The ADEPT Group, Inc.

Services at the interface of energy, economics and environment

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FINAL REPORT

Develop and Demonstrate Propane Medium Duty Engine
January 1997 – July 1998
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Report prepared by The ADEPT Group Inc. (ADEPT) with support and consultation from Cummins Engine Company (Cummins) for the South Coast Air Quality Management District

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Many other parties, not identified above, contributed to the project's success (i.e., other field test-sites, Cummins' distributors, LPG/dealers or marketers etc).

Glossary of Acronyms

ASTM	American Society of Testing and Measurement
AFV	Alternative Fuel Vehicle
bhp	brake horsepower
CARB	California Air Resources Board
CC	Clean Cities
CCP	Cummins Cal Pacific
CCVS	closed crankcase ventilation system
CFFV	Clean Fuel Fleet Vehicle
CFR	Consolidated Fuel Research
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CR	compression ratio
CTC	Cummins Technical Center
CVS	constant volume sampling
DF	deterioration factor
DOE	U.S. Department of Energy
ECM	engine control module
EPA	U.S. Environmental Protection Agency
ETS	Engineering Test Services Facility (Cummins)
ft	feet
g/bhp/hr	grams per brake horsepower per hour
GVW	gross vehicle weight
HC	hydrocarbons
HD	heavy-duty
hp	horsepower
ICM	ignition control module
lb	pounds
LEV	low-emission vehicle
LNG	liquefied natural gas
LPG	liquefied petroleum gases
N_2	nitrogen
NAA	nonattainment area
NMHC	non-methane hydrocarbons
NO_x	oxides of nitrogen
NPGA	National Propane Gas Association
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
OCTA	Orange County Transit Authority

OEM	original equipment manufacturer
0_2	oxygen
PC	personal computer
PM	particulate matter
psig	pounds per square inch gauge
PTO	power take-off
PVC	Propane Vehicle Council
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
SwRI	Southwest Research Institute
THC	total hydrocarbons
ULEV	ultra-low emission vehicle

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Executive Summary

In late 1994, the Cummins B5.9 Propane (LPG)[1] Engine Development, Certification, and Demonstration Project was organized by Cummins Engine Co. (Cummins), the propane industry, and The ADEPT Group (ADEPT). Cummins began engine development in 1995 and continued through 1997, building upon its extensive experience with natural gas engines, specifically the B5.9G[2]. This project's objective was to successfully develop and certify an LPG (HD-5) dedicated medium-duty original equipment manufacturer (OEM) engine that could be put into production (see Figure 1). This project was co-funded by South Coast Air Quality Management District (SCAQMD), Cummins, the National Renewable Energy Laboratory (NREL), Natural Resources Canada (NRCan), Propane Vehicle Council (PVC), and Superior Propane. Several field-test sites throughout North America provided vehicles and staff to help demonstrate "field-test" and "market-seed" engines.[3]

SCAQMD co-funded the following project tasks: (1) Engine Development, Certification Testing, and Engine Optimization, (2) California Air Resources Board (CARB) and U.S. Environmental Protection Agency (EPA) Engine Certification, and (3) demonstration of two B5.9LPG engines at the City of Pasadena transit shuttle fleet. This report describes the conduct and completion of these tasks.

Tasks 1 and 2 focused on maximizing sub-system commonality with the B5.9 diesel and natural gas models (ignition, controls and air/fuel management) and optimizing LPG sub-systems with respect to fuel delivery, power cylinder, combustion performance, and emissions. Data for engine optimization was collected from laboratory facilities and from the field. During the project, Cummins logged more than 9,000 hours on 48 engines in various lab-testing activities and more than 300,000 miles in the field with 11 vehicles. In September 1997, Cummins launched the B5.9LPG into limited production. In May 1998, the engine was put into full production.

The personnel at the below sites conducted all testing and engine optimization activities:

- Cummins Alternative Fuel Division Engineering staff in the Cummins Technical Center (CTC) in Columbus, IN: Vinod Duggal, Jim Branner, Jr., Mostafa Kamel, Madison Rye, Mike Haub, Dave Dunnuck, and Jeff Mahon.
- Engineering Test Services (ETS) facility in Charleston, SC: Joel Evans.
- Southwest Research Institute (SwRI) staff (lower-tier subcontractor) in San Antonio, TX: Kent Spreen.

[1] Also known as liquefied petroleum gases (LPG).
[2] Compressed or Liquid Natural Gas
[3] "Field-test" engines were the first prototype engines put into demonstration. "Market-seed" engines were a pre-production engines where a chassis OEM was involved.

ADEPT served as project manager and administrator of the SCAQMD, NREL, and PVC funds and as coordinator for the City of Pasadena field-test site. The following personnel participated in demonstration site activities:

- ADEPT: Alex Spataru, Alina Kulikowski-Tan, James Hendersen, Jared Meyer, Jeff Thayer, Tracy Wilcox, and Kris Yi.
- AZ Bus Sales: Tom Orr
- City of Pasadena: Terri Slimmer, Diane Cotto, Rohan Karuppu
- Cummins Alternative Fuel Division Engineering: Vinod Duggal, Jim Branner, Jr., Madison Rye, Mike Haub, Frank Shapiro
- Cummins Cal Pacific: Bob Polzel, Greg Doyle, Dave Bouchard, Phil Stutzel
- Laidlaw: Jesse Saavedra, Eddie Van Natta
- Mutual Propane: Steve Moore, Roger Wheeler

Background

This project's goal was to develop and advance technology to allow optimum use of LPG as an alternative transportation fuel and achieve substantial vehicle emissions. For LPG to be a viable replacement to diesel, it must be demonstrated that its impact on air quality will be favorable to that of existing diesel fuels without any significant performance loss.

Because of U.S.'s continuing concern about air pollution, Congress enacted the Clean Air Act Amendments in 1990 (CAAA). The CAAA's provisions have forced broad changes in fuels and vehicles. For example, reformulated gasolines, clean diesels, and alternative fuels are receiving wide attention as industry struggles to comply with the CAAA. Also, to meet their air quality standards, many of the non-attainment areas (NAA) across the country will need to use more alternative fuels. Of the major transportation sectors, the medium-duty vehicle sector (e.g. package delivery vans, trucks, and shuttle buses) may offer a good opportunity for urban emissions reduction since many of these vehicles are operated in urban environments. Therefore, additional research and development of alternative fueled, medium-duty engines and vehicles is important to this project's funders.

DOE projected that there were about 381,000 alternative fuel vehicles (AFVs) at the end of 1997. Out of these, 271,000 operate on LPG. This represents more than 71% of the entire alternative fuel vehicles (AFVs) in the USA. In 1997 (in total gasoline equivalent gallons) LPG accounted for about 77% of all alternative transportation fuels used in the U.S.

The B5.9 diesel was selected because Cummins was willing to pursue production and due to B5.9 engine platform popularity. The B5.9 diesel version is used worldwide with millions sold since its introduction. The base platform for the B5.9LPG project was the B5.9G engine. The B5.9G development and certification program began in 1991. It was launched into production in 1994. More than 800 B5.9G engines are now in service in the U.S. and abroad. This engine is offered

by more than 30 bus and truck vehicle OEMs.
In light of federal and California emission reduction goals, the 1997 B5.9LPG engine certification target was the EPA Clean Fuel Fleet Vehicle (CFFV) ultra-low-emission vehicle (ULEV) certification and CARB Optional Low NO_x (see Table 1). The EPA CFFV program applies to fleets of 10 or more vehicles, which are centrally fueled or capable of being centrally fueled, in the 22 NAA. For heavy-duty vehicles (8,500-26,000 lbs gross vehicle weight [GVW]), the requirement is 50% of new vehicles purchased starting in 1999. A low-emission vehicle (LEV) counts as 1.0 credit, whereas an ULEV vehicle counts as 1.87 credits. Heavy-duty (HD) vehicles greater than 26,000 lbs. GVW can generate credits for NAA fleets, though not required to, as part of this program.

Note that CARB LEV and ULEV emission standards do not apply to the B5.9LPG engine because it is not used in applications of less than 14,000 lbs GVW. The CARB Optional Low NO_x emissions levels refer to vehicle applications of 14,000 lbs GVW or higher. See Table 1 for further details.

Emissions	Emissions Standards			Emissions Certification[4]	
(g/bhp-hr)	EPA CFFV LEV	EPA CFFV ULEV	CARB HD[5]	1997 B5.9LPG	1998 B5.9LPG[6]
NO_x	--	--	5.0[7]	2.2	2.3
THC	--	--	1.3	0.9	0.8
NO_x+THC	3.8	2.5	--	3.1	3.1
PM	0.10	0.05	0.10	0.02	0.01
CO	14.4	7.2	15.5	3.6	1.0
HCHO	--	0.025	--	--	--
EPA CFFV	--	--	--	LEV	LEV
CARB Low NO_x	--	--	--	2.5	2.5

Table 1: CARB/EPA Transient Heavy-Duty Vehicle Emissions Standards

Introduction

The B5.9G is a six-cylinder, in-line configuration, four-cycle engine with three ratings covering 150 to 230 hp range. The overall B5.9LPG engine development strategy was to:

1. Build upon the B5.9G engine experience, which uses a base diesel platform.
2. Maximize sub-system commonality with the B5.9 diesel and natural gas models (ignition, controls and air/fuel management).
3. Optimize LPG sub-systems: (a) fuel delivery, (b) power cylinder, (c) combustion

[4] 96 inches maximum distance from the turbocharger exhaust outlet to the catalyst inlet.
[5] EPA (>8,500 lbs GVW), CARB (>14,000 lbs GVW)
[6] Closed crankcase ventilation system required by 1998 EPA Certification
[7] Optional low NO_x (0-3.5 in 0.5 increments for 1997; 0-2.5 for 1998)

performance, and (d) emissions.
4. Obtain 1997 CARB and EPA Certification.

The engine optimization and precertification testing process included the following elements:

1. Complete engine functional specification.
2. Refine and complete natural gas engine components modification for LPG and LPG-specific components.
3. Refine and complete engine software calibration modifications (e.g., O_2 sensor).
4. Select and optimize LPG specific items (i.e. oxidation catalyst, integral vaporizer/regulator.)
5. Pre-certification testing and analysis:
   a. Establish certification-testing parameters.
   b. Test for performance ranges with HD-5 specification LPG fuel.
   c. Test for mechanical development (i.e. vibration, leakage, hydrostatic, and deformation) and durability (including 500 and 1,000 hours, and pre-certification transient emissions).

See Figure 1 for a side view of the B5.9LPG engine.

