

The Effect of Fuel Composition on Performance and Emissions of a Variety of Natural Gas Engines

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ABSTRACT

Work was performed to determine the feasibility of operating heavy-duty natural gas engines over a wide range of fuel compositions by evaluating engine performance and emission levels. Heavy-duty compressed natural gas engines from various engine manufacturers, spanning a range of model years and technologies, were evaluated using a diversity of fuel blends. Performance and regulated emission levels from these engines were evaluated using natural gas fuel blends with varying methane number (MN) and Wobbe Index in a dynamometer test cell. Eight natural gas blends were tested with each engine, and ranged from MN 75 to MN 100. Test engines included a 2007 model year Cummins ISL G, a 2006 model year Cummins C Gas Plus, a 2005 model year John Deere 6081H, a 1998 model year Cummins C Gas, and a 1999 model year Detroit Diesel Series 50G TK. All engines used lean-burn technology, except for the ISL G, which was a stoichiometric engine.

Performance testing consisted of monitoring engine knock or auto-ignition, as well as engine power levels and overall engine operability. Emissions of total hydrocarbons (HC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), oxides of nitrogen (NO_x), nitrogen dioxide (NO_2), particulate matter (PM), and carbon dioxide (CO_2) were measured using procedures developed by the United States Environmental Protection Agency (EPA) for heavy-duty, on-highway engines. The engines showed no sign of auto ignition throughout the program, with slight differences in power levels with the various test fuels. All lean burn engines showed increased NO_x and HC emission levels with decreased MN and increased Wobbe level, while the

stoichiometric ISL G showed no clear trend in NO_x or HC levels with the various fuels.

INTRODUCTION

With known variation in end-use natural gas composition, the effect of fuel composition on natural gas engine performance and emissions is an ongoing concern [1], [2], [3]. Fuel related performance issues include auto ignition, engine and aftertreatment durability, fuel economy, as well as engine operability and power output. Variation in emission levels due to fuel composition is of interest to air quality regulators and agencies, where the impact on the environment can be estimated with data presented in this paper when used in conjunction with engine inventory models. This program evaluated engine performance and emission levels of Cummins, John Deere, and Detroit Diesel engines using natural gas fuel blends of varying methane number (measure of fuel knock resistance) and Wobbe Index (measure of fuel interchangeability). The objective of the research was to first determine if the engines would have operational problems when running with the various fuels. Provided engine performance and operation were not negatively affected, emission tests were performed to characterize emission trends over the range of fuels tested.

This paper discusses the engines evaluated during the program, the test fuels and compressed natural gas (CNG) blending procedures, engine dynamometer tests including durability operation and standardized emission tests, as well as engine performance and emission results. This paper summarizes detailed results included in a comprehensive final report prepared for Southern California Gas Company [4].

TECHNICAL APPROACH

The Cummins ISL G, C Gas Plus, and C Gas engines and aftertreatment systems were procured in new condition and were operated for 125 hours in a steady-state test cell to break-in the engines and age the catalysts. Following break-in operation, the engines were installed in a transient capable emission test cell for performance and emissions testing. This section of the report reviews the test engines and their histories, the fuels used during the program, as well as the procedures used for durability and emissions testing.

TEST ENGINES

Table 1 lists the five heavy-duty natural gas engines evaluated during the program with relevant specifications. All engines used lean-burn technology, except for the ISL G, which was a stoichiometric engine. Lean burn engines benefit from reduced combustion temperatures and NO_x emissions, as well as improved efficiency due to the use of excess combustion air [5], [6]. However, stoichiometric natural gas engines, with use of mature three-way catalyst technology and exhaust gas recirculation (EGR), may be the best alternative for meeting stringent emission regulations [7], [8], [9], [10].

