NREL/TP-425-7618 • UC Category: 1504 • DE95009250

Hardware Assembly and Prototype Testing for the Development of a Dedicated Liquefied Propane Gas Ultra Low Emission Vehicle

IMPCO Technologies
Seattle, WA

NREL technical monitor:
C. Colucci

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
Under Contract No. DE-AC36-83CH10093

Prepared under Subcontract Number ZAW-4-12244-01

July 1995

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INTRODUCTION

On February 3, 1994, IMPCO Technologies, Inc. started the development of a dedicated LPG Ultra Low Emissions Vehicle (ULEV) under contract to the Midwest Research Institute National Renewable Energy Laboratory Division (NREL). The objective was to develop a dedicated propane vehicle that would meet or exceed the California ULEV emissions standards. The project is broken into four phases to be performed over a two year period. The four phases of the project include: Phase I) System Design, Phase II) Prototype Hardware Assembly and Testing, Phase III) Full-Scale Systems Testing and Integration, Phase IV) Vehicle Demonstration. This report describes the approach taken for the development of the vehicle and the work performed through the completion of Phase II dynamometer test results.

Work was started on Phase II (Hardware Assembly and Prototype Testing) in May 1994 prior to completion of Phase I to ensure that long lead items would be available in a timely fashion for the Phase II work. In addition, the construction and testing of the interim electronic control module (ECM), which was used to test components, was begun prior to the formal start of Phase II. This was done so that the shortened revised schedule for the project (24 months) could be met.

There was a significant modification to the Phase II work plan namely, the addition of engine dynamometer testing of the system components. Due to the extremely short intake runners on the Chrysler 3.3 L V-6 engine, there was concern that cylinder-to-cylinder "charge robbing" could be a problem which would result in large air fuel ratio variations. This could adversely affect the emissions performance of the engine, especially the hydrocarbon emissions which are critical in meeting ultra-low emission vehicle (ULEV) standards. Discussions were held with staff members from Chrysler who agreed this could be a serious problem. IMPCO decided that a test engine was required to assess this effect and to test fuel system components prior to the start of vehicle testing. We obtained a test engine from Chrysler and conducted a program to evaluate fuel system components and assess the air fuel ratio variability. This additional work was conducted within the schedule for Phase II without any delay being introduced in the project duration.

In this report, a brief summary of the activities of each combined Phase I and II tasks will be presented, as well as project management activities. A technical review of the system is also given, along with test results and analysis. During the course of Phase II activities, IMPCO staff also had the opportunity to conduct cold start performance tests of the injectors. The additional test data was most positive and will be briefly summarized in this report.

DESCRIPTION OF INJECTION SYSTEM

A sequential multiport injection technique and after-treatment catalyst were selected as the method most likely to meet California ULEV standards. This fuel injection technique allows precise control of both fuel quantity and fuel timing to each cylinder individually; this fueling control is used to obtain the optimum conditions for engine and catalyst performance.

Gaseous liquefied propane gas (LPG) injection was selected to avoid hot start problems associated with LPG injectors namely, fuel vaporization at the injector tip that results in an excessively small fuel flow rate. The gaseous LPG injection system (see Figure 1) consists of five major components: the gaseous injector, the fuel rail, the regulator/vaporizer, the electronic controller, and the catalyst.

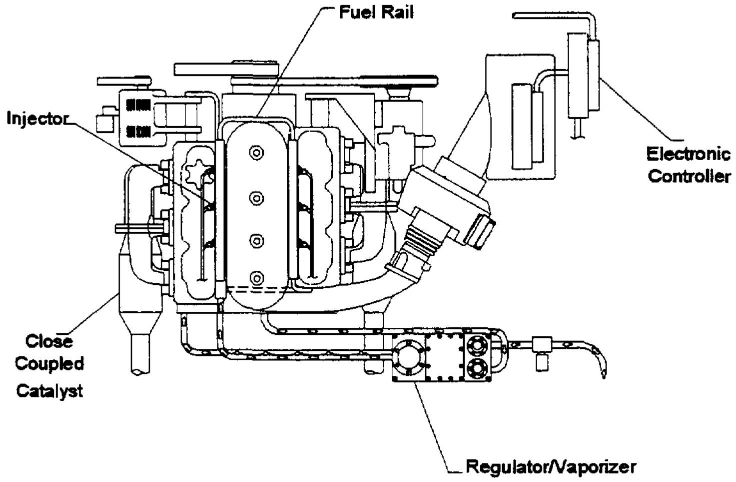


Figure 1. LPG Injection System

The gaseous injectors contain a sonic fuel metering orifice and a solenoid activated valve to turn the flow on and off. The fuel delivery to each engine cylinder is linearly proportional (above the injectors minimum opening time) to the time that the injector is opened during each engine cycle. The design layout of the IMPCO gaseous injectors was selected to fit the standard gasoline injector envelope for universality among engine families. The basic dimensions and specifications of the injector are given in Appendix A.

The fuel rail provides a low restriction fuel path between the injector and the regulator/vaporizer. It is comprised of a stainless steel tubing with six o-ring sealed injector connectors and a high pressure flexible rubber hose for connecting to the fuel regulator. The diameter of the stainless steel tubing hose was selected to provide minimal pressure drop of the fuel over all engine fuel flow rates.

The regulator/vaporizer uses engine coolant to convert the liquid LPG drawn from the fuel tank to a vapor and then regulates the output pressure of the gaseous LPG to 18 psig. The basic dimensions and specifications of the regulator are given in Appendix B.

The electronic control system is comprised of an engine management computer and separate transmission/vehicle computers. The engine management will be performed by a modified 32-bit in-house fuel management computer (IMPX), although the transmission and remaining automotive features will be managed by the existing original equipment manufacturer (OEM) computers. The IMPX computer will access the OEM wiring harness through a custom interface to acquire all pertinent engine control signals. This custom interface is incorporated in the design of the computer and will enable it to be easily fitted in the engine compartment. The gaseous injectors will be driven through the OEM wiring harness, but all other engine management signals additional to the OEM system will be directly wired to the computer. Appendix C shows the electronic interface as described above.

Two catalyst manufacturers, Engelhard and Allied Signal, are formulating special LPG coatings that are being applied to 1.5 liter Corning (150 x 88 x 137 mm-long pear shaped, triangular wall, 340 cells per inch) substrates for each engine bank. This design allows for the catalysts to be attached to short, low-thermal mass exhaust manifolds for optimum catalyst lightoff. This should allow for the efficient catalysis of emissions within 20 seconds of engine start. Appendix D shows a three-dimensional representation of the exhaust manifolds and catalysts to be used in the vehicle.

A dynamometer test program is being used to test each engine component and to develop the basic controller algorithms. The dynamometer provides steady state engine operation so that control parameters can be optimized without extraneous transient input. The engine transient calibration will take place in the vehicle during Phase III of the project.

