LPG Fuel Composition Study on A Cummins B5.9-195LPG Engine

A Report to:	ADEPT Group Inc. 1575 Westwood Blvd., Suite 200 Los Angeles, CA 90024-5620 USA
Attention:	Mr. Alex Spataru President
Tel: Fax:	(310) 478-8448 (310) 478-5658
Submitted by:	Aurobindo Das Brian Manicom Mehboob Sumar Engine Technologies
Tel: Fax:	(905) 822-4111 (905) 823-1446
Final Report No:	98-1-05-01-01-11516 (Revision 2) 15 Pages; 7 Appendices
Date:	November 10, 1998

TABLE OF CONTENTS Page

LIST OF TABLES:

LIST OF FIGURES:

TABLE OF CONTENTS (Cont'ds):

LIST OF APPENDICES:

SUMMARY

This report summarizes the emissions tests carried out by ORTECH on behalf of the ADEPT Group, Inc. (ADEPT). This work was conducted as the first phase of the LPG fuels blends evaluation study project managed by ADEPT on behalf of a project Task Group headed by the California Air Resources Board (ARB). The test objective was to identify which alternative LPG fuel blends could provide equivalent or better emissions than certification LPG fuel while maintaining engine performance within manufacturer's specifications.

Five fuel blends were tested in addition to certification LPG (the reference fuel). The test to test variation (δ**)** was determined from repeated emission tests using certification fuel (reference fuel) only. This method was deemed most appropriate by ORTECH and ADEPT (the project manager) and may or may not be in concurrence with the approach selected by ARB staff, for its determination of δ. The following pass/fail criterion was established by the project Task Group for each emission species measured:

$$\mathbf{Xc \le Xr\ (1+n\delta)}$$

where **Xc** is the averaged emissions calculated for the candidate fuel
Xr is the averaged emissions calculated for the reference (cert.) fuel
δ is the coefficient of variability
and **n** is a factor of 2

A comparison was made using the above criterion for the following eight emission components:

- THC total hydrocarbon
- NMHC non methane hydrocarbon
- CO carbon monoxide
- NO_x nitric oxides
- PM particulate matter
- OFP ozone forming potential
- THC + NO_x sum of components
- NMHC + NO_x sum of components

Engine mass emissions are summarized in Table 1. The mean of the weighted averages of each test sequence are presented.

Table 1: Mass Emissions Summary
(All values are mean of weighted average)

			EMISSION VALUES (g/bhp-hr)										
Engine Data			Criteria Emissions						Species				
Fuel	Work bhp-hr	BSFC lb/bhp-hr	NMHC	THC	CO	NOx	PM	CO2	Carbonyls	C2 to C5	C6 to C12	NMOG	Ozone
1	12.02	0.503	0.671	0.702	0.407	3.178	0.007	667	0.037	0.651	0.001	0.689	1.143
2	11.97	0.509	0.636	0.670	0.489	3.257	0.008	674	0.032	0.816	0.000	0.849	1.338
3	12.05	0.528	0.815	0.856	0.618	3.234	0.007	675	0.032	0.798	0.001	0.832	1.360
4	12.01	0.518	0.736	0.782	0.816	3.026	0.006	680	0.033	0.740	0.001	0.775	1.237
5	11.96	0.508	0.594	0.623	0.324	3.633	0.007	674	0.041	0.476	0.001	0.518	1.068

Fuel#2 (Phillips) is included in the mean of weighted averages of fuel #2

The following table is a summary of fuel performance. Emissions satisfying the criterion requirements are denoted by a (√), others are shown as a grayed area:

Table 2: Emissions Summary

Fuel	THC	NMHC	CO	NO_x	PM	OFP	THC+ NO_x	NMHC +NO_x
Cert	√	√	√	√	√	√	√	√
1	√	√	√		√	√	√	√
2	√	√	√		√		√	√
3	√	√			√		√	√
4	√	√		√	√		√	√
5	√	√	√		√	√		

The data summarized in Table 2 is presented in Table 3 as the percentage deviation from the criterion. A minus sign (-) indicates that the fuel met the criterion requirements:

Table 3: Percentage Deviation From Criterion

Fuel	THC	NMHC	CO	NO_x	PM	OFP	THC $+NO_x$	NMHC $+NO_x$
Cert	-21.3	-22.0	-28.2	-5.5	-20.3	-12.8	-9.6	-9.6
1	-34.9	-35.7	-24.2	3.2	-13.7	-7.2	-6.7	-6.6
2	-37.9	-39.0	-8.8	5.8	-7.3	8.7	-5.6	-5.6
3	-20.6	-21.8	15.2	5.0	-15.4	10.4	-1.6	-1.8
4	-27.5	-29.4	52.1	-1.7	-24.7	0.4	-8.4	-8.7
5	-43.8	-44.4	-39.6	15.9	-30.6	-13.3	0.4	0.7

Aurobindo Das, Ph.D.
Supervisor, Engine Technologies

Stephen A. Carter
Manager, Systems Technologies

Brian Manicom
Engine Technologies

1. INTRODUCTION

This report documents the results obtained from medium-duty transient emissions tests conducted on a spark ignited, catalyst-equipped Cummins B5.9-195 LPG engine. The engine was tested with five alternative LPG fuels with varying amounts of propane, propylene and butane as presented in Tables 3.2(a) and 3.2(b). This report documents the results of the test program.

The engine was installed in an ORTECH motoring/absorbing dynamometer test cell. Engine performance was verified using ARB certification fuel. Next, baseline emissions tests were conducted using cert fuel to identify the test variability. The calculated standard deviation for each emission component was used to determine the equivalence criteria. To be deemed emissions-equivalent to cert fuel, each gaseous and particulate emission from the test fuel had to be within two standard deviations of the baseline[1]. A fuel which was not emissions-equivalent was deemed to have failed.

2. OBJECTIVE

The objective of this project was to evaluate the impact of LPG fuel composition on engine exhaust emissions at the same performance levels. Factors evaluated were: torque, power, brake specific fuel consumption (BSFC), nitric oxides (NO_x), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), particulate matter (PM), HC species (C2 - C12), and carbonyls[2].

3. TEST SET-UP

3.1. Engine Set-Up and Commissioning

The test engine was a catalyst-equipped Cummins B5.9-195 LPG engine (ORTECH sample number 98E11A0004) supplied by ADEPT. The engine specifications are summarized in Table 3.1.1.

[1] As indicated in the Summary, a pass/ fail criterion of the different fuel blends is: $Xc \leq Xr\,(1+2\delta)$. Since $\delta = \sigma / Xr$, where σ is the standard deviation of the reference fuel, this equation can be written as $Xc \leq Xr+2\sigma$. Therefore, a candidate fuel is said to pass if all its emissions were within two standard deviations of the reference fuel emissions.

[2] Both HC species and carbonyls are constituents of the non-methane organic gases (NMOG) responsible for ozone formation.

Table 3.1.1: Engine Specifications

Type of engine:	Spark ignited, turbocharged, 4 stroke
Power rating (@2600 rpm):	195 bhp (146 kW)
Peak torque (@1600 rpm):	420 lb-ft (569 N-m)
No. of operating cylinders:	6 in-line
Bore and stroke:	4.02 x 4.72 in. (102 x 120 mm)
Displacement:	389 cu. in. (5.9 liters)
Compression ratio:	9:1

Engine setup was instrumented to measure engine parameters as shown in Table 3.1.2. For a complete list of engine instrumentation and safety limits, refer to Table A1 of Appendix A. Table A2 presents a sample of the test cell printout.

Table 3.1.2: Measured Engine Parameters

Temperatures	Pressures	Others
intake air	intake air restriction	engine speed
charge air	compressor out	engine torque
compressor in / out	intercooler out	air flow rate
coolant in / out	intake manifold	fuel flow rate
oil gallery / sump	turbo in / out	emissions
fuel inlet / outlet	catalyst in / out	
exhaust	oil gallery	
turbo in / out	fuel (LPG) supply	
catalyst in / out	exhaust back pressure	

A water cooled heat exchanger was incorporated into the engine's cooling system which employed a 50-50% mix of water and ethylene glycol. The engine oil used was "Mobile Delvac Super GEO 15W40", as per Cummins specs. Engine operating parameters were set at rated power as follows:

- intake restriction: 4.4 kPa (17.5 "H2O),
- exhaust back pressure: 13.5 kPa (4.0 "Hg),
- manifold air temperature: 52 °C (125 °F),
- pressure drop between compressor outlet and mixer inlet: 13.5 kPa (4.0 "Hg).

Test cell instrumentation was calibrated prior to start up according to ORTECH's standard operating procedures.

Engine performance was verified to ensure conformance with Cummins specifications. As shown in Figure 3.1, engine power and torque were within 0.12% and 2.62% from the published ratings, respectively. Additional engine performance parameters are presented graphically in Figures A-1 to A-8 in Appendix A.

