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# Performance and emissions of a compression-ignition direct-injected natural gas engine with shielded glow plug ignition assist

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ABSTRACT

Performance and emissions experiments were conducted on a compression-ignition direct-injected natural gas engine (DING) equipped with a shielded glow plug ignition assist system. Tests were conducted at three different intake pressures (34.5 kPag, 68.9 kPag, 103.4 kPag), and four nominal (targeted) equivalence ratios (0.2, 0.3, 0.4, 0.5). $CH_4$, $NO_x$, CO and PM emissions were measured and analyzed, showing that emissions levels are influenced by the DING engine's combustion modes and intake pressure. Premixed combustion which dominates at low equivalence ratios resulted in higher levels of $CH_4$ and $NO_x$ emissions, while mixing-controlled combustion, which develops at higher equivalence ratios, resulted in elevated CO and PM levels. Higher intake pressure was found to improve all emissions levels. The most significant effect was the reduction of PM and CO emissions due to improved fuel charge mixing and air entrainment that results from a pressure-driven momentum increase of the engine's air swirl field. Brake specific emissions and fuel consumption were estimated and compared against levels reported in the literature for dual-fuel port-injection, and High-Pressure Direct-Injection (HPDI) natural gas engines. The most significant finding was that the DING engine exhibits lower fuel consumption and PM emissions levels when compared to values reported in the literature for HPDI engines. The PM emissions advantage was attributed to a higher proportion of premixed combustion and the absence of a diesel pilot in DING engine operation. Lastly, PM size distributions were analyzed, showing that the DING engine produces PM that is smaller than PM of a conventional diesel engine, but similar to the PM reported in the literature for HPDI engines.

## 1. Introduction

Natural gas has several advantages for use in automotive engines. It is relatively inexpensive, widely available, has a well-established distribution infrastructure, and is thought to be a cleaner burning fuel when compared to gasoline and diesel in terms of both greenhouse gas (GHG) and regulated emissions. The transportation sector is a tremendous source of GHG emissions. In the US, for example, transportation consumes 29% of primary energy, with 92% of that coming from petroleum [1]. Much research has been focused on substituting biomass derived fuels to make the sector's energy consumption more sustainable [2,3]. The use of natural gas in place of gasoline or diesel fuel produces approximately 30% less $CO_2$ emissions when compared on the same energy content basis [4]. Although natural gas is sometimes viewed as an interim solution to reducing GHG emissions – substituting a fossil fuel with lower $CO_2$ emission for another fossil fuel – the use of renewable natural gas (RNG), which can be produced from biomass sources by anaerobic digestion or by combining gasification and catalytic processes, can provide long-term sustainable GHG reductions.[1] A study of the resource base of Canadian biomass waste estimated total greenhouse gas reduction of 107 Mt $CO_2$ eq/year for Canada, with potential of replacing 130% of current residential and commercial use of natural gas [5]. In the future, RNG may also be produced from hydrogen and carbon dioxide, where the hydrogen is generated by electrolysis using electricity from renewable sources [6].

Natural gas use in spark ignition (SI) engines for heavy duty and passenger vehicles is already quite established, with approximately 23 million natural gas vehicles on the road globally in 2016 [7]. SI natural gas engines have favorable emissions performance, having been shown to emit lower levels of carbon monoxide (CO), non-methane hydrocarbons (NMHC), and particulate matter (PM) emissions when compared to engines fueled by gasoline and diesel [8,9]. However, natural

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[1] A wide range of gaseous fuels, collectively called biogas, can be produced from biomass. RNG refers specifically to a higher quality (high methane content) biogas that has the same volumetric energy density as natural gas and is effectively a drop-in replacement for natural gas. Biogas containing large amounts of inert gases ($CO_2$, $N_2$) is not suitable for high pressure direct injection due to increased compression work requirements, compared to natural gas or RNG, and the need for larger fuel injectors.

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**Nomenclature**

| | |
|---|---|
| $\phi_a$ | actual equivalence ratio or equivalence ratio (determined through test results analysis) |
| $\phi_n$ | nominal equivalence ratio – targeted test equivalence ratio |
| P1 | 34.5 kPag intake pressure test condition |
| P2 | 68.9 kPag intake pressure test condition |
| P3 | 103.4 kPag intake pressure test condition |
| BMEP | brake mean effective pressure |
| BSFC | brake specific fuel consumption |
| CAD | crank angle degrees |
| CI | compression ignition |
| CNG | compressed natural gas |
| DING | direct-injected natural gas |
| DPF | diesel particulate filter |
| EEPS | engine exhaust particle sizer |
| EGR | exhaust gas recirculation |
| EPA | environmental protection agency |
| FTIR | Fourier transform infrared spectroscopy |
| FTP | federal test procedure |
| GHG | greenhouse gas |
| HEPA | high-efficiency particulate air |
| HPDI | high pressure direct injection |
| IMEP | indicated mean effective pressure |
| LNG | liquefied natural gas |
| NMHC | non-methane hydrocarbons |
| OEM | original equipment manufacturer |
| RNG | renewable natural gas |
| RPM | revolutions per minute |
| SCR | selective catalytic reduction |
| SI | spark ignition |
| THC | total hydrocarbon |
| ULSD | ultra-low-sulfur diesel |

