Final Report of California Air Resources Board (ARB) Liquified Petroleum Gas (LPG) Fuel Blends Evaluation Project

Contractor: The ADEPT Group, Inc.
Subcontractors: Bodycote Laboratory, Southwest Research Institute, Dixie Laboratories, Consulting Solutions, and Hertz Engineering.

Cosponsors: American Automobile Manufacturers Association, ARCO Products Co., California Air Resources Board, Cummins Engine Co., Engine Manufacturers Association, Equilon Martinez Refining Co., Ford Motor Co., GFI, IMPCO, National Propane Gas Association, National Renewable Energy Laboratory, Natural Resources Canada, Propane Education and Research Council, Propane Gas Association of Canada Inc., Railroad Commission of Texas Alternative Fuels Research and Education Division, Tosco Refining Co., and Western Propane Gas Association.

I. Background

Propane, or Liquefied Petroleum Gas (LPG), the most prevalent and easily accessible alternative fuel in the United States, is used in ten times as many vehicles as other alternative fuels combined. In California, there are about 35,000 vehicles running on LPG. Despite LPG's wide use, there was no consensus on what should be a commonly accepted LPG fuel standard for motor vehicles. The California Air Resources Board (ARB) initiated a process to enact such a standard for LPG used in motor vehicles.

The ARB adopted Section 2292.6 of Title 13, California Code of Regulations, went into effect on 01/01/93. ARB included a max. limit of 10% by vol. on propene content of vehicular LPG. That propene limit was to decline to 5% on 01/01/95. However, in 1994, ARB delayed the effective date of the 5% propene limit to 01/01/97. In 1997, ARB again delayed the effective date of the propene limit to 01/01/99. In the interim, the propene limit remained at 10% vol.. ARB delayed the effective date of the propene limit out of concerns raised by vendors of commercial propane (who supply motor vehicle LPG) that too little commercial propane available to them meets the specifications set by ARB.

When ARB adopted specifications for vehicular LPG, it set essentially identical standards for motor vehicle fuel sold commercially in California and fuel used for emission standard certification testing of new motor vehicles. Commercial LPG fuel specifications are set to ensure that motor vehicles certified on LPG use fuel of quality similar to certification fuel, so that vehicles will achieve their emission standards in actual use.

II. Project Objectives

The project's objectives were: (1) identify which alternative LPG fuel blends could provide equivalent or better emissions than certification LPG fuel while maintaining engine performance within manufacturers' specifications; (2) once equivalent or better emission blends are identified, conduct appropriate combustion & performance tests to demonstrate that engine performance remains within manufacturers' specifications, and (3) once combustion & performance tests of equivalent or better emission blend/s were satisfactorily completed, conduct

appropriate durability tests to demonstrate that engine wear on the subject blend/s remains within manufacturers' specifications.

III. Project Task Group

A Task Group was created to gather pertinent data and maximize consensus. ARB chaired the Task Group. Aside from SCAQMD, the Task Group included: refiners, LPG distributors, LPG industry associations, engine manufacturers, engine manufacturers' associations, vehicle OEM's, sub-systems manufacturers, the Canadian Government, and the State of Texas.

The Task Group agreed that specific tests are to be conducted; that test data is to be jointly reviewed; and that test results and Task Group comments will assist ARB in its rule making process. The ADEPT Group, Inc. (ADEPT) was hired by the Task Group as Project Manager, to insure that all tests are conducted per agreed-upon protocols, that pertinent test data is properly reviewed and reported, and to prepare and distribute monthly reports as well as a Final Report. ADEPT was also charged to raise and manage all funds needed to conduct the Task Group agreed-upon protocols.

IV. Status

Following a 12/11/99 hearing, the ARB Board adopted the below regulation:

Specification	Value	Test Method
Propane	85.0% (min.) *a*	ASTM D 2163-87
Vapor Press. @ 100°F	208 psig (max.)	ASTM D1267-89 ASTM D 2598-88 *b*
Volatility residue: evaporated temp., 95% or butanes	-37 °F (max.) 5.0 vol.% (max.)	ASTM D 1837-86 ASTM D 2163-87
Butenes	2.0% (max.)	ASTM D 2163-87
Pentenes and heavier	0.5 vol.% (max.)	ASTM D 2163-87
Propene	10.0 vol.% (max.)	ASTM D 2163-87
Residual matter: residue on evap. of 100ml. Oil stain observed.	0.05 ml (max.) pass *c*.	ASTM D 2158-89 ASTM D 2158-89
Corrosion, copper strip	No. 1 (max.)	ASTM D 1838-39
Sulfur	80 ppmw (max.)	ASTM D 2784-89
Moisture Content	Pass	ASTM D 2713-86
Odorant	*D*	

a. Propane shall be required to be a min. of 80.0 vol. % starting on 01/01/93. As of 01/01/97, the min. propane content shall be 85.0 vol. %.

b. In case of dispute about a product's vapor pressure, the value determined by Test Method ASTM D 1267-89 shall prevail over the value calculated by Practice ASTM D 2598-88.

c. Acceptable product shall not yield a persistent oil ring when 0.3 ml solvent residue mixture is added to a filter paper, in 0.1 ml increments and examined in daylight after 2 min. as described in ASTM 2158-89.

d. LPG, upon vaporization at ambient conditions, must have a distinctive odor potent enough for its presence to be detected down to a concentration in air of not over 1/5 (one-fifth) of the lower limit of flammability.

Within five years from effective date of adoption or implementation, whichever comes later, of amendments approved on 12/11/98, ARB, in consultation with the Secretary for Environmental Protection, shall review the provisions of this chapter to determine whether it should be retained, revised or repealed.

V. Methodology

Completed project tasks were: (1) Procure specific LPG blends for fuel specification, octane, emission, and performance tests: (2) procure three original equipment manufacturer (OEM) dedicated LPG engines/vehicles for testing (two Cummins B5.9LPG medium-duty engines and a Ford F150

bi-fuel light-duty truck); (3) conduct fuel specifications and octane tests on all test fuels; (4) conduct emission tests on both engine and vehicle per recognized ARB and FTP procedures; (5) conduct combustion & performance tests on B5.9 LPG engine with a LPG blend selected by ARB per Task Group approved protocol, and (6) conduct durability tests on B5.9LPG engine with the same LPG blend used in step (5) per Task Group approved protocol.

The LPG blends that the Task Group agreed to examine were:

Fuel	Propane	Propene	n-Butane
Cert. Fuel	93.5 ± 1%	3.5 ± .5%	1.9 ± .5%
Test Fuel # 1	85.0 ± 1%	10.0 ± .5%	5.0 ± .5%
Test Fuel # 2	80.0 ± 1%	15.0 ± .5%	5.0 ± .5%
Test Fuel # 3	80.0 ± 1%	10.0 ± .5%	10.0 ± .5%
Test Fuel # 4	76.0 ± 1%	3.8 ± .5%	20.0 ± .5%
Test Fuel #5	77.0 ± 1%	21.0 ± .5%	2.0 ± .5%

The Task Group specified tests did not cover butenes, pentenes and heavier hydrocarbons, sulfur, or odorant issues. ARB Staff handled these specifications outside the Task Group forum.

A. Fuel Properties and Octane Tests

Each test fuel was analyzed to verify fuel properties. The octane rating of the first four fuels was determined. The candidate fuels were ranked with the first being the most similar to Certification Fuel. Fuel ranking is based on parameters such as lower heating value and octane.

Dixie Services Inc. (Dixie) conducted tests to determine octane ratings. A higher octane number means an engine can run more efficiently and will have less tendency to knock.

The Research Octane Number (RON) is obtained in a single cylinder laboratory engine. The Motor Octane Number (MON) is obtained in a more widely representative test engine. Because engine designs vary greatly, neither RON nor MON is accurate in depicting on-road engine behavior in the average engine. The Anti-Knock Index (AKI) is the average of RON and MON. AKI is usually the best representation of a fuel's actual on-road octane number.[1]

Fuel	RON	MON	AKI
Cert. Fuel	108.4	96.1	102.3
Test Fuel # 1	107.7	94.6	101.2
Test Fuel # 2	106.6	93.7	100.2
Test Fuel # 3	107.0	94.1	100.6
Test Fuel # 4	106.8	94.4	100.6

Gas chromatography (GC) analysis was conducted for each fuel to verify properties of fuel samples used throughout the program. Dixie conducted the GC work.

B. Emissions Tests

The objective was to evaluate the impact of LPG fuel composition on engine exhaust emissions at the same performance levels. Key emissions criteria were: total hydrocarbons (THC), carbon monoxide (CO), oxides of nitrogen (NO_x), ozone forming potential (OFP), and non-methane organic gases (NMOG). The Medium-duty Emission tests were conducted on a Cummins 6B LPG engine at Bodycote ORTECH Inc. (Mississauga, Ontario). The Light-duty Emission tests were conducted on a Ford F150 Bi-fuel truck at ARB Haagen Smit Laboratory (El Monte, CA).

Emissions tests at both laboratories included Fuel #5 (added to protocol by Tosco Refining Co.).

Light-duty Emission Results[2] (Percent change in emissions relative to Certification Fuel emissions)					
Fuel	THC	CO	NO_x	NMOG	OFP
1	-8	1	-7	-2	3
2	4	2	9	9	40
3	-5	-22	28	-1	13
4	27	37	1	34	38
5	-24	5	25	-5	24

In above Light-duty Emission results, the Fuel #1 slight rise in OFP and CO was within testing error.

Medium-duty Emission Results[3] (Percent deviation from criterion)					
Fuel	THC	CO	NO_x	NMOG	OFP
Cert.	-21.3	-28.2	-5.5	-9.6	-12.8
1	-34.9	-24.2	3.2	-6.6	-7.2
2	-37.9	-8.8	5.8	-5.6	8.7
3	-20.6	15.2	5.0	-1.8	10.4
4	-27.5	52.1	-1.7	-8.7	0.4
5	-43.8	-39.6	15.9	-0.7	-13.3

Exhaust emissions for Fuel #1 were similar to Certification Fuel.

C. Combustion & Performance Tests

These tests were to evaluate the impact of LPG fuel composition on steady-state performance of a B5.9 LPG engine. Tests were conducted at Southwest Research Institute (SwRI) in San Antonio, TX.

The objective was achieved by operating the engine with two (2) different fuel blends over four (4) different engine speeds (2,800, 2,600, 1,640, and 1,460 rpm) and at four (4) different engine loads (100%, 75%, 50%, and 25%) for each speed. The engine parameters evaluated were: torque, power, brake thermal efficiency, average peak in-cylinder pressure, average peak pressure location, indicated mean effective pressure (IMEP), coefficient of variation of IMEP, ten percent burn angle, combustion duration, maximum rate of pressure rise, and cumulative heat release.

Overall engine performance was not affected by fuel blend. The engine produced full power (145 kW) at each engine speed with both blends.

D. Durability Tests

The objective of these tests was to run a B5.9 LPG engine on Fuel #1 (HD-10) fuel for 500 hours. Tests were conducted at Bodycote ORTECH Inc. (Mississauga, Ontario).

The engine was disassembled, critical dimensions measured, and photos taken at 0 hours and after 500 hours of durability tests. Valve recession measurements were taken at the 0, 100, 300, and 500-hour marks. Measurements before the 500-hour period were compared with final measurements.

Oil analysis was performed every 50 hours to provide an early excessive wear warning as well as to insure that there was a reliable scientific evaluation of engine wear. Hertz Engineering, a Canada-based specialist in the field, was hired to monitor and analyze the oil analysis results.

Fuel #1 was difficult to procure in the quantity needed to run 500 hours of durability tests. ADEPT sent one of its engineers to Toronto to procure various fuel components, blend the fuel, and monitor all fuel procurement activities, including tank rental and test site installation.