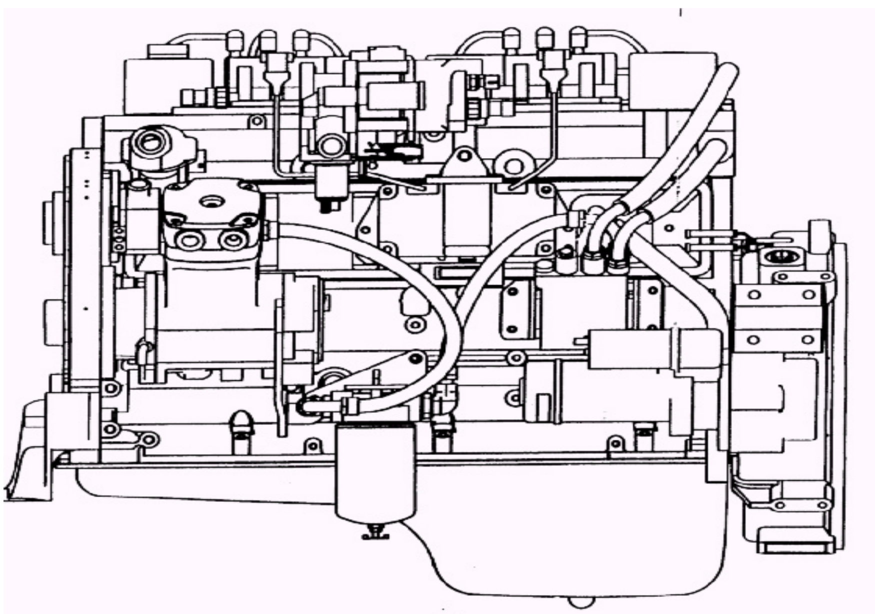

Figure 1: B5.9LPG Engine

This engine was designed for use with HD-5 LPG specification fuel as described in Table 2. Certification with and without an oxidation catalyst was planned, though Cummins expected (based on previous work) that a catalyst would be needed to meet the total hydrocarbons (THC)[8] requirement for CARB and EPA. Certification deterioration factor (DF) tests were not required

[8] This is an LPG-specific issue because of the chemical structure and hydrocarbon (HC) content of LPG.

because Cummins had an approved DF for a spark-ignited, lean-burn natural gas engine, the B5.9G, upon which the B5.9LPG was based. The DF was determined to be the same for a spark ignited engine family (i.e., B5.9) independent of fuel type (compressed natural gas [CNG], liquefied natural gas [LNG], and LPG). This DF was based on a 1,200-hour engine test conducted at Cummins in 1994. The CARB and EPA (40 Consolidated Fuel Research [CFR] 86) certification requirements are as follows:

- One cold cycle (1/7 weighted)
- One hot cycle (6/7 weighted)
- Composite average result
- Established DF factor.

In 1997 Cummins conducted formal certification testing on B5.9LPG engines three times with engine analysis and data optimization between and after each test series:

1. February 1997 at SwRI: Initial testing did not achieve desired emissions targets.
2. August 1997 at SwRI: 1997 EPA LEV and CARB Optional Low NO_x certifications were achieved with an oxidation catalyst.
3. November 1997: 1998 EPA CFFV LEV and CARB Optional Low NO_x certification were successful with lower PM and CO emissions than achieved in August 1997. The emissions were generated by a 1998 vintage B5.9LPG engine with a CCVS (no CCVS in the engine in August 1997; CCVS is a 1998 EPA requirement).

The Task Discussion reviews the work conducted in the following sections: Engine Optimization to LPG; Optimization Refinements Resulting from Field Experience; Precertification Testing and Certification Testing; and Field Test/Market Seed Engine Demonstration at the City of Pasadena.

Engine Optimization to LPG[9]

Completion of Functional Specification for B5.9LPG Engine

The B5.9LPG is a lean burn, spark-ignited engine with electronic management. The engine's design targets for the B5.9LPG operating on HD-5 LPG were:

- 195 rated hp at 2,800 rpm and 420 ft-lb peak torque at 1,600 revolutions per minute (rpm)
- 285 ft-lb at 800 rpm at wide open throttle
- EPA CFFV ULEV targets (g/bhp-hr) with a catalyst:[10] NO_x + THC 2.5; CO 7.2; and particulate matter (PM) 0.05 (See Table 1)
- Integrated fuel handling and ignition subsystems (see Figures 2 and 3)
- Engine protection and PC-based diagnostics (see Figure 5)

[9] There are several references to suppliers throughout the report. ADEPT and Cummins are not authorized to identify them in this report. For further inquiries, please contact Cummins Alternative Fuels Group.
[10] A catalyst is required for the B5.9LPG to meet the heavy-duty THC standard.

- Engine-mounted controllers
- Compression ratio (CR) of 9:1
- Maximize parts commonality with B5.9G engine (only 10 new LPG-specific parts)

These targets were met with the exception of emissions (EPA CFFV LEV, instead of ULEV) and rated horsepower speed (achieved at a lower speed of 2,600 rpm).

Refinements and Completion of Modified Natural Gas Engine Components for LPG, LPG Specific Components, and Engine Software Calibration

The following B5.9 engine components were added, modified, or optimized (or all three) for the LPG application:

1. Piston (compression ratio)
2. Integral (Vaporizer/Pressure Regulator/Shut-off Valve) Evaporator
3. Vaporizer coolant hoses
4. Fuel hoses
5. Fuel assembly housing
6. Mass flow sensor
7. Fuel metering valve
8. Engine control module (ECM) software
9. Engine wiring harness
10. Catalyst

Two B5.9G product enhancements were incorporated in the B5.9LPG engine to maintain parts commonality: (1) a high-temperature exhaust manifold[11] and (2) a revised fuel-metering valve.[12] Figure 2 illustrates the B5.9LPG subsystem engine integration, including those items specifically added for the LPG application.

[11] Initially released on the B5.9 diesel engine platform.
[12] Initially released on the B5.9G engine platform.

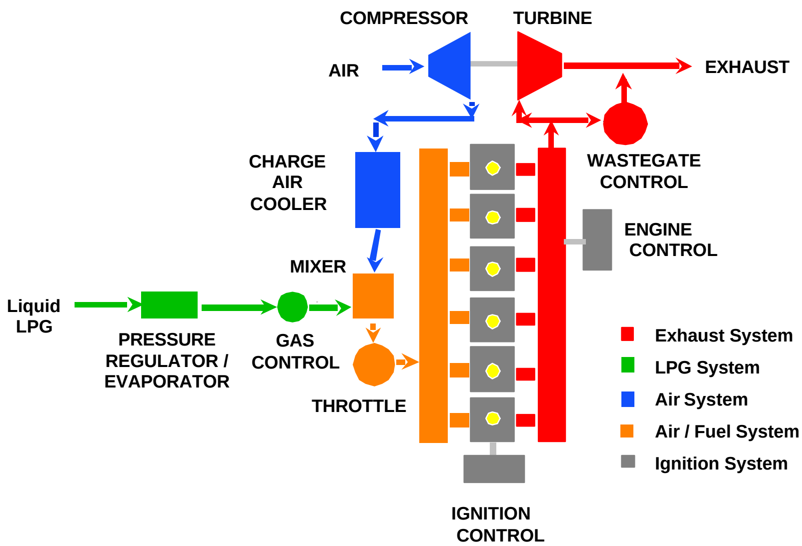

Figure 2: B5.9LPG Engine Integration

Piston/Combustion Chamber Design

Cummins' evaluation of the engine operating margins (detonation) indicated a need for increased knock margin at rated power [195 hp at 2,800 rpm]. This optimization process led to rated horsepower speed change from 2,800 to 2,600 rpm while governed speed was maintained at 2,800 rpm. The LPG-specific piston was also redesigned to lower the CR from 9.5:1 to 9:1 (the B5.9G CR is 10.5:1).

The CR was reduced due to the lower octane rating of LPG versus that of natural gas. The piston bowl geometry was modified to achieve a CR of 9:1 while meeting internal piston design standards. This modification also expanded the knock margin. The new piston was implemented for durability and field-test engine evaluation. Operating margin evaluation work continued throughout the certification period.

Engine-Mounted Vaporizer/Regulator - LPG Specific Item[13]

The combination vaporizer/pressure regulator design for performance and durability continued to be optimized with the supplier. Although the supplier produces vaporizer/regulators for other LPG engine applications, this effort is B5.9LPG specific because of the engine's operating requirements (i.e., turbocharged and engine-mounted). This subassembly was the primary reliability concern during performance and field tests. Figure 3 illustrates the sequence of fuel handling from the vehicle tank to the engine.

[13] This item was added to the engine for the LPG application rather than a modification of an existing engine part.

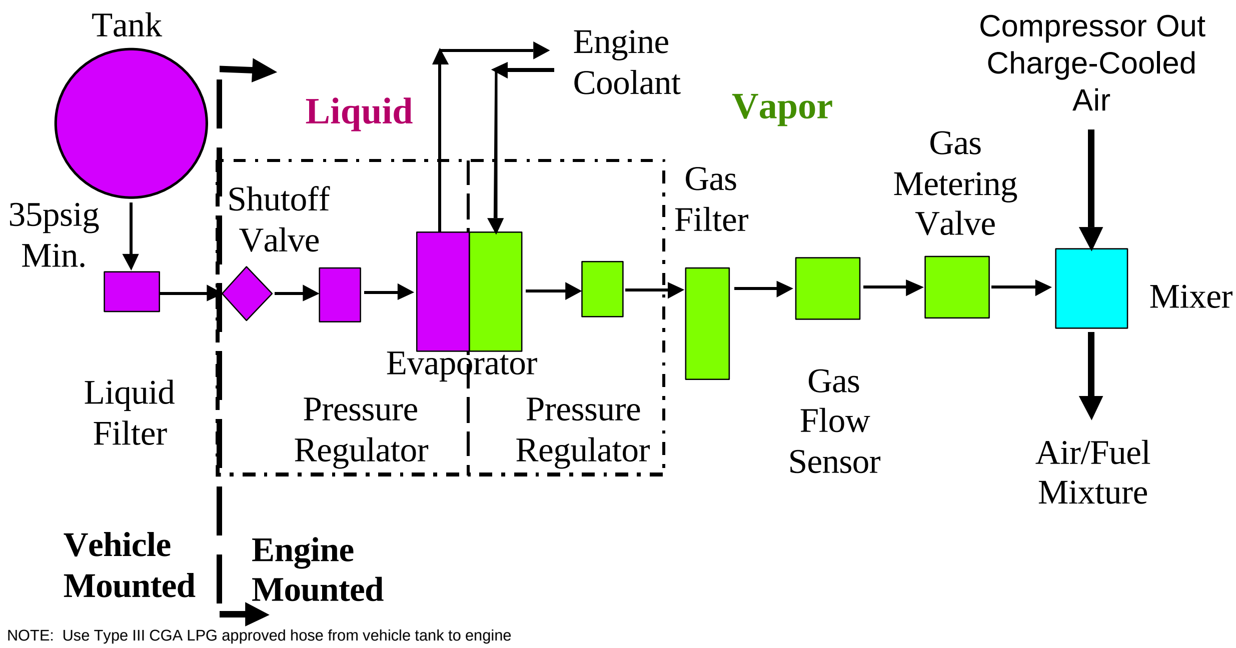

Figure 3: B5.9LPG Engine - Fuel Delivery Sub-system

Catalyst - LPG Specific Item

Initially Cummins applied the B5.9G catalyst to the B5.9LPG engine. This catalyst did not meet emissions reduction targets in the first phase of certification tests. Subsequently, Cummins selected an oxidation catalyst for the B5.9LPG engine from its current supplier for the C8.3G engine. This new catalyst provided higher THC reduction efficiency than the B5.9G catalyst. See further discussion on page 22 under “Certification Testing”.