DESCRIPTION OF WORK PERFORMED

In this section, the major accomplishments of each combined Phase I and Phase II tasks are described.

Task 1. Fuel Formulation, Blending and Testing

Based on our extensive experience with LPG vehicles, we have found that for lowest emissions, Aerosol Grade Propane (AGP), which is 99.8% pure propane and usually produced for aerosol can propellant, would have been used as the vehicle fuel. While AGP is readily available through normal LPG distribution channels, it is more expensive than other grades of propane and does not have the wide distribution network. Thus, for practical reasons and future commercialization of the LPG system being developed, HD-5 propane, which is the industry standard for vehicle grade propane, will be used in the program.

A sample of HD-5 specification propane was obtained from a local distributor. A local Seattle test laboratory was chosen to perform analysis on the fuel samples used in our testing to ensure that they meet the HD-5 specification. The laboratory is well-equipped to perform the tests and has started preparations for the fuel verification tests and analysis. Periodic testing will be conducted throughout the engine and vehicle development testing program to ensure that the fuels continue to meet the HD-5 specification.

Task 2. Fuel Storage and Handling System Design

The HD-5 fuel used in this program was stored at the distributor's facility. Commercially available fuel storage and handling systems have proven to be very reliable in existing LPG vehicles, and no further design work was required.

A local fuel storage site was selected and a pumping station was installed for vehicle refueling by the end of February 1994. HD-5 specification propane, verified at an independent laboratory, was used for all vehicle testing. The fuel storage tank has been cleaned for the first HD-5 delivery in late February 1994.

A conventional Manchester 17.7-gallon Seal Tight fuel tank was ordered and received from a commercial source. The propane fuel tank was installed in the trunk of the vehicle (see Appendix E for layout). A RegO 7547 series back check fill valve and the accompanying fill line will be installed when the gasoline tank is removed, which will occur after the vehicle is running on propane in the early stages of Phase III.

Task 3. Engine System Design, Development, and Assembly

In the request for the proposal on this project, a Chevrolet Lumina with a 3.1 l V-6 engine was identified as a likely candidate for this project. The team has assessed this automobile as well as two others, including a Ford Taurus with a 3.0 l V-6 and a Chrysler LH with either a 3.3 l V-6 or a 3.5 l V-6. A technical evaluation criteria was developed to help select the most suitable engine/vehicle combination to meet ULEV standards using gaseous LPG injection. The factors considered in this analysis included:

- Combustion chamber design
- Valve system design
- Cylinder head materials
- Piston and ring pack design
- Inlet manifold design
- Capability to add close coupled catalysts
- Baseline emissions.

An evaluation matrix was then generated to help select the most appropriate engine/vehicle combination based on the capability for ULEV levels. For each technical attribute, three possible scores were considered: unacceptable, acceptable, and greater than acceptable. The results of this evaluation are summarized in Table 1 below.

Table 1. Engine/Vehicle Evaluation Matrix for LPG ULEV Vehicle Selection

	Lumina 3.1 l	Taurus 3.0 l	Chrysler 3.3 l	Chrysler 3.5 l
Combustion Chamber Design	G	A	G	A
Valve System Design	G	A	G	G
Piston & Ring Pack Design	A	A	A	A
Inlet Manifold Design	A	A	A	A
Capability to Add Close Coupled Catalyst	U	U	G	G
Baseline Emissions	G	A	G	G

Note: U= Unacceptable, A= Acceptable, and G= Greater than Acceptable

Based on the evaluation matrix, we concluded that the Chrysler LH with the 3.3 L V-6 was the most suitable engine/vehicle combination. The distinguishing selection criterion was the capability to fit a close coupled catalyst onto this engine without extensive vehicle modifications. The Chevrolet Lumina and Ford Taurus feature transverse engine layouts that make the addition of the close coupled catalyst extremely difficult on one bank of cylinders. Because it is believed that close coupled catalysts will be an important part of the emissions control system, the inability to add them on the Chevrolet or Ford is a serious restriction. The Chrysler 3.3 l V-6 engine was also selected based on its superior combustion chamber design for lower hydrocarbon emissions with gaseous fuels.

Test Engine Evaluation

In the original work plan, no engine dynamometer test work had been included. However, due to the short runner design of the inlet manifold on the Chrysler LH 3.3 L V-6 engine, we believed that "charge robbing" between cylinders could be a problem. As a result, it was necessary to determine if this in fact would be a problem with gaseous fuels supplied to the engine. Chrysler agreed to supply a test engine which was similar to the engine in the test vehicle.

The work plan was modified to include engine test work to evaluate these effects. The objective of the engine testing was to evaluate the magnitude of "charge robbing" between cylinders and the performance of the fuel system components (See Figure 1). The test engine was received from Chrysler in June, and after receipt of the engine, work was started on preparing it for dynamometer testing. Preparation included the design and fabrication of a coupling between the engine flywheel and dynamometer. A number of engine components supplied by Chrysler were also required to complete the mounting of the engine onto the dynamometer, these components arrived in August.

An engine controller was necessary to operate the LPG injection system on the dynamometer engine. Accordingly, an interim ECM was developed based on the existing IMPCO AFE (Alternative Fuel Electronic) computer. This enabled us to manage the dynamometer engine in a limited capacity for evaluation of the intake system and for basic component testing. Extensive hardware and software modifications were required to make the AFE computer compatible for control of the injectors. We further had to design an ignition driver system for the dynamometer test engine because an OEM computer was not available to drive the ignition coils. The ignition driver was then built, bench tested, and transferred onto the engine in the test cell. The ignition driver module worked as designed, and allowed ignition timing to be varied.

LPG Vapor Injector Design Modifications

Four major changes were made to the LPG vapor injector design during the course of phase II to extend the linear flow range, reduce injector unit-to-unit variation, and improve injector durability. First, the pintle support bearings were moved into a single component of the assembly so that the bearing alignment, and consequently the pintle location, could be controlled by a single boring operation. This allowed looser component tolerances, lower manufacturing costs, and tighter control of the magnetic circuit for improved injector linearity and unit-to-unit repeatability. Second, the pintle mass was reduced to improve response time, and linearity and lessen impact forces for better durability. Bench durability testing with the above two modifications to the injector was conducted and more than 290 million cycles were completed.

Frequent problems with the durability of the upper pintle stop (which was replaced with various materials at a maximum interval of 80 million cycles to allow for the continued testing of the rest of the components) led to the third major modification. The injector pintle stops were relocated to allow for a thicker upper stop, of the same thickness as the original (durable) lower stop, and consequently, a wider selection of materials. The new upper pintle stop completed 185 million cycles on the first stop material tested. A second material has been selected for further durability improvements that will start testing February 1995. The goal is to have the injector last for at least 900 million cycles, which will correspond to a projected distance of 400,000 miles for the vehicle. The final change was to the magnetic material used throughout the entire magnetic path of the injector. Two injectors using different magnetic material were fabricated and will be tested in-house prior to ordering the final parts that will use the material determined to have the better performance.

