**BEFORE THE PUBLIC UTILITIES COMMISSION**

**OF THE STATE OF CALIFORNIA**

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| Order Instituting Rulemaking to Establish Policies and Rules to Ensure Reliable, Long-Term Supplies of Natural Gas to California. | R.04-01-025<br>(Filed January 22, 2004) |

# SUPPLEMENT TO COMMENTS OF SAN DIEGO GAS & ELECTRIC COMPANY (U 902 G) AND SOUTHERN CALIFORNIA GAS COMPANY (U 904 G) ON NATURAL GAS QUALITY ISSUES

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February 14, 2005

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In the "Comments of San Diego Gas & Electric Company and Southern California Gas Company on Natural Gas Quality Issues" filed February 11, 2005, the SWRI "Cummins" report was inadvertently omitted from Attachment "B." Accordingly, a revised Attachment "B" that includes the SWRI "Cummins" report is attached hereto.

DATED this 14th day of February, 2005, and Los Angeles, California.

Respectfully submitted,

By: ____________________
David J. Gilmore

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# ATTACHMENT B

# Heavy-Duty CNG Vehicle Natural Gas Quality Study

As part of the on-going efforts to understand the potential impact of changes in natural gas quality standards within California, SDG&E and SoCalGas have assessed how compressed natural gas (CNG) vehicles may react to fuel composition outside the current CARB CNG fuel specification[1]. In particular, SDG&E and SoCalGas have focused on older, heavy-duty CNG vehicles, which have less adaptable control systems than light-duty CNG vehicles.

As of the end of October, 2003, SDG&E and SoCalGas had surveyed customers with known fleets of heavy-duty CNG vehicles as well as all customers billed under the G-NGV tariffs. These surveys collected the following information:

- Number of heavy-duty, CNG engines by manufacturer make and model
- Engine production year
- Engine expected life (based on customer feedback).
- Fleet type (transit, school bus, waste hauler, street sweeper, other)

The results of the survey are summarized in Exhibit 1, which shows the complete inventory of all heavy-duty CNG vehicles within Southern California as of October, 2003.

Based upon the results of the survey, SDG&E and SoCalGas began to contact heavy-duty CNG engine manufacturers to obtain fuel specification and performance data for each engine make and model operating in significant numbers. For the purpose of comparison, each of the manufacturer fuel specifications was reduced to a Methane Number (MN) as well as the current CARB CNG fuel specification, which ranges from MN 72.5 to MN 108.4[2]. The results of the heavy-duty CNG engine

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[1] The CARB CNG fuel specification is located in California Code of Regulations Title 13, Division 3, Chapter 5, Article 3, Section 2292.5.

[2] The Methane Number (MN) is a measure of the knock resistance of the fuel, calculated using the formula MN = 1.624*(MON)-119.1, where MON = -406.14+508.04(H/C)-173.55(H/C)2+20.17(H/C)3 and H/C is the reactive hydrogen/carbon ratio.

manufacturer discussions are summarized in Exhibit 2, which shows that only 17.8% of the engine makes and models in the inventory can operate on natural gas that is less than MN 80. However, more than half of the entire inventory is made up of engines manufactured by Detroit Diesel Corporation ("Detroit Diesel"). According to discussions with Detroit Diesel, a single CNG fuel specification was developed for the initial version of the Series 50G engine, but never updated as subsequent, more advanced versions of the engine were developed and commercialized. Since there are a large number of these more advanced versions of the Series 50G engine in operation, it is of great interest to all stakeholders to understand whether it is possible to update the Series 50G fuel specification. Unfortunately, all efforts by SDG&E and SoCalGas to engage Detroit Diesel in this effort have been met with little or no response.

Although most of the heavy-duty CNG engines produced today are capable of operating on natural gas below MN 73, this only represents a small fraction of the engines in the inventory. The impact of this fact is illustrated in Exhibit 3, which shows how the inventory of heavy-duty CNG engines that cannot operate on natural gas below MN 73 changes over time. The majority of these engines are forecast to the end of their useful life by 2019.

SDG&E and SoCalGas subsequently contracted with a third-party heavy-duty CNG engine expert, the Southwest Research Institute (SWRI), to develop reports that include theoretical assessments of the fuel specification range that relevant Cummins and Detroit Diesel heavy-duty CNG engines could safely operate within. Further, each report was to provide options (engine retrofit, engine replacement) and estimated costs for engines incapable of operating on natural gas below MN 73. The SWRI "Cummins" report is included as Exhibit 4.

The SWRI "Cummins" report assesses the ability of Cummins heavy-duty engines no longer in production to operate on the lowest possible MN natural gas that still meets the SoCalGas Rule 30 natural gas quality standards (approximately MN 70). The Cummins engines evaluated include the L10 Phase 1, L10 Phase 2, L10 Phase 3, B5.9G, and C8.3G. The report recommends that all of the engines evaluated be retrofitted or replaced in order to operate reliably on varying natural gas composition. Based on the report cost estimates as well as the number of each engine make and model in the inventory, the following table shows the total costs estimated for each option:

| Cummins Engine Model | Estimated Number of Engines | Engine Retrofit | Engine Replacement |
|---|---|---|---|
| L10 Phase 1 | 81 | $1,057,200 | $3,315,000 |
| L10 Phase 2 | 5 | $206,000 | $275,000 |
| L10 Phase 3 | 618 | $879,800 | $24,795,000 |
| B5.9G | 95 | $1,140,000 | Not recommended |
| C8.3G | 173 | $2,076,000 | Not recommended |
| Total | 972 | $5,359,000 | $28,385,000 |

Although the engine retrofit option appears to be the lowest cost option, it should be noted that these costs assume no significant problems in developing and installing engine retrofits for each engine make and model. Further, the issue of manufacturer acceptance and potential impact of third party retrofits on manufacturer guarantees and/or warrantees have not been addressed. Lastly, since the cost estimate was based on theoretical studies and inventory data collected solely through SDG&E and SoCalGas records, it should be stressed that these figures are only an estimate that may change as more data is collected over time.

A CARB Staff Report released on December 21, 2001 entitled "Proposed Amendments to the California Alternative Fuels for Motor Vehicle Regulations" offers several insights on the impact of changing natural gas fuel composition on various heavy-duty CNG engines and can be found at http://www.arb.ca.gov/regact/cng-lpg/isor.pdf. Page I-3, Part 2d of the report offers the following response to the question "How will these proposed amendments affect engine performance?"

> "Engine manufacturers recommend that open loop and first generation closed loop technology CNG engines utilize fuel that meets a minimum MN of 80. This specification allows these

> engines to properly operate and maintain performance. Advanced technology closed loop engines are equipped with improved feedback controls which allow these engines to operate on a broader range of fuel quality. Engine manufacturers believe that advanced technology engines can properly operate on CNG with a MN of 73."

Page I-6 of the report offers the following response to the question "How will the proposed amendments affect exhaust emissions?"

> "Test results show that for dedicated light-duty NGVs, large variations in fuel composition produced only slight variations, both increases and decreases, in emissions and driveability. Also bi-fuel vehicles had only modest changes in emissions and performance with changes in CNG quality. Heavy-duty vehicle test data shows that fueling advanced generation engine technologies with MN 73 fuel produced no discernible impact on the particulate matter (PM) and oxides of nitrogen ($NO_X$) emissions when compared to emissions from higher quality fuels with MN greater than 80. There were very small increases in carbon dioxide ($CO_2$) and non-methane hydrocarbon (NMHC) emissions."

Although the engine testing in the report did not include every make and model of heavy-duty CNG engine currently in operation throughout Southern California, the test results suggest that changing the CARB CNG fuel specification to a Methane Number standard as low as MN 73 will not affect the emissions and performance of modern heavy-duty CNG engines.

SDG&E and SoCalGas are currently working with SWRI to develop a set of heavy-duty CNG engine testing procedures that will be used to test engines currently in operation in Southern California. These tests will serve to validate conclusions reached in the SWRI "Cummins" and "Detroit Diesel" reports as well as the CARB Staff Report entitled "Proposed Amendments to the California Alternative Fuels for Motor Vehicle Regulations." Regardless of the outcome of these engine tests, however, it is imperative that key stakeholders interested in changing natural gas quality specifications realize that heavy-duty

CNG engine manufacturers must be receptive to any recommended changes in order to ensure engine warrantees (implicit or explicit) are not invalidated through the use of fuel that does not meet the manufacturer engine fuel specification or the use of engine retrofit equipment. This is particularly important with respect to Detroit Diesel, since Detroit Diesel engines make up over 50% of the existing inventory of CNG heavy-duty engines and Detroit Diesel has been unresponsive to requests to update their engine fuel specification.