Cummins demonstrated the capability to meet EPA CFFV LEV emission levels (see Table 1) for the B5.9LPG engine with an oxidation catalyst through preliminary steady-state and transient pre-certification emissions tests at CTC.

Fuel-Metering Valve Technologies (Vapor Side-Fuel Plumbing)

As a turbocharged spark-ignited engine with single-point gaseous fuel injection, the B5.9LPG engine requires a minimum fuel supply pressure to the engine to reach rated power. The minimum fuel supply pressure, with margin, was set at 35 pounds per square inch gauge (psig) to the engine at the upstream side of the shutoff valve, prior to the vaporizer/regulator. This 35-psig requirement was derived from an evaluation of LPG characteristics at low temperatures, flow-pressure losses through the engine's fuel system and the need to overcome maximum turbocharger boost pressure at rated power for single-point fuel injection.

In a vehicle fuel system, saturated LPG tank pressure is a function of temperature. In cold-weather operation, a temperature can be reached where the fuel supply pressure to the engine cannot meet the 35-psig requirement (see Figure 4). At such temperatures, delivery of liquefied LPG in the engine affects the engine fuel supply and, therefore, engine performance.[14] For such cold weather operation, the vehicle LPG fuel system requires special equipment such as a heating blanket or in-tank pump to maintain 35 psig. The shaded region in Figure 4 highlights the region between minimum pressure supplied by such a pump (35-psig line) and the LPG saturated pressure/temperature curve. Because engine block water is used to vaporize the fuel, cold weather operation also requires engine block and oil pan heaters.

Cummins held a meeting with a LPG vehicle fuel system supplier to discuss the cold-weather requirements for the lean-burn, turbocharged B5.9LPG engine. This supplier was developing a pressurized vehicular fuel tank system that would meet the 35-psig liquid fuel supply requirement to the engine. A prototype of this system was used for Cummins cold-weather testing for a pressurized vehicle fuel storage system.

Vehicle and laboratory cold-weather startability tests[15] at CTC demonstrated the capability of providing 35 psig minimum LPG supply to the engine. In March 1997, the engine started successfully at:

- 32°F minimum ambient temp., with an unpressurized vehicle fuel system
- 10°F ambient temp., with an engine block heater and an unpressurized vehicle fuel system
- -10°F ambient temp., with addition of a pressurized vehicle fuel system.

In April 1997, further vehicle and laboratory cold weather startability tests demonstrated the capability of successfully providing 35 psig minimum LPG supply at:

- 32°F minimum ambient temp., with an unpressurized vehicle fuel system
- 5°F ambient temp., with engine block and oil pan heaters, and an unpressurized vehicle fuel system
- -17°F ambient temp., with addition of a pressurized vehicle fuel system; engine warm up at idle was required to assure full rated power capability.

There were two reasons for the expansion in the test temperatures minimum thresholds: (1) the addition of an oil pan heater allowed a cold start of the engine at even lower temperatures, and (2) the discovery that the engine would start at ambient temperatures between -17°F to 10°F, but could not attain full rated power until engine was warm (block water for 100% fuel vaporization).

[14] For the B5.9LPG, the LPG must be sustained in a gaseous phase. As illustrated in Figure 4, cold weather can cause a bi-phase fuel condition that would affect engine performance. This is a LPG specific issue. Previously used strategies to address this issue include on-board heating of fuel.

[15] The CTC facility uses dedicated refrigerated test cells for cold temperature startability and performance tests.

Additional cold-weather tests, which confirmed these test results, were conducted in June 1997.

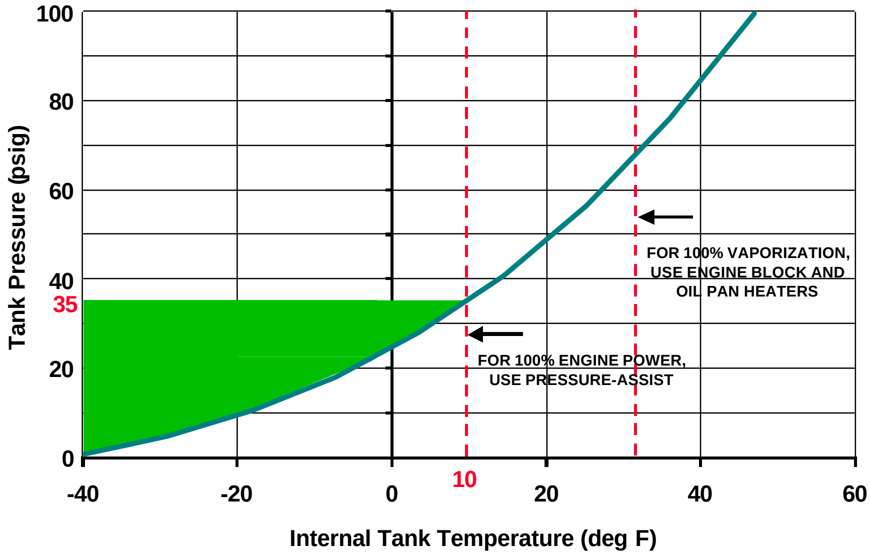

Figure 4: Vehicle LPG Tank -- Cold Ambients Effect[16]

ECM Software Recalibration

The tasks for ECM software development included:

- Concept engine controls,
- Development engine controls,
- Optimization of performance and emissions, and
- Production engine controls.

Engine operating margins evaluation work resulted in a requirement to lower peak rated horsepower speed (2,600 rpm) while maintaining governed speed at 2,800 rpm. The ECM software calibration was revised to tailor to optimum LPG operation. Components that required calibration table modifications were:

- Air/fuel ratio,
- Ignition timing,
- Rated speed,
- Turbocharger boost pressure, and
- Gas flow sensor.

[16] Pressure assist refers to the use of special equipment such as a pump to deliver fuel versus an unpressurized fuel system.

Figure 5 shows the engine control module (ECM) and ignition control module (ICM) interface, and the various functions and sub-system controls.

This rated horsepower speed change and the piston revision implemented in spring of 1997 provided the required detonation margin at rated power (based on validation tests conducted at CTC). The software calibration revision was downloaded into the ECM's of all field-test and market-seed engines, with no issues reported.

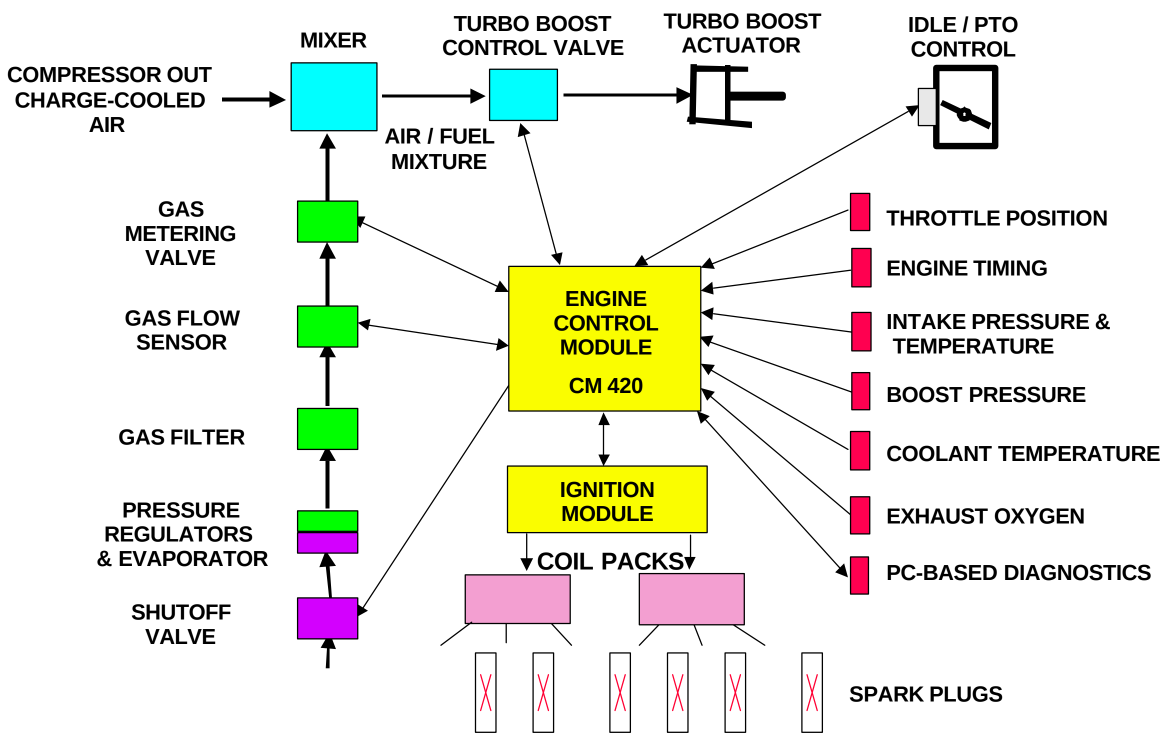

Figure 5: B5.9LPG Engine Electronic Control Sub-system

Engine Optimization and Refinements Resulting from Field Experience

Engine Software Algorithm

In March 1997, one of the field test issues required software algorithm testing to validate resolution. All five LPG bobtail trucks' engines stalled occasionally in the field after completing power take-off (PTO) operation for off-loading LPG fuel while the engine was at PTO speed (1,000 rpm). A temporary fix was provided during engine operation (modified driver procedures

before and after PTO operation). The modified drivers' procedures included pressing the accelerator to increase the engine speed above idle speed before engaging in PTO.
Subsequently, an ECM software revision was validated in the laboratory and provided a permanent solution to this engine stalling issue. The software revision was downloaded into field test engines' ECM.