Regulator and Engine Dynamometer Tests

A two-stage LPG regulator was used to control inlet pressure to the propane injectors. The regulator was expected to supply sufficient propane in vapor form to allow the engine to be started at temperatures down to -20°F. However, between -10° and -20°F, the fuel pressure is determined by the vapor pressure of the fuel, which is approximately 12 psig at -20°F. The specially designed LPG regulator was assembled and bench testing was conducted. This version of the regulator was based on a previous design but included four additional features designed to improve performance. These features were an outlet fuel temperature thermostat, o-ring sealing of fuel chambers, thermostatically-controlled fuel-diverting-to-heating element, and a "cool" fuel inlet design to avoid fuel flow restriction associated with inlet flow vaporization. In addition to the extensive bench testing of the regulator, engine dynamometer tests were conducted. In all these tests, the regulator operated satisfactorily and performed to our design specifications.

Air Mass Sensing

The Chrysler LH engine uses a speed-density-based fuel control system. We did not believe such an approach would provide sufficient control of the air fuel ratio under all operating regimes for meeting ULEV standards. As a result, we decided to incorporate actual air mass sensing using the patented IMPCO air mass sensor technology to directly measure the air flow into the engine. The combination of air mass sensing and speed density flow calculations combine the advantages of each method under all operating regimes. The use of an air mass sensor also greatly reduces the development time normally associated with determining speed density flow calculation parameters. To fit the air mass sensor into the vehicle inlet air stream, a special air mass sensor housing was required. The air mass sensor was custom-fabricated to fit in this housing. After construction of the housing, the air mass sensor was mounted and preliminary testing started.

The preliminary results indicated that some additional modifications to the air mass sensor/housing unit were required. Further testing of the air mass sensor was started in September upon completion of the necessary design modifications. Based on these test data, a problem with the original design was identified and thus created some problems with the accuracy of the air mass sensor. We concluded that the sensor must be mounted further upstream in the flow. Design modifications to the vehicle intake system are now underway to accommodate the sensor's new location.

Engine Dynamometer Testing

The Chrysler engine to be used for our engine dynamometer testing was prepared and installed in the engine dynamometer cell. All of the engine components necessary for the test program were installed prior to the setup of the engine in the test cell. The ignition system software was also completed and tested, which allowed us to completely control ignition timing. As mentioned earlier, the fully integrated design of the air mass sensor in the Chrysler intake system has presented some problems. As a result, we installed a standard IMPCO 3" air mass sensor (AMS) for use with the dyno engine to enable engine operation and the testing of system components.

Following installation of the engine and instrumentation, the engine was started and the ignition timing set to specifications. The closed-loop fuel control was also implemented and worked well; however, further closed-loop calibration will be required to optimize operation. Before detailed testing of the engine started, an accelerated engine break-in schedule was conducted using LPG as the fuel. This involved approximately 13 hours of operation under varying speeds and loads on the dynamometer. Upon completion of the engine break-in, performance data was collected using LPG as the fuel. The power achieved was lower than expected, which could possibly be due to the engine not being completely broken-in. Following these tests, the engine was converted back to gasoline operation, and a standard Chrysler break-in schedule was re-run on gasoline (detailed in Appendix F) to ensure that the rings were fully bedded-in. A baseline gasoline power curve was obtained and then compared to Chrysler's. There was a good match between the test data and the Chrysler Specification, so that we are now confident that the engine has been fully broken-in. The engine was converted back to LPG where the power was measured to be down 3% as compared to that of gasoline; the break specific fuel consumption was also measured to be down 5% as compared to that of gasoline (see Appendix G). The power loss is suspected to be a result of reduced engine volumetric efficiency on gaseous fuels, although the decrease in fuel consumption is a benefit of LPG.

Cylinder-to-Cylinder System Testing

A cylinder-to-cylinder sampling system was constructed and installed on the engine. This system allows the air fuel ratio to be conclusively determined in individual cylinders. Cylinder-to-cylinder air fuel ratio testing was conducted using both LPG and gasoline, resulting in the cylinder-to-cylinder air fuel ratio variation curves given in Appendix H showing an increase in variation with LPG as compared with gasoline. This air fuel ratio variation exists in the same pattern on both fuels, and has not been seen on previous test engines using the same LPG fuel system. The pattern persisted when the injectors were rearranged, it is therefore believed that the cause of the problem is specific to the intake system.

Modifications to the intake system as shown in Figure 2 were tested on the dynamometer and had no significant effect on distribution. The effect of fuel injection timing was evaluated and found to have a marked influence on cylinder-to-cylinder air fuel ratio distribution as would be expected if "charge robbing" were the cause of the problem. Accordingly, an "extended intake manifold" was constructed that increased the intake runner length by 12 inches as shown in Figure 3. The cylinder-to-cylinder air fuel variation curves given in Appendix I show that although the modified intake manifold eliminates charge robbing, as indicated by the cylinder-to-cylinder air fuel ratio variation being unaffected by injection timing, an unacceptable air fuel variation persists. Accordingly, additional design changes to the intake manifold are now being pursued.

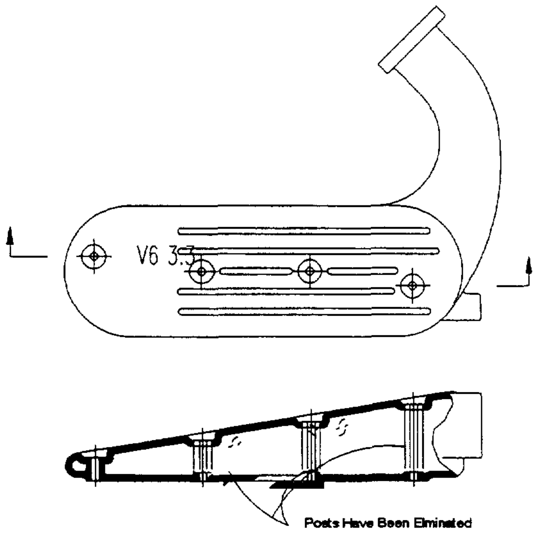


Figure 2. Modification to OEM Manifold

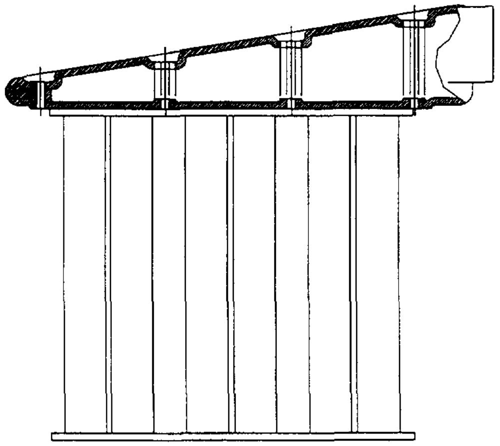


Figure 3. Manifold Extension to OEM Manifold

Task 4. Emissions Control System Development

Proper operation of the catalytic converter is essential to achieve ULEV levels. As a result, significant effort was devoted to coordinate all catalyst/vehicle compatibility and packaging issues prior to assembly on the vehicle. Specially coated 1994 style LPG close coupled catalyst substrates were ordered from Engelhard corporation of Iselin, New Jersey. The coating of the catalyst substrates were completed in September and forwarded to a fabricator for proper installation of the catalyst substrates into containers (that is, "canning" the catalysts).