# Exhibit 1

| Engine Type | SoCalGas | % | SDG&E | % | Total | % | Cumulative % |
|---|---|---|---|---|---|---|---|
| Detroit Diesel - 50G Series (Oct 1998 through Sep 2002) | 1,567 | 53.4% | 128 | 28.6% | 1,695 | 50.1% | 50.1% |
| Cummins - L10 Phase 3 | 618 | 21.1% | 0 | 0.0% | 618 | 18.3% | 68.4% |
| John Deere - 6081H | 301 | 10.3% | 102 | 22.8% | 403 | 11.9% | 80.4% |
| Cummins - C8.3G | 103 | 3.5% | 70 | 15.6% | 173 | 5.1% | 85.5% |
| Cummins - C8.3G Plus | 53 | 1.8% | 105 | 23.4% | 158 | 4.7% | 90.1% |
| Cummins - B5.9G | 81 | 2.8% | 14 | 3.1% | 95 | 2.8% | 93.0% |
| Cummins - L10 Phase 1 | 74 | 2.5% | 7 | 1.6% | 81 | 2.4% | 95.4% |
| Detroit Diesel - 50G Series (Oct 2002 to present) | 76 | 2.6% | 0 | 0.0% | 76 | 2.2% | 97.6% |
| Cummins - B5.9G Plus | 13 | 0.4% | 13 | 2.9% | 26 | 0.8% | 98.4% |
| John Deere - 6068H | 6 | 0.2% | 9 | 2.0% | 15 | 0.4% | 98.8% |
| Tecogen | 14 | 0.5% | 0 | 0.0% | 14 | 0.4% | 99.2% |
| Mack - E7G Series | 10 | 0.3% | 0 | 0.0% | 10 | 0.3% | 99.5% |
| Caterpillar - Dual Fuel | 10 | 0.3% | 0 | 0.0% | 10 | 0.3% | 99.8% |
| Cummins - L10 Phase 2 | 5 | 0.2% | 0 | 0.0% | 5 | 0.1% | 100.0% |
| Detroit Diesel - 50G Series (1994 through Sep 1998) | 1 | 0.0% | 0 | 0.0% | 1 | 0.0% | 100.0% |
| Total | 2,932 | 100.0% | 448 | 100.0% | 3,380 | 100.0% | |

| Fleet Type | SoCalGas | % | SDG&E | % | Total | % | Cumulative % |
|---|---|---|---|---|---|---|---|
| Transit | 2,425 | 82.7% | 344 | 76.8% | 2,769 | 81.9% | 81.9% |
| School Bus | 259 | 8.8% | 104 | 23.2% | 363 | 10.7% | 92.7% |
| Waste Hauler | 179 | 6.1% | 0 | 0.0% | 179 | 5.3% | 98.0% |
| Street Sweeper | 37 | 1.3% | 0 | 0.0% | 37 | 1.1% | 99.1% |
| Other | 32 | 1.1% | 0 | 0.0% | 32 | 0.9% | 100.0% |
| Total | 2,932 | 100.0% | 448 | 100.0% | 3,380 | 100.0% | |

# Exhibit 2

| Engine Manufacturer | Engine Model | Inventory | | Manufacturer Fuel Requirements | Minimum Methane Number[1] | Notes |
|---|---|---|---|---|---|---|
| | | count | % | | | |
| Cummins | L10 Phase 1 | 81 | 2.4% | Cummins Engineering Standard (CES) 20067, which is a prescriptive specification for natural gas composition. The Wobbe index must be between 1300 and 1377 as measured by ASTM D 3588. | 83.8 | Engine no longer produced. |
| | L10 Phase 2 | 5 | 0.1% | | | Engine no longer produced. |
| | L10 Phase 3 | 618 | 18.3% | Cummins Engineering Standard (CES) 14604. The methane number based on SAE 922359 must not be below 80 and the higher heating value must not be below 975 BTU/scf. | 80 | Engine no longer produced. |
| | B5.9G | 95 | 2.8% | | | Engine no longer produced. |
| | C8.3G | 173 | 5.1% | | | Engine no longer produced. |
| | B+5.9G | 26 | 0.8% | Cummings Engineering Standard (CES) 14608. The methane number based on SAE 922359 must not be below 65 and the lower heating value must not be below 18,800 BTU/lbm. | 65 | - |
| | C+8.3G | 158 | 4.7% | | | - |
| Detroit Diesel | 50G (manufactured from 1994 through September, 1998) | 1 | 0.0% | Detroit Diesel provided a prescriptive specification for natural gas composition. The Wobbe index must be between 1290 and 1380 as measured by ASTM D 3588. | 83.7 | Engine no longer produced. |
| | 50G (manufactured from October, 1998 through September, 2002) | 1,695 | 50.1% | | | Engine no longer produced. |
| | 50G (manufactured after September, 2002) | 76 | 2.2% | | | - |
| John Deere | 6068H | 15 | 0.4% | John Deere provided a minimum Motor Octane number of 118. | 72.5 | Engine no longer produced. |
| | 6081H | 403 | 11.9% | | | Discussions with John Deere indicate the 6081-HFN04 engine currently in production can operate on a minimum Octane number of 116 (implies a minimum Methane Number of 69.3). |
| All | | 3,346 | 99.0% | - | - | - |

[1] Minimum methane number was calculated, if not explicitly specified, using "worst case" gas composition data from the manufacturer fuel requirements.

**Exhibit 3**

# Southern California CNG Heavy-Duty Engine Demographics

(Makes and models unable to operate on sub MN 73 natural gas, per existing fuel specifications)

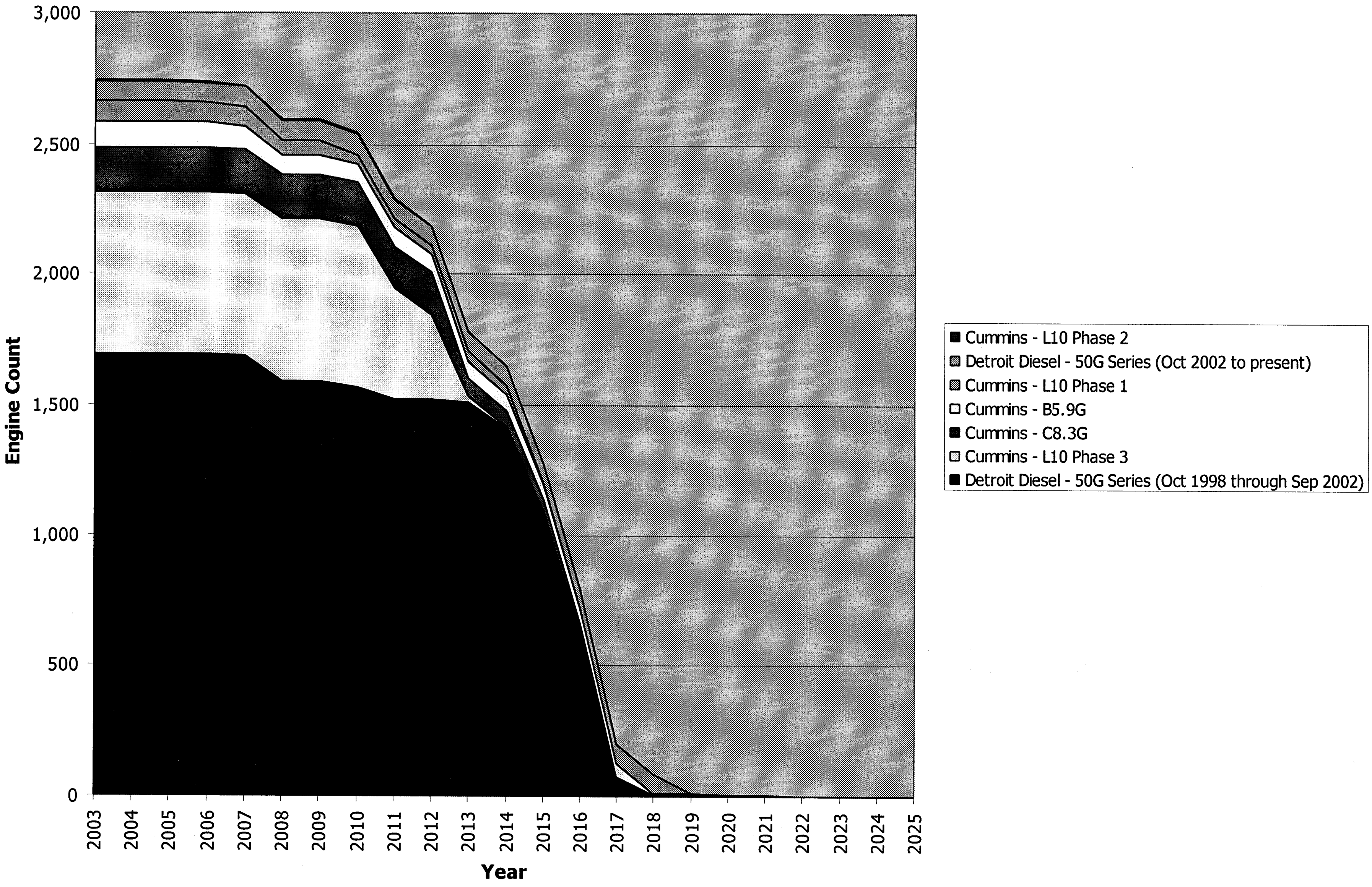

**Exhibit 4**

# Paper Study on the Effect of Varying Fuel Composition on Cummins Gas Engines

## FINAL REPORT

## SwRI Project No. 03.32.40.10646

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**December 13, 2004**

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**Engine and Emissions Research Department**

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## 1. INTRODUCTION

A paper study was conducted to examine the effect of varying fuel composition on specific Cummins natural gas engines. The fuel composition range was bounded by the specification in California Public Utilities Commissions (CPUC) Rule 30, and used a composition expected to represent LNG imports. The specifications for CPUC Rule 30 are shown in Table 1. Available options to best enable these engines to operate on the fuel composition range are described in the following sections.