Other Data Collected from the Field

Oil consumption data and analysis for the field-test vehicles showed results equal to fleets operating the B5.9G 195-hp engine. Cummins anticipated this outcome because the hardware affecting oil consumption is identical for both engine versions. No issues were found with wear metals, contaminant metals, additive metals, non-metallic components, or lube fluids.

B5.9LPG engine shutdowns were observed in the field. These shutdowns were correlated with the following conditions: voltage power supply below ECM and/or ICM capability, failure of the evaporator assembly, and fuel control valve failures. Analysis of these occurrences is completed. In the ECM/ICM voltage drop incidences there appeared to be vehicle electric system instabilities and faulty vehicle wiring. Also, abnormal voltage swings are experienced in the transit shuttle application itself.[17]

Pre-Certification Testing

From July 1997 to August 1997, two pre-production B5.9LPG engines were subjected to pre-certification tests (steady-state emissions), performance and emissions optimization, and constant volume sampling (CVS) transient emissions analysis. These tests, in addition to field-test vehicle performance (driveability) tests, served to optimize the engine for limited production, scheduled for the third quarter of 1997. All pre-certification tests were conducted at CTC.

Performance, durability, and field-test engine data were used to develop an optimum performance and emissions baseline established on both steady state and CVS transient emissions tests. Enhancements were validated in the laboratory on the performance and durability engines, as well as, in vehicles via field test engines.

All testing was conducted on HD-5 specific LPG. The LPG had the following component percentages: 94.6-95.8% propane, 0.3-0.8% propene 0.4-1.6% iso-butane, and 0.1-0.2% n-butane. A contract propane marketer that supplies LPG fuel for Cummins' facilities' forklifts supplied the HD-5 specification fuel. Cummins qualified the contents of the fuel in a CTC laboratory analysis. The HD-5 fuel specification is shown in Table 2.

[17] For further detail please contact Cummins' Alternative Fuels Group.

Constituents	Requirement	Test Method
Propane, volume %	90.0 Minimum	ASTM D 2163
Propylene, volume %	5.0 Maximum	ASTM D 2163
Butane & Heavier, volume %	2.5 Maximum	ASTM D 2163
Hydrogen Sulfide	Pass	ASTM D 2420
Total Sulfur, ppmw	123	ASTM D 2784
Oxygen, weight %	0.5 Maximum	ASTM D 1945
$CO_2 + N_2$	3.0 Maximum	ASTM D 1945

(Note: California specification for propane is 85% min. by volume)

Table 2: Propane Gas (HD-5) Fuel Specification

Propane for the City of Pasadena field tests was supplied by Mutual Propane and was randomly sampled and tested per the tests identified in Table 2 to determine whether or not the fuel met HD-5 specifications. After testing, it was determined that the fuel indeed satisfied the required specifications. Detailed information is available in Appendix C.

A focus area was the evaluation of combustion operating margins for rated power of 195 hp. Adequate knock margin was not initially achieved. Engine performance and combustion optimization work increased the detonation margin at rated power while preserving engine performance targets. (See "Piston Combustion Chamber Design" discussion and Figure 6)

As part of preparing for certification testing, Cummins conducted the following tests:

1. Mechanical development testing included:
   - Vibration,
   - Leak, and
   - Hydrostatic.
2. Performance development tests included:
   - 500-hour "hot box" (elevated system temperatures),
   - 500-hour thermal cycle, and
   - 500-hour hot endurance.
3. Additional development tests conducted:
   - 1,000-hour peak power overload,
   - 250-hour overload, and
   - 250-hour idle speed.

For performance development tests, the cylinder head was instrumented for dynamic in-cylinder (#1) pressure measurement for some of the performance and development tests. The engines were also instrumented for the following parameters:

-Engine speed	-Fuel temp.	-Fuel pressure
-Torque	-Intake temp.	-Intake pressure
-Throttle position	-Exhaust gas oxygen	-Turbine inlet temp.
-Fuel flow	-Air flow	-Turbine inlet pressure
-Blowby pressure	-Exhaust port temp.	-Exhaust port pressure
-Compressor out-pressure	-Compressor outlet temp.	

A Cummins proprietary high-speed data acquisition system was used in conjunction with the in-cylinder pressure transducer to analyze:

-Combustion duration	-Coefficient of variance
-Rate of combustion	-Start of combustion

The tendency for knock and misfire, and the engine heat release were evaluated using this engine data and to calculate:

-Air/fuel ratio	-Power
-Brake specific fuel consumption	-Thermal efficiency

Cummins inspected the test engines for pitting, scuffing, abrasion, and excessive wear through visual and micromeasurement methods, and found no problems. Areas under inspection for wear were found to be within base engine specifications. In these development areas, a variety of data-based analyses were compared to results for the B5.9G and diesel engines using Cummins' internal standards. No major issues were raised during these tests. Some of the major components analyzed for reliability and durability were:

-Cylinder head and overhead	-Spark plugs
-Fuel handling sub-system	-Turbocharger
-Crankshaft and bearings	-Camshaft and bearings
-Ignition subsystem	-Other base diesel/natural gas components
-Power cylinder	

Figure 6 illustrates the final performance curve resulting from the above testing and optimization. The dash line denotes stoichiometric gasoline LPG conversions torque peak capability of an engine with a similar horsepower rating.

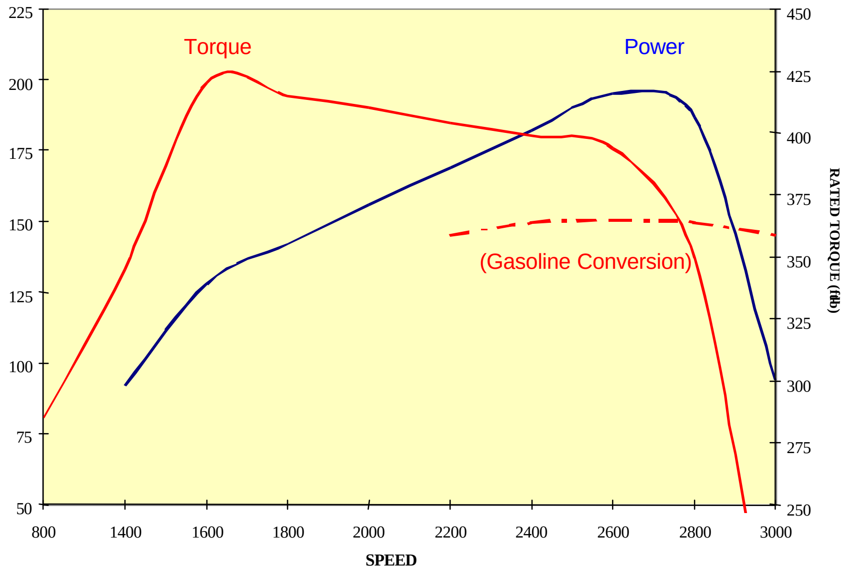

Figure 6: B5.9LPG Final Engine Performance

Noise Testing

As part of its engine development program (but not part of the SCAQMD project contract), Cummins conducted engine noise testing. A one-meter free-field noise measurement, per SAE J1074, showed a significant noise reduction along the full-load torque curve when compared to a B5.9 diesel. (See Figure 7)

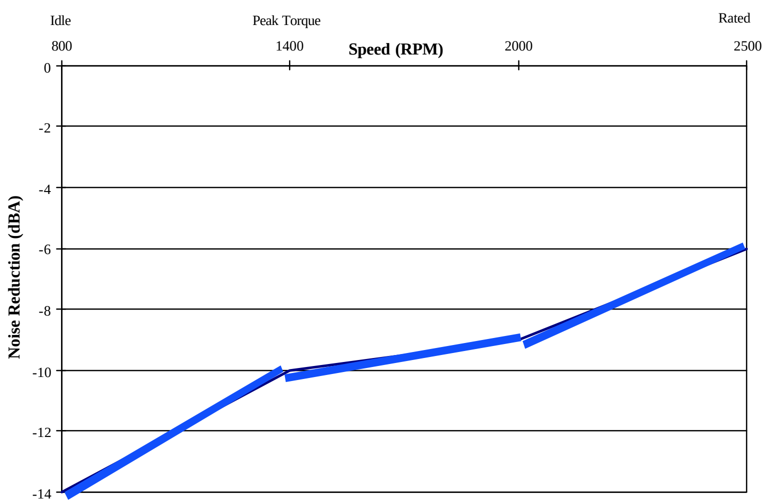

Figure 7: Noise Analysis – Baseline B5.9 Diesel Engine

Certification Testing

The three certification tests will be described as Phases I-III.

Cummins selected SwRI as the testing subcontractor based on an established and successful history with SwRI and because the CTC test facilities are not EPA certified for testing spark-ignition engines. The team that conducted and completed the certification program included the following members:

- Cummins: Vinod Duggal, Jim Branner Jr., Mostafa Kamel, Jeff Mahon, and Dave Dunnuck.
- SwRI: Kent Spreen.

The SwRI tests were conducted in a cell equipped and calibrated to perform the EPA Heavy-Duty Engine Transient Federal Test Procedure CFR 40 No. 86. The LPG test fuel was composed of: 94.3% propane, 3.8% propene, and 1.9% n-butane.[18] No tests were conducted without a catalyst.

Cummins did not conduct a DF test on the B5.9LPG engine because they had an approved DF. The premise for DF testing is to determine how various hardware and controls will deteriorate over a period of useful emissions life. The natural gas engine DF was applied to the B5.9LPG engine. This DF was based on a 1,200-hour engine test. The DF's used for the B5.9LPG engine is shown in Table 3.

Pollutant	EPA DF	CARB DF
NO_x	1.007	1.007
THC	1.000	1.000
CO	13.935	13.935
PM	1.000	1.000

Table 3: B5.9LPG Engine Deterioration Factors

The DF for carbon monoxide (CO) is relatively large. DFs are based on the slope of catalyst deterioration over time which, in the case of CO, resulted in a relatively high DF.

Phase I

[18] For information about test fuel sources contact the Cummins' Alternative Fuels Group.

The certification B5.9LPG engine was built at the Cummins Rocky Mount, NC plant to utilize the manufacturing process system prototyping (e.g., customer order entry, engine assembly, software download, engine test, etc). The 120-hour certification conditioning test of the engine and oxidation catalyst was completed at CTC. Subsequently, the engine was shipped to SwRI where an engine control problem (i.e., excessive vibration of the fuel control valve) occurred during preparation for emission certification tests. The engine was shipped back to Cummins for further troubleshooting.

The certification test was rescheduled after successful testing at Cummins. The engine control problem reoccurred at SwRI. Further trouble-shooting by Cummins staff at SwRI revealed that a solid engine test cell mounting arrangement at SwRI caused excessive vibrations which induced the fuel system control problem. Soft-mounting of the engine in the SwRI test cell resolved the excessive engine vibration of the fuel control valve. The certification test was rescheduled and completed in February 1997. The results indicated that the B5.9LPG engine with the catalyst failed to meet CARB and EPA heavy-duty certification due to high THC emissions (1.3 g/bhp/hr).

Cummins rescheduled a second certification test for July 1997 after a thorough emissions failure analysis, combustion operating margins evaluation, and performance and emissions optimization at CTC. Data analysis to understand certification test failure was conducted from March to June 1997. It revealed that:

1. The engine was out of the rated power production specification (>5% limit), thus producing higher than expected THC, and
2. The engine catalyst was located too far from the engine exhaust outlet, resulting in reduced catalyst THC effectiveness. (Note: LPG fuel has higher THC emissions than natural gas.)

A CARB and EPA emissions certification plan for the second series of certification testing was prepared in April 1997.

Cummins continued to optimize emissions and performance to assure NO_x and THC emissions met EPA CFFV targets. Due to SwRI test-cell unavailability, certification tests were delayed until August 1997.

Phase II

In July 1997, transient emissions tests conducted at CTC showed capability to meet EPA CFFV and CARB Optional Low NO_x emission levels with the latest production version of the B5.9LPG. Cummins reduced the maximum distance from the turbocharger outlet to the catalyst inlet from 155 inches to 96 inches for lower cold start HC emissions. The second certification test with a production B5.9LPG engine was scheduled for August 1997 at SwRI. Two changes were applied to the B.9LPG engine: (1) the CR was lowered from 9.5:1 to 9.0:1, and (2) a C8.3G catalyst was utilized instead of the B5.9LPG catalyst.

In August 1997, the 120-hour engine and catalytic converter conditioning test for certification was completed at ETS. Subsequently, the second engine CARB and EPA emissions certification tests were completed at SwRI. These tests were conducted on a production B5.9LPG engine, which included the ECM software calibration revision described earlier. Cummins submitted its applications for 1997 CARB and EPA emissions certification. The certification data, with deterioration factors, and the regulated EPA CFFV emission standards, are described in Table 1.

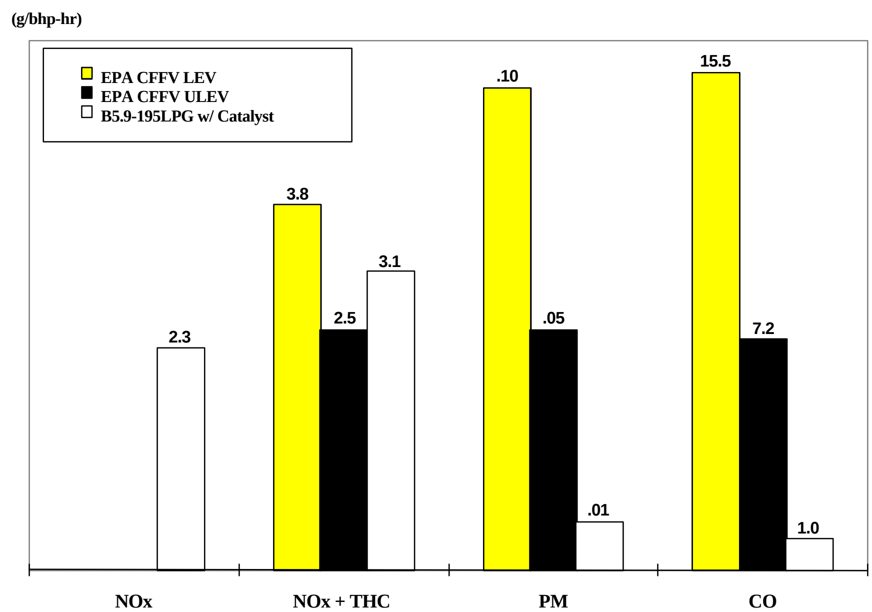

Figure 8: 1998 B5.9LPG EPA CFFV Certified Emissions

In September 1997, Cummins received the EPA CFFV LEV certificate for the B5.9LPG engine with a catalytic converter (see Appendix 2 for documentation). The B5.9LPG was the first dedicated heavy-duty spark-ignited LPG engine to receive EPA CFFV LEV certification. Cummins' target for this program was the EPA CFFV ULEV standard. A LPG engine must certify to a total hydrocarbon (THC) emission level while a natural gas engine has only to certify to a non-methane hydrocarbon (NMHC) emission level.

In October 1997, Cummins received the California Air Resources Board (CARB) Optional Low NO_x (2.5 g/bhp-hr) certificate for the B5.9LPG engine with a catalytic converter (see Attachments for documentation). The B5.9LPG was the first dedicated heavy-duty spark-ignited LPG engine to receive the CARB Optional Low NO_x certification. Cummins planned to recertify in 1997 the B5.9LPG engine with close crankcase ventilation system (CCVS) to 1998 EPA CFFV and CARB

Optional Low NO_x standards.

Phase III

In November 1997, Cummins completed the emission certification 120-hour conditioning tests at ETS on the B5.9LPG engine with a production CCVS and catalytic converter. CCVS is an EPA requirement for 1998 certification for heavy-duty spark ignited engines and was not funded as of the SCAQMD contract. Subsequently, Cummins completed the 1998 EPA and CARB emissions certification tests at SwRI for the B5.9LPG engine with CCVS. Cummins received emission certification from EPA and CARB for 1998 in December 1997. These results are shown in Figure 8 in comparison to the EPA CFFV ULEV and LEV standards, and in Figure 9 in comparison to the 5.9 liter diesel engine. See Table 1 for the test results with DF.

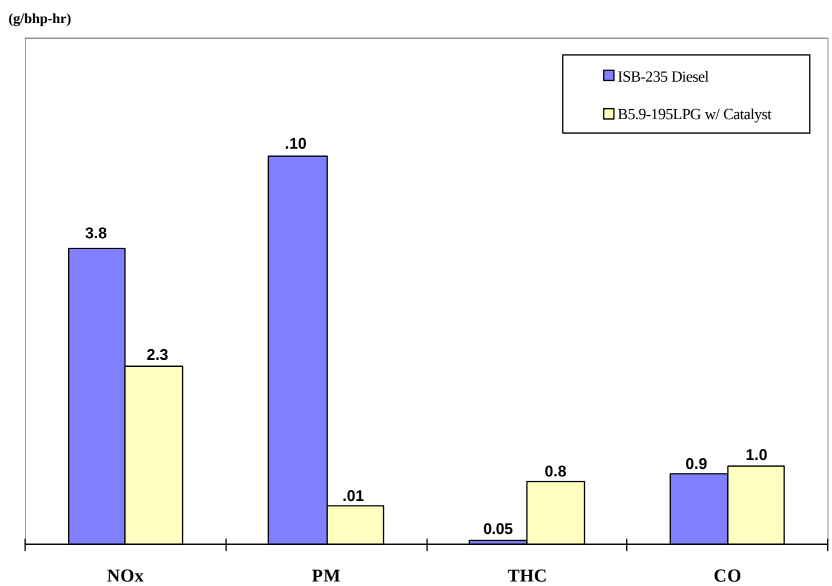

Figure 9: 1998 B5.9 EPA HD Certified Emissions

Field Test/Market Seed Engine Demonstration at the City of Pasadena

The City of Pasadena (City) was solicited and selected as the demonstration site after a joint review and analysis of six candidate sites by ADEPT, Mutual Propane, and Cummins. The City was selected because of the following reasons:

1) existing facility circumstances appeared to accommodate unconstrained achievement of LPG applications;
2) The City had decided that other alternate fuels (e.g. CNG) were not an option and expressed interest specifically in LPG;

3) The City's management and fleet operations were enthusiastic, supportive, and capable of demonstrating the B5.9 LPG engine;
4) The City proposed application met Cummins field staff's desired duty cycle for testing a field test engine;
5) The City was interested to expand its LPG powered fleet should the demonstration prove successful; and
6) The City's existing fleet operated B5.9 diesel engines enabling a B5.9LPG repower and the City planned on future Cummins B5.9 engines use.

Cummins conducted field test negotiations with Laidlaw (who own and operate the City demonstration vehicles) and the City. An agreement was signed by Cummins, Laidlaw, City, and Mutual Propane. The agreement facilitated the transfer of engine ownership to the City at the end of the one-year demonstration. Mutual Propane was committed to supplying HD-5 specification LPG fuel for the demonstration, installation of refueling facility, and on-board LPG tanks. It was signed into effect in June 1996 and finalized in July 1996. Three transit shuttle vehicles were selected for the demonstration. Two served as field test/market seed demonstrations and one as the diesel control vehicle.

Bus #	Chassis Model	Model	Vin #	ESN #
560	Bluebird Q Bus	1994	1BAGEBSA0RF061094	44994446
566	Bluebird Q Bus	1994	1BAGEBBA9RF058727	45450499
564	Bluebird Q Bus	1994	1BAGEBSA8RF061098	45265227

Table 4: Demonstration and Control Vehicles

On August 13, 1996, the City was awarded a Conditional Use Permit for the on-site LPG refueling facility. The demonstration vehicle, Bus 564, was delivered to Cummins Cal Pacific distributor (CCP) for engine installation on September 9, 1996. The installation was completed and the vehicle was delivered to Laidlaw's facilities on October 28, 1996. Upon receipt of the vehicle, Laidlaw and the City determined the vehicle should not be put into service due to unresolved and/or incomplete installation issues. These issues are typical for a first time repower and were:

1. Multiple fuel lines installed. They were chafing vehicle body.
2. Loose fittings at and around LPG fuel tank. Laidlaw tightened these upon City's request, but was not asked to do any further work to vehicle.
3. Vehicle was running really rough, as if it needs a tune up.
4. Throttle play was at 3/4 (i.e. vehicle does not immediately react).
5. Rear engine start was not working.
6. Air compressor for pneumatic system appeared to have clunking sounds, and was different from the one that came with vehicle.

7. Number of loose wires and power steering lines that were unsecured.
8. Power steering lines leaking.
9. Fuel gauge not functioning.
10. Windows were left down and vehicle interior was dirty.

On November 6, 1996, an engine and LPG refueling certification refresher training was held at the Laidlaw's operations facilities for Laidlaw's maintenance crew and City staff. This was provided by CCP and Mutual Propane. At the end of the training, the group reviewed each installation issue and specific parties committed to solve each problem. Within two days, CCP, AZ Bus Sales, and Mutual Propane had jointly addressed and/or resolved all the issues.

The buses were operated on the City's downtown route which operated 8 hours a day, 6 days a week, 52 weeks a year. The route averages 26 stops per hour.

The below narrative describes, in chronological order, the City field test/demonstration.

December 1996: Bus 564 demonstration vehicle continued to have installation-related problems. The regulator was replaced. By the end of the month, the vehicle was in regular service. Routine data collection had not yet begun. Mr. Dave Bouchard of CCP replaced Mr. Frank Shapiro in routine support of the Pasadena field test site.

January 1997: Cummins renewed the California Air Resources Board (ARB) experimental permit for demonstration engine #1. Laidlaw began weekly data reports and continued to submit them for eight weeks.

February 1997: Bus 564 demonstration vehicle continued in regular service. Laidlaw continued its weekly data reports. The weekly system changed to monthly starting March.

During February, Bus 564 experienced two problems: (1) The fuel gauge was not properly working (repaired by Mutual Propane) and (2) the vaporizer/regulator was leaking, which was replaced by CCP. Laidlaw switched its engine oil from Mobil Delvac (which is prescribed by Cummins) to a specially formulated Unocal oil since Unocal is Laidlaw's contracted supplier. Cummins had requested a sample for analysis, since at this time the Unocal oil was not a Cummins approved oil for the B5.9LPG engine. Laidlaw formally requested that Unocal provide a low ash oil that met Cummins' specifications. Unocal chemists worked with Mr. Frank Shapiro of Cummins to finalize their oil's chemistry.[19] An oil analysis conducted by Cummins' Laboratory was completed in April 1997. It concluded that the specially formulated UNOCAL oil could be used in the B5.9LPG engine on an on-going basis. Subsequently, Cummins agreed to honor the engine's warranty.

[19] Unocal donated their services and oil to the project.

ADEPT requested City authorization to purchase the second demonstration engine. The City was trying to assess what was the best timing for such a transaction considering that the summer months experience the highest service demand. The City interviewed OCTA regarding their experience with LPG during the summer to determine what was the best time to start the second installation.

March 1997: On March 12, ADEPT held a "check-up" meeting with CCP, Mutual Propane, A-Z Bus Sales, City, and Laidlaw. This meeting's goals were: (1) review the experience to date; (2) address any outstanding problems; and (3) coordinate the second bus (Bus 566) engine installation. Copies of the first installation work orders were provided to review any changes that may be made to the second installation. ADEPT issued a purchase order for the second engine (with tentative delivery in April). Cummins' Laboratory, Lubricon, conducted the first oil analysis and found no unusual "wear-and-tear".

Overall engine performance observations for Bus 564 in March was the following: general operations performance was slightly above average vis-à-vis the diesel engines in the fleet; the drivers enjoyed the marked noise reduction; however, they noted reduced acceleration and thus, expressed preference for the diesel units.[20] The vehicle continued to be in full revenue service. No down-time was experienced.

April 1997: The team prepared for two activities/events:(1) the second engine installation in Bus 566; and (2) promotional and public education regarding the project.

The installation in Bus 566 was scheduled to occur from May 27th through June 30th. A press conference was tentatively scheduled for May 22nd, Transit Appreciation Day. The City wished to include other transit-related promotions as well (i.e. bicycling, carpooling).

Operation of Bus 564 demonstration vehicle was positive and without incident.

May 1997: Coordination efforts continued for the second engine installation in June. In late May demonstration Bus 564 experienced power surge problems which affected the performance of the electronic control module. Following several alternator changeouts and extensive investigation by CCP, CCP staff changed the power source for the ECM from the alternator to the starter. This change resolved the power surge problem (seemed to be a more stable power source). The oil analyses indicated normal wear and tear.

While coordinating the May 22 press conference, it was decided to postpone the event due to lack of City resources. However, ADEPT and the City continued to prepare for the display of

[20] The rated horsepower and peak torque for the diesel control vehicle was 190 hp and 480 ft-lb torque.

Bus 564 at the June Clean Cities Conference in Long Beach, CA.

June 1997: The second engine installation was underway. Bus 564 was on display at the Clean Cities Conference.

July 1997: The second engine installation was completed. Demonstration Bus 566 was put into field test operation and it was released for road service long enough to run for nearly half as many hours as Bus 564 during the month. Bus 566 ran smoothly, but drivers reported acceleration to be slower than Bus 564. Oil sample analysis continued with Bus 564 but not with Bus 566 since it was not deemed technically necessary by Cummins field support staff. The Cummins field test contract was amended to include the second bus. It completed circulation for signature by the project partners on July 11, 1997. The repower of Bus 566 had a reduced number of startup issues.

August 1997: Both demonstration buses were in operation. Bus 566 continued to experience slower acceleration than Bus 564. Bus 566 was also down for some time due to transmission problems. Cummins field support staff investigated the Bus 566 problems.

Cummins recommended that a chassis dynometer test be conducted as soon as possible at its distributor, CCP. Due to miscommunication between ADEPT and Cummins, ADEPT coordinated a chassis dynometer test on Bus 566 but this was not effective due to lack of Cummins staff presence and proper test plan coordination. Cummins rescheduled a new chassis dynometer test for both LPG buses at a later date. CCP returned both original B5.9 diesel engines to Laidlaw per the agreement.

ADEPT and Cummins prepared and submitted a project summary for the SCAQMD Annual Technology Advancement Office (TAO) Conference.

Mutual Propane prepared an alternative fueling plan for the City in the event of unforeseen problems with the on-site fueling station.

September 1997: Cummins factory support staff, CCP distributor staff, and City/Laidlaw staff continued to investigate the reported poor acceleration on the second demonstration bus (initially identified in August). The reason was not yet determined. Both buses were in revenue service throughout September. Bus 566 was driven only on short routes due to the acceleration problem and the drivers' reluctance to drive it. Laidlaw estimated that the bus was operated only 60% of the time throughout September.

October 1997: Bus 564 was in regular service with no major problems reported. It also underwent a diagnostics chassis dynamometer test. Bus 566 continued to experience acceleration problems. CCP staff determined that this problem was due to oil leaking into the fuel control valve and into the gas mass sensor housing. These parts were removed and replaced, as well as the evaporator. A new upgraded evaporator was installed.

November 1997: Both Buses 564 and 566 were in regular service for the majority of the month. Bus 564 underwent replacement of the fuel control valve and wire harness insulation next to the muffler. There was also an evaporator upgrade. Bus 566 experienced a fuel leak at the outlet fuel line of the evaporator. Bus #2 also experienced inactive fault codes due to low battery voltage levels at the ignition control module (ICM) and at the electronic control module (ECM).

December 1997: Buses 564 and 566 were in regular service for the majority of the month. Cummins activated the balance of the two-year base engine warranty for Bus 564 as the one-year field test had been completed. The engine emission identification plates were updated on Bus 564 to certified levels. The ARB exemption permit for Bus 564 expired on December 9, 1997 and was no longer required. Both buses experienced engine shut downs in operation. On Bus 564 the ECM was recalibrated. On Bus 566 the ICM was replaced.[21] Also, the gear-housing gasket was replaced due to an oil leak.

January 1998: Buses 564 and 566 were in regular service.

Both buses continued to experience an intermittent[22] engine “shut down” problem which disrupted service. In the event the engine could not restart, Laidlaw had towed the bus. The ICM was replaced on both vehicles. In addition, the O_2 sensor and the idle speed were readjusted twice on Bus 566 as part of the trouble-shooting. Both CCP and Cummins investigated the matter throughout the following months since Cummins was not experiencing this reoccurring problem on other B5.9LPG powered vehicles.

February 1998: The mechanics INSITE[23] training provided by CCP was held on February 16th and 17th. Mutual Propane provided supplemental training on LPG and on the fuel system technology[24]. ADEPT assisted Laidlaw to buy the laptop and the engine data communications link.

Buses 564 and 566 were in regular service. On several occasions Bus 566 experienced the intermittent “engine shut down” whereas Bus 564 did not. Each time the engine did not restart, the bus was taken out of service. Cummins and CCP continued to trouble-shoot. CCP installed a power identification light for the electronic control module (ECM), replaced an OEM fuse, and switched the coolant hoses on the evaporator as part of the intermittent shut down problem

[21] An internal electrical component failure was fixed. This repair was validated and incorporated into production.
[22] Approximately every two weeks.
[23] INSITE: Proprietary Cummins maintenance, troubleshooting and diagnostics software for the B5.9LPG engine.
[24] Mutual Propane is a distributor for GFI products.

trouble-shooting.

March 1998: Bus 564 operated in regular service without difficulty. Bus 566 continued to experience the intermittent (about every two weeks) "engine shut down" problem[25]. CCP replaced the ignition coils and engine wiring harness on Bus 566 as part of the intermittent shut down problem trouble-shooting. Analysis of ignition coils and engine wiring harness at Cummins showed no failure mode.

April 1998: Bus 564 ran without incident. However, Bus 566 continued to experience intermittent engine "shut down". CCP rewired a power light to the CIM power supply. On April 20th, Cummins sent Mr. Mike Haub, B5.9LPG Service Engineer, to CCP to assist with this trouble-shooting. Bus 566 was returned on April 21. A faulty vehicle wiring harness, power supply to ICM, appeared to be the cause of the intermittent engine shut down problem.

The City extended its conditional use permit for the LPG refueling station into August 1998. At that time the City would find another source for LPG, or relocate the facility.

May 1998: Buses 564 and 566 were in regular service. On May 9th, the exhaust manifold was replaced on Bus 566 due to an exhaust leak. No other operational problems were reported. The intermittent shut down problem with Bus 566 seemed resolved. Cummins staff determined that this problem was not due to an engine component failure.

June 1998: Buses 564 and 566 were in regular service.

July 1998: Bus 566 was in regular service. Bus 564 experienced engine shut down due to a low idle speed setting. The speed was reset, hence, the issue was resolved. Bus 566 completed the one-year field test. Cummins activated the balance of the two-year base engine warranty.

August 1998: Buses 564 and 566 were in regular service.

September 1998: Buses 564 and 566 were in regular service.

October 1998: Buses 564 and 566 were in regular service.

Table 5 summarizes the engine related work orders during the data collection period. Some of the components on Buses 564 and 566 were changed due to component revision or upgrade (i.e. fuel control valve, vaporizer, exhaust manifold). Some of these components were changed as part of a trouble-shooting procedure. Further analysis of some components by Cummins showed no failure mode (i.e. trouble-shooting intermittent engine shut down on Bus 566, which

[25] Engine Codes 459 and 462 indicate occurrence of spark timing signal loss and spark reference signal loss.

was due to vehicle issues).