Discussions were also held with a second supplier of specially coated catalytic substrates, Allied Signal. A representative of the company visited IMPCO in Seattle during October. As a result of the meeting, Allied Signal has agreed to supply a specially formulated LPG catalyst substrate coating as well as Engelhard. Thus, during Phase III work of the project, we will have two different catalytic converter coatings to evaluate so that the best performing catalyst (substrate coating) can be selected.

In November an opportunity existed to obtain 1996 specification close coupled catalysts that can be mounted closer to the exhaust manifold. The latter design offers superior performance in start-up mode as it will start to oxidize CO and HC and reduce NOx more quickly than the 1994 design. This is due to the increased thermal loading that can be applied to the catalyst as a result of the reduced distance between the catalyst and exhaust manifold. Accordingly two sets of 1996 close coupled catalyst substrates were ordered, received and forwarded to the catalyst substrate coating suppliers, Engelhard and Allied Signal for coating. The two sets of catalysts are now in the process of being "canned" by a third party source and then will be shipped back to IMPCO for testing to begin in March 1995.

The Chrysler LH test vehicle was shipped from Seattle to IMPCO's emission test facility in Cerritos, California during August 1994. Baseline emission tests were conducted on the vehicle to ensure that there were no component failures on the vehicle prior to converting the engine to run on propane. The total vehicle mileage at the time of the test was approximately 1000 miles, which was enough to ensure proper engine break-in on gasoline. The vehicle emissions measured were under the federal emission standards (see Appendix J) which indicated that the engine systems were operating properly. The typically required 4000-mile aging of the catalyst was ignored because the purpose of the initial emissions test was to verify if all other emissions-related components of the OEM system were in working order.

IMPX ECM

To take full advantage of the precise fuel control available through gaseous LPG injection and to maximize the benefits of the specially coated close coupled catalytic converters, the ECM must have access and control of all engine parameters. To accomplish this end, IMPCO has developed a powerful engine controller based on the Motorola MC68332 micro controller, which boasts a Timer Processor Unit, Queued Serial Module and a 32-bit processor capable of running at 16MHz and handling underhood automotive electronics temperatures specified in SAE J1455. This controller, designated IMPX, accesses the OEM wiring harness to acquire the coolant temperature, manifold pressure, intake air temperature, crank position sensor, cam position sensor, exhaust gas recirculation (EGR) position sensor, throttle position sensor, oxygen sensors, ignition switch, and brake switch. This custom interface is incorporated into the design of the computer and enables it to be easily fitted in the engine compartment. Six gaseous injectors are driven through the OEM wiring harness, but all other engine management signals in addition to the OEM system are directly wired to the computer. These signals include, but are not limited to, a fuel shut-off solenoid, fuel pressure, fuel temperature, instrumentation, and spare input/output (I/O). Appendix C depicts the electronic interface as described above.

Engine control signals common to both gasoline and LPG operation, such as ignition timing and EGR, will be modified by the IMPX in a method least intrusive to the operation of the OEM ECM. This will ensure that the OEM ECM continues to operate normally so that no false trouble codes are set. The ignition timing control will be accomplished by shifting the CAM and crank shaft sensor signals into the OEM ECM to advance or retard the timing for LPG operation with respect to the gasoline timing. This will allow the OEM ignition coil drivers located in the OEM ECM to be used to drive the standard high output ignition coils. The EGR control signal from the OEM ECM will be intercepted so that the IMPX can directly control the EGR valve.

As mentioned earlier, an interim ECM is being used to control the fuel and ignition systems for engine dynamometer testing until the IMPX ECM is ready. The IMPX ECM will be used to run the propane injectors, ignition advance map, and EGR control valve on the dynamometer engine and in the vehicle. We plan to have a preliminary version of the IMPX completed for testing on the dynamometer engine in January 1995.

Major effort was devoted to the hardware and software modifications for the IMPX computer. The timing processing unit (TPU) micro-code used to read the crankshaft and camshaft sensors was completed and tested on the bench. Both the hardware and software worked as planned. The IMPX micro-code for the PC-Calibrator interfacing algorithms was also completed and bench tested. The engine interfacing hardware, required for electrical interfacing between the IMPX and the dynamometer engine, was designed, built, and bench tested. Final integration of the IMPX computer to the dynamometer engine will be conducted in January 1995.

Task 5. Vehicle System Integration

Integrating the fuel and control systems into the vehicle is critically important to achieve the emission and performance goals for the project. Major effort will be on all aspects of the vehicle system integration. The integration of the IMPX into the dynamometer engine will be conducted first, followed by the vehicle system integration. The vehicle systems integration of the IMPX will be conducted by connecting the IMPX computer between the OEM ECM and the OEM wiring harness (see Appendix C). The IMPX will allow most of the information to pass through to the OEM ECM unaltered, but will modify other signals, such as the crank shaft and cam shaft position signals. Other signals from the engine which are not present with the propane injection system, such as gasoline fuel injector feedback, will be generated by the IMPX to maintain proper operation of the OEM ECM.

Task 6. Engine Component Testing

The LPG regulator and vapor injectors that will be used on the vehicle underwent cold start testing on a proprietary 6l V-8 engine at an engine test laboratory. The engine was started at -20°F and successfully operated under these extreme conditions, although the fuel pressure was only 12 psig. Based on these tests, we now have confidence that the system will be able to successfully start and operate at low ambient temperatures.

The injector durability testing has been run to 185 million cycles (103,000 vehicle miles equivalent) to where a problem with the top stop was encountered. A redesign of this stop is expected to improve the durability to beyond the goal of 900 million cycles (over 400,000 vehicle miles equivalent).

Task 7. Project Management

Discussions were held with National Renewable Energy Laboratory (NREL) staff regarding the draft report summarizing the Phase I work and a review meeting for Phase I work was held in Seattle with Chris Colucci of NREL. IMPCO staff made presentations summarizing the detailed design work carried out in Phase I of the project. In addition, a summary of the Phase II work in progress was made.

IMPCO staff presented a paper entitled “Dedicated Propane Ultra-Low Emission Vehicle” at the Annual Automotive Technology Development Contractors’ Coordination Meeting held in Dearborn, Michigan on October 15, 1994. Preliminary results on the vapor injector were presented, along with a review of the program.