Engine Performance Verification Using Cert. Fuel

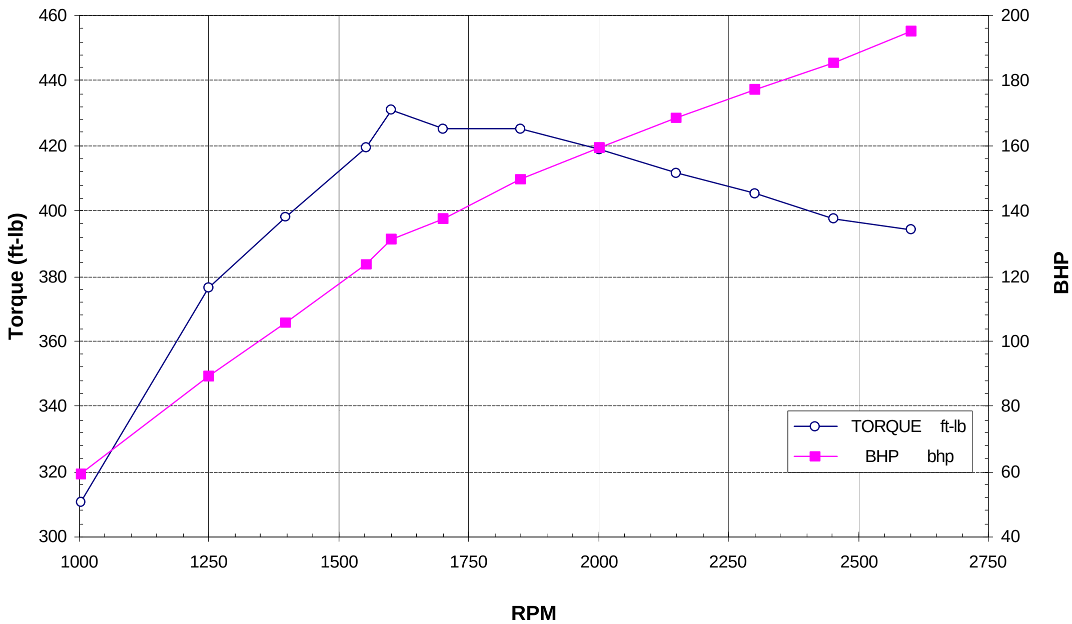


Figure 3.1

3.2. Test Fuel Compositions

Test fuels conforming to specifications established by the LPG Task Group were procured by ADEPT from Aeriform and Phillips. All tests originally proposed were conducted using fuel supplied by Aeriform; follow up tests were conducted using Phillips fuel.

Tables 3.2 (a) and 3.2 (b) present the fuel compositions provided by Aeriform and Phillips, respectively:

Table 3.2 (a): Aeriform Fuels - Chemical Composition (Volume %)

Fuel ID	Fuel Blend	Propane	Propylene	N-Butane
#NA18973	Cert	94.42 %	3.68 %	1.90 %
#73977	1	85.28 %	9.86 %	4.86 %
#8490J	2	81.15 %	14.15 %	4.70 %
#73991	3	80.07 %	9.97 %	9.96 %
#8493J	4	76.34 %	3.78 %	19.88 %

Table 3.2 (b): Phillips Fuels - Chemical Composition (Volume %)

Fuel ID	Fuel Blend	Propane	Propylene	N-Butane
CS-173518	Cert	95.01 %	2.99 %	2.00 %
CS-178001	2	80.06 %	14.94 %	5.00 %
CS-176670	5	77.08 %	21.32 %	1.60 %

3.3. Test Facilities

Test Cell

The test program was carried out in an ORTECH FTP-capable test cell with a 450 HP absorbing/ 430 HP motoring dynamometer.

Combustion/Dilution Air System

Engine combustion air temperature was controlled to a dry-bulb temperature of 23° ± 3°C. Engine combustion air humidity was controlled to a dew point of 15° ± 1°C. Dilution air for the emission tunnel was filtered, dried, and controlled to a temperature of 23° ± 3°C.

Emission Facilities and Sampling Methodology

All exhaust samples were drawn from the diluted exhaust of the dilution tunnel. This 2000 cfm double dilution PDP-CVS (Positive Displacement Pump- Constant Volume Sampler) meets all specifications of the US. Federal Code of Regulations (CFR-40).

The engine's entire exhaust was directed through a mixing orifice into a 10" primary tunnel where it was mixed with primary dilution air. At a distance of approximately 10 tunnel diameters downstream, samples are withdrawn through heated lines and pumped to the gaseous bench for real time analysis of the regulated gaseous emissions. A second sample is withdrawn at this point to the carbonyl sample system. A third diluted exhaust flow is withdrawn into the secondary tunnel. The test sample is mixed with secondary dilution air in order to bring the sample temperature below 52°C. The sample is then passed through a particulate filter holder which collects the sample for particulate analyses. A fourth sample is withdrawn to the bag bench for the collection of speciation and cycle-composite gaseous samples. All components in contact with the exhaust samples are made of stainless steel or teflon.

Emissions were measured using equipment and procedures meeting the standard certification requirements as described in the EPA CFR-40 Subpart N for heavy-duty engines as well as in the California Non-Methane Organic Gas Test Procedures. Equipment and techniques used are listed below for the different emissions:

Carbon Dioxide	- nondispersive infrared analyzer (NDIR; Horiba AIA-220)
Carbon Monoxide	- nondispersive infrared analyzer(NDIR; Horiba AIA-220)
Total Hydrocarbons	- flame ionization detector (FID; Beckman 404)
Oxides of Nitrogen	- chemiluminescence analyzer (CL; Beckman 955)
Methane/NMHC	- gas chromatography (GC; SRI Instruments 9300)
Total Particulate	- teflon-coated glass fibre filters (Pallflex T60A20-HT) analyzed by weight differential

Carbonyl samples were collected using DNPH coated silica cartridges (Waters Sep-Pak. XPoSure Aldehyde Samplers). They were subsequently analyzed using high performance liquid chromatography (HPLC ;Waters LC Module 1).

HC Speciation samples were collected using Tedlar sample bags with subsequent analysis by gas chromatography. The sample is pretreated by an Entech Instruments Inc. (model 7100) automated cryogenic concentrator for water removal, CO_2 removal and sample cryofocusing. A Hewlett Packard 6890 gas chromatograph with flame ionization detector (FID) is used to analyze the treated and concentrated sample. Data acquisition and component identification is performed using a Hewlett Packard GC Chemstation with G2070AA software.

Background samples were collected from the emission tunnel dilution air and analyzed for each emission component for the background correction of mass emissions.

3.4. Test Methodologies

The overall Test Protocol for the project is presented in appendix B. This protocol requires the use of specific tests as detailed below.

EPA emission certification procedures for Heavy-Duty Engines (Code of Federal Regulations, Title 40, Part 86, Subpart N, from 86.1301-90 to 86.1344-94 published by the Office of the Federal Register National Archives and Records Administration).

The following topics are covered by this procedure:
- Equipment, instrumentation and emission analyzer calibration procedures
- Emission sampling, measurement, and calculation methods
- Engine mapping procedure
- Engine transient test cycle generation and test cycle validation methods

California Non-Methane Organic Gas Test Procedures (Published by California Environmental Protection Agency, Air Resources Board)

- Method 1002: Determination of C_2 to C_5 hydrocarbons in automotive source samples by gas chromatography
- Method 1003: Determination of C_6 to C_{12} hydrocarbons in automotive source samples by gas chromatography
- Method 1004: Determination of aldehyde and ketone compounds in automotive source samples by high performance liquid gas chromatography

FTP Heavy Duty Transient Cycle:

The test cell dynamometer and throttle controllers were tuned to ensure that torque and speed responses of the engine followed the command cycle within acceptable limits as prescribed by EPA. This tuning was performed using the baseline (certification) fuel.

A computer generated torque curve (@ 8 rpm/sec) was used in the generation of the reference FTP cycle with the objective of ensuring results' repeatability. Once the reference FTP cycle was generated, no changes were made until the end of testing. Cycle validation (i.e. regression analysis) was confirmed each time a FTP cycle was run. The 20 minute reference cycle is illustrated in Appendix C.

4. RESULTS AND CONCLUSIONS

4.1. Effect of ECU Supply Voltage on Engine Performance and Emissions

During preliminary tests, it was noticed that gaseous emissions varied markedly with ECU supply voltage. This behavior was investigated by varying the ECU supply voltage from 12.0V to 14.1V and measuring engine power and lambda at rated conditions. The results are presented in Figures 4.1(a) and (b) respectively.
FTP cycle gaseous emissions were also measured as ECU supply voltage was varied from 12.3V to 13.6V as in Figure 4.1(c). After discussing the results with ADEPT and Cummins it was decided to select an ECU supply voltage of 13.3V for all tests, as that voltage resulted in a power output of 195 bhp @ 2600 rpm.

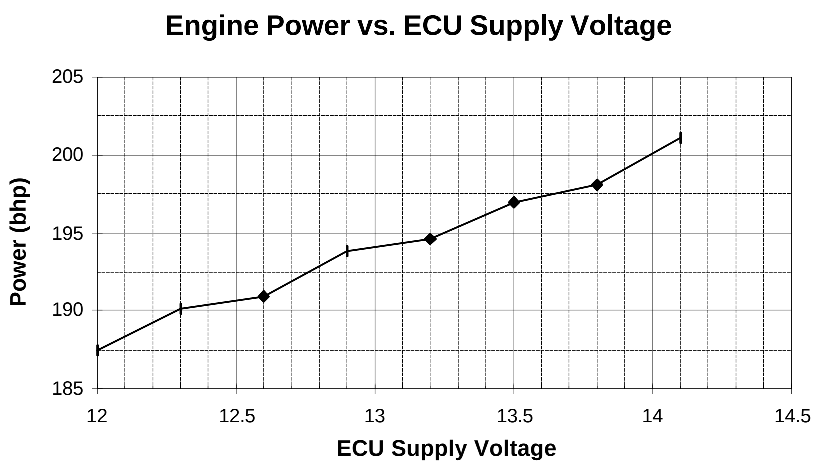


Figure 4.1(a)