(See Table 1 after last section of paper)

Shown in Figure 1, the ISL G was released in 2007 and replaced the Cummins L Gas Plus and C Gas Plus engines in North America. The ISL G engine used stoichiometric combustion with cooled EGR, as well as a passive three-way catalyst to meet 2010 EPA and California Air Resources Board (ARB) emissions regulations for heavy-duty on-highway engines. The engine was electronically controlled and turbocharged. Oxygen sensors were used at the turbocharger outlet and after the three-way catalyst. Originally purchased at the 280 hp (209 kW) rating, the ISL G electronic control module (ECM) was reprogrammed by Cummins Southern Plains (CSP) with a 320 hp (239 kW) calibration prior to engine break-in testing. According to Cummins Westport, no hardware modifications were necessary to change the ISL G power rating from 280 to 320 hp. Prior to emissions testing, the ISL G was serviced under Cummins Campaign Number 0814. The campaign involved reprogramming the engine with the new calibration, removing the silicon seal from the oxygen sensor, changing the orientation of the oxygen sensor connector, and changing the location of the engine knock sensor.

(See Figure 1 after last section of paper)

The C Gas Plus engine had been marketed for over six years. This six-cylinder engine used lean-burn combustion, and was electronically controlled and turbocharged. As in field operation, an oxygen sensor at the turbocharger outlet was

used for closed-loop air-fuel ratio (AFR) control. No engine problems or faults occurred during the 125-hour durability testing with the C Gas Plus engine. However, replacement of the fuel pressure regulator remedied an intermittent misfire problem evident during transient cycle FTP tests.

The 1998 model year Cummins C Gas engine was acquired in new condition. The oxidation catalyst purchased for the C Gas Plus was also used with the C Gas engine. The lean-burn C Gas engine was turbocharged, electronically controlled and used closed-loop AFR control with an oxygen sensor. Preparatory hot-start transient cycle FTPs resulted in NO_x levels near 3.9 g/hp·hr, exceeding the certification standard of 2.5 g/hp·hr. Cummins Southern Plains checked the engine timing sensor and found the sensor to be out of alignment. After correcting the alignment of the timing sensor, engine NO_x levels dropped below the certification standard. After the timing correction, the C Gas engine completed emissions testing with no problems. As with the other engines, the C Gas engine showed no evidence of knock throughout the program.

The John Deere 6081H natural gas engine and aftertreatment were procured in used condition. An attempt was made to purchase a new 6081H at the beginning of the project; however, John Deere had discontinued production of the engine late in 2007 and no new engines could be located through the distributor network. The 6081H had been in operation for 4,400 hours and approximately 60,000 miles (96,560 km). Noted engine service included replacement of two turbochargers. The 2005 model year engine used lean-burn combustion with an oxidation catalyst. The engine was turbocharged, electronically controlled, and used an exhaust oxygen sensor for AFR feedback control. Initial hot-start cycle FTP tests resulted in NO_x levels of 2.2 g/hp·hr, slightly above the 1.8 g/hp·hr certification standard. John Kubesh from Electronic MicroSystems, LLC, replaced and calibrated the oxygen sensor, after which NO_x levels dropped below the regulatory limit. The 6081H performed all testing with no problems or faults.

The DDC S50G TK natural gas engine was acquired in used condition for testing at SwRI in 2006. When tested in 2006, the engine required several parts and repairs. The engine received a new knock sensor, ignition module, exhaust manifold, and fuel temperature sensor. The engine also required a new oxygen sensor. A direct replacement for the oxygen sensor was not available from DDC, as the original oxygen sensor had been replaced with a new oxygen sensor and module. Prior to testing in 2006, the ECM was replaced and reprogrammed with the correct program and calibration files supplied by Detroit Diesel. The 8.5 liter DDC TK engine was a 1999 model year and used lean-burn combustion with no exhaust aftertreatment. The engine was turbocharged,

electronically controlled, and used an exhaust oxygen sensor for AFR feedback control.

TEST FUELS

Fuel for durability operation, initial engine run-in, and diagnostic efforts was natural gas from a commercial pipeline. The pipeline gas was approximately 95 percent methane by volume, with the balance being ethane, propane, nitrogen, and carbon dioxide. High-pressure pipeline natural gas was available at the durability test cell and was supplied directly to the engines during engine and aftertreatment break-in procedures. SwRI transported the line gas to the transient emissions test cell in a spherical pressure vessel containing approximately 13,000 scf (368 m³ STP) of gas at 3,000 psig (207 bar).