In October 1994, IMPCO staff discovered a problem with the use of the interim ECM with the OEM ECM. As a result, the interim ECM will be used solely to operate the test engine and will not be used in the vehicle as we had originally planned. Instead, the IMPX computer will be used exclusively in the vehicle. This modification in the work plan will not introduce any changes to the project schedule as the work of IMPCO staff has been redirected to speed up efforts on the IMPX computer.

SUMMARY

All of Phase II tasks in the original statement of work have been successfully completed. All major components have been prototyped and tested for basic operation and compatibility as an integrated system. The work conducted in Phase II indicates that the system components have been sufficiently developed to be installed in the vehicle.

The addition of an engine dyno with a test engine has enabled extended testing of the fuel management system and its components for steady state operation prior to installation in the test vehicle. The engine test data have indicated that both the regulator and injectors are working very well. The present durability of the LPG injectors is anticipated to be about 145,000 miles based on bench testing. We expect to improve this to greater than 400,000 miles when further modifications are made to the injector design.

Additional work in the form of engine dynamometer testing to evaluate the anticipated problem with cylinder charge robbing has been performed. It is apparent that some additional work in the form of modifications to the OEM intake manifold to reduce cylinder charge robbing will be necessary. This will be especially important to minimize hydrocarbon emissions.

The ECM hardware (32-bit IMPX) and basic software are nearing completion and will be integrated in the test vehicle. An interim ECM to operate the test vehicle in the initial stages will not be used because of extensive modifications would be required and would therefore adversely impacting the project schedule. For the engine testing on the engine dynamometer, an interim computer has been used that will be phased out for the next stage of the project.

Concurrent with the preparation of the components for final installation in the test vehicle, refinement and testing of the components will continue. With the successful completion of Phase II, Phase III work is now under way, and the project is currently on schedule and on budget. The project Gantt chart and cost breakdown are given in Appendix K.

Appendix A
Technical Data Sheet R50203A

GASEOUS FUEL INJECTOR

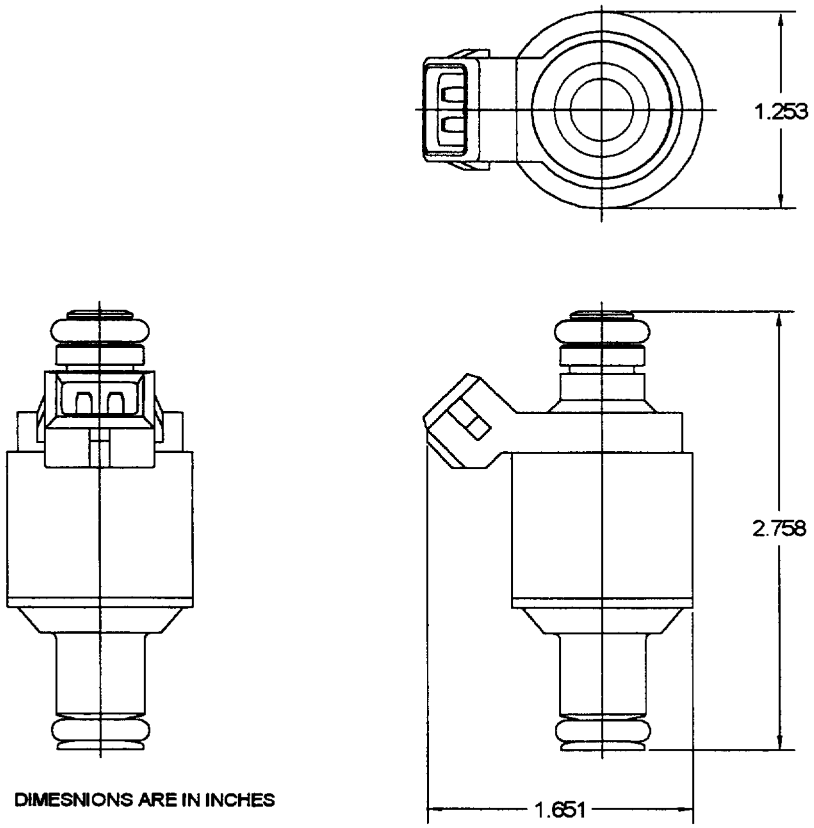
IMPCO®

DESCRIPTION

THE GASEOUS INJECTOR WAS DESIGNED FROM THE GROUND UP FOR LONG LIFE AND QUIET OPERATION WITH GASEOUS FUELS, SUCH AS NATURAL GAS AND LPG. THE OVERALL DIMENSIONS WERE SELECTED FOR DIRECT REPLACEMENT OF STANDARD AUTOMOTIVE MULTIPOINT INJECTORS, BUT ARE EASILY ADAPTABLE FOR SINGLE POINT A PPLICATIONS. THE INJECTORS INCORPORATE A FAST-ACTING SOLENOID COUPLED WITH A PRECISION SONIC METERING NOZZLE TO MEET THE TIGHT FUEL CONTROL REQUIREMENTS OF PRESENT AND FUTURE LOW EMISSIONS ENGINES.

MAXIMUM RATINGS

POWER	24 VDC
FUEL FLOW	20 LBS/HR (CNG) 30 LBS/HR (LPG)
VIBRATION	10 G @ 50-2000
SHOCK	20 G
OPERATING TEMP.	-40 TO +150 DEG
PRESSURE	200 PSIG