**Table 1. CPUC Rule 30 Specification**

| Specification | Min | Max |
|---|---|---|
| BTU/cu. Ft. | 970 | 1150 |
| Wobbe Index | 1272* | 1437* |
| Methane Number | NA | NA |
| Methane (%) | NA | NA |
| Ethane (%) | NA | NA |
| Propane (%) | NA | NA |
| Inerts (%) | 0 | 4 |

* Theoretical Min and Max based on CPUC Rule 30 Gas Quality Specification

## 2. BACKGROUND

The composition of natural gas is typically methane with small amounts of ethane, propane, butane, carbon monoxide, nitrogen, and other trace components. It is possible for natural gas composition to vary, depending on the source of the natural gas. Replacing the methane content with higher hydrocarbon components such as ethane, propane, butane, etc. can cause natural gas engines to knock due to the lower knock resistance of the fuel, which could cause severe damage to the engine. In addition, decreasing methane content and increasing the amount of heavy hydrocarbons can vary the metered equivalence ratio to the engine and modify the burn rates of the air/fuel mixture, affecting performance and emissions. Even inert components such as nitrogen and carbon dioxide can cause performance problem, such as misfire, in a natural gas engine. The extent of the effects of natural gas composition on an engine depends on the individual engine (combustion chamber design, fuel delivery system, etc.), the power level of the engine (higher power reduces the knock margin), and the engine control system (open loop or closed loop, carburetor or fuel injection, etc.).

One of the major concerns of varying natural gas composition is engine knock. The anti-knock property of a natural gas fuel can be expressed as a methane number. Pure methane has a methane number of 100, and pure hydrogen has a methane number of 0. The percentage of methane in a methane-hydrogen mixture is the methane number of that mixture. This is similar to the scale used for the octane number of gasoline. Octane rating is not an appropriate scale for natural gas since the octane scale only goes up to 120, and methane has an octane rating in excess of 120. Since the methane number of various natural gas compositions can vary considerably, there may be a problem with knock on some engines.

The determination of the methane number of a fuel is conducted under a prescribed engine test. During the test, the compression ratio of the engine is increased until knock is detected. Mixtures of methane and hydrogen are then run in the engine. The mixture that produces knock at the same compression ratio as the fuel being tested determines the methane rating of that fuel. The time and cost associated with performing the test makes this approach impractical. Two mathematical alternative methods to determine methane number for the gas composition are the California Air Resources Board (CARB) method and the AVL method. The CARB method uses the equation developed in SAE Paper 922359, which is:

$$MN = 1.624*(-406.14+508.04*(H/C)-173.55*(H/C)^2+20.17*(H/C)^3)-119.1$$

The AVL method uses a proprietary program to calculate methane number. Some examples of methane number calculations of some gas compositions are shown in Table 2. The AVL method produces an average of 0.6% lower MN than the actual test value using gases 1-4. The CARB method produces and average of 8.6% higher MN than the actual test value using gases 1-4. The CARB method also produces an average of 7.9% higher MN than the AVL method using all of the gases presented in Table 2.

**Table 2. Methane Number Comparison**

| | Gas 1 | Gas 2 | Gas 3 | Gas 4 | CARB * | 70 MN by CARB Method | | | 70 MN by AVL Method | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Methane | 100.0 | 95.0 | 90.1 | 85.0 | 90.45 | 78.1 | 85.4 | 89.05 | 81.0 | 88.2 | 92.5 |
| Ethane | 0.0 | 3.0 | 6.0 | 6.5 | 4.02 | 21.9 | 7.3 | 0.0 | 19.0 | 5.9 | 0.0 |
| Propane | 0.0 | 0.5 | 0.7 | 3.0 | 2.01 | 0.0 | 7.3 | 10.95 | 0.0 | 5.9 | 7.5 |
| Butane | 0.0 | 0.5 | 0.8 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $CO_2$ | 0.0 | 0.2 | 0.7 | 1.0 | 84.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Nitrogen | 0.0 | 0.8 | 1.7 | 3.5 | 3.52 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| H/C | 4.00 | 3.89 | 3.82 | 3.72 | 3.88 | 3.64 | 3.64 | 3.64 | 3.68 | 3.70 | 3.74 |
| Wobbe | 1354 | 1358 | 1350 | 1337 | 1328 | 1445 | 1444 | 1444 | 1433 | 1427 | 1416 |
| Actual MN | 100.0 | 85 | 79 | 72 | | | | | | | |
| CARB MN | 108.4 | 94.0 | 86.2 | 76.5 | 89.0 | 70.0 | 70.0 | 70.0 | 73.2 | 74.7 | 78.2 |
| AVL MN | 100.0 | 84.4 | 77.9 | 71.7 | 81.3 | 67.8 | 66.5 | 64.3 | 70.0 | 70.0 | 70.0 |

* Natural Gas Composition Used to Certify and Engine for CARB

In addition to the anti-knock quality, how an engine operates on a low methane number fuel may be important. The low methane number is usually a result of high hydrocarbons in the fuel. High hydrocarbons in natural gas change the energy density (energy content per volume) of the fuel, the hydrogen to carbon (H/C) ratio of the fuel, and the burn rates in the engine. The energy density change needs to be accounted for in the fueling system. If it is not accounted for, the change in energy density may increase both the power and equivalence ratio. A power and/or equivalence ratio increase will reduce the knock margin of an engine. The change in H/C ratio can effect the equivalence ratio on closed loop systems. The Universal Exhaust Gas Oxygen (UEGO) sensor used for closed loop control of equivalence ratio is typically calibrated for a specific H/C ratio. As the H/C ratio increases, the calibration of the UEGO sensor will cause the engine to run richer than desired, which reduces the knock margin. With increased burn rates, the combustion phasing (ignition timing relative to minimum for best torque (MBT)), effectively advances, reducing the knock margin.

Knock for this study was determined by a correlation of data using methane number, compression ratio, BMEP, engine speed, equivalence ratio, ignition timing and manifold air temperature as the inputs. Determination of knock is only an estimate based on a correlation. The actual knock can be determined by knock testing of the engine.

## 3. TECHNICAL DISCUSSION/RESULTS

There are five specific engines of interest for this study. A list of the engines is shown in Table 3. None of these engines has knock detection. The first two engines have similar fueling systems, and the last three engines have similar fueling systems. The following technical discussions of these engines will be grouped by fuel system, either carburetor/open loop or fuel valve/mixer/closed loop.

**Table 3. Specific Engines of Interest**

| Engine | Model | Fuel Induction | Fuel Control |
|---|---|---|---|
| Cummins L10G | Phase 1 | Carburetor | Open Loop |
| Cummins L10G | Phase 2 | Carburetor | Open Loop |
| Cummins L10G | Phase 3 | Fuel Valve/Mixer | Closed Loop |
| Cummins B5.9G | | Fuel Valve/Mixer | Closed Loop |
| Cummins C8.3G | | Fuel Valve/Mixer | Closed Loop |

Table 4 shows the properties of the CARB certification gas and the richest case gas used for the analysis that meets CPUC Rule 30 (using the CARB method to determine methane number). This richest case gas is representative of LNG imports and is limited by the maximum energy content. The Methane Number of the CARB gas is 89.0 (CARB method) or 81.3 (AVL Method). The Methane Number of the richest case gas is 70.9 (CARB Method) or 67.8 (AVL Method).

**Table 4. Gas Properties**

| Property | CARB Gas (for certification) | Richest Case Gas |
|---|---|---|
| Methane | 90.45 | 84.00 |
| Ethane | 4.02 | 8.10 |
| Propane | 2.01 | 6.30 |
| Butane | 0.00 | 0.00 |
| N2 | 3.52 | 1.60 |
| CO2 | 0.00 | 0.00 |
| AVL MN | 81.3 | 67.8 |
| CARB MN | 89.0 | 70.9 |
| BTU/SCF | 1035 | 1150 |
| Wobbe Index | 1323 | 1430 |

### 3.1 Carburetor/Open Loop Fuel Systems

The two engines with a carburetor/open loop fuel system are the Cummins L10G Phase 1 and L10G Phase 2. Both of these engines use an Impco carburetor for fuel induction and fuel metering. Engine specifications are shown in Table 5.

**Table 5. Engine Specifications**

| Engine | L10G Phase 1 | L10G Phase 2 |
|---|---|---|
| Configuration | Inline 6 | Inline 6 |
| Aspiration | Turbocharged & Aftercooled | Turbocharged & Aftercooled |
| Bore (mm) | 125 | 125 |
| Stroke (mm) | 136 | 136 |
| Displacement (l) | 10 | 10 |
| Compression Ratio | 10.5:1 | 10.5:1 |
| Power (kW) | 179 | 194 |
| Power (bhp) | 240 | 260 |
| Torque (N-m) | 1017 | 1152 |
| Torque (lb-ft) | 750 | 850 |
| BMEP (bar) | 12.8 | 14.5 |
| Year Model | 1991-1993 | 1994-1995 |

The Cummins fuel standard for these two engines is CES 20067. This specifies a chemical composition as shown in Table 6 and a Wobbe index of 1300 to 1377. A fuel with a Wobbe index of 1377 should have a MN number of approximately 88 (CARB method) or 80 (AVL Method).

**Table 6. CES 20067 Chemical Composition**

| Constituents | Requirements |
|---|---|
| Methane | 90.0% volume minimum |
| Ethane | 4.0% volume maximum |
| Propane | 1.7% volume maximum |
| Butane and Heavier | 0.7% volume maximum |
| Carbon Dioxide and Nitrogen | 3.0% volume maximum |
| Hydrogen | 0.1% volume maximum |
| Carbon Monoxide | 0.1% volume maximum |
| Oxygen | 0.5% volume maximum |
| Sulfur | 0.001% weight maximum |

The equivalence ratio or phi (stoichiometric air-fuel ratio divided by the actual air-fuel ratio) can vary as the methane number changes with a carburetor/open loop system. A lower methane number usually results in a higher equivalence ratio (richer operation) for a given carburetor setting due to the change in molecular weight of the fuel. The typical equivalence ratio for a carburetor/open loop system is 0.70. It is not recommended to set the equivalence ratio less than 0.70 for an open loop system due to possible lean misfires. Actual equivalence ratio information for these engines was not available.

Power can also vary due to the energy density changes of the fuel changes in carburetor/open-loop systems. Assuming the efficiency of the engine does not change, there will be an increase in power by 11.1% with an open loop system when changing from the CARB gas to the richest case gas.

Variation in burn-rate is another parameter that varies when an open-loop/carburetor system encounters varying gas composition. Both the increase in equivalence ratio and change in fuel properties increase the burn rate. Increasing the burn rate at a constant ignition timing effectively advances the combustion process, which decreases the knock margin of an engine. If an engine is operating at an ignition timing that is retarded from the minimum for best torque (MBT), an increase in burn rate will bring the engine closer to MBT (effectively advancing ignition timing). Ignition timing information for these engines was not available.

The following assumptions were made regarding the L10G Phase 1 and Phase 2 engines for this study:

- The Phase 1 engine was designed to operate at an equivalence ratio of 0.75 on CARB gas
- The Phase 2 engine was designed to operate at an equivalence ratio of 0.70 on CARB gas
- Ignition timing is 20 °BTDC for both Phase 1 and Phase 2 engines
- The Manifold Air Temperature is 150 °F (worst case)

### *3.1.1 L10G Phase 1 Engine*

The Cummins L10G Phase 1 engine is rated at a BMEP of 12.8 bar. With the change from CARB gas to richest case gas, the BMEP is increased to 14.2 bar. The equivalence ratio is increased from 0.750 to 0.835. This engine is expected to knock on the richest case gas.

To prevent the engine from knocking (with no knock margin), the lowest MN gas that this engine could run is predicted to be 81.5 (CARB method) or 74.5 (AVL method). This fuel has a Wobbe index of 1415. SwRI recommends that this engine not run on a methane number less than 88 (CARB Method) or 80 (AVL Method). This fuel could have a Wobbe index of approximately 1377, which is equivalent to the limit specified by Cummins in CES 20067. CES 20067 does not specify a minimum methane number, but a possible richest case gas that conforms to CES 20067 could have 92.7% methane (methane number is limited by the minimum Wobbe Index of 1377), 4% ethane, 1.7% propane, 0.7% butane, and 0.9% nitrogen. This fuel has a methane number of 90.6 (CARB Method) or 77.6 (AVL Method). This fuel has a higher Methane Number than the SwRI recommendation using the CARB Method, but a lower Methane Number than the SwRI recommendation using the AVL method. Since SwRI believes that the AVL Methane Number is more accurate, it is believed that the SwRI recommendation has a higher actual methane number than the Cummins specification. Cummins, in this case, may have a less conservative minimum Methane Number than the SwRI recommendation. To be able to run on the richest case gas, the BMEP of the engine would need to derated to 8.9 bar, which would reduce the peak torque from 750 ft-lb to 520 ft-lb (no knock margin). An alternative to reducing power is to retard ignition timing. Timing would need to be retarded approximately 4 degrees to run the engine (at zero knock margin). Operation of the engine on the richest case gas would require additional retarding of ignition timing to provide some knock margin.

One possible method to overcome the increased equivalence ratio and increase in power when changing from CARB gas to the richest case gas is to readjust the carburetor for the richest case gas. If the carburetor were adjusted to the recommended oxygen percentage in the exhaust using the richest case gas, the equivalence ratio would be 0.752 and the power would remain essentially unchanged. However, the engine would still likely knock. Retarding the ignition timing and/or reducing the equivalence ratio is expected to provide enough knock margin to operate on the richest case gas. A turbocharger change may be necessary to retain power if equivalence ratio was reduced to mitigate knock on the richest case gas. This option requires consistent gas quality (composition of the gas does not significantly change from the gas used to set the carburetor).

If CARB gas is used with the above carburetor setting for the richest case gas, the equivalence ratio would drop to 0.676, and power would be reduced by 9.9%. It is not recommended to operate this engine on CARB gas with the revised carburetor setting due to the lack of lean misfire margin.

In order to operate this engine on both high and low methane number gas, the addition of an electronic fuel valve and a closed-loop fueling system is required. If the equivalence ratio remains the same as the original engine, it will still knock on the richest case gas. To prevent knocking on the richest case gas, either the ignition timing must be retarded and/or the equivalence ratio reduced. A turbocharger change may be necessary if a leaner equivalence ratio is used. In addition, knock detection can be used to minimize ignition timing retard. Adding a knock detection system will enable the ignition timing to be retarded only when needed, such as when operating the engine on a low methane number gas, and allow the engine to run continuously on the low methane number gas. Retarding ignition timing will reduce the tendency to knock, but will also reduce power and engine efficiency. The power loss will depend on the severity of knock, which depends on the particular engine and on the methane number of the fuel. It is estimated that the ignition timing will be retarded by one degree to operate on the richest case gas. A one degree ignition timing retard will result in approximately a 2% power loss.

A summary of the Cummins L10G Phase 1 engine is shown in Table 7. The costs are per engine and assume 50 engines will use the option, where the cost of the development work is equally divided among the 50 engines and is added to the per engine hardware and installation costs. The wide range in cost of the carburetor adjustment and ignition timing retard is due to the choice of verifying the effects of the option in a laboratory test cell. Further details on the options are presented in section 3.3.

**Table 7. Cummins L10G Phase 1 Summary**

| Option | Min MN (CARB/AVL) | Max MN (CARB/AVL) | Notes | Approx. Cost |
|---|---|---|---|---|
| Original Configuration | 88 / 80 | No Limit | | |
| Carburetor adjusted for richest case gas | 79.3 / 73 | 87.8 / 78.9 | Turbo Change may be necessary to maintain power. | $100 to $2,600 |
| Carburetor adjusted for richest case gas with retard ignition timing | 70.9 / 67.8 | 87.8 / 78.9 | Turbo Change may be necessary to maintain power. | $100 to $2,600 |
| Closed-Loop Fuel System | 65 / 62.9 | No Limit | Turbo Change may be necessary to maintain power.<br>Must have knock detection to meet min MN specification. | $11,200 to $25,000 |
| Turbocharger Change | | | This is an additional cost for the above three options. | $5000 to $5,800 |
| Replace Engine | Depends on engine, see Table 14 | No Limit | | $36,500 to $41,500 |

If a consistent gas composition is used in these engines while in service, the recommendation is to readjust the carburetor and retard the ignition timing. It is recommended to perform development tests to ensure a proper knock margin. The one time development cost would be approximately $125,000, and the cost for each engine would be approximately $100, which is the cost of labor to perform the adjustments. The assumption here is that the possible power loss is acceptable and a turbocharger change will not be necessary.

If the engine needs to run on a variety of gas compositions, the recommendation is to add a closed loop fuel system that includes knock detection. Cummins does not have a kit for the L10 engine with closed loop fuel system and knock detection. But, a commercially available retrofit kit is produced by Eco Power Systems and is CARB certified. This commercially available kit is a closed loop retrofit fuel system for the L10 engine. It has the capability of knock detection, but currently does not use it. Knock detection could be added for a one-time development cost of approximately $150,000. The cost per engine of the closed loop fuel system with knock detection will be approximately $11,200, which includes $10,000 for the kit and $1,200 for 12 hours of labor to install the kit (this estimates labor rate at $100/hour). The Eco Power Systems retrofit kit is capable of 300 bhp at 2100 rpm and 900 ft-lbs at 1500 rpm. This rating exceeds the L10 Phase 1 and 2 rating, and matches the Phase 3 rating.

An engine replacement is not recommended for vehicles with the L10 Phase 1 engine due to the age of the vehicles. These vehicles should be ready for retirement in the near future and may require significant upgrades to install a newer engine.

### *3.1.2 L10G Phase 2 Engine*

The Cummins L10G Phase 2 engine is rated at a BMEP of 14.5 bar. With the change from CARB gas to richest case gas, the BMEP is increased to 16.1 bar. The equivalence ratio is increased from 0.700 to 0.779. This engine is expected to knock on the richest case gas.

To prevent the engine from knocking (with no knock margin), the lowest MN gas that this engine could run is predicted to be 79.3 (CARB method) or 73.0 (AVL method). This fuel has a Wobbe index of 1416. SwRI recommends that this engine not run on a methane number less than 85 (CARB Method) or 78 (AVL Method). This fuel will have a Wobbe index of approximately 1383, which is above the limit specified by Cummins. A Wobbe index of 1377 results in a methane number of approximately 88 (CARB method), therefore the SwRI recommendation (based on methane number) is 3% lower than the Cummins recommendation. The difference could be a more conservative fuel specification by Cummins. The assumption is that the Phase 2 engine operates at an equivalence ratio that is leaner than Phase 1 engine, therefore it should be able to operate on a lower MN gas, even at the higher power rating. To be able to run on the richest case gas, the BMEP of the engine would need to derated to 11.3 bar, which would reduce the peak torque from 850 ft-lb to 665 ft-lb (no knock margin). An alternative to reducing power is to retard ignition timing. Timing would need to be retarded approximately 4 degrees to run the engine (at zero knock margin). Operation of the engine on the richest case gas, would require additional retarding of ignition timing to provide some knock margin.

One possible method to overcome the increased equivalence ratio and increase in power when changing from CARB gas to the richest case gas is to readjust the carburetor for the richest case gas. If the carburetor were adjusted to the recommended oxygen percentage in the exhaust using the richest case gas, the equivalence ratio would be 0.702 and the power would remain essentially unchanged. The engine is not expected to knock, but there will be very limited knock margin. Retarding the ignition timing is expected to provide enough knock margin to operate on the richest case gas. This option requires consistent gas quality (composition of the gas does not significantly change from the gas used to set the carburetor).

If CARB gas is used with the above carburetor set for the richest case gas, the equivalence ratio of the engine would be 0.631. The engine is expected to misfire at this equivalence ratio. It is not recommended to operate this engine on CARB gas with the revised carburetor setting due to lean misfire.

In order to operate this engine on both high and low methane number gas, the addition of an electronic fuel valve and a closed-loop fueling system is required. If the equivalence ratio remains the same as the original engine, it not expected to knock, but there is not enough knock margin to operate this engine on the richest case gas. To prevent knocking on the richest case gas, either the ignition timing must be retarded and/or the equivalence ratio reduced. A turbocharger change may be necessary if a leaner equivalence ratio is used. In addition, knock detection can be used to minimize ignition timing retard. Adding a knock detection system will enable the ignition timing to be retarded only when needed, such as when operating the engine on a low methane number gas, and allow the engine to run continuously on the low methane number gas. Retarding ignition timing will reduce the tendency to knock, but will also reduce power and engine efficiency. The power loss will depend on the severity of knock, which depends on the particular engine and on the methane number of the fuel. It is estimated that the ignition timing will be retarded by four degrees to operate on the richest case gas. Four degrees of ignition timing retard will result in approximately an 11% power loss.

A summary of the Cummins L10G Phase 2 engine is shown in Table 8. The costs assume 50 engines will use the option. The wide range in cost of the carburetor adjustment and ignition timing retard is due to the choice of verifying the effects of the option in a laboratory test cell. Further details on the options are presented in section 3.3.

**Table 8. Cummins L10G Phase 2 Summary**

| **Option** | **Min MN** (CARB/AVL) | **Max MN** (CARB/AVL) | **Notes** | **Approx. Cost** |
|---|---|---|---|---|
| Original Configuration | 85 / 78 | No Limit | | |
| Carburetor adjusted for richest case gas | 76.2 / 71 | 82.6 / 75.3 | Turbo Change may be necessary to maintain power. | $100 to $2,600 |
| Carburetor adjusted for richest case gas with retard ignition timing | 70.9 / 67.8 | 82.6 / 75.3 | Turbo Change may be necessary to maintain power. | $100 to $2,600 |
| Closed-Loop Fuel System | 65 / 62.9 | No Limit | Turbo Change may be necessary to maintain power. Must have knock detection to meet min MN specification. | $11,200 to $25,000 |
| Turbocharger Change | | | This is an additional cost for the above three options. | $5000 to $5,800 |
| Replace Engine | Depends on engine, see Table 14 | No Limit | | $36,500 to $41,500 |

If a consistent gas composition is used in these engines while in service, the recommendation is to readjust the carburetor and retard the ignition timing. It is recommended to perform development tests to ensure a proper knock margin. The one time development cost would be approximately $125,000, and the cost for each engine would be approximately $100, which is the cost of labor to perform the adjustments. The assumption here is that the possible power loss is acceptable and a turbocharger change will not be necessary.

If the engine needs to run on a variety of gas compositions, the recommendation is to add a closed loop fuel system that includes knock detection. Cummins does not have a kit for the L10 engine with closed loop fuel system and knock detection. but, a commercially available retrofit kit is produced by Eco Power Systems. This commercially available kit is a closed loop retrofit fuel system for the L10 that engine has the capability of knock detection, but currently does not use it. Knock detection that is developed and in commercial use could be added for a one-time development cost of approximately $150,000. The cost per engine of the closed loop fuel system with knock detection will be approximately $11,200, which includes $10,000 for the kit and $1,200 for 12 hours of labor to install the kit (this estimates labor rate at $100/hour). The Eco Power Systems retrofit kit is capable of 300 bhp at 2100 rpm and 900 ft-lbs at 1500 rpm. This rating exceeds the L10 Phase 1 and 2 rating, and matches the Phase 3 rating.

An engine replacement is not recommended for vehicles with the L10 Phase 2 engine due to the age of the vehicles. These vehicles should be ready for retirement in the near future and may require significant upgrades to install a newer engine.

### 3.2 Fuel Valve/Mixer/Closed-Loop Fuel Systems

The three engines that use a fuel valve/mixer/closed loop system are the Cummins L10G Phase 3, B5.9G and C8.3G. All of these engines use an electronically controlled fuel valve, which supplies fuel to a mixer in the intake system. Closed loop air-fuel ratio is performed through a Universal Exhaust Gas Oxygen (UEGO) sensor, also known as a wide-ranging exhaust gas oxygen sensor. Engine Specifications are shown in Table 9.

**Table 9. Engine Specifications**

| **Engine** | **L10G Phase 3** | **B5.9G** | **C8.3G** |
|---|---|---|---|
| Configuration | Inline 6 | Inline 6 | Inline 6 |
| Aspiration | Turbocharged & Aftercooled | Turbocharged & Aftercooled | Turbocharged & Aftercooled |
| Bore (mm) | 125 | 102.1 | 114.0 |
| Stroke (mm) | 136 | 119.9 | 135.1 |
| Displacement (l) | 10 | 5.9 | 8.3 |
| Compression Ratio | 10.5:1 | 10.5:1 | 10.5:1 |
| Power (kW)<br>Power (bhp) | 224<br>300 | 172<br>230 | 205<br>275 |
| Torque (N-m)<br>Torque (lb-ft) | 1220<br>900 | 678<br>500 | 1017<br>750 |
| BMEP (bar) | 15.3 | 14.4 | 15.4 |
| Year Model | 1996-1999 | | |

The Cummins fuel standard for these three engines is CES 14604. This specifies a minimum methane number of 80 using the CARB method and a minimum higher heating value of 975 BTU/Standard Cubic Feet. It is typically the minimum methane number requirement, instead of the minimum higher heating value, that causes a knock problem in an engine.

Since these engines have a closed loop air-fuel ratio control system, the equivalence ratio does not change significantly with change in MN. The UEGO sensor uses oxygen content in the exhaust to determine equivalence ratio. There is a small change in equivalence ratio with a change in MN due to the change in the hydrogen to carbon ratio of the fuel. Equivalence ratio information for these engines was not available. However, closed loop fuel systems operate around an equivalence ratio of 0.65 at high load conditions. Power of the engine does not change significantly with a change in MN since the equivalence ratio does not significantly change.

The change in fuel properties from a high to a low MN increases the burn rate. Increasing the burn rate at the same ignition timing advances the combustion process and decreases the knock margin of an engine. If an engine is operating at an ignition timing that is retarded from minimum for best torque (MBT), an increase in burn rate will bring the engine closer to MBT (effectively advancing ignition timing). Ignition timing information for these engines was not available.

The assumptions about the L10G Phase 3, B5.9G and C8.3G engines are as follows:

- These engines operate at an equivalence ratio of 0.65 at the high load points

- Ignition timing is 23 °BTDC for these engines
- The Manifold Air Temperature is 150 °F (worst case)

### *3.2.1 L10G Phase 3 Engine*

The Cummins L10G Phase 3 engine is rated at a BMEP of 15.3 bar. With the change from CARB gas to richest case gas, the power increases by 0.1% which is an insignificant change in BMEP. The equivalence ratio increases slightly from 0.650 to 0.652. This engine is still not expected to knock, but there is little to no margin from knock. Since there is no knock detection, it is not recommended to operate this engine on the richest case gas.

The lowest methane number that this engine could run is predicted to be 70.7 (CARB Method) or 67.6 (AVL Method). SwRI recommends that this engine not run on a methane number less than 76 (CARB Method) or 73 (AVL Method). The SwRI recommendation is 5% lower than the Cummins recommendation. The difference could be due to a more conservative fuel specification by Cummins.

To operate this engine on the low methane number gas, either ignition timing could be retarded or knock detection added. Retarding ignition timing will reduce the tendency to knock, but will also reduce power and engine efficiency. This affects the engine when it operates on either a high or a low methane number gas. Adding knock detection will only affect the engine when operating on a low methane number gas. There will be approximately a 1.5% power loss on the richest case gas.

A summary of the Cummins L10 Phase 3 engine is shown in Table 10. The costs assume 50 engines will use the option.

**Table 10. Cummins L10G Phase 3 Summary**

| **Option** | **Min MN (CARB/AVL)** | **Max MN (CARB/AVL)** | **Notes** | **Approx. Cost** |
|---|---|---|---|---|
| Original Configuration | 80 / 73.4 | No Limit | | |
| Add Knock Detection | 65.0 / 62.9 | No Limit | . | $5,300 |
| Replace Engine | Depends on engine, see Table 14 | No Limit | | $36,500 to $41,500 |

The recommendation for this engine is to add the knock detection to these engines. The cost of developing a commercially available knock module for this engine is approximately $200,000. The cost per engine to purchase and install the hardware is approximately $1,100. Further details on the options are presented in section 3.3.

### *3.2.2 B5.9G Engine*

The Cummins B5.9G engine is rated at a BMEP of 14.4 bar. With the change from CARB gas to richest case gas, the power increases by 0.1% which is an insignificant change in BMEP. The equivalence ratio increases slightly from 0.650 to 0.652. This engine is still not expected to knock, but there is little to no margin from knock. Since there is no knock detection, it is not recommended to operate this engine on the richest case gas.

The lowest methane number that this engine could run is predicted to be 69.8 (CARB Method) or 66.7 (AVL Method). SwRI recommends that this engine not run on a methane number less than 77 (CARB Method) or 73 (AVL Method). The Cummins fuel specification for this engine is a minimum MN of 80 using the CARB method. The SwRI recommendation is 4% lower than the Cummins recommendation. The difference could be due to a more conservative fuel specification by Cummins.

To operate this engine on the low methane number gas, either ignition timing could be retarded or knock detection added. Retarding ignition timing will reduce the tendency to knock, but will also reduce power and engine efficiency. This affects the engine when it operates on either a high or a low methane number gas. Adding knock detection will only affect the engine when operating on a low methane number gas. Adding knock detection can be through an aftermarket supplier or through Cummins in an upgrade to the Plus version. A possible aftermarket knock detection module is the Safeguard Individual Cylinder Knock Control System, which is manufactured by J&S Electronics. This module is unique in that it has the capability to retard timing on a coil-on-plug ignition system. Two of the four-channel modules, part number 1004-4CH V.1, will be needed for the Cummins engine.

A summary of the Cummins B5.9G engine is shown in Table 11. The costs assume 50 engines will use the option. Further details on the options are presented in section 3.3.

**Table 11. Cummins B5.9G Summary**

| **Option** | **Min MN** (CARB/AVL) | **Max MN** (CARB/AVL) | **Notes** | **Approx. Cost** |
|---|---|---|---|---|
| Original Configuration | 80 / 73.4 | No Limit | | |
| Add Knock Detection | 65.0 / 62.9 | No Limit | . | $5,300 |
| OEM Upgrade to Plus | 65.0 / 62.9 | No Limit | | $12,000 |

The recommendation for these engines is to either add knock detection if the quantity of engines that use the knock detection is 20 or more at a one time cost of $200,000 and a cost per engine of $1,100. If the quantity of these engines is 19 or fewer, then the recommendation is to upgrade the engine to the Plus version at a cost of $12,000 per engine. Other possible advantages of the Plus upgrade are a full backing by Cummins for the modification and possible reduction in emissions, depending on the calibration differences.

### *3.2.3 C8.3G Engine*

The Cummins C8.3G engine is rated at a BMEP of 15.4 bar. With the change from CARB gas to richest case gas, the power increases by 0.1% which is an insignificant change in BMEP. The equivalence ratio increases slightly from 0.650 to 0.652. This engine is still not expected to knock, but there is little to no margin from knock. Since there is no knock detection, it is not recommended to operate this engine on the richest case gas.

The lowest methane number that this engine could run is predicted to be 70.7 (CARB Method) or 67.6 (AVL Method). SwRI recommends that this engine not run on a methane number less than 76 (CARB Method) or 73 (AVL Method). The SwRI recommendation is 5% lower than the Cummins recommendation. The difference could be due to a more conservative fuel specification by Cummins.

To operate this engine on the low methane number gas, either ignition timing could be retarded or knock detection added. Retarding ignition timing will reduce the tendency to knock, but will also reduce power and engine efficiency. This affects the engine when it operates on either a high or a low methane number gas. Adding knock detection will only affect the engine when operating on a low methane number gas. Adding knock detection can be done through an aftermarket supplier or through Cummins in an upgrade to the Plus version. A possible aftermarket knock detection module is the Safeguard Individual Cylinder Knock Control System, which is manufactured by J&S Electronics. This module is unique in that it has the capability to retard timing on a coil-on-plug ignition system. Two of the four-channel modules, part number 1004-4CH V.1, will be needed for the Cummins engine. A summary of the Cummins C8.3G engine is shown in Table 12. The costs assume 50 engines will use the option. Further details on the options are presented in section 3.3.

**Table 12. Cummins B8.3G Summary**

| **Option** | **Min MN** (CARB/AVL) | **Max MN** (CARB/AVL) | **Notes** | **Approx. Cost** |
|---|---|---|---|---|
| Original Configuration | 80 / 73.4 | No Limit | | |
| Add Knock Detection | 65.0 / 62.9 | No Limit | . | $5,300 |
| OEM Upgrade to Plus | 65.0 / 62.9 | No Limit | | $12,000 |

The recommendation for these engines is to either add knock detection if the quantity of engines that use the knock detection is 20 or more at a one time cost of $200,000 and a cost per engine of $1,100. If the quantity of these engines is 19 or fewer, then the recommendation is to upgrade the engine to the Plus version at a cost of $12,000 per engine. Other possible advantages of the Plus upgrade are a full backing by Cummins for the modification and possible reduction in emissions, depending on the calibration differences.

## 3.3 Scope of Work and Cost of Technology

A scope of work and estimated cost of implementing the technologies described above is presented in this section. The possible modifications covered in this section and which engine(s) it applies to is shown in Table 13. A summary of the cost of the modifications is shown in Table 14.

**Table 13. List of Possible Modifications for Low Methane Number Gas**

| Modification | L10 (1) | L10 (2) | L10 (3) | B5.9G | C8.3G |
|---|---|---|---|---|---|
| Carburetor Adjustment | X | X | | | |
| Ignition Timing Retard | X | X | | | |
| Closed Loop Electronic Fuel Control | X | X | | | |
| Turbocharger Matching | X | X | | | |
| Knock Detection | X | X | X | X | X |
| Plus Upgrade | | | | X | X |
| Replace Engine | X | X | X | | |

**Table 14. Cost of Possible Modifications for Low Methane Number Gas**

| Modification | Development Costs | Hardware and Installation Costs |
|---|---|---|
| Carburetor Adjustment | $125,000[1] | $100 |
| Ignition Timing Retard | $125,000[1] | $0 |
| Closed Loop Electronic Fuel Control[a] | $150,000[2] | $11,200 |
| Closed Loop Electronic Fuel Control[b] | $1,000,000 | $7,500 |
| Turbocharger Matching | $15,000[3] | $4,500 |
| Knock Detection | $200,000 | $1,300 |
| Plus Upgrade | $0 | $12,000 |
| Replace Engine | $75,000 | $25,000-$30,000 |
| a Commercially available product<br>b Develop a new product | 1 These can be combined so that the development cost for both the carburetor adjustment and timing retard is $125,000<br>2 To add knock detection<br>3 Assumes the engine is already in a test cell for development work | |

### *3.3.1 Carburetor Adjustment*

A carburetor adjustment (for a particular gas) applies to the L10 Phase 1 and 2 engines. The carburetor adjustment would require a maintenance procedure to set the oxygen concentration in the exhaust as described by the Cummins procedure. This procedure requires an instrument to measure the oxygen concentration in the exhaust. The procedure from the Cummins manual is as follows:

- Start engine, operate until the coolant temperature reaches 60 °C (140 °F)
- Once at operating temperature, raise the engine rpm to rated speed and load
- Measure the exhaust oxygen using an oxygen meter
- Adjust the exhaust oxygen by turning the power valve on the carburetor
- Turn the valve clockwise to lean the air/fuel mixture, which will cause the exhaust oxygen to increase
- Turn the valve counterclockwise to richen the air/fuel mixture, which will cause the exhaust oxygen to decrease
- Allow adequate time between adjustments for the oxygen meter to react to the new conditions, this can take up to 30 seconds

- Adjustment is complete when the meter displays the correct specifications for 30 seconds at the rated engine conditions
- Measure turbine inlet temperature, it may be necessary to advance ignition timing to reduce the turbine inlet temperature to less than 732 °C (1350 °F)

The time to perform this procedure is approximately one hour. Assuming a shop rate of $100 per hour, the cost of this adjustment is $100. This cost does not include any testing to verify engine operation on a low methane number gas. Development costs for knock testing would cost approximately $125,000 and could be combined with knock testing for timing retard at no additional cost.

### *3.3.2 Ignition Timing Retard*

Ignition timing retard applies to the L10 Phase 1 and 2 engines. The ignition retard can be accomplished through the existing Altronics ignition module. The Altronics ignition module has a switch with seven settings for ignition timing. Each switch interval changes ignition timing by 1.9 degrees. Information from the Los Angeles Metropolitan Transportation Authority indicates that the ignition timing on the Altronics ignition module can be retarded by 5.7 degrees. The limit on ignition timing retard is a turbine inlet temperature of 732 °C (1350 °F). There is no cost associated with this option since it is a simple adjustment using normal hand tools. To verify sufficient knock margin, knock testing should be conducted. Knock testing would cost approximately $100,000, and could be combined with the knock testing for carburetor adjustments at no additional cost.

The ignition timing on the L10 Phase 3, B5.9G and C8.3C engines is integrated into the engine controller. Modification of the ignition timing would require either a calibration change by Cummins or custom electronics to modify the ignition timing signal to the ignition coils.

### *3.3.3 Closed Loop Electronic Fuel Control*

Closed loop electronic fuel control applies to the L10 Phase 1 and 2 engines. Eco Power System has a CARB certified retrofit kit to upgrade the Phase 1 engines with a closed loop electronic fuel control system. This kit can also be applied to the Phase 2 engines, but it is not yet CARB certified. Certification for the Phase 2 engines is planned for the future. The Eco Power Systems retrofit kit is capable of 300 bhp at 2100 rpm and 900 ft-lbs at 1500 rpm. This rating exceeds the L10 Phase 1 and 2 rating, and matched the Phase 3 rating. The cost of this kit is approximately $10,000 per engine in a quantity of 50. Installation time is approximately 12 hours for each kit. The total cost per engine is approximately $11,200. The electronic control module used for this kit includes knock detection, although it is not currently implemented. It is estimated that the cost of developing the knock detection for the L10 engine would be approximately $150,000. The cost per engine for 50 engines would be approximately $15,200 with the knock detection development costs distributed among the 50 engines.

To develop a system for the L10 engines would require an engine control system, a fuel system, and the associated accessories. One possibility is to use the Woodward OH2 engine control system. This is a full authority system with fuel injection control, ignition timing control, and knock detection. The development cost of this system is approximately $1,000,000 and will take approximately 1 year. This would include knock detection for operation on the low methane number gas. The cost for a kit and installation on an engine would be approximately $7,500 per engine. The cost per engine for 50 engines would be approximately $27,500, with the development costs distributed among the 50 engines. The higher cost (for 50 engines) of the Woodward system compared to the Eco Power system is from the initial development of the system needed for the Woodward system, which is already included in the per kit cost of the Eco Power system.

The cost of the Eco Power System and the cost of developing a system for the L10 are the same per engine if considering 200 engines.

### *3.3.4 Turbocharger Matching*

Turbocharger matching, to maintain rated power and torque, would require installation of an engine in a test cell and running performance tests on various turbochargers. The cost of the turbocharger matching would be approximately $15,000 (this assumes that a turbocharger will be supplied at no cost to SwRI and an engine is already installed in a test cell). The cost to replace a turbocharger is approximately $4,500.

### *3.3.5 Knock Detection*

Knock detection can be applied to all of the engines, but this is primarily for the L10 Phase 3, B5.9G, and C8.3G engines. The L10 Phase 1 and 2 engines could have knock detection integrated into the closed loop fueling upgrade kit. Adding knock detection would require a development project to add and calibrate the electronics to detect knock and retard ignition timing. One possible solution is to use the J&S Electronics Safeguard Individual Knock Control System. This system is able to detect knock and control individual coils for ignition timing retard. The cost of developing this knock control system would be $200,000 (assuming that major development work is not necessary to make this system functional) for each engine type. The development costs are to select the appropriate knock sensor, test for the proper the location of the knock sensor on the engine, verify operation, and set the threshold limits. These units sell for approximately $500 each. Two units are needed along with a custom wiring harness. The total hardware cost is approximately $1,200. The cost to install a unit on an engine would be approximately $100. The cost per engine for 50 engine is $5,300, with the development costs distributed among the 50 engines.

### *3.3.6 Cummins OEM Plus Upgrade*

The Plus upgrade applies only to the B5.9G and C8.3G engines. The plus upgrade includes knock detection, which allows the engine to operate on a gas with a methane number as low as 65 based on SAE 922359 and a lower heating value as low as 18,800 BTU/lbm. The upgrade is only possible if the engine and engine support equipment (radiators, aftercoolers, etc.) are in good condition and the support equipment is properly sized. The cost of the upgrade kit for either engine is approximately $10,000. Installation time is approximately 20 hours for each kit. The total cost per engine is approximately $12,000. This cost estimate does not include upgrades to the base engine or the support equipment.

### *3.3.7 Engine Replacement*

Engine replacement applies to the L10 engines. The B5.9G and C8.3G can be upgraded to the B5.9G Plus and the C8.3G Plus respectively instead of being replaced, therefore engine replacement is a considerably more expensive option that will not be considered in this report. Due to the expense of replacing an engine, this option would be viable if the engine is in need of a major overhaul or if a full engine warranty is important to the user when any changes are performed on the engine.

The L10 Gas engine is no longer being produced. The Phase 1 engines were produced from 1991 to 1993. Vehicles with these engines are 11-13 years old. A typical life of a transit bus is 12 years, which means that these busses are ready for retirement, and an engine replacement may not be cost effective. The Phase 2 engines were produced from 1994 to 1995. Vehicles with these engines are 9-10 years old. Depending on the cost of a vehicle, this may or may not be cost effective. In addition, these older vehicles may require significant upgrades to auxiliary equipment (radiators, aftercoolers, etc.). The recommendation for vehicles with L10 Phase 1 or Phase 2 engines is not to perform an engine replacement, but to replace the vehicles. Phase 3 engines were produced from 1996 to 1999. Vehicles with these engines are 4-8 years old. An engine replacement for the Phase 3 engines may be cost effective. Alternatives to the L10 engine are the Caterpillar C10 dual fuel, the Detroit Diesel Series 50, the John Deere 8.1L, the Cummins C Gas Plus, and the Cummins L Gas Plus engines. Specifications of these engines are shown in Table 15.