Incident/ Upgrade Type	Bus 564 Recurrence	Bus 566 Recurrence
Fuel Control Valve	4	3
Vaporizer	3	5
ECM/ICM	2	4
Exhaust Manifold	2	1
Alternator	2	0
Engine Testing	4	1
Piston Upfit/GFM Sensor	1	1
Front Cover Gasket	0	4
Idle Speed	0	2
Ignition Coil	0	1

Table 5: B5.9LPG Engine Work Order Recurrence

Monthly data collection for the City of Pasadena Cummins B5.9 Propane Engine Demonstration Project concluded in August 1998. Although the demonstration period for Bus 564 ended earlier, data collection continued through August 1998. Both buses continue to be in service.

Tables 6, 7, and 8 summarize demonstration mileage and hours.

Demonstration Vehicle

Bus # 564 Starting Mileage = 46,169 Initial Hour Reading = 146

Year	Month	Mileage*	Miles*	Miles (subtotal)*	Hours*	Net Hours*
1997	January	47,467	1,298	1,298	327.6	181.6
1997	February	49,493	2,026	3,324	561.7	234.1
1997	March	51,325	1,832	5,156	777.0	215.3
1997	April	52,672	1,347	6,503	930.7	153.7
1997	May	53,842	1,170	7,673	1,071.0	140.3
1997	June	55,591	1,749	9,422	1,260.8	189.8
1997	July	57,817	2,226	11,648	1,520.0	259.2
1997	August	59,138	1,321	12,969	1,673.1	153.1
1997	September	60,435	1,297	14,266	1,827.0	153.9
1997	October	61,785	1,350	15,616	1,979.0	152.0
1997	November	63,150	1,365	16,981	2,134.0	155.0
1997	December	-	-	-	-	-
1998	January	65,600	2,450	19,431	-	-
1998	February	67,351	1,751	21,182	2,606.0	472.0
1998	March	69,135	1,784	22,966	2,780.0	174.0
1998	April	71,524	2,389	25,355	3,040.0	260.0
1998	May	74,602	3,078	28,433	3,376.0	336.0
1998	June	75,766	1,164	29,597	3,507.0	131.0
1998	July	76,828	1,062	30,659	3,628.0	121.0
1998	August	-	-	-	-	-
1998	September	78,897	2,069	32,728	3,873.0	245.0
1998	October	80,127	1,230	33,958	4,020.0	147.0

Note 1: Range of in-use hours per month over demonstration period = 121 - 472
Note 2: Average in-use hours per month = 203.9
Note 3: Range of miles per month over demonstration period = 1,062 - 3,078
Note 4: Average number of miles per month = 1,698
*Data not collected due to unavailable staff or other circumstance.

Table 6: Tabulated Field Test Report Data for Bus #564

Demonstration Vehicle

Bus # 566 Starting Mileage = 45,910 Initial Hour Reading = 3.5

Year	Month	Mileage*	Miles*	Miles (subtotal)*	Hours*	Net Hours*
1997	July	46,913	1,003	1,003	120.3	117
1997	August	47,268	355	1,358	156.6	36
1997	September	-	-	-	-	-
1997	October	49,811	2,543	3,901	453.0	296
1997	November	50,916	1,105	5,006	577.0	124
1997	December	-	-	-	-	-
1998	January	52,787	1,871	6,877	-	-
1998	February	53,539	752	7,629	854.0	277
1998	March	54,734	1,195	8,824	988.0	134
1998	April	56,560	1,826	10,650	1,187.0	199
1998	May	59,333	2,773	13,423	1,493.0	306
1998	June	60,334	1,001	14,424	1,604.0	111
1998	July	61,191	857	15,281	1,706.0	102
1998	August	-	-	-	-	-
1998	September	64,388	3,197	18,478	2,079.0	373
1998	October	65,472	1,084	19,562	2,206.0	127

Note 1: Range of in-use hours per month over demonstration period= 36 - 373
Note 2: Average in-use hours per month = 183.5
Note 3: Range of miles per month over demonstration period = 355 - 3,197
Note 4: Average miles per month = 1,505
*Data not collected due to unavailable staff or other circumstance.

Table 7: Tabulated Field Test Report Data for Bus #566

Control Vehicle
Bus #560 Starting Mileage = 60,290

Year	Month	Mileage*	Miles*	Miles (subtotal)*	Gallons[2]
1997	February	61,167	877	877	538.8
1997	March	62,922	1,755	2,632	481.7
1997	April	65,101	2,179	4,811	553.8
1997	May	67,675	2,574	7,385	466.7
1997	June	69,318	1,643	9,028	706.0
1997	July	72,630	3,312	12,340	444.8
1997	August	74,167	1,537	13,877	398.9
1997	September	75,911	1,744	15,621	599.5
1997	October	78,089	2,178	17,799	-
1997	November	81,214	3,125	20,924	-
1997	December	-	-	-	-
1998	January	85,196	3,982	24,906	-
1998	February	-	-	-	-
1998	March	89,785	4,589	29,495	-
1998	April	92,624	2,839	32,334	-
1998	May	96,318	3,694	36,028	-
1998	June	97,777	1,459	37,487	-
1998	July	99,236	1,459	38,946	-
1998	August	-	-	-	-
1998	September	104,818	5,582	44,528	-
1998	October	106,762	1,944	46,472	-

Note 1: Range of miles per month over demonstration period = 877-5,582
Note 2: Average number of miles per month[26] = 2582
*Data not collected due to unavailable staffing or other circumstance.

Table 8: Tabulated Field Test Report Data for Bus #560

Review of the data revealed several inconsistencies. After June 1997, both buses (#564 and #566) were supplied from the same LPG refueling tank. The City and Mutual Propane's data combines fuel used by both buses from July 1997 on. Thus, it is not possible to discern the quantity of fuel each bus drew from the tank. ADEPT found the most reasonable approach is to take a longer-

[26] Bus 560 was operated on the same exact route as Buses 564 and 566. However, the higher mileage was a reflection of the greater down time experienced by Buses 564 and 566 as well as from preference of the drivers.

term perspective regarding fuel consumed in both the demonstration buses and control bus #560 (to compare with buses #564 and #566).

Before July 1997, bus #564 was recorded to use about 2.0 miles per gallon (LPG). After July 1997, both #564 and #566 used approximately 2.2 miles per gallon (LPG). Over the duration of the demonstration period, the control bus #560 used about 3.7 miles per gallon (diesel). ADEPT asked the City to monitor and track the mileage and fuel consumption closely for a short period of time to illustrate a snapshot of what the miles per gallon were likely to be. Tables 9A, 9B, and 9C summarize the miles per gallon for each bus during the month of January 1999.

Bus 560 Diesel Log (January Snapshot)			
Date	**Hours**	**Gallons**	**Miles**
8-Jan	-	20.0	110,920
9-Jan	-	0.0	0
10-Jan	-	18.5	111,004
11-Jan	-	18.0	111,178
12-Jan	-	16.0	111,263
13-Jan	-	16.5	111,353
14-Jan	-	17.0	111,440
15-Jan	-	23.0	111,554
16-Jan	-	0.0	0
17-Jan	-	19.0	111,641
18-Jan	-	0.0	0
19-Jan	-	16.5	111,732
Average Miles/ Diesel Gallon =		**4.94**	

Table 9A: Miles per Gallon (January 1999) for Bus 560

Bus 564 Log (January Snapshot)			
Date	**Hours**	**Gallons**	**Miles**
8-Jan	4,223	25.0	81,855
9-Jan	-	0.0	0
10-Jan	-	16.0	0
11-Jan	-	0.0	0
12-Jan	-	0.0	0
13-Jan	4,240	65.0	82,011
14-Jan	-	0.0	0
15-Jan	-	0.0	0
16-Jan	-	0.0	0
17-Jan	4,252	48.2	82,115
18-Jan	4,264	42.3	82,224
19-Jan	-	0.0	0
Average Miles/ Propane Gallon =		**1.88**	**(Diesel equivalent= 2.91 mpg)**

Table 9B: Miles per Gallon (January 1999) for Bus 564

Bus 566 Log (January Snapshot)			
Date	**Hours**	**Gallons**	**Miles**
8-Jan	-	0.0	0
9-Jan	-	0.0	0
10-Jan	2,429	47.0	67,340
11-Jan	-	0.0	0
12-Jan	2,434	16.6	67,375
13-Jan	-	0.0	0
14-Jan	2,443	27.2	67,457
15-Jan	-	0.0	0
16-Jan	-	0.0	0
17-Jan	2,455	53.0	67,566
18-Jan	-	0.0	0
19-Jan	2,468	46.0	67,684
Average Miles/ Propane Gallon =		**1.81**	**(Diesel equivalent= 2.81 mpg)**

Table 9C: Miles per Gallon (January 1999) for Bus 566

The fuel price per propane gallon of HD-5 LPG was on average $0.63 with a range of $0.49 to $0.81 on normalized fuel costs alone. The HD-5 LPG diesel equivalent average was $0.98 per gallon, which was competitive with diesel. The price per diesel gallon was on average $1.07 with a range of $0.94 to $1.20. The LPG BTU content was 83,200 BTU/gallon (lower heating value). The "ARB Diesel" BTU content was 129,350 BTU/gallon (lower heating value). Thus, one gallon of diesel fuel equals approximately 1.55 gallons of LPG on a BTU equivalency.

ADEPT is aware that there were services rendered to Bus 564 prior to 2/28/97 and since 1/23/98 and to Bus 566 prior to 9/30/97 and since 3/20/98. ADEPT and City/Laidlaw did not have all the work orders at the time of this analysis.

In July 1998, ADEPT conducted a driver's survey to assess driver feedback from the demonstration. Twelve drivers were interviewed. Please refer to Appendix B as the results to the 26 inquiries are self-explanatory.

On November 15th, a demonstration closeout meeting was held at City to address outstanding issues. Following several subsequent teleconferences the parties agreed to the following additional support items to close out the demonstration:

- Cummins Cal Pacific will extend the Cummins Engine Co. two year warranty on the City of Pasadena's B5.9 LPG engine (ESN 45450499) by six (6) months to end on May 30, 2000.

- Cummins Cal Pacific will provide to the City of Pasadena, and/or its operator Laidlaw, one additional mechanics/INSITE training by November 30, 1999.

- Cummins Cal Pacific agrees to provide LPG fuel system parts for ESN 45450499 free of charge, for warrantable failures, to the City of Pasadena and/or its operator Laidlaw from June 1, 2000 to November 30, 2000.

- The City of Pasadena's operator, Laidlaw, agrees to pay all labor charges for ESN 45450499 from June 1, 2000 to November 30, 2000.

- Mutual Propane will provide technical support consultations related to propane refueling and propane fuel gauges and tanks on as-needed basis at no charge as long as buses 564 and 566 are in service. Technical consultation includes: fueling training, assistance with troubleshooting and/or parts ordering.

Project Promotions

Throughout the project, ADEPT and Cummins promoted the project on various fronts. Below is a list of noted media coverage about the project.

- Passenger Transport article entitled: "San Antonio System to Add 283 New Vehicles by 2002" March 1998.
- Butane Propane News article, re: City of Pasadena field site, June 1997.
- School Transportation News, article "Propane Gas Bus Popularity Increasing in Texas", August 1997.
- SCAQMD Annual Report 1997.

Cummins and PVC jointly sponsored a campaign to display the B5.9LPG engine at various events around North America. These events are listed in chronological order.

- Technical presentation and engine display at the Propane Vehicle Conference (Orlando, FL) February 2-4, 1997.
- Engine display at the Midwest LPGA Trade Show (Indianapolis, IN) March 8-10, 1997.
- Ottawa Truck Commando 30 yard spotter with engine display at the Truck Maintenance Council Show, March 1997, then transferred to a Los Angeles dealer for customer demonstrations.
- Engine display at the Southeast National Propane Gas Association (NPGA) Trade Show (Atlanta, GA) April 6-8, 1997.
- Engine and Suburban FL70 field-test truck display at the Western LPG Trade Show (San Diego, CA) April 24-26, 1997.
- B5.9LPG technical presentation and engine display at the Windsor Alternate Fuels Conference (Windsor, Ontario, Canada) June 8-10, 1997.
- Engine display at the Oklahoma Pupil Transportation Conference (Oklahoma City, OK) June 8-11, 1997.
- Engine and the City's demonstration vehicle display at the DOE Clean Cities (CC) Conference (Long Beach, CA) June 25-26, 1997.
- Engine display at the DOE CC Regional Conference (St. Louis, MO) July 30, 1997.
- Engine display at Southwest Propane Gas Trade Show and Convention (Dallas, TX) August 19-20, 1997.
- Engine display at the DOE Regional CC Conference (Atlanta, GA) September 4, 1997.
- Engine display at the NPGA Trade Show and Convention (Providence, RI) September 26-28, 1997.
- Engine display at the National Association of Pupil Transportation (school bus) Conference (Indianapolis, IN) November 4-5, 1997.
- Technical presentation at the SCAQMD Technology Advancement Office Conference

December 4, 1997[27].

- Technical presentation and engine display at the Propane Vehicle Conference (February 11, 1998).
- Engine display and presentation at the Southeast LPG Conference (Atlanta, GA) April 5-7, 1998.
- Engine display at the Midwest LPG Conference (Indianapolis, IN) April 25-27, 1998.
- Engine display for the Southwest LPG Conference (Dallas, TX) May 11-12 1998.
- Technical presentation and engine display for the DOE CC Conference (Washington, D.C.) May 31-June 3, 1998.

This promotional campaign continues into the 1999 year.

ADEPT and Cummins worked jointly to promote the use of the engine at additional sites. In Texas, two sites are in development. Another has been consulted in Sacramento, CA. Many more have started throughout the U.S., Australia, and Mexico as a result of Cummins promotions. Table 10 shows the sites that have B5.9LPG engines in use or on order as of October 1998.

[27] Both ADEPT and Cummins conducted the presentation.

OEM/User Field Tests					
Customer	Location	OEM	Application	Qty	Status (Miles)
Suburban Propane	Sacramento Area	Freightliner FL 70, Repowers	LPG Bobtail	4	38,200 - Unit #1 53,200 - Unit #2 45,500 - Unit #3 36,400 - Unit #4
Superior Propane	Toronto, Canada	FL 80 – Repower	LPG Bobtail	1	33,300
Western Transit	Pinole, CA	Thomas, Repowers	Shuttle Bus	2	56,700 - Unit #1 63,000 - Unit #2
				Total:7	
OEM/User Market Tests					
Customer	Location	OEM	Application	Qty	Status (Miles)
Delta Liquid Energy	Paso Robles, CA	Freightliner FL 70	LPG Bobtail	1	9,700
City of Pasadena	California	Bluebird Q Bus, Repowers	Shuttle Bus	2	27,100 - Unit #1 12,300 - Unit #2
UPS	Minneapolis, MN	Ottawa Truck	Yard Spotter	1	In Service
Ranger Die Casting	Lynwood, CA	Freightliner FL 70	LPG Bobtail	1	9,000
				Total:5	
Limited Production					
Customer	Location	OEM	Application	Qty	Status (Miles)
Allegheny Steel	New Castle, IN	Hoist Lifttruck	MD Forklift	1	In Service
Allied Signal	Albuquerque, NM	Ottawa Truck	Yard Spotter	1	In Service
Automotriz Uribe	Mexico City	Freightliner FL70	Regional Delivery	1	In Service
City of Santa Rosa	California	Freightliner FL70	Regional Delivery	1	In Service
CC Ind. School Dist.	Corpus Christi, TX	Blue Bird, Repower	School Bus	1	Planned
CC Regional Transit	Corpus Christi, TX	Champion/Spartan	Shuttle Bus	6	On Order
CC Regional Transit	Corpus Christi, TX	Repowers	Shuttle Bus	3	1 On Order
Delta Liquid Energy	Paso Robles, CA	Freightliner FL70	LPG Bobtail Deliv.	1	Operational
Elgas	Australia	Freightliner FL80	Regional Delivery	1	Operational
FEMSA (Coca Cola)	Mexico City	Freightliner FL70	Regional Delivery	1	In Service
Garber Post	Montgomery, IN	Ottawa Truck	Yard Spotter	1	In Service
Kleenheat Gas	Australia	Freightliner FL80	Regional Delivery	1	Operational
LA DoT	Los Angeles, CA	El Dorado	Shuttle Bus	30	30 In Service
LA DoT	Los Angeles, CA	El Dorado	Shuttle Bus	17	On Order
L.A. Murphy	Australia	Freightliner FL80	Regional Delivery	1	Operational
Northwest Trek Tram	Tacoma, WA	AAI-ACL/Spartan	Shuttle Bus	2	Engines Installed
Oneil Gas	Choudrant, LA	Freightliner FL70	LPG Bobtail Deliv.	4	Planned
Paratransit	Sacramento, CA	Thomas Repowers	Shuttle Bus	2	Planned
Solar Turbines	San Diego, CA	United Tractor	Yard Tug	1	In Service
UPS	Minneapolis, MN	Ottawa Truck	Yard Spotter	4	In Service
Various Customers	Not Available	Ottowa Truck	Yard Spotter	8	2 Engines Shipped
Various Customers	Not Available	Freightliner FL70	Not Available	3	On Order
VIA Transit	San Antonio, TX	Trolley	Shuttle Bus	15	Planned
VIA Transit	San Antonio, TX	Champion/Spartan	Shuttle Bus	66	On Order
VIA Transit	San Antonio, TX	Chance Coach	Trolley	5	Planned
Western Propane	Santa Maria, CA	Freightliner FL70	LPG Bobtail	1	Operational
Western Transit	Pinole, CA	Thomas, Repowers	Shuttle Bus	2	In Service
White River Dist.	TBD	Freightliner FL70	LPG Bobtail Deliv.	1	Planned
			Total:	181	

Table 10: Sites with Cummins B5.9LPG Engines in Use or On Order

Project Conclusions

1) This project was successful in that it resulted in the first heavy-duty dedicated LPG fuel engine with the below attributes:
   a) PC-based diagnostics (INSITE software)
   b) Minimum engine life to overhaul of 300,000 miles[28]
   c) Two year base engine warranty with unlimited mileage
   d) CARB and EPA emissions warranty for five years or 100,000 miles with a catalyst.
   e) B5.9LPG offered by the following OEMs: Champion, El Dorado, Freightliner Truck, Ottawa, and Spartan Chassis as of October 1998.

2) The engine optimization and precertification tests for the B5.9LPG project were completed and met the EPA CFFV LEV and CARB Optional Low NO_x certification standards. As illustrated in Tables 1 and 3 and Figures 8 and 9, the PM and CO emissions are very low, with NO_x emissions substantially low. The ULEV emissions target was not met due to the challenges of higher levels of total HC. In addition to HC content, LPG's high heat of combustion may yield higher emissions. Oxidizing catalysts will continue to be required to meet increasingly stringent emission standards. A heavy-duty LPG spark-ignited engine must meet a THC requirement whereas the natural gas engine is required to meet a NMHC standard. Cummins met all of the other B5.9LPG engine development program targets.

3) B5.9LPG engine shutdowns were observed in the field. These shutdowns were correlated with the following conditions: vehicle voltage drops to the ECM/ICM, evaporator failures, and fuel control valve failures. Also, there were four front-cover gasket failures. Analysis of these occurrences is ongoing. Some of the problems are attributed directly to installation issues with the repower of the two buses even though the engine platform was the same. Repowers are more prone to installation-related problems than a chassis OEM installation. This increase in difficulties was anticipated and the chassis OEM, Bluebird, was asked to participate but declined. Additional detail may be obtained at a later date from Cummins' Alternative Fuels Division.

4) Regular fuel testing by fleet operators is critical. Maintenance of HD-5 fuel quality is a requirement of the B5.9LPG warranty. Even though all LPG providers made efforts to ensure HD-5 compliance, field tests indicated a wider range of fuel quality was supplied.

5) Additional research and development are recommended in the following areas:

[28] Engine life to overhaul is based on the expected life of the bottom-end components – crankshaft, camshaft, bearings, etc. for which 300,000 miles is the expectation. Although B5.9LPG engine experience is limited, Cummins L10G engine life experience lends to their expectation that B5.9LPG engine life will be longer than diesel. This is predominantly due to the lack of soot or fuel in oil, and lower thermal cycling of the engine over the operating range.

a) EPA CFFV ULEV capability
b) Wider range fuel capability for combustion, performance, and emissions
c) Parts supplier research and development to increase performance and durability of LPG specific parts:
   i) Evaporator issues remain unresolved.
   ii) An octane sensor can help improve LPG engine performance. Such a sensor, as part of ECM control, can advise actual fuel quality of the charge about to be introduced in the combustion chamber (a known octane value input to the ECM allows to adjust certain combustion control parameters like air/fuel ratio or ignition timing, or both). Thus, the engine may be more efficient and tolerant of a broader range of LPG fuel.
   iii) On-board fuel supply sub-systems and components require further research and development. For instance, an accurate LPG fuel level gauge is needed.

6) Additional marketing/promotion activities are recommended to:
   a) Increase the number of vehicle OEMs offering the engine.
   b) Increase awareness of this engine's availability on international markets.

In summary, this project was a success in that it fostered an engine that met engine performance targets while significantly reducing emissions. The engine development program illuminated critical design differences between natural gas and LPG engines. Further research and development is needed for LPG-specific components provided by outside suppliers.

In its first year of production, Cummins received almost 200 orders. Warranty service experience for this engine will not be known for some time but is expected to be similar to the B5.9G engine.

Disclaimer

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APPENDIX