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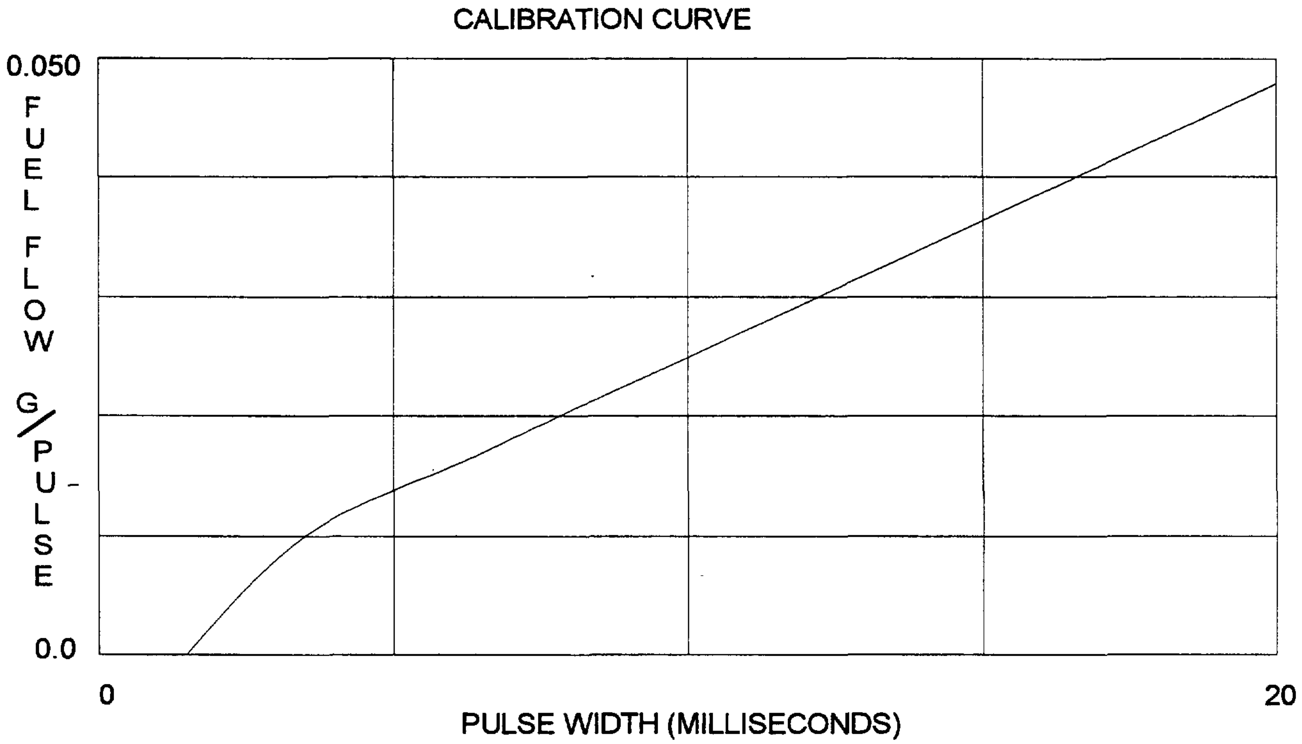
Appendix A

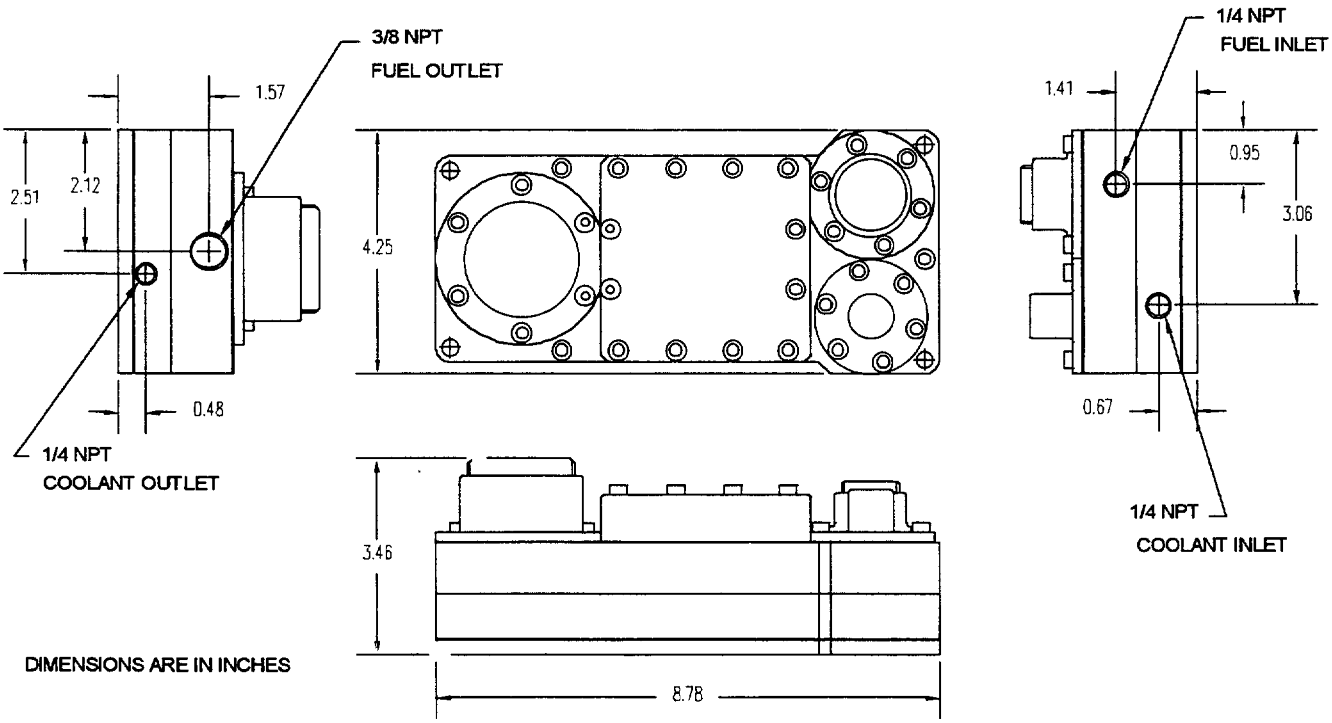


OPERATING SPECIFICATIONS

MAXIMUM VOLTAGE	24 VDC
MAXIMUM CURRENT	4 AMPS PEAK 1 AMP CONTINUOUS
IMPEDANCE	2 OHMS TYPICAL
OPERATING VOLTAGE RANGE	6 TO 24 VDC
DYNAMIC FLOW RANGE	0 TO 20 Lbs/Hour (CNG) 0 TO 30 Lbs/Hour (LPG)
MINIMUM OFF TIME BETWEEN PULSES	5 ms
OPERATING LIFE	200 MILLION CYCLES
OPERATING PRESSURE	100 psig (CNG) 18 psig (LPG)
OPERATING TEMPERATURE RANGE	-40 TO 150°C
MAXIMUM PRESSURE	200 psig
MAXIMUM VIBRATION	10 G @ 50 to 2000 Hz
MAXIMUM SHOCK	20 G
UNIT TO UNIT VARIABILITY	+/- 2 %
MAINTENANCE	NONE REQUIRED