gas SI engines suffer from lower power output compared to their gasoline counterparts due to knock limitations [8,9]. A recent experimental study examined the potential for improved efficiency and reduced $CO_2$ emissions that could be achieved by downsizing and optimizing a stoichiometric turbocharged SI engine for natural gas operation [10]. Through a combination of downsizing, higher compression ratio, EGR use and careful optimization, this study suggests that reductions in specific $CO_2$ emissions (g/kWh) on the order of 25–34% could be achieved at part load conditions and 45% at full load, with full load equaling the full load achieved on gasoline [10]. Since natural gas typically has an octane rating lower than that of the pure methane used in this study, smaller reductions would be expected in practice. Other recent studies of direct injection SI natural gas engines have shown that use of partially stratified combustion, achieved by control of fuel injection timing, can reduce fuel consumption and improve the trade-off between knock and combustion stability [11,12].

Like gasoline engines, exhaust aftertreatment is needed for SI natural gas engines to meet emissions regulations. Use of a 3-way catalyst together with stoichiometric engine operation is a proven and effective technology. An example of this approach is the Cummins Westport ISL G engine that has been certified to heavy-duty engine emissions standards. Table 1 compares the emissions of this engine operating on natural gas with emissions of the Cumming LS 9 diesel engine from which it is derived. Measured over the federal test procedure (FTP) transient test cycle, the natural gas engine has comparable $NO_x$ emissions (0.13 vs 0.14 g/bhp-hr) and much lower $CO_2$ emissions (463 vs 564 g/bhp-hr, an 18% reduction). However, the emissions of CO and methane are higher. A newer version of this engine, the ISL G Near Zero, has been released to provide an engine offering that meets the new EPA/CARB Near Zero NOx emissions standard. This newer version has achieved emissions of 0.02 g/bhp-hr $NO_x$, which is below the Near Zero $NO_x$ standard. This newer version also meets the 2017 environmental protection agency (EPA) greenhouse gas emission requirements [13].

Utilization of natural gas in compression-ignition (CI) engines can potentially achieve the high efficiencies of diesel engines, but with improved PM emissions performance [8,9]. However, achieving ignition in natural gas CI engines is more challenging than in diesel engines. Natural gas is highly resistant to compression ignition and requires some form of ignition assist [8,9,16–19]. The primary solution to this issue has been to use a two-fuel system. Here, a diesel pilot injection is used to achieve controlled compression ignition, while natural gas provides most of the combustion heat release. There are two distinct approaches to a two-fuel system. The most common, often termed "dual-fuel", uses throttle body or port injection of natural gas which is essentially premixed with the intake air, and is ignited by a late-cycle direct-injected diesel pilot. The diesel pilot burns in a diffusion flame, igniting the premixed air/natural gas charge. Upon ignition, natural gas burns in a premixed flame. This engine configuration generally produces lower CO and PM emissions, but higher levels of $NO_x$ and

**Table 1**
Comparison of natural gas engine technologies. All results from heavy-duty FTP transient test.

| | | Stoichiometric SI NG comparison[a] | | HPDI NG comparison[b] | | Dual-fuel NG comparison[c] | |
|---|---|---|---|---|---|---|---|
| Engine model | Units | Cummins-westport ISLG | Cummins L9 330 | Westport GX 475 | Cummins ISX15 | Retrofit NG fumigation module | Mack MP8-505C |
| Fuel | | CNG | ULSD | LNG | ULSD | CNG + ULSD | ULSD |
| Technology | | SI Natural gas | Diesel | HPDI Natural gas | Diesel | Dual-fuel NG | Diesel |
| Aftertreatment | | 3-way catalyst | DPF, SCR | DPF, SCR | DPF, SCR | DPF, SCR | DPF, SCR |
| Max. power | hp | 320 | 310 | 486 | 583 | – | 505 |
| Max. torque | ft-lbs | 1000 | 1100 | 1750 | 2050 | – | 1810 |
| NOx | (g/bhp-hr) | 0.13 | 0.14 | 0.11 | 0.16 | 0.08 | 0.14 |
| PM | (g/bhp-hr) | 0 | 0 | 0.002 | 0.001 | N/A | N/A |
| NMHC | (g/bhp-hr) | 0.04 | 0 | 0.01 | 0.02 | 1.0 | BDL[d] |
| Methane | (g/bhp-hr) | 1.97 | 0.02 | No data | No data | 4.94 | BDL |
| CO | (g/bhp-hr) | 7.1 | 0.1 | 0.04 | 0 | 3.96 | 0.23 |
| $CO_2$ | (g/bhp-hr) | 463 | 554 | 466 | 614 | 493.7 | 520.8 |
| Brake thermal efficiency | % | N/A | N/A | N/A | N/A | 33.5 | 35.1 |

Table notes:
[a] Data for ISL-G from 2016 certification data [14]; Data for L9 330 from 2017 certification data [14].
[b] Data for GX475 and ISX15 from 2010 certification data [14] as the GX475 is no longer in production.
[c] Data for dual-fuel comparison from Besch et al. [15].
[d] Below detection limit.