Much work went into the definition and selection of proper test conditions and

of the appropriate engine test cycle. Durability test conditions were:

- Constant 100% peak power;
- Water out temperature ≈ 225° F;
- Intake manifold temperature ≈ 155° F;
- Air inlet restriction at 20" H_2O;
- At rated RPM speed;
- Measure blow-by over time (oil losses);
- Record any drop in power;
- Monitor wear metals in 50-hr oil samples;
- Measure and note valve lash (adjust if needed);
- Change lubrication at 250-hr point.

The selected test cycle was:

- Engine runs at 60% rated power, for 10-hr run-in period;
- Engine stabilization period at 60% rated power for 25 hours;
- Engine runs at 100% rated power for remainder of test period;
- Engine is to run idle during final 15 minutes of the hour prior to sampling/measuring.

Above conditions and test cycle were verified with Cummins Engine Co. and were found to be to their satisfaction.

Results indicated that wear on the test engine was within expectations. No excess wear was noted.

At one interim test point, high copper PPM counts were found in the oil. Subsequently, this condition appeared to have corrected itself.

The test had one interruption due to a failed spark plug. The spark plug was replaced and the engine again performed as expected. The durability tests continued without any other interruptions.

Fuel #1 passed the Task Group agreed upon Durability tests.

VI. Results

Following emissions tests at Bodycote & ARB El Monte laboratories, ARB Staff concluded that combustion & performance as well as durability tests would be conducted only on Fuel #1. Combustion & performance tests were conducted at SwRI. A new B5.9LPG engine was bought for these tests. Fuel #1 satisfactorily passed these tests. Durability tests were subsequently conducted at Bodycote on the same B5.9LPG engine on which emissions tests were previously conducted. The Task Group, and specifically its Cummins Engine Co. representative, agreed to the use of the same engine for durability tests. Hertz Engineering was hired to assist with crucial tribology related engine wear issues. Consulting Solutions was hired to deal with crucial fuel blends preparation issues, as ADEPT had to procure the necessary components, the mixing and storage tanks, and blend the needed test fuels. Fuel #1 satisfactorily passed the agreed-upon durability tests protocol.

Benefits: Project benefits include: (1) the enactment of an ARB LPG fuel standard that is based on all pertinent parties' commonly agreed-upon tests (managed by an agreed-upon objective entity) that describe pertinent effects of various propane, butane, and propene mixes; (2) consensus building, increased dialogue, and a common forum for principally concerned parties (refiners, LPG distributors and retailers, engine manufacturers, air quality regulators); (3) increased knowledge of how LPG behaves in current engine technology; (4) indication of future work needed to fully understand how emissions from LPG dedicated engines are formed; (5) determination of products and services needed to field

implement this regulation; and (6) a common knowledge base for future rule making purposes.

Project was monitored by federal agencies in U.S. and Canada as well as by several EEC entities.

Costs: Program co-funding totaled $669,110 from U.S. and Canadian public, institutional, and private sources. Funding included $136,500 in in-kind contributions.

VII. Field Application Issues

The enactment of an ARB standard facilitates motor vehicle use of LPG in California. Issues still being resolved are: (1) entity/ies responsible to certify that the quality of the LPG fuel sold in California conforms with the ARB enacted standard, (2) standard enforcement methods, and any field exceptions to this standard, and (3) commercial availability of practical tools for the LPG distributors, dealers, and/or users to rapidly and cost-effectively assess the quality of the LPG fuel intended for motor vehicle use.

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[1] Garrett, T.K. Automotive Fuels and Fuel Systems Volume 1. Society of Automotive Engineers, Inc. Warrendale, PA, 1991. Pg. 14.

[2] Table is excerpt from ARB final report titled *Exhaust Emissions Test Results from a 1998 Ford F-150 LPG/Gasoline Bi-Fueled Light-Duty Truck using Six LPG Fuel Blends*. July 1999. Pg. 5.

[3] Table is excerpt from Bodycote final report titled *LPG Fuel Composition Study on a Cummins B5.9-195LPG Engine*. November 1998. Pg. 3.