Appendix B
Technical Data
LPG INJECTOR PRESSURE REGULATOR

IMPCO®

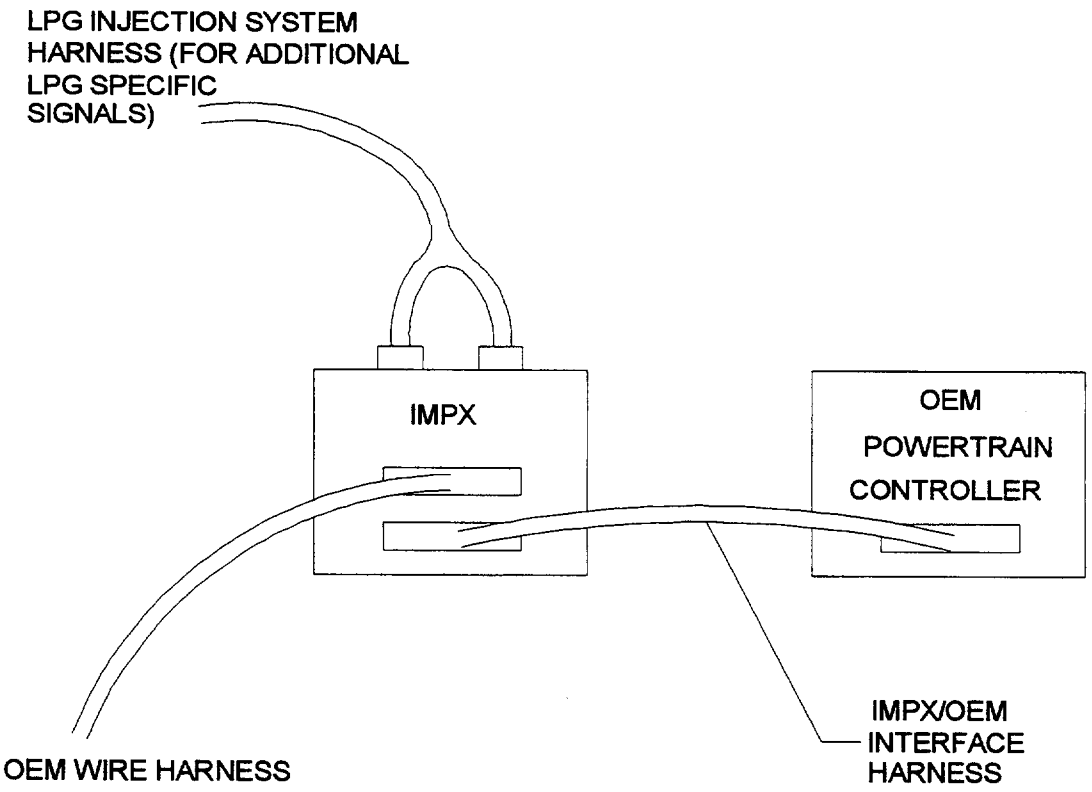


OPERATING SPECIFICATIONS

DYNAMIC FLOW RANGE	0 TO 150 LBS/HOUR
OUTLET PRESSURE	18 PSIG
OUTLET PRESSURE VARIATION	LESS THAN 1 %
FLOW PRESSURE DROOP	LESS THAN 2 %
CRACKING PRESSURE DROOP	LESS THAN 5 %
OPERATING TEMPERATURE RANGE	-20° TO 150° C
MAXIMUM INLET PRESSURE	250 PSIG
MINIMUM INLET PRESSURE	25 PSIG
MAXIMUM VIBRATION	10 G
MAXIMUM SHOCK	20 G
UNIT TO UNIT VARIABILITY	+/- 2 %
MAINTENANCE	NONE REQUIRED