Natural gas blends of varying methane number and Wobbe Index were produced by SwRI, as specified by Southern California Gas Company. Each custom fuel was blended with high-purity methane, ethane, propane, and nitrogen in a pressure vessel containing approximately 7,000 scf (198 m³ STP) of gas at 3,000 psig (207 bar). The compositions of the blends were analyzed using a Hewlett Packard Micro-GC per ASTM D1945. The fuel blends for each engine had similar target gas compositions, with the exception of the C Gas engine which was tested at MN 78 rather than MN 75. Target gas compositions supplied by SCG are shown in [Table 2](#). Blending accuracies were within one percent for methane, and 0.5 percent for ethane, propane, and nitrogen. The methane number of each fuel blend is a measure of the knock resistance of the fuel and was calculated using the ARB mathematical method. The Wobbe Index is a measure of the interchangeability of fuel gases and was calculated by dividing the higher heating value by the relative density of the fuel.

(See [Table 2](#) after last section of paper)

TEST PROCEDURES

Engines were operated in a durability test cell for engine break-in and catalyst aging as well as a transient test cell for performance and emissions testing. This section of the report discussed the procedures used during durability and transient test cell operation.

Durability Operation

Engine and aftertreatment break-in procedures were performed at SwRI in a steady-state durability test cell. [Figure 2](#) shows the Cummins C Gas Plus engine and oxidation catalyst during durability operation. Prior to durability operation, the intake air restriction, exhaust restriction, charge air cooler (CAC) restriction, CAC outlet temperature, and engine coolant outlet temperature were set according to the engine manufacturers' specifications. The

engines were operated at rated power and peak torque to verify engine performance. While operating in the durability test cell, a number of engine and test cell parameters were monitored and recorded at 1 Hz.

(See [Figure 2](#) after last section of paper)

The durability test cell was computer controlled and incorporated a number of automated safety functions that allowed the test cell to operate continuously. Based on recommendations from the manufacturers, all engines were operated at rated power condition for the 125-hour break-in procedure. The engines were shut down every 25 hours to check engine lubricating oil levels and test cell hardware. The engine lubricating oil and lubricating oil filters were changed at 75 hours of accumulated durability operation. The 125-hour operation at rated condition is generally accepted as an appropriate break-in cycle for most engines.

Performance and Emissions Testing

Performance and emissions testing was performed in a transient test cell with a full flow constant volume sample (CVS) system. Prior to commencement of the fuel composition study, work was performed to insure the engines were operating soundly, had no ECM fault codes, met stated power and torque levels, and were below pertinent emission standards.

The test procedure followed for each fuel blend is outlined in [Table 3](#). Based on recommendation by Cummins, an effort was made to update the AFR tables (if used) by operating the engines over a matrix of steady-state speed and load points after switching to a new fuel. The AFR tables are updated based on feedback from the engine's oxygen sensor to control the air-fuel-ratio of the engine. According to Cummins, the preparatory testing listed in [Table 3](#) was adequate to update the engines' electronic control devices and limit fuel-to-fuel interaction. The next step was to operate the engine at wide open throttle (WOT) over a series of steady-state speeds to look for the occurrence of engine knock, or auto ignition. During this operation, knock detection signals from the ECM were monitored (if available) to determine the presence of knock. In addition, the feedback torque signal from the dynamometer torque meter was monitored for noticeable perturbations from the mean torque value.

(See [Table 3](#) after last section of paper)

Emissions testing was performed according to procedures outlined in the Code of Federal Regulations (CFR) Title 40 Part 86 Subpart N for heavy-duty on-highway engines. The test sequence conducted for each fuel included one cold-start transient cycle Federal Test Procedure (FTP) test and three hot-start transient cycle FTP tests. Regulated emissions of total hydrocarbons (HC), non-methane hydrocarbons

(NMHC), carbon monoxide (CO), oxides of nitrogen (NO_x), nitrogen dioxide (NO₂), and particulate matter (PM) were measured for each test. All measurements were made using established measurement techniques with a full flow CVS dilution tunnel.

PERFORMANCE RESULTS

This section of the report contains summaries and results for durability and transient test cell operation, knock evaluation, and engine performance. Throughout the program, no engines showed evidence of engine knock or auto ignition.

FULL LOAD LUG CURVE RESULTS

Shown in [Figure 3](#), a full-load lug curve or torque map was generated for each fuel blend with each engine. The lug curves were generated by operating the engines at WOT and performing an 8 rpm/sec speed sweep from below low idle to high idle. Engine performance showed slight variation with the different fuel blends. The ISL G, C Gas, and C Gas Plus engines showed similar torque output with the various fuels, while the John Deere 6081 and DDC TK engines showed more variation.

(See [Figure 3](#) after last section of paper)

A unique FTP command cycle was generated for each test fuel. The ideal work performed by running the speed and load combinations of the FTP command cycle, known as the cycle reference work, are shown in [Figure 4](#) versus test fuel methane number and [Figure 5](#) versus Wobbe Index. Based on the engines' torque maps, the reference work corresponds to the overall performance of the engine when operated on the various fuels. Although similar, slight variations in the cycle reference work were observed. The ISL G showed no clear trends with engine performance or cycle work with the different test fuels. All other engines showed a trend of increasing power output as the methane number of the fuel decreased and Wobbe Index increased. Cycle work trends were similar to NO_x and were likely caused by related combustion characteristics, such as increased cylinder temperature and pressure and effective ignition timing. Please refer the Emission Results section for this discussion.

(See [Figure 4](#) after last section of paper)

(See [Figure 5](#) after last section of paper)

AIR-FUEL RATIO CONTROL

With the exception of the ISL G, all engines were designed and calibrated to run lean. Running an air-to-fuel ratio (AFR) leaner than stoichiometric reduced peak combustion temperatures, and therefore, reduced the emission of nitrogen oxides (NO_x) [12]. All engines used an oxygen sensor for

closed-loop AFR feedback control. With the exception of the Cummins C Gas, all engines used an active AFR learning process based on oxygen sensor feedback. The purpose of this learning process was to compensate for varying gas compositions and different engine operating conditions, and to continually correct the AFR of the engine to maintain the desired lambda. These AFR adjustments were stored in tables and updated during engine operation. Lambda is the ratio of the measured AFR over the stoichiometric AFR. Values less than one indicate the engine is running rich, while values greater than one indicate the engine is running lean. However, the AFR learning process is only able to make AFR corrections by a limited amount.

[Figure 6](#) shows the mean hot-start lambda results for each fuel blend. Changes in lambda for the ISL G were relatively small compared to the lean-burn engines, indicating the ISL G effectively controlled AFR with the various fuel blends. Clear trends for AFR were difficult to distinguish with the various blends for the ISL G. The C Gas Plus showed decreased lambda with lower MN fuels. Lambda also tended to be lower with high Wobbe fuels. Lambda levels showed significant variation with the John Deere engine. With high Wobbe blends, there appeared to be a trend of decreased lambda with lower MN test fuels. As with the C Gas Plus, C Gas lambda values decreased as MN decreased, indicating the engine ran richer with lower MN fuel. However, with the C Gas engine, lambda did not show a trend with Wobbe level. With the DDC TK, all high Wobbe blends showed decreased lambda levels, indicating the engine ran richer with high Wobbe fuel. Lambda decreased as MN decreased with low Wobbe fuels.

(See [Figure 6](#) after last section of paper)

EMISSION RESULTS

This section of the report contains summarized results for regulated emission species and brake-specific fuel consumption. Linear trendlines were added to charts in this report to display visual data trends only, and are not intended to represent accurate relationships for the data presented. [Figure 7](#) shows the average brake-specific NO_x value of the three hot-start cycle tests for each engine and each fuel. With the ISL G, hot-start average brake-specific NO_x showed little variation with any of the test fuels. All NO_x levels were below the ARB and EPA regulatory standard of 0.20 g/hp-hr. The consistency of the ISL G NO_x data may be attributed to the high conversion efficiency of the passive, three-way catalyst. However, cold-start tests, with reduced catalyst activity, also showed no clear trends with the various fuels. All lean burn engines showed increased NO_x as the test fuel methane number decreased. As shown in [Figure 8](#), high Wobbe blends also showed higher NO_x compared to low Wobbe blends with lean burn engines.

(See [Figure 7](#) after last section of paper)

(See [Figure 8](#) after last section of paper)

Non-linear regression functions were used to relate the average hot-start cycle NO_x emission levels with Wobbe level and methane number for a given engine. The functional form of the regression models is shown in [Equation 1](#) where the unknown parameters a , b , and c were estimated using Marquardt's method. A similar form of this function was used in previous estimates of brake-specific NO_x levels from Detroit Diesel heavy-duty natural gas engines [13]. With limited data, a linear model was used for this analysis, with results shown in [Table 4](#). The Cummins C Gas Plus and C Gas engines showed similar function coefficients with high R-Squared and low root-mean-squared-error. The 6081 and TK analyses resulted in much different curve fits and higher variability of the data. However, these results were similar to previous analysis for the DDC TK engine [13]. The regression results for the ISL G data were poor, with R-Squared below 50 percent, indicating the ISL G showed no strong trends with Wobbe level or MN.

$$\text{Average } \text{NO}_x \left(\frac{\text{g}}{\text{hp} \cdot \text{hr}} \right) = a + b * \frac{\text{Wobbe}}{\text{MN}^c}$$

Equation 1. Function Used to Estimate Average Hot-Start Brake-Specific NO_x

(See [Table 4](#) after last section of paper)

Engine-out NO_x levels are highly dependent on combustion temperature [12]. In a lean-burn engine, combustion temperature is sensitive to the combustion mixture air-fuel ratio and flame speed [4]. A decrease in lambda causes oxidation of more fuel and reduced diluents, resulting in higher combustion temperatures and increased cylinder pressures. Increased combustion temperatures yield increased formation of NO_x .

Another factor that may have impacted NO_x levels was the adiabatic flame speeds of the fuel blends. Fuels with faster burn rates effectively advance the ignition timing of the engine, causing higher in-cylinder pressures and temperatures. Flame speed is dependent on both the composition of the natural gas fuel, and the amount of dilution in the combustion mixture. Fuels with higher concentrations of ethane and propane have higher flame speeds. As the methane number of the fuel decreases, the concentrations of ethane and propane increase. Dilution of the combustion mixture is dependent on the amount of inert material in the fuel as well as the inert material from the excess combustion air. Fuels with more inert material have slower burn rates, as do leaner combustion mixtures, due to increased dilution. High Wobbe index fuel blends have less

inert material than low Wobbe blends. Low Wobbe index fuels have increased diluents, causing slower, cooler combustion. Low methane number fuels have increased concentrations of ethane and propane, causing increased flame speed and subsequent combustion temperature increases.

[Figure 9](#) shows the average hot-start cycle total hydrocarbon results for the various engines and fuels. Although HC emission levels were similar for the various fuels with the stoichiometric ISL G, all lean burn engines showed increased HC with higher MN fuels. Based on visual interpretation of the chart, Wobbe level appeared to have little effect on HC emission levels. Reduction in HC as MN decreased may have been caused by more complete oxidation of the fuel as combustion temperatures increased.

(See [Figure 9](#) after last section of paper)

Non-methane hydrocarbon emission results are shown in [Figure 10](#). NMHC increased as methane number decreased for all engines. Hydrocarbon emissions from gas engines are predominately unburned fuel, therefore, the non-methane hydrocarbon fraction of total hydrocarbon is typically similar to the percentage of non-methane material in the test fuel. As the NMHC fraction of the fuel increased with lower MN blends, the emissions of NMHC also increased. As with HC, NMHC trends due to Wobbe level were difficult to distinguish.

(See [Figure 10](#) after last section of paper)

Carbon monoxide levels showed little variation with the various fuel blends. [Figure 11](#) shows the hot-start average CO results for all engines and fuels. CO increased slightly as the MN of the test fuel decreased with the ISL G, C Gas, and DDC TK engines. However, all brake-specific CO results were well below the ARB and EPA regulatory standard of 15.5 g/hp·hr.

(See [Figure 11](#) after last section of paper)

[Figure 12](#) shows the mean hot-start cycle PM levels for each engine and all fuel blends. Particulate matter levels were similar with the various test fuels. All PM levels were below the ARB and EPA regulatory limits. PM levels with the John Deere 6081 and DDC TK engines, both procured in used condition, were lower than the Cummins engines, which started the project in new condition. A major source of PM in gas engines is the engine lubricating oil. It is likely that the John Deere and DDC engines had less oil consumption than the engines purchased in new condition. Natural gas engines typically use engine hardware from diesel applications, including cylinder liners and piston rings. When operated in a gas configuration, with much less compression and lower cylinder pressures, complete break-in time for the engines

may be increased. Therefore, elevated PM levels for the new Cummins engines may have been due to the relative green state of the Cummins engines, even after the 125-hour break-in operation. PM levels may decrease with further engine operation for the engines purchased in new condition.

(See [Figure 12](#) after last section of paper)

The brake-specific fuel consumption (BSFC) for each engine is shown in [Figure 13](#) for low and high Wobbe blends. BSFC was affected by both MN and Wobbe level. Low Wobbe fuels resulted in increased fuel consumption, while high Wobbe fuels yielded decrease fuel consumption. Changes in brake-specific fuel consumption were mainly due to variations in the energy density of the test fuels. Other factors that likely impacted fuel consumption were AFR and charge burn rate.

(See [Figure 13](#) after last section of paper)

[Figure 14](#) shows the ISL G hot-start cycle average brake-specific fuel consumption percent difference versus ARB certification fuel for the various test fuels. Also shown is the lower heating value (LHV) percent difference versus ARB fuel for the test blends. The LHV for each fuel was calculated as energy content per mass of fuel, while BSFC was calculated as mass of fuel per work. As shown in [Figure 14](#), the BSFC percent differences nearly resembled the LHV percent differences of the test fuels. Low Wobbe blends showed increased fuel consumption, while high Wobbe blends showed decreased fuel consumption.

(See [Figure 14](#) after last section of paper)

SUMMARY/CONCLUSIONS

This program demonstrated that heavy-duty natural gas engines, from a variety of manufactures and core technologies, could operate on a wide range of fuel compositions with little change in performance and no evidence of auto ignition. Slight changes in engine performance were observed with all engines with the various test fuels with the exception of the ISL G. Engine power increased slightly as the MN of the test fuels decreased and Wobbe level increased.

Emission trends were also evaluated to determine the potential environmental impact of running the current fleet of natural gas engines with different fuel compositions. All lean burn engines showed increased NO_x and HC emission levels with decreased MN and increased Wobbe level. The stoichiometric ISL G showed no clear trend in NO_x or HC levels with the various fuels. Although HC decreased with lower MN fuels, NMHC increased as MN decreased with all engines. The NMHC increase was predominately due to the increased NMHC fraction of lower MN fuels. PM and CO

showed no strong trends with MN or Wobbe level, and were well below ARB and EPA regulatory limits.

Fuel related performance and emission differences were likely due to changes in combustion characteristics. For example, increased NO_x and power may have been caused by fuels with faster burn rates, effectively advancing ignition timing. Similarly, variation in AFR likely affected emission levels and performance, with richer combustion causing increase NO_x and power.

BSFC was affected by both MN and Wobbe level. Low Wobbe fuels resulted in increased fuel consumption, while high Wobbe fuels yielded decrease fuel consumption. Changes in brake-specific fuel consumption were mainly due to variations in the energy density of the test fuels. Other factors that likely impacted fuel consumption were AFR and charge burn rate.

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