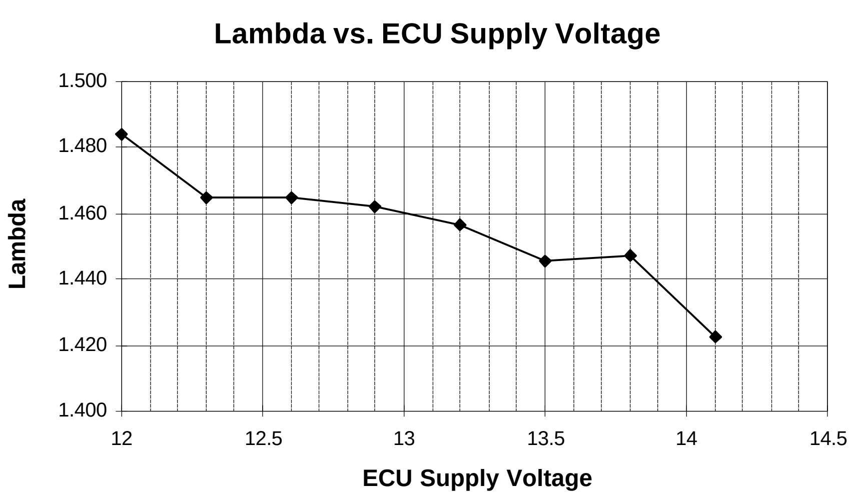


Figure 4.1(b)

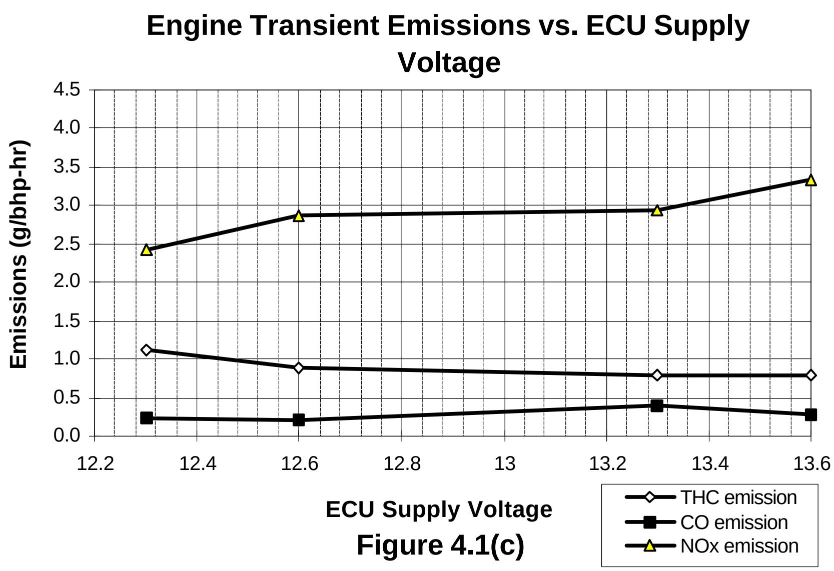


Figure 4.1(c)

4.2. Effect of LPG Fuel Composition on Engine Performance

Prior to starting emissions tests, engine performance was verified using the baseline certification fuel and each fuel blend. For each fuel, a wide open throttle (WOT), manual torque curve was obtained. Engine power and torque are presented in Figures 4.2.1(a) and (b).

Engine performance was specifically confirmed at rated speed, and with the five (5) different fuel blends. With respect to cert fuel, engine power with the test fuels increased by 2.1% to 4.5% where engine torque fluctuated between $\pm$ 0.1% (see Appendix D).

Additional parameters such as lambda, spark timing, and fuel flow rate are presented in Appendix E.

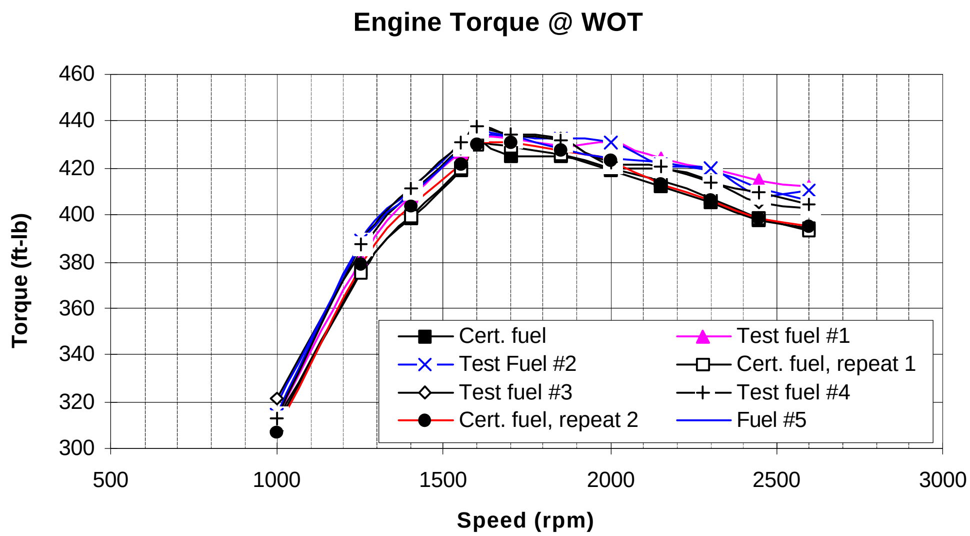


Figure 4.2.1(a)

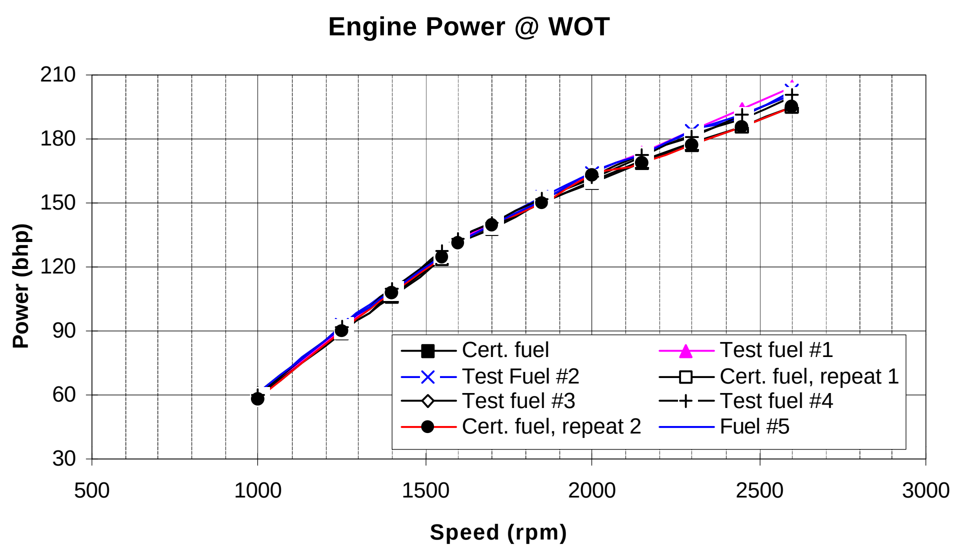


Figure 4.2.1(b)

After the verification of engine performance at WOT, performance was also monitored during emissions testing using the EPA cycle. As shown in Figures 4.2.2(a) and (b), different fuel compositions had very little impact on engine work but differences can be observed on fuel consumption.

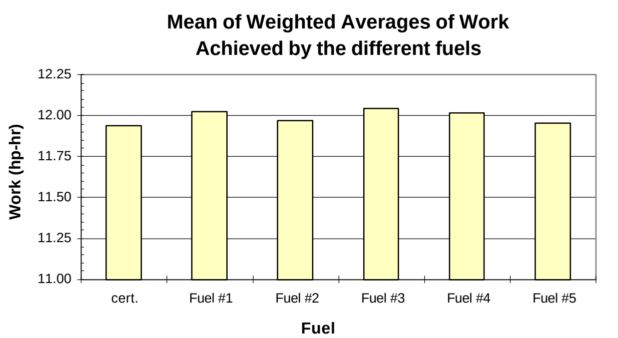


Figure 4.2.2(a)

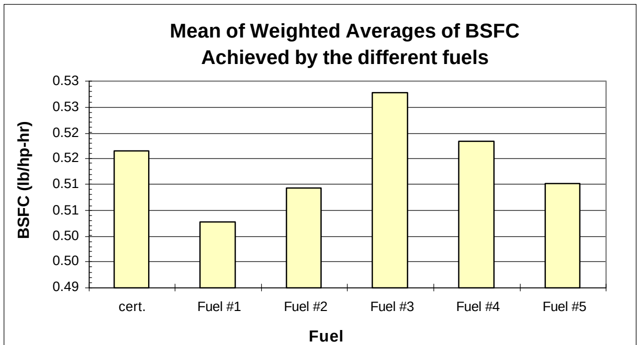


Figure 4.2.2(b)

4.3. Effect of LPG Fuel Composition on Engine Emissions

Engine emission tests were conducted in conformance with the LPG test protocol. Each set of emission tests comprised 1 cold and 3 hot cycles with a weighted average of 1:6. Initially, three sets of emission tests were conducted using the reference fuel to gather baseline data. Other test fuels were then tested, at least twice, in the order of the most likely fuel to pass. Additional tests involving the reference fuel were conducted to monitor any emission drifts that may have occurred.

All fuels, including the reference fuel, were evaluated by comparing the mean of the weighted averages to the acceptance criterion (i.e. $X_c \leq X_r (1+2\delta)$), as shown in Figure 4.3.

In Table 4.3.1, emissions satisfying the criterion are denoted by (√). Numerical representation of the same results are given in Table 4.3.2 as percentage deviation from the criterion. Refer to Appendix F for more detailed results of gaseous and particulate emissions, and to Appendix G for THC speciation and NMOG results.

Table 4.3.1: Emissions Summary

Fuel	THC	NMHC	CO	PM	OFP	THC+NO_x	NMHC +NO_x
Cert	√	√	√	√	√	√	√
1	√	√	√	√	√	√	√
2	√	√	√	√		√	√
3	√	√		√		√	√
4	√	√		√		√	√
5	√	√	√	√	√		

Table 4.3.2: Percentage Deviation From Criterion

Fuel	THC	NMHC	CO	NO_x	PM	OFP	THC $+NO_x$	NMHC $+NO_x$
Cert	-21.3	-22.0	-28.2	-5.5	-20.3	-12.8	-9.6	-9.6
1	-34.9	-35.7	-24.2	3.2	-13.7	-7.2	-6.7	-6.6
2	-37.9	-39.0	-8.8	5.8	-7.3	8.7	-5.6	-5.6
3	-20.6	-21.8	15.2	5.0	-15.4	10.4	-1.6	-1.8
4	-27.5	-29.4	52.1	-1.7	-24.7	0.4	-8.4	-8.7
5	-43.8	-44.4	-39.6	15.9	-30.6	-13.3	0.4	0.7

Figure: 4.3: Effect of LPG Fuel Compositions on Engine Emissions

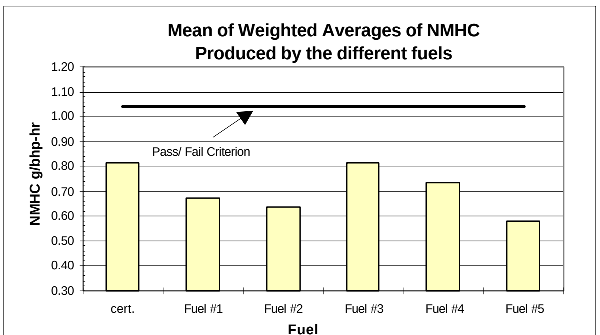


Figure 4.3.1

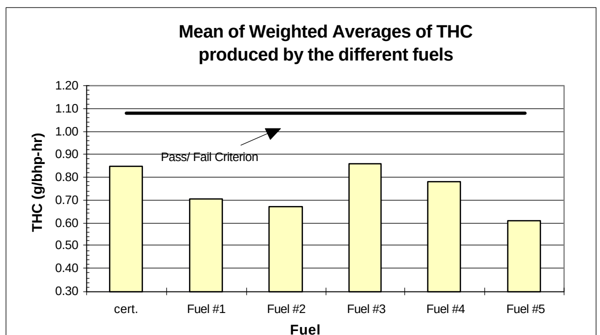


Figure 4.3.2

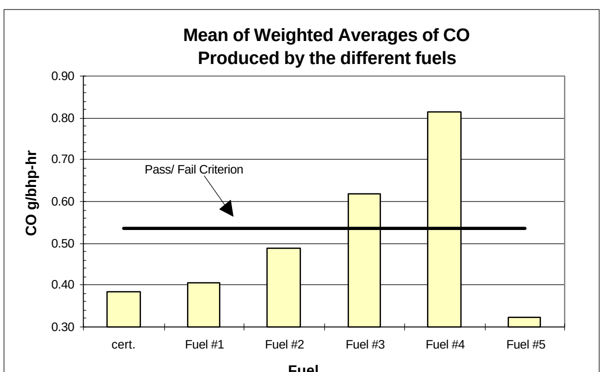


Figure 4.3.3

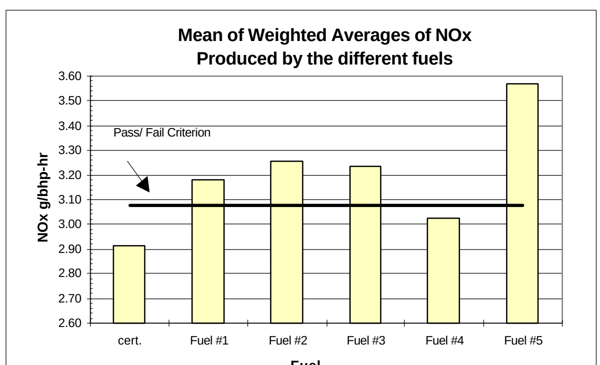


Figure 4.3.4

Figure: 4.3: Effect of LPG Fuel Compositions on Engine Emissions (cont'd.)

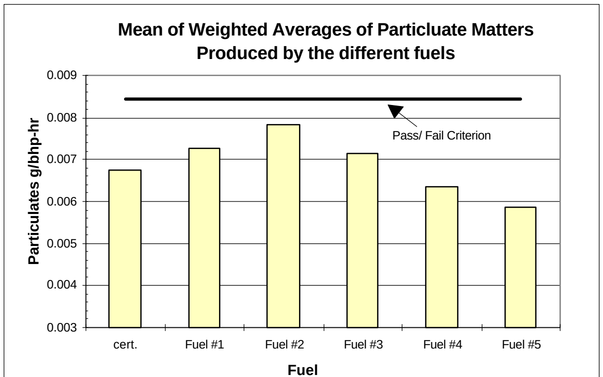


Figure 4.3.5

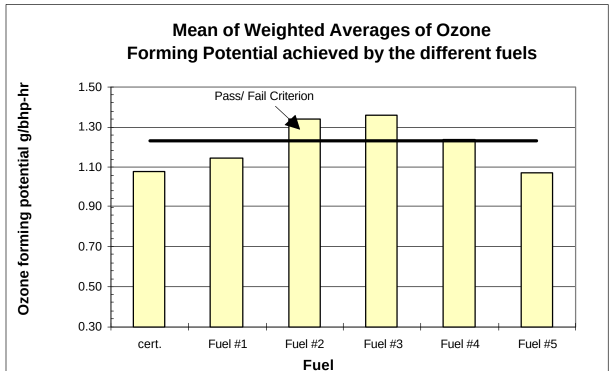


Figure 4.3.6

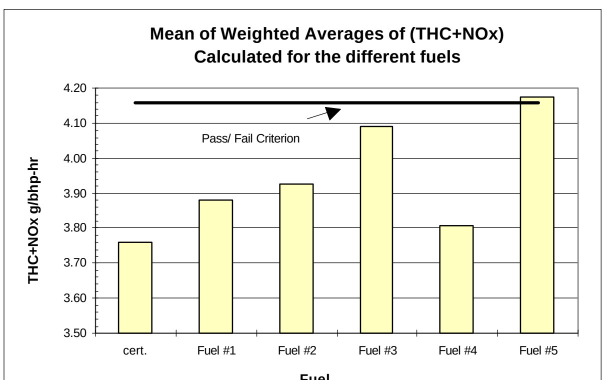


Figure 4.3.7

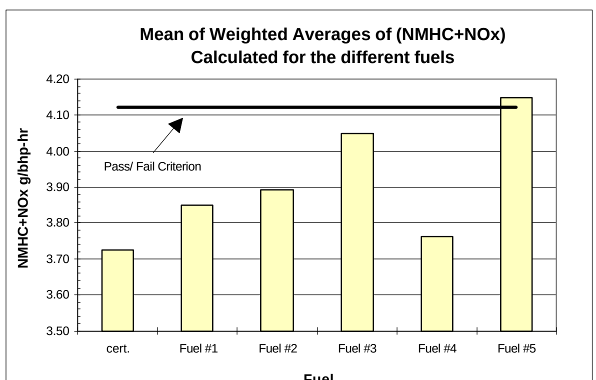


Figure 4.3.8

APPENDIX A

Engine Setup and Commissioning

1. **Table A1: Instrumentation List**
2. **Table A2: Sample of Test Cell Printout**
3. **Figure A1: Engine Performance Using Cert Fuel**

TABLE A1: INSTRUMENTATION VERIFICATION CHECKLIST

TEMPERATURES, PRESSURES, MISCELLANEOUS, SAFETY

Item	Test Req.	Units	Safety Min	Limits Max	Comments	Alarm Action	TB ID#	Chan#	Calib.	Initial
High Temp. (Type K)										
Exhaust temp. Cyl. #1	Y	°C	450	760	tEXH1	Y				
Exhaust temp. Cyl. #2	Y	°C	450	760	tEXH2	Y				
Exhaust temp. Cyl. #3	Y	°C	450	760	tEXH3	Y				
Exhaust temp. Cyl. #4	Y	°C	450	760	tEXH4	Y				
Exhaust temp. Cyl. #5	Y	°C	450	760	tEXH5	Y				
Exhaust temp. Cyl. #6	Y	°C	450	760	tEXH6	Y				
Exhaust temp. Cyl. #7										
Exhaust temp. Cyl. #8										
Combined exh. temp.										
Turbocharger IN	Y	°C	450	760	tTURBO-IN					
Turbocharger OUT	Y	°C		650	tTURBO-OUT					
Catalyst IN	Y	°C			tCAT-IN	Y				
Catalyst OUT	Y	°C			tCAT-OUT	Y				
Other										
Low Temp. (Type T)										
Intake air downstream of LFE (5~10 D away from LFE)	Y	°C			tLFE					
Compressor IN	Y	°C			tCOMPRE-IN					
Compressor OUT	Y	°C		140	tCOMPRE-OUT					
Intake air of engine, <122 cm from intake manifold port										
Charge air, located downstream of intercooler	Y	°C	25	52	tCHARGE	Y				
Cell air	Y	°C		70	tCELLAIR					
Coolant IN	Y	°C	60		tIN-COOL					
Coolant OUT	Y	°C		100	tOUTCOOL	Y				
Oil gallery	Y	°C		130	tOIL	Y				
Oil sump	Y	°C		130	tSUMP	Y				
Fuel#1 IN	Y	°C			tIN-FUEL					
Fuel#1 OUT										
Dynamometer Water										
Front Dyno Bearing	Y	°C		65	tF-BRG	Y				
Rear Dyno Bearing	Y	°C		65	tR-BRG	Y				

TBID#, Chan#, Calib, Initial for ORTECH use only.

TABLE A1 (cont'd.): INSTRUMENTATION VERIFICATION CHECKLIST

TEMPERATURES, PRESSURES, MISCELLANEOUS, SAFETY

Item	Test Req.	Units	Safety Min	Limits Max	Comments	Alarm Action	TB ID#	Chan#	Calib.	Initial
Pressures										
Intake air restriction	Y	kPa		4.4	pIN-REST					
Exhaust backpressure	Y	kPa		13.5	pEXHBP					
Downstream of compressor	Y	kPa			pCOMP-OUT					
Downstream of intercooler	Y	kPa			pINTER-OUT					
Intake manifold	Y	kPaA		193	pIMP					
LFE: static pressure	Y	"H2O			pLFESTAT					
LFE: delta P	Y	"H2O			pLFE					
Turbo IN pressure	Y	kPa			pTURBO-IN					
Turbo OUT pressure	Y	kPa			pTURBO-OUT					
Catalyst IN	Y	kPa			pCAT-IN					
Catalyst OUT	Y	kPa			pCAT-OUT					
Fuel (LPG) supply	Y	kPa	242	1518	pFUEL-IN	Y				
Crankcase										
Oil gallery	Y	kPa	69	450	pOIL	Y				
Oil filter IN										
Oil filter OUT										
Cylinder pressure Kistler#1										
Other										
Emissions										
NOx	Y									
THC	Y									
CO	Y									
CO2	Y									
CH4	Y									
NMHC	Y									
C2-C12 (speciation)	Y									
Carbonyls	Y									
PM	Y									

TBID#, Chan#, Calib, Initial for ORTECH use only.

TABLE A1 (cont'd.): INSTRUMENTATION VERIFICATION CHECKLIST

TEMPERATURES, PRESSURES, MISCELLANEOUS, SAFETY

Item	Test Req.	Units	Safety Min	Limits Max	Comments	Alarm Action	TB ID#	Chan#	Calib.	Initial
Miscellaneous										
Engine speed	Y	rpm	800	2875	SPEED	Y				
Engine torque	Y	ft-lb		440	TORQUE					
Engine torque	Y	Nm			TORQUE					
Throttle position	Y	%			POSIT					
Air flow rate	Y	kg/hr			fAIR					
LPG flowrate	Y	kg/hr		40	fFUEL	Y				
Coolant flowrate										
Blowby flowrate										
Oil consumption										
BSFC	Y	g/kw -hr			BSFC					
Engine power	Y	bhp		205	BHP					
Engine power	Y	kw			KW					
Barometric pressure	Y	kPa			pBARO					
Wet-bulb temperataure	Y	°C			tWET					
Dry-bulb temperature	Y	°C			tDRY					
Intake air humidity	Y	°C dp			tDEW-POINT					
f factor										
Smoke										
ECU supply voltage	Y	volt	12	14	vBATTERY	Y				
Lambda	Y				LAMBDA					
Spark angle	Y	°CA			SPK-ANGLE					
Safety										
Engine speed	Y	rpm		2875		Y				
Oil pressure	Y	kPa	69			Y				
Coolant temperature	Y	°C		100		Y				

TBID#, Chan#, Calib, Initial for ORTECH use only.

TABLE A2: TEST CELL PRINTOUT OF ENGINE AND ENVIRONMENTAL PARAMETERS

ORTECH Corporation
Run # 965
Started 05/21/98
at 14:30
TEST ID:: 5.9l LPG ADEPT
OPERATOR:: IC
FUEL:: CERT FUEL
ENGINE ID:: 5.9l CUMMINS LPG
PROJECT NUMBER:: 11516
COMMENT:: MANUAL TORQUE CURVE TEST CERT FUEL

Date		05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98
Wall	Time	14:30	14:31	14:31	14:32	14:32	14:32	14:33	14:33	14:33	14:33
Engine	Time	024:29:00	024:29:00	024:29:00	024:29:00	024:29:00	024:29:00	024:29:00	024:29:00	024:29:00	024:29:00
Stage#		0	0	0	0	0	0	0	0	0	0
>SPEED	rpm	2749	2749	2749	2602	2602	2602	2452	2452	2452	2302
>LOAD	ft-lb	499.9	499.9	499.9	499.9	499.9	499.9	499.9	499.9	499.9	499.9
SPEED	rpm	2748	2743	2749	2601	2599	2602	2451	2450	2453	2302
TORQUE	ft-lb	355.6	348.9	350.8	396.9	392.9	393.2	398.2	395.8	399.5	406.2
BHP	bhp	186	182.2	183.6	196.5	194.4	194.8	185.8	184.6	186.5	178
KW	kW	138.7	135.9	136.9	146.5	144.9	145.2	138.5	137.7	139.1	132.7
Nm	NM	482.1	473.1	475.6	538.1	532.7	533.1	539.9	536.7	541.7	550.8
POSIT	%	100.2	100.2	100.2	100.2	100.2	100.2	100.2	100.2	100.2	100.2
FUELFLOW	kg/hr	33.57	33.42	33.28	34.9	34.85	34.9	32.7	32.69	32.61	30.47
AIRFLOW	kg/hr	794	789	795	825	829	825	786	793	783	723
LAMBDA	--	1.431	1.456	1.449	1.44	1.448	1.463	1.451	1.476	1.448	1.44
TIMING	degs-BTD	22.3	22.6	22.2	21.3	21.3	21.4	21.1	21.2	21	21
tCELLAIR	\`C	30.5	31	30.8	32.3	32.3	32.3	33.1	33	33.2	33.5
tIN-COOL	\`C	79.9	80.6	80.7	79.9	79.9	79.8	79.2	79.2	79.1	78.8
tOUTCOOL	\`C	84.8	85.3	85.6	85.2	85.1	85.2	84.8	84.7	84.8	84.7
tSUMP	\`C	101.8	102.3	102.5	105.5	105.5	105.5	105.7	105.5	105.5	105.7
tGALLERY	\`C	96.1	97	97.2	97.8	97.8	97.8	99.5	99.5	99.5	99.5
tIN-FUEL	\`C	27.9	27.8	27.9	27.8	27.8	27.8	27.9	27.8	27.9	28
tLFE	\`C	28.1	28.1	28.1	28.4	28.5	28.5	28.1	28.1	28.1	28.3
tINTAKE	\`C	28	28	27.9	28.2	28.3	28.2	28.2	28	28.2	28.2
tCOMP-OU	\`C	121.6	122.1	122.2	134.3	134.7	134.7	132.1	132.1	132	128.6
tINTER-O	\`C	49.2	49.4	49.5	51.5	51.7	51.6	51.3	51.3	51.3	50.8
tCHARGE	\`C	49.1	49.4	49.5	51.3	51.4	51.4	51.2	51.3	51.3	50.9
pINT-RES	kPa	3.9	3.8	3.8	4.1	4.0	4.0	3.9	3.7	3.9	3.5
pCOMP-OU	kPa	105.1	104.4	106.4	122.8	121.7	122.3	118.7	119	119	112.1
pINTER-O	kPa	91.7	91.2	93.1	109.2	108.1	108.8	106	106.6	106.3	101

TABLE A2 (cont'd.): TEST CELL PRINTOUT OF ENGINE AND ENVIRONMENTAL PARAMETERS

ORTECH Corporation
Run # 965
Started 05/21/98
at 14:30
TEST ID:: 5.9l LPG ADEPT
OPERATOR:: IC
FUEL:: CERT FUEL
ENGINE ID:: 5.9l CUMMINS LPG
PROJECT NUMBER:: 11516
COMMENT:: MANUAL TORQUE CURVE TEST CERT FUEL

Date		05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98	05/21/98
Wall	Time	14:30	14:31	14:31	14:32	14:32	14:32	14:33	14:33	14:33	14:33
pIMAP	kPaA	181.4	181	182.8	198.9	197.9	198.5	196.7	197.3	196.9	192.6
pOIL	kPa	421.3	418.1	417.4	403.4	402.8	402.9	395.9	396.3	395.9	392.7
pFUEL-RE	kPa	1165.1	1163.8	1162.3	1151.9	1151.7	1151.1	1146.9	1146.2	1145.8	1144.3
p123COMB	kPa	140.9	139.1	140.7	155.4	154.1	153.5	144	141.2	144.4	130.3
p456COMB	kPa	109.8	106.6	102.5	128.8	125.7	122.2	118	106.5	120.4	108
pEXHBP	kPa	11.5	11.5	12	12.8	12.7	12.9	11.6	11.9	11.7	10.3
pCAT-OUT	kPa	7.3	7.4	7.7	8.4	8.4	8.5	7.5	7.7	7.5	6.4
vBATTERY	volts	13.26	13.26	13.26	13.26	13.26	13.26	13.26	13.26	13.26	13.26
vLFE	volts	3.957	3.928	3.959	4.116	4.138	4.116	3.919	3.945	3.898	3.592
tEXH1	\`C	709.9	710.7	711	715.1	715.4	715.7	705.8	706	706	697.1
tEXH2	\`C	714.5	716.6	716.9	726.4	727	727.4	720.5	720.2	720.2	713.1
tEXH3	\`C	712.7	714.8	715.1	725.2	725.6	725.5	719	719	719.1	712.7
tEXH4	\`C	702.3	704.9	705.2	716.2	717.2	717.4	710.1	710	710.1	702.8
tEXH5	\`C	734.7	736.7	737.2	744.6	745	745	737.2	736.9	737.1	727.6
tEXH6	\`C	700.2	701.4	702	707.5	708.2	708.5	697.8	697.6	697.7	688.5
t123 COM	\`C	751.3	752.6	753.7	759.1	759	759.1	749.5	750.6	750.3	740.8
t456COMB	\`C	751.1	753.1	753.1	757.4	757.4	758	745.9	746.9	746.4	735.1
tCAT-IN	\`C	630.6	633	633.9	635.1	635.6	635.8	634.5	634.3	634.1	632
tCAT-OUT	\`C	623.1	626.1	627.2	631.6	632.3	632.7	632.6	632.7	632.6	630.9
tSTACK	\`C	560.7	566.5	568.5	584.2	585	585.7	589.9	590.3	590.3	590.7
tDEW-POI	\`C	14.3	14.3	14.3	14.3	14.3	14.4	14.3	14.3	14.3	14.3
pLFE	inH2O	7.876	7.824	7.885	8.207	8.248	8.216	7.803	7.864	7.769	7.157
pLFESTAT	inH2O	3.42	3.356	3.297	3.638	3.49	3.539	3.413	3.287	3.477	3.079
tWET	\`C	16	16	16	16	16	16	16	16	16	16
tDRY	\`C	26	26	26	26	26	26	26	26	26	26
pBARO	kPaA	99.6	99.6	99.6	99.6	99.6	99.6	99.6	99.6	99.6	99.6

ENGINE PERFORMANCE VERIFICATION USING CERTIFICATION FUEL

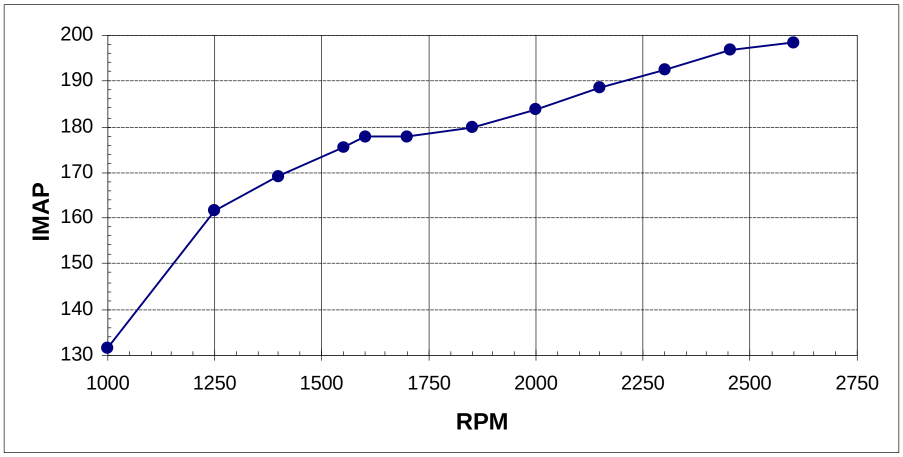


Figure A-1

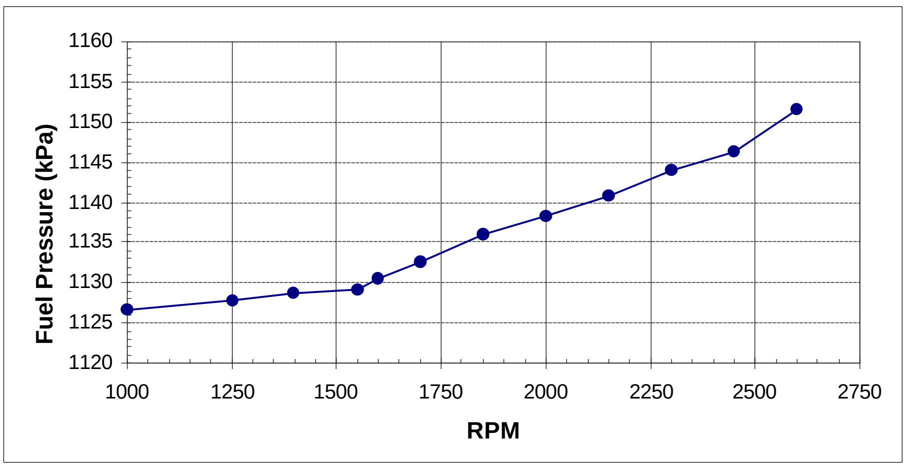


Figure A-2

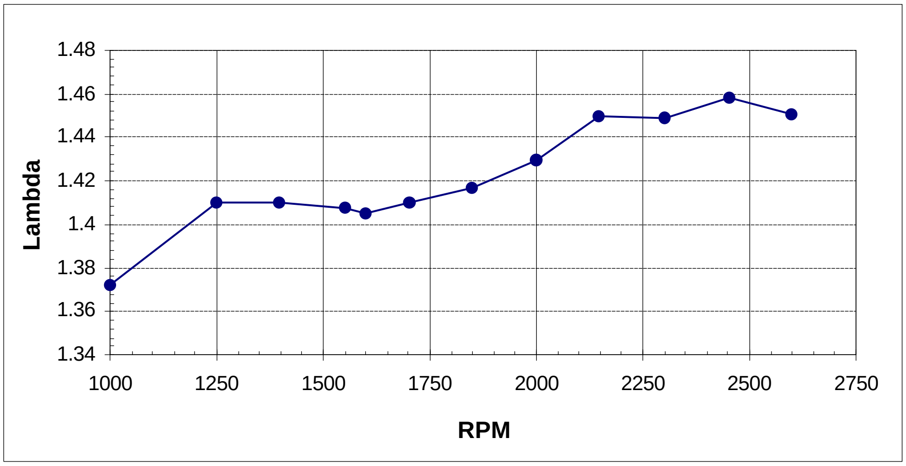


Figure A-3

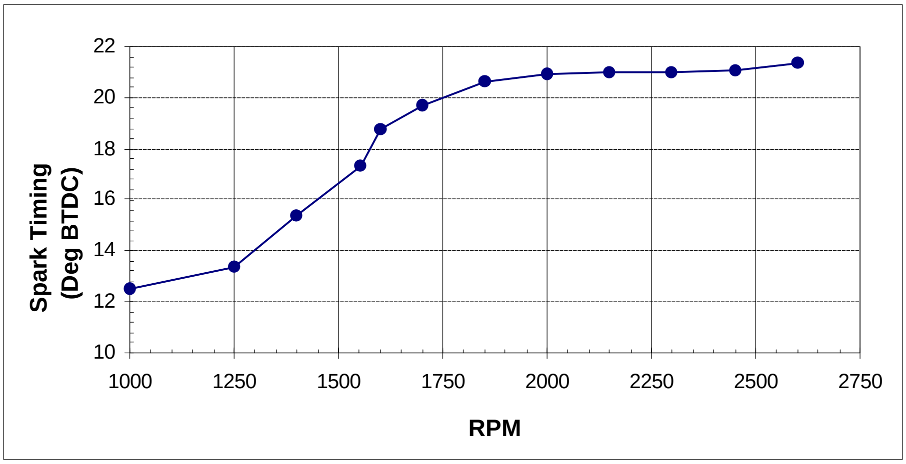


Figure A-4

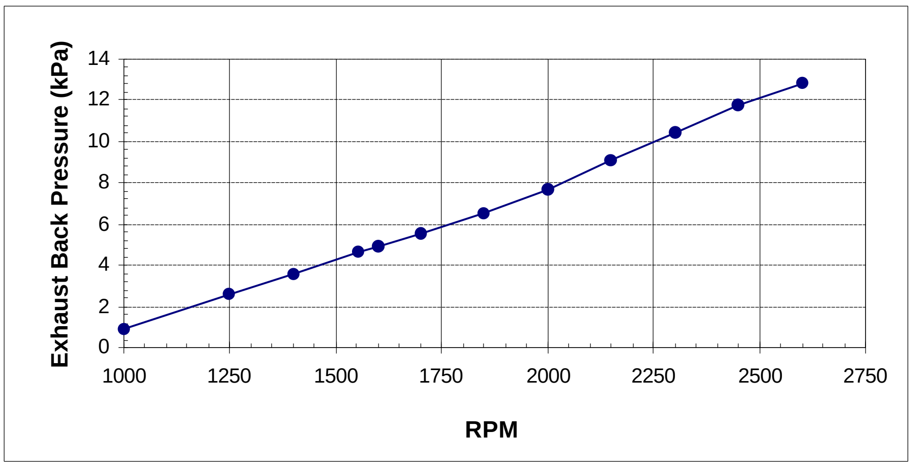


Figure A-5

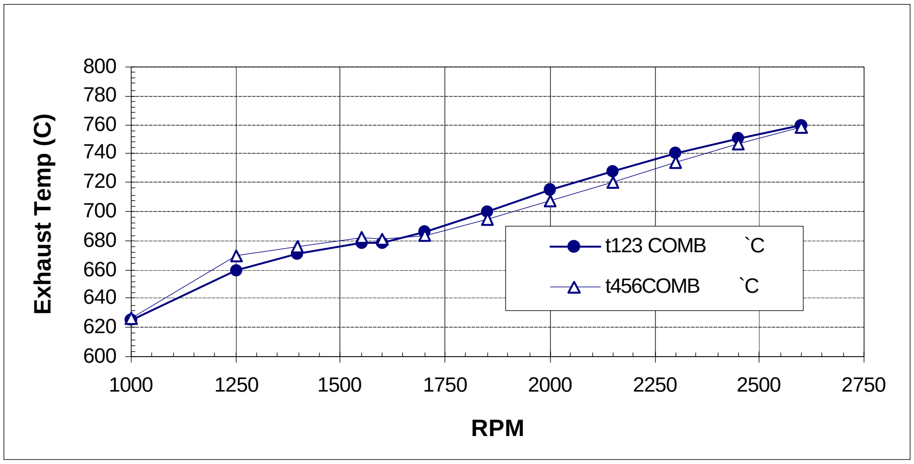


Figure A-6

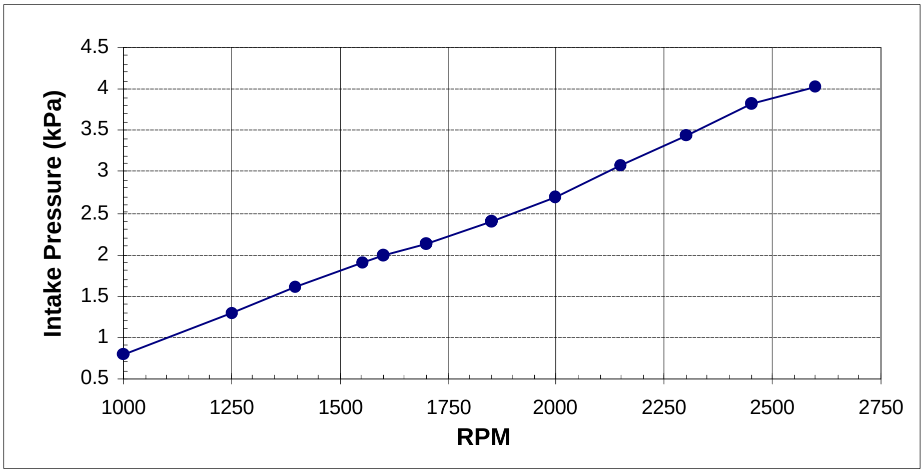


Figure A-7

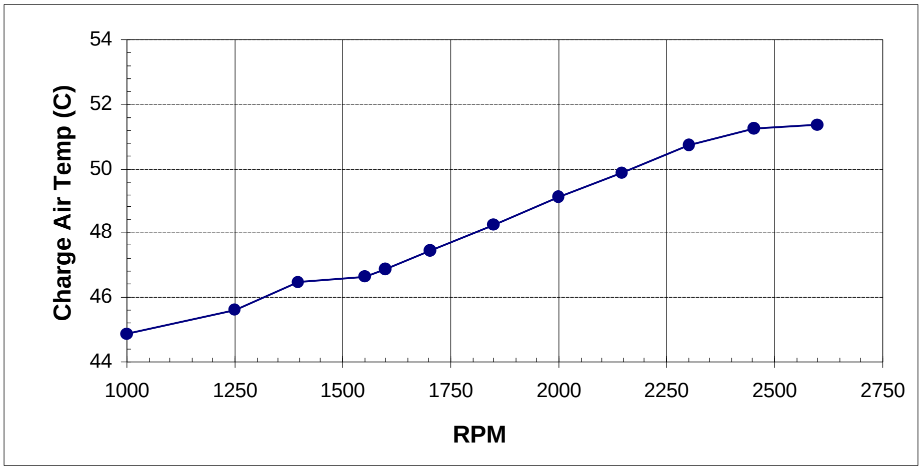


Figure A-8

Appendix B

Test Protocol

Test Protocol

1. General

- Speed, torque, and gaseous analyzers will be calibrated following Code of Federal Regulations, Title 40, Part 86, Subpart N
- All other sensors will be calibrated following ORTECH Standard Operation Procedures (ISO 9002).
- The transient test procedures will be EPA certification procedures for Heavy-Duty Engines documented in Code of Federal Regulations (Title 40, Part 86, Subpart N).
- THC speciation and Carbonyls related test procedures will follow the appropriate methods in the California Non-Methane Organic Gas Test Procedures (Published by California Environmental Protection Agency, Air Resources Board).

2. Test Order, LPG Fuel Blends and Analyses

Test order	Fuel	Propane	Propylene	N-butane
1	Cert. fuel	94.42%	3.68%	1.90%
2	Test fuel #1	85.28%	9.86%	4.86%
3	Test fuel #2	81.15%	14.15%	4.70%
4	Cert. fuel	94.42%	3.68%	1.90%
5	Test fuel #3	80.07%	9.97%	9.96%
6	Test fuel #4	76.34%	3.78%	19.88%
7	Cert. fuel	94.42%	3.68%	1.90%

3. Engine Parameter Setup

Run engine at rated condition (2600 rpm, WOT), stabilize oil and coolant temperatures, and set the following parameters:

- Intake restriction: 4.4 kPa (17.5 “H_2O)
- Exhaust back pressure: 13.5 kPa (4 “Hg)
- Charge air temperature in intake manifold: 52 °C (125 °F)
- Air pressure drop from compressor outlet to mixer inlet: 13.5 kPa (4 “Hg)
- ECU supply voltage: 13.3 volt

4. Transient Emissions Tests on Five LPG Fuel Blends

4.1 Prior to official emission tests, complete following items:

- Tune the dynamometer and the throttle to pass transient cycle validation criteria using certification fuel. The settings will be used in all subsequent tests.
- Condition the emission tunnel for PM and THC
- Identify analyzer ranges for gaseous emissions
- Quality control setup and preliminary sample range setup on GC speciation analyzer.

Commence Official Emission Tests

4.2 Run engine on the certification fuel, and confirm the engine parameter setup at rated condition (refer to Item 3).

4.3 Conduct an auto torque map to generate a baseline transient test cycle to be used for all subsequent tests.
- Mapping speed: 800 rpm ~ 2870 rpm @8 rpm/sec. increment
- Curb idle transmission torque: 10 ft-lb @ 800 rpm

Emission Tests on Certification Fuel (i.e. Baseline)

4.4 Day 1: Run 1 cold start transient cycle and 2 hot start transient cycles, measure and calculate the following emissions:
- Total Hydrocarbon (THC)
- Methane (CH_4)
- Non-Methane Hydrocarbons (NMHC)
- Carbon Monoxide (CO)
- Oxides of Nitrogen (NOx)
- Carbon Dioxide (CO_2)
- Particulate Matter (PM), post analyzed
- THC speciation and Carbonyls, 1 cold and 1 hot samples, post analyzed for

4.5 Day 2: Repeat preceding tests without THC speciation and Carbonyls measurement. Perform a manual torque map after the emission tests.

Emission Tests on LPG Fuel Blends

4.6 Change fuels as described in Item 5 below.

4.7 Repeat Item 4.2, 4.4 and 4.5 using the test fuels in the order listed in Item 2.

4.8 Note: After testing fuel #2, change to certification fuel (Item 5), and run 3 hot start transient cycles with only gaseous and PM measurements.

5. LPG Fuel Switching

5.1 Close the valve on the fuel cylinder, and run engine to deplete all fuel in the fuel line.

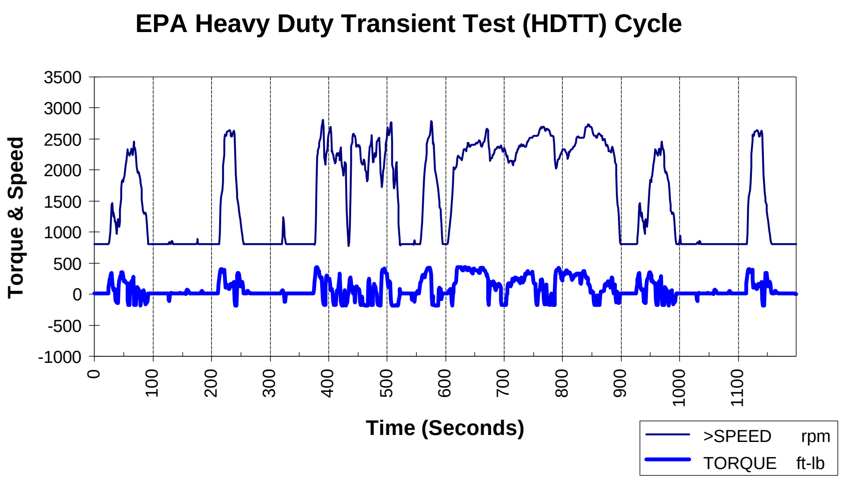
5.2 Change the fuel cylinder, and replace the liquid / vapour fuel filters. Run engine on the new test fuel for 15 min. to flush the fueling system.

5.3 Perform a manual torque map and listen for engine knock. Stop test if knocking is observed!

5.4 Run two transient cycles to identify analyzer ranges for gaseous emissions, to condition the emission tunnel, and to check cycle validation (i.e. regression) criteria. Continue Item 4.7.

Appendix C

EPA Heavy Duty Transient Test (HDTT) Cycle

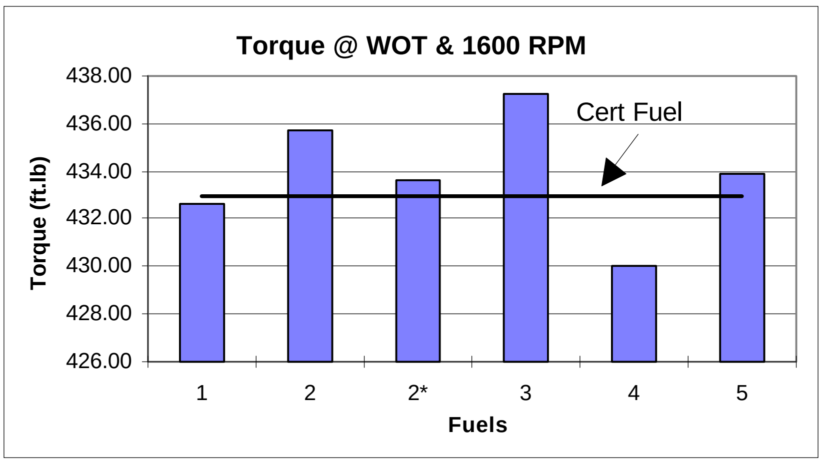

EPA Heavy Duty Transient Test (HDTT) Cycle
Torque & Speed
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
100
200
300
400
500
600
700
800
900
1000
1100
Time (Seconds)
>SPEED rpm
TORQUE ft-lb

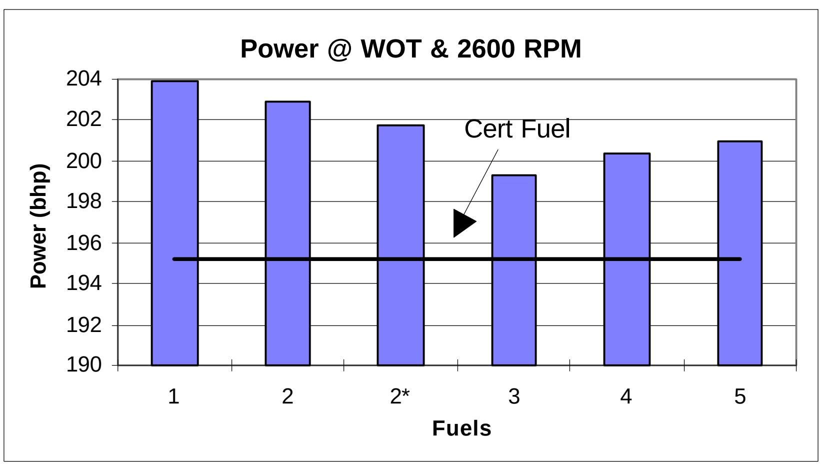
Appendix D

Comparison of Power and Torque From the Different Fuel Blends @ WOT & Rated Speed

Engine performance using the different test fuels was validated prior to emissions testing. This was carried out by comparing engine torque @ WOT and 1600 RPM, and engine power @ WOT and 2600 RPM to corresponding conditions using cert fuel. Percentage difference is illustrated in the following table. A negative sign indicates that the test fuel's performance lagged behind cert fuel:

Fuel	1	2	3	4	5
Torque (ft.lb)	-0.06 %	0.65 %	0.99 %	-0.67 %	0.21 %
Power (bhp)	4.50 %	4.0 %	2.13 %	2.68 %	2.97 %





2*: Phillips Fuel Blend

Appendix E

Engine Performance Validation @ WOT

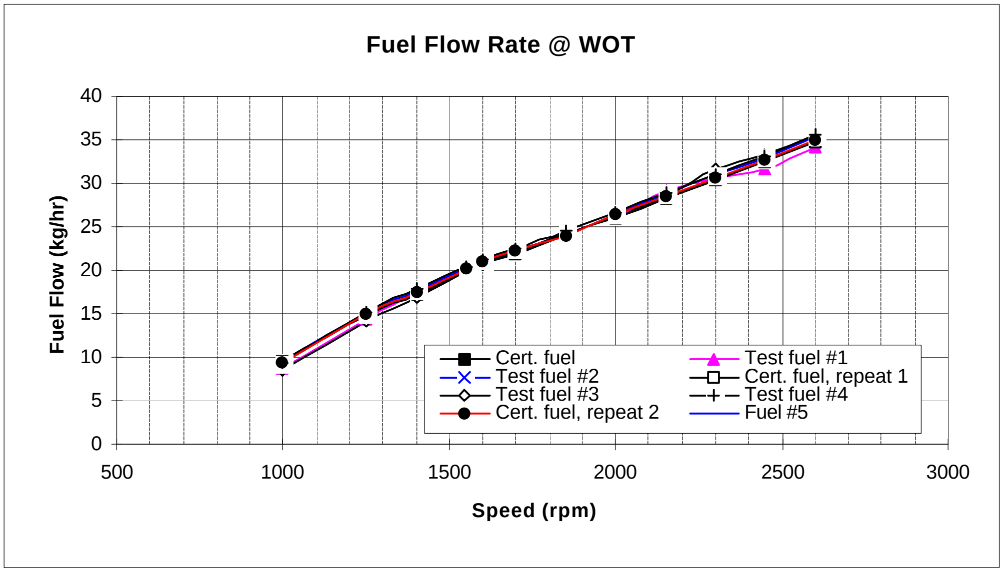


Figure E1

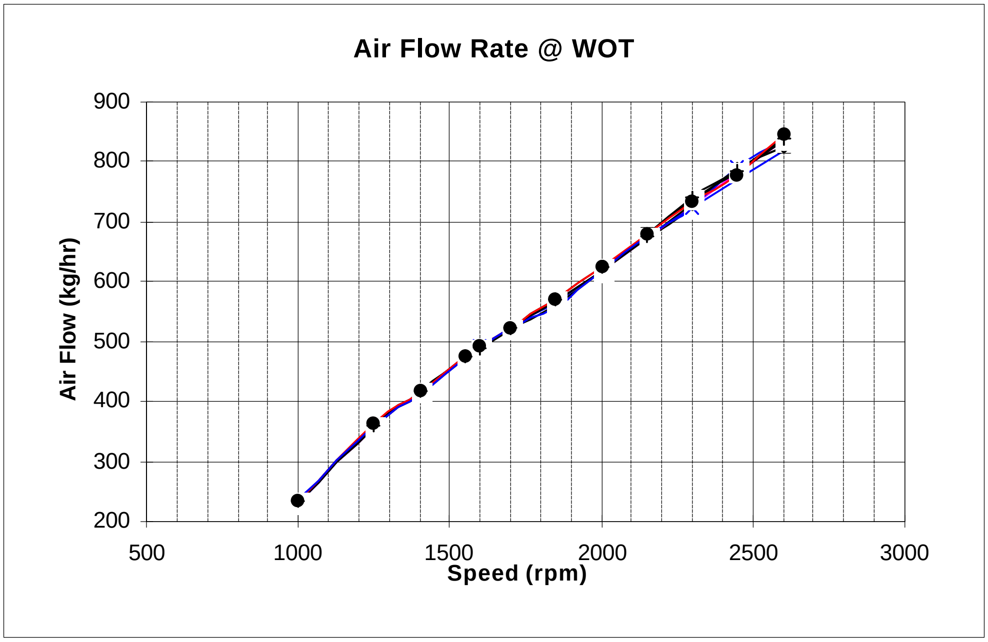


Figure E2

Note: Legend applies to Figures E1 to E4

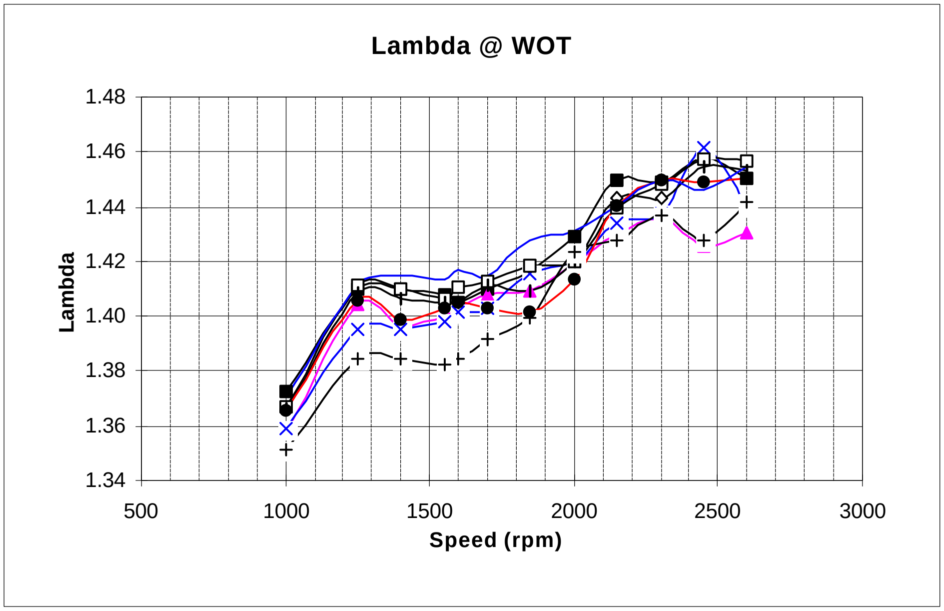


Figure E3

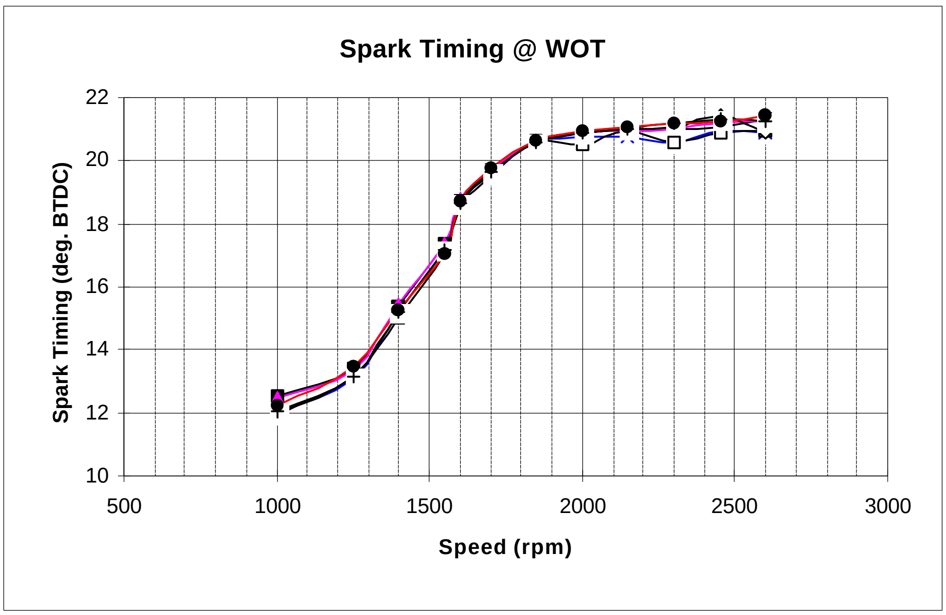


Figure E4

APPENDIX F

Details of Gaseous Emissions/ Performance Results

APPENDIX G

Details of THC Speciation / NMOG Results