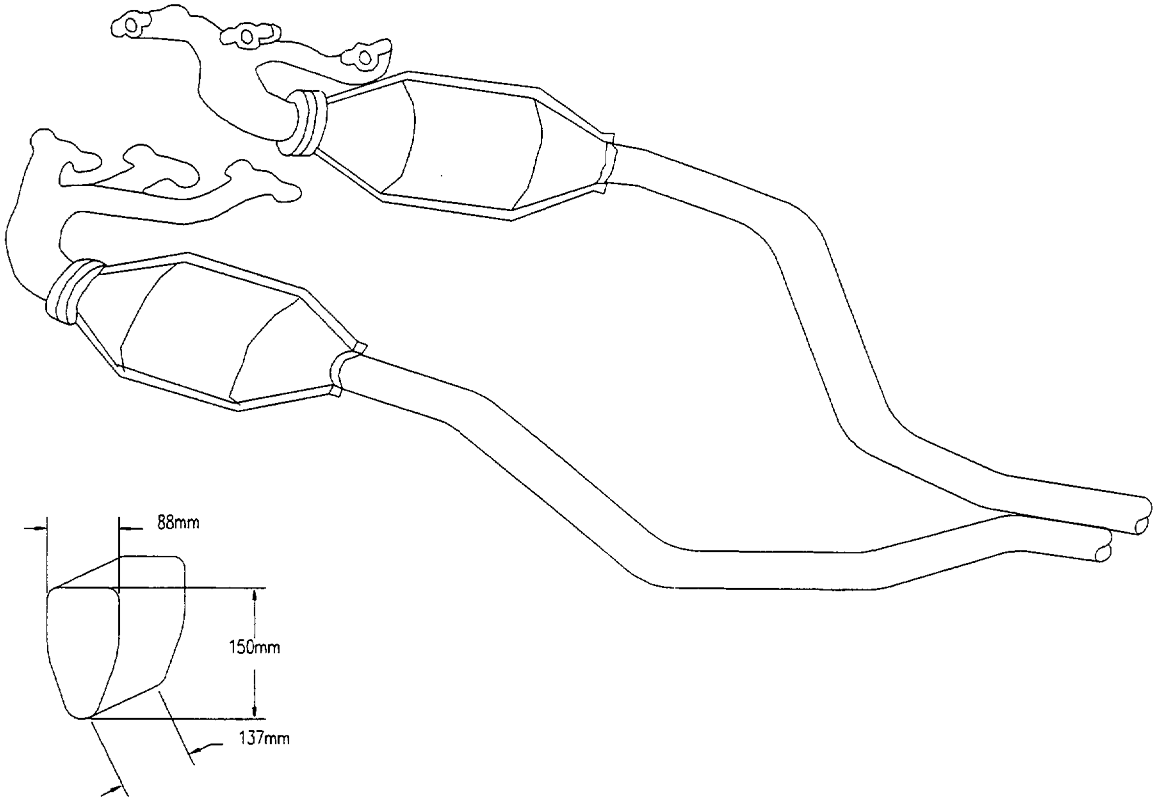
Appendix C

VEHICLE ELECTRONIC INTERFACE DIAGRAM



Appendix D

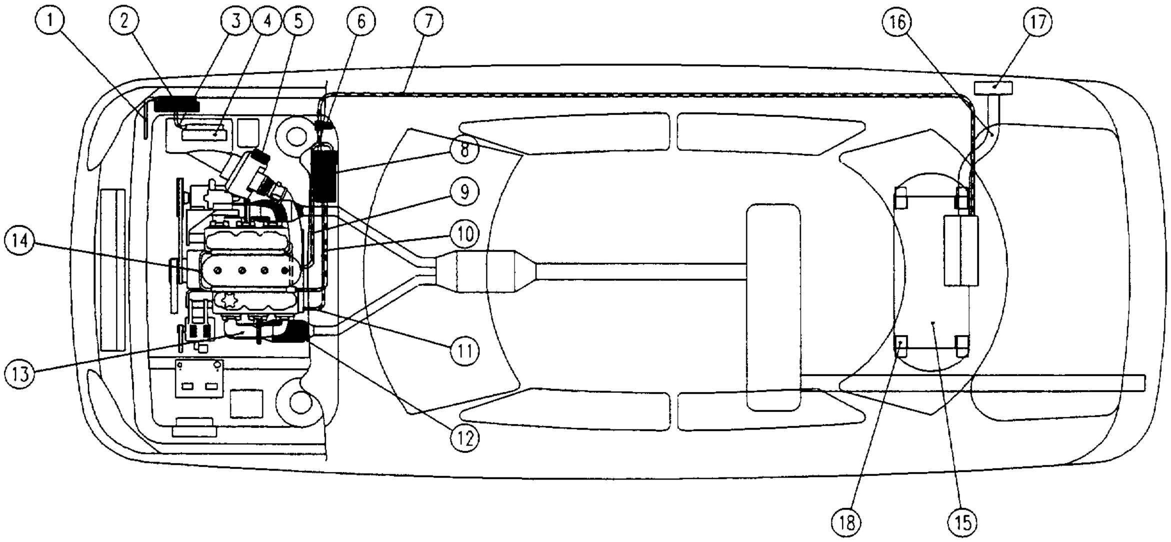
CHRYSLER 3.3L V6 INTREPID CLOSE COUPLE MANIFOLD AND CATALYST



CATALYST SUBSTRATE PROFILE

Appendix E

SYSTEM COMPONENTS LOCATION



ITEM	DESCRIPTION
1	OEM HARNESS
2	IMPX COMPUTER
3	IMPCO HARNESS
4	OEM COMPUTER
5	AIR MASS SENSOR
6	IMPCO SHUT OFF VALVE
7	FUEL LINE (LPG IN)
8	IMPCO REGULATOR
9	COOLANT TO REGULATOR
10	FUEL LINE (TO INJECTORS)
11	COOLANT FROM REGULATOR
12	LPG CLOSE COUPLED CATALYST
13	LOW THERMAL INERTIA MANIFOLD
14	FUEL RAIL & INJECTORS
15	MANCHESTER LPG FUEL TANK (IN TRUNK)
16	FILL LINE SAFETY MANIFOLD
17	REMOTE LPG FILL BLOCK
18	TANK MOUNTING BRACKETS

Appendix F

CHRYSLER 3.3L INTREPID V6 DYNAMOMETER ENGINE BREAK-IN DATA

1. Install P/T spark plugs: RN14MC5 0.050" gap

2. Warm engine until temperatures stabalizes (1600 rpm // 350 MAP)

3. Run engine per the schedule below (fuel synchronized to Cyl 2)

Cum. Hrs after Point	Hrs. @ Point	rpm	Torque (ft-lbs)	Spark Adv deg BTDC	A/F Ratio	Oil Press (psig)	Man. Vac (in Hg)
1	1	1600	67	29	14.6		12.5

4. With engine fully warm, operate engine at 2400 rpm // wide open throttle (WOT) // A 12.5 for 3 minutes immediately measure and record the corrected torque.

Wet bulb 58 °F
Dry bulb 66 °F
Baro 29.99 in Hg @ 72°F
Torque 182 ft-lbs Correction factor 0.967 176 ft-lbs

5. Run engine per the schedule below (fuel synchronized to Cyl 2)

Cum. Hrs after Point	Hrs. @ Point	rpm	Torque (ft-lbs)	Spark Adv deg BTDC	A/F Ratio	Oil Press (psig)	Man. Vac (in Hg)
2	1	1600	67	27	14.6	40	14
3	1	2000	93	27	14.6	40	11
4	1	2400	120	27	13.3	47	7

6. Install WOT spark plugs: RN6YC 0.035" gap

7. Run engine per the schedule below (fuel synchronized to Cyl 2)

Cum. Hrs after Point	Hrs. @ Point	rpm	Torque (ft-lbs)	Spark Adv deg BTDC	A/F Ratio	Oil Press (psig)	Man. Vac (in Hg)
5	1	2800	134	29	12.5	50	6
6	1	3200	147	29	12.5	52	4.5

8. Drain engine oil and examine sample for particle contamination.
Refill engine with eil. Type: Mobil 1

9. With engine fully warm, operate engine at 2400 rpm // WOT // A/F 12.5
for 3 minutes immediately measure and record the corrected torque.

Wet Bulb 55.5 °F
Dry Bulb 79 °F
Baro 29.98 in Hg @ 68°F
Torque 181 ft-lbs Correction factor 0.965 175 ft-lbs

10. For the following, cycle the engine at high speed/load condition for 4 minutes
Low speed load condition for 1 minute (fuel synchronized to Cyl 2)

Cum. Hrs after Point	Hrs. @ Point	rpm	Torque (ft-lbs)	Spark Adv deg BTDC	A/F Ratio	Oil Press (psig)	Man. Vac (in Hg)
9	3	3600	120	29	12.5	60	9
		1600	40	29	14.6	30	15
12	3	4000	147	29	12.5	60	5.5
		1600	40	29	14.6	27	14

11. With engine fully warm, operate engine at 2400 rpm // WOT // A/F 12.5
for 3 minutes immediately measure and record the corrected torque.

Wet Bulb 57 °F
Dry Bulb 79 °F
Baro 29.99 in Hg @ 70°F
Torque 180 ft-lbs Correction factor 0.988 178 ft-lbs

Appendix G

DYNAMOMETER ENGINE TEST DATA

Chrysler 3.3l Intrepid V6 Dynamometer Test Data
Fuel System Type: Multiport Gasoline Fuel Injection

Wet Bulb	51	°F	Vp	0.81	kPa
Dry Bulb	65	°F	18.3	°C	
Baro	29.99	in Hg	Comp	-0.11	102 kPa
Baro Temp	68	°F	Corr	0.96	

RPM	A/F Ratio	Spark Adv.	Pulse Width	BV	AMS	Torque	Corr Torque	Corr HP	Fuel Cons.
	(LBT)	(MBT)	ms	volts	#/hr	ft-lbs	ft-lbs	HP	lbs/HP-hr
2000	13.75	28 deg BTDC	8.72	14.6	396	185	178.05	67.80	0.425
2400	13.35	31 deg BTDC	9	14.6	477	186	179.02	81.81	0.437
2800	13.2	31 deg BTDC	9.12	14.6	549	187	179.98	95.95	0.433
3200	13.3	31 deg BTDC	9.3	14.6	643	190	182.87	111.42	0.434
3600	13.3	29 deg BTDC	9.44	14.6	749	189	181.90	124.69	0.452
4000	13.3	29 deg BTDC	9.88	14.6	828	192	184.79	140.74	0.442
4400	13.3	29 deg BTDC	10.24	14.6	978	191	183.83	154.01	0.477

Chrysler 3.3l Intrepid V6 Dynamometer Test Data
Fuel System Type: Multