Appendix E – CNG Engine Performance

The variation in CNG composition seen throughout the South Central Coast and southern San Joaquin Valley can adversely affect engine performance. These effects can include misfire, stumble and underrated operation[1] as well as engine knock and overheating. These effects are dependent on the engine's ability to tolerate or compensate for the variation in fuel composition.

A. Stoichiometric Burn Engines

Engines designed for an air/fuel ratio that can completely burn the fuel without excess air remaining are called stoichiometric burn engines. Light-duty engines are stoichiometric burn engines. Stoichiometric burn engines have been used for light-duty application because they can be equipped with three-way catalyst exhaust after-treatment technology to meet light-duty vehicle exhaust emissions standards.[2] Additionally, the stoichiometric exhaust properties allow the use of a standard stoichiometric exhaust gas oxygen sensor for feedback control of the air/fuel ratio.[3] This feedback control improves engine performance with variable gas properties. However, these advantages come at a price of reduced fuel economy and higher combustion temperatures.

Stoichiometric light-duty engines are also more tolerant of variations in fuel composition. Stoichiometric conditions contain neither excess air nor excess fuel that would serve to dilute the combustion products and reduce combustion temperatures. Consequently, stoichiometric conditions are hotter or more severe than off-stoichiometric conditions and are more likely to cause knock, or detonation, than either richer (more fuel) or leaner (less fuel) conditions. Detonation occurs when there is uncontrolled combustion with multiple flame fronts rather than the combustion proceeding smoothly along a flame front from a single source of ignition, the spark plug.[4, 5] Detonation can be extremely damaging to hardware. Consequently, stoichiometric engines are designed to tolerate the most severe conditions, thus, changes in air/fuel ratio due to variable fuel quality moves the engine operation off stoichiometric to more benign conditions.[6]

B. Lean-Burn Engines

Engines designed to operate at an air/fuel ratio with more air than required to completely burn the fuel, referred to as excess air or lean fuel conditions, are called lean-burn engines. Medium and heavy-duty engines are usually designed as lean-burn engines because these engines are more fuel-efficient and produce lower combustion temperatures than stoichiometric burn combustion. This engine technology has been used to meet applicable exhaust emission standards without the use of after-treatment technology. Excess air both ensures that all the fuel is burned and dilutes the combustion products to reduce the combustion gas temperature. The lower combustion temperatures minimize NOx emissions without after-treatment as well as increase hardware life.

Lean-burn engines are more susceptible to problems arising from variable fuel quality. Most lean-burn heavy-duty engines are designed to operate close to the lean mis-fire zone to minimize

NOx emissions.[1] The lean mis-fire zone is the operating zone where there is too little fuel for the air provided to sustain the burning process. Changes in fuel quality for a lean burn engine can result in mis-fire if the change results in leaner conditions, or detonation and/or overheating if the change results in richer conditions.

C. Open Loop and Closed Loop Systems

All light duty stoichiometric burn engines include feedback controls that process information from the exhaust to aid in engine operation. This is called a closed loop system. Lean-burn engines can be designed either with or without feedback controls. Engines without feedback controls are called open loop systems. Open loop systems use a predetermined "map" of load and speed to determine the engine fuel injection requirements.[1] A certain fuel composition must be assumed to generate this "map". Consequently open loop systems are less tolerant of changes in fuel composition. Engines with closed loop systems have computers that use measurements of the oxygen content of the exhaust stream combined with information about the mode of operation (i.e. throttle level and fuel flow) to adjust engine operation for fuel quality.[1] The exhaust stream oxygen concentration allows the computer to determine how much excess air the engine is running. Light duty stoichiometric burn engines can use a standard stoichiometric exhaust gas oxygen sensor for the necessary feedback controls. However, lean burn heavy-duty engines require a special sensor, (such as a universal exhaust gas oxygen (UEGO) sensor) and/or a special computerized program for engine control.[3] Consequently, not all lean-burn closed loop systems provide the same degree of engine control. First generation systems are more susceptible to fuel quality related operational problems than more recent advanced generation systems. In general however, closed loop systems are more tolerant of changes in fuel composition.

Some higher compression ratio heavy-duty lean burn engines include an additional feedback for knock detection. Higher compression ratio makes an engine more susceptible to knock or detonation. If knock is detected via an accelerometer, the spark plug timing can be retarded, or caused to spark later in the cycle, to reduce knock.[5, 7] Retarding the timing, however, can reduce fuel economy.

D. Gas Quality Requirements

Two measures of CNG gas quality are the Wobbe Index and the methane number. The Wobbe Index is a measure of the fuel interchangeability with respect to its energy content and metered air/fuel ratio.[6, 8] Thus, changes in Wobbe Index can affect the engine's metered air/fuel ratio and power output.[9] The Wobbe Index is calculated from the energy content, or higher heating value of the gas, and the relative density of the gas. The relative density of the gas is the ratio of the gas density to the density of air.