**Table 15. Possible Replacements for the L10G**

| **Make** | **Model** | **Liters** | **Bhp @ rpm** | **ft-lb @ rpm** | **Min MN (CARB/AVL)** |
|---|---|---|---|---|---|
| Caterpillar | C10 | 10 | 315<br>@ 1800 | 1050<br>@ 1200 | 82.1 / 75.1 |
| DDC | Series 50 | 8.5 | 275<br>@ 2100 | 890<br>@ 1200 | 86.3 / 77.9 |
| John Deere | 8.1 | 8.1 | 250<br>@ 2200 | 900<br>@ 1500 | 73.0 / 65.4 |
| Cummins | C Gas Plus | 8.3 | 280<br>@ 2400 | 850<br>@ 1400 | 65.0 / 62.9 |
| Cummins | L Gas Plus | 8.9 | 320<br>@ 2300 | 1000<br>@ 1400 | 65.0 / 62.9 |

The cost of a new engine is approximately $25,000-$30,000. The cost of integrating a new engine into a vehicle is approximately $75,000. This is the cost of installing the first engine into a particular chassis and includes the engineering and design work to install an engine into a chassis, it does not include the cost of the engine. Subsequent engine replacements (same engine into the same vehicle) would cost approximately $10,000. This cost assumes that the engine support equipment (radiators, aftercoolers, etc.) are in good condition and properly sized. This cost estimate does not include upgrades to the support equipment. This cost also assumes a transmission or axle modification is not necessary. A transmission or axle modification (or replacement) would be necessary if the torque and/or power curves of the replacement engine is significantly different from the original engine, or if the original transmission is not able to handle the torque of the new engine. For 50 vehicles (same engine into the same vehicle), the cost per vehicle would be $36,500 to $41,500.

The difference in the rated power and rated torque of replacement engines are shown on Table 16. A discussion of each replacement engine is presented below.

**Table 16. L10 Engine Replacement Power and Torque Difference**

| **Speed Difference (rpm)** | | **Power Difference (bhp)** | | |
|---|---|---|---|---|
| | **L10 All Phases (2100 rpm)** | **L10 Phase 1 (240 bhp)** | **L10 Phase 2 (260 bhp)** | **L10 Phase 3 (300 bhp)** |
| Caterpillar C10 | -300 | 75 | 55 | 15 |
| DDC Series 50 | 0 | 35 | 15 | -25 |
| John Deere 8.1L | 100 | 10 | -10 | -50 |
| Cummins C Gas Plus | 300 | 40 | 20 | -20 |
| Cummins L Gas Plus | 200 | 80 | 60 | 20 |
| **Speed Difference (rpm)** | | **Torque Difference (ft-lb)** | | |
| | **L10 All Phases (1300 rpm)** | **L10 Phase 1 (750 ft-lb)** | **L10 Phase 2 (850 ft-lb)** | **L10 Phase 3 (900 ft-lb)** |
| Caterpillar C10 | -100 | 300 | 200 | 150 |
| DDC Series 50 | -100 | 140 | 40 | -10 |
| John Deere 8.1L | 200 | 150 | 50 | 0 |
| Cummins C Gas Plus | 100 | 100 | 0 | -50 |
| Cummins L Gas Plus | 100 | 250 | 150 | 100 |

The Caterpillar C10 is a dual fuel engine, which will require diesel fuel on the vehicle in addition to the natural gas. This engine has more power and torque than all of the L10 engines. The rated engine speed on this engine is 300 rpm less then the L10 engines, and the rated torque speed 100 rpm less then the L10 engines. The difference in rated power speed will require a transmission change (replacement or reprogramming) and an axle ratio change. This engine also has a higher torque than the L10 engines which could also require a transmissions and axle change. According to the manufacturer, this engine will not be able to operate on the richest case gas. Replacement of the L10 engine with the Caterpillar engine should not be an option since this engine will not operate on the richest case gas. This engine meets the California's optional low $NO_X$ levels and US LEV emissions standards, but is not yet certified for sale in the United States.

The Detroit Diesel Series 50 engine is still available. However, starting in 2007, it is expected that gas engines will not be marketed by Detroit Diesel. This engine has more power and torque than the Phase 1 and 2 engines, but less power and torque than the phase 3 engine. The rated power speed is the same as the L10 engines, and the rate torque speed is 100 rpm less than the L10 engines. This engine may not require a transmission or axle modification. According to the manufacturer, this engine will not be able to operate on the richest case gas, although this engine has knock detection which should protect it from knocking on low methane number fuels. Replacement of the L10 engine with the Detroit Diesel engine should not be an option since this engine is not designed to operate on the richest case gas, unless the manufacturer agrees to warrant the engine on a low methane number gas. This engine is currently certified for buses in California.

The John Deere 8.1L engine had more power and torque than the Phase 1 engine, less power but more torque than the Phase 2 engine, and less power and same torque as the Phase 3 engine. The rated power speed is 100 rpm more than the L10 engines and the rated torque speed is 200 rpm higher than the L10 engines. The difference in rated torque speed will require a transmission change (replacement or reprogramming). According to the manufacturer, this engine will not be able to operate on the richest case gas, although this engine has knock detection which should protect it from knocking on low methane number fuels. Replacement of the L10 engine with the John Deere engine should not be an option since this engine is not designed to operate on the richest case gas, unless the manufacturer agrees to warrant the engine on a low methane number gas. This engine is currently certified for buses in California.

The Cummins C Gas Plus engine has more power and torque than the Phase 1 engine, more power and the same torque as the Phase 2 engine, and less power and torque than the Phase 3 engine. The rated power speed is 300 rpm more than the L10 engines, and the rated torque speed is 100 rpm more than the L10 engines. The difference in rated power speed and torque will require a transmission change (replacement or reprogramming) and an axle ratio change. This engine will operate on the richest case gas.

The Cummins L Gas Plus engine has more power and torque than all of the L10 engines. The rated power speed is 200 rpm more than the L10 engines, and the rated torque speed is 100 rpm more than the L10 engines. Although there is a difference in rated power and torque speeds, power and torque appear to be sufficient to provide the same driveability as the L10 engines without a transmission or axle modification. There may still be a concern with the ability of the transmission and/or axle to handle the torque. This engine will operate on the richest case gas. This engine is a new offering from Cummins and is now available for orders.

## 4. CONCLUSIONS

The conclusions of this study are summarized below. Note that in all cases, a change in engine calibration or hardware is recommended to ensure reliability under the richest case gas scenario. Recommended modifications of this type will likely require re-certification from an emission standpoint. The following list recommends steps for each engine.

- Cummins L10 Phase 1 Engine
  - Engine will knock on the richest case gas
  - To allow the engine to operate on the richest case gas but not allow the engine to operate on CARB certification gas:
    - The carburetor setting should be changed for the richest case gas at a lean equivalence ratio along with a turbocharger change to maintain power.
    - The ignition timing should be retarded.
  - To allow the engine to operate on richest case gas and CARB certification gas:
    - A fuel valve with closed-loop fuel control at a lean equivalence ratio should be added along with a turbocharger change to maintain power.
    - Knock detection should also be included. Most modern engine controllers have the capability to detect knock and retard ignition timing, so this should be incorporated into the closed loop fuel controller.

- Cummins L10 Phase 2 Engine
  - Engine will knock on richest case gas
  - To allow the engine to operate on the richest case gas but not allow the engine to operate on CARB certification gas:
    - The carburetor setting should be changed for the richest case gas.
    - The ignition timing should be retarded.
  - To allow the engine to operate on the richest case gas and CARB certification gas:
    - A fuel valve with closed-loop fuel control at a lean equivalence ratio should be added along with a turbocharger change to maintain power.
    - Knock detection should also be included. Most modern engine controllers have the capability to detect knock and retard ignition timing.

- Cummins L10 Phase 3, B5.9G, or C8.3G Engines
  - Engine is not expected to knock on the richest case gas
    - There is currently very little knock margin.
  - To allow the engine to operate on the richest case gas and CARB certification gas:
    - The ignition timing should be retarded or knock detection added.
    - The B5.9 and C8.3 engines can be upgraded to the Plus version, which includes knock detection hardware and software.

# CERTIFICATE OF SERVICE

I hereby certify that I have this day served a copy of the foregoing **SUPPLEMENT TO COMMENTS OF SAN DIEGO GAS & ELECTRIC COMPANY (U 902 G) AND SOUTHERN CALIFORNIA GAS COMPANY (U 904 G) ON NATURAL GAS QUALITY ISSUES** on all known interested parties of record in R.04-01-025 by electronic mail a copy thereof properly addressed to all parties included on the list appended to the original document filed with the Commission.

Dated at Los Angeles, California, this 14th day of February, 2005.

Becky Roberts

Becky Roberts

S:LAW/DATA/DGILMORE/R.04-01-025 (GAS OIR)/SUPP2COMM-NATLGAS–2.14.05