDI engine to operate with such a fuel. The second fuel (MN54) was a particularly ethane- and propane-rich fuel that was selected as being representative of an LNG supply that had weathered severely. It should be noted that typical CNG fuel compositions would be higher than MN75, to avoid knock in modern spark-ignited NG engines.