Wobbe Index = Higher Heating value / (relative density)

The methane number is a measure of the knock resistance of the fuel. Knock, or detonation, can be extremely damaging to an engine. Knock occurs when there is uncontrolled combustion with multiple flame fronts rather than smooth combustion proceeding along a flame front initiated at the spark plug.[4,5]Knock can result from the heat produced by compression of the air/fuel gas mixture in the piston. The knock resistance of the fuel is a function of the fuel composition. Methane has a very high knock resistance. The heavier hydrocarbons in CNG, such as ethane, propane, and butane, have lower knock resistance and thus reduce the overall knock resistance of the fuel. Methane number and how it is determined in explained in Appendix D.

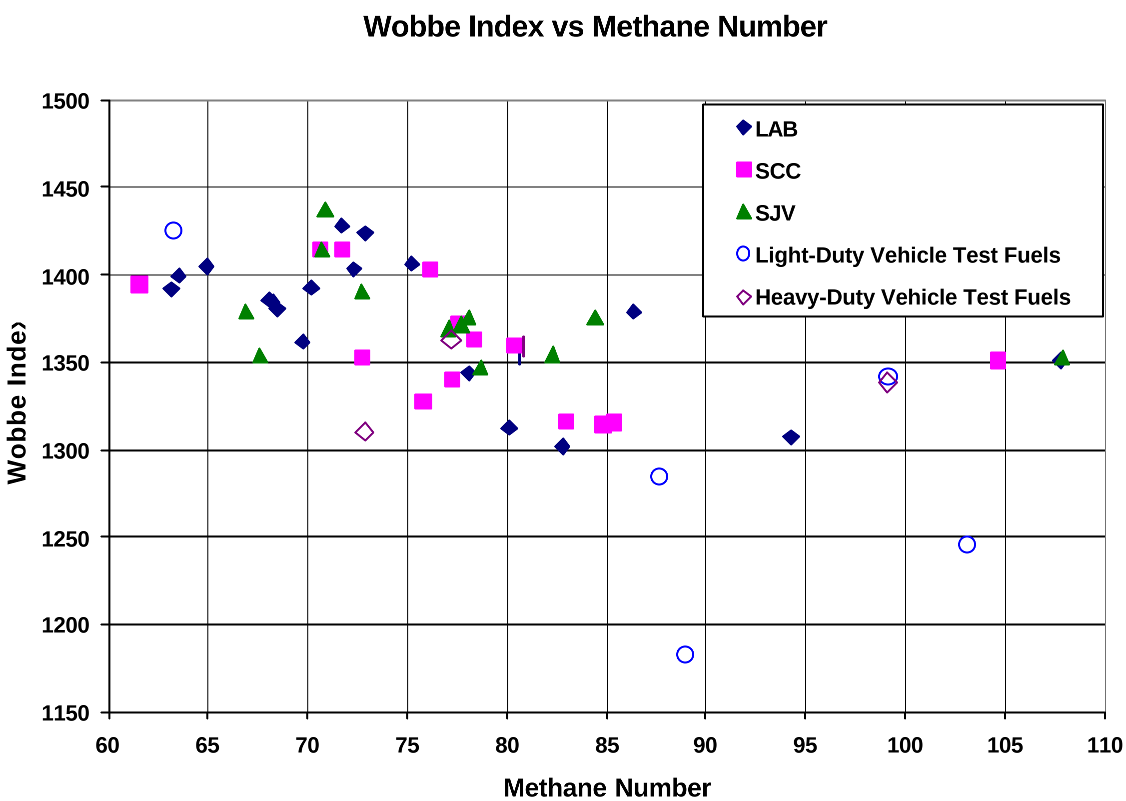
1. Light Duty Engines

Light duty natural gas engines run at stoichiometric burn conditions (sufficient air to completely burn the fuel without excess air remaining) and use closed loop control, making them extremely tolerant of the natural gas fuel variations seen in California. A survey of light duty vehicle manufacturers indicated that fuel quality requirements for light duty engines are more frequently cited in terms of Wobbe Index.

Wobbe Index values given as vehicle requirements range from approximately a minimum of 1300 BTU/ft3 to a maximum of 1400 to 1500 BTU/ft3.[10, 9] This requirement range encompasses the entire fuel quality range reported for the California South Central Coast (SCC), southern San Joaquin Valley (SJV), and the Los Angeles Basin (LAB) regions of approximately 1300 BTU/cu.ft. to 1450 BTU/cu.ft., as shown in Figure 1 below.[11] From this figure it can also be seen that this range encompasses methane numbers down to 65 to70.

Testing to determine the effect of fuel quality on emissions and driveability, discussed in Appendix B, was conducted using eight light-duty natural gas vehicles (NGV) with five different fuel qualities, ranging from a Wobbe Index of 1182 BTU/cu.ft. to 1425 BTU/cu.ft.[12] Staff calculated the methane number range for these fuels to be MN 65 to MN 100. The Wobbe Index and methane number for these test fuels are shown plotted in Figure E-1. Test results showed that for dedicated NGVs, even large variations in fuel composition produced only small variations in the emissions and driveabliltiy, while bifuel vehicles had only modest changes in emissions and performance.[12, 13]

Figure E-1: Wobbe Index and Methane Number Variations of California CNG Fuel [11, 12, 15]



2. Heavy Duty Engines

A survey of heavy duty vehicle manufacturers indicated that fuel quality requirements for heavy duty engines are more frequently cited in terms of methane number or motor octane number. Motor octane number and methane number are linearly related, as shown in Appendix D. A methane number of 80 is required for both open loop and first generation closed loop lean-burn heavy duty engines. However, more recent advanced generation closed loop lean-burn heavy-duty engines can tolerate a fuel quality down to a methane number of 73. Additionally, there are closed loop engines recently certified by ARB as a low emissions engine that can tolerate methane numbers as low as 65.[14]

Testing to determine the effect of fuel quality on emissions was conducted on seven heavy-duty vehicles using four fuels.[15] The results of this testing is summarized in Appendix B. The seven vehicles included five closed loop systems and two open loop systems. Three of the closed loop systems were recent advanced generation systems and the others were first generation systems. The results from one of the closed loop systems, an LNG vehicle, were excluded from the final data presentation due to problems with the vehicle operation. The four fuels tested included a high quality commercial grade fuel with a methane number of 99, a high ethane fuel with a methane number of 81, a high C3+ fuel with a methane number of 79, and a high inerts, ethane and C3+ fuel with at methane number of 73. Only the high quality commercial grade fuel complied with the current CNG motor vehicle fuel specifications. Based on staff calculations, the CNG certification fuel equates to a methane number of approximately 86 to 87 and the CNG in use fuel equates to a methane number of approximately 80 to 82. The high ethane fuel with a methane number of 81 is comparable in terms of methane number to the current minimum fuel quality specifications. Consequently, the emissions effects of allowing advanced generation closed loop systems to use fuel with a methane number of 73 can be evaluated based on a comparison to the methane number 81 fuel. There were increases in carbon dioxide (CO_2) and nonmethane hydrocarbon (NMHC) emissions of six percent and approximately 10 percent respectively. There were no discernable impacts on the other emissions.

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[3] Clark, Nigel n., Atkinson, Christopher M., Lyons, Donald W., Mott, Gregory E., and deJong, Remco J., "Development of a Closed Loop Fuel Management System for a Lean Burn Natural Gas Engine", Proceedings of the 1994 Automotive Technology Development Contractors' Coordination Meeting, *Society of Automotive Engineers, Inc.*, SAE P-289, 1994

[4] "Octane Determination in Piston Engines," http://www.prime-mover.org/Engines/GArticles/octane.html.

[5] Bohacz, R.T., "The Causes of Engine Knock, and How to Eliminate it," http://www.zhome.com/ZCMnL/PICS/detonation/detonation.html.

[6] King, Steven R., "The Impact of Natural Gas Composition on Fuel Metering and Engine Operational Characteristics", Southwest Research Institute, *Society of Automotive Engineers, Inc.*, SAE 920593, 1992.

[7] Paul Delong of John Deere, Telephone conversation with ARB Staff, 3/6/01.

[8] <u>North American Combustion Handbook</u>, Vol. I, Third Edition, North American Mfg. Co., Cleveland, OH 44105, 1986.

[9] SAE Standard J1616, Surface Vehicle Recommended Practice, Recommended Practice for Compressed Natural Gas Vehicle Fuel, *Society of Automotive Engineers, Inc.*, Feb 1994.

[10] Ben Knight of Honda R&D Americas, Email message to ARB Staff, 18 June 2001.

[11] Compiled Southern California Gas Data provided to ARB Staff on July 18, 2001, August 1, 2001, and August 2, 2001.

[12] Bevilacqua, Oreste M., Ph.D., "Natureal Gas Vehicle Technology and Fuel Performance Evaluation Program", File No. Z-19-2-13-96, Clean Air Vehicle Technology Center, April 1, 1997.

[13] Bevilacqua, Oreste M., Ph.D., "Impact of Natural Gas Composition on Light-Duty Vehicle Emissions, Fuel Econogy and Driveability, Project Overview", Clean Air Vehicle Technology Center.

[14] Cummins Press release, "Cummins Westport Inc. C8.3G Plus natural gas engine certified by California," http://www.cummins.com/na/pages/en/mediaresources/pressreleases/pressrelease.cfm?uuid=D51BA786-073E-11D4-985C0004AC33EA57, Vancouver, B.C., 32 July 2001.

[15] Bevilacqua, Oreste M., Ph.D., "Impacts of Natural Gas Fuel Composition on Tailpipe Emissions and Fuel Economy", ARB Public Workshop on the Alternative Fuels Regulations, Sacramento, CA, June 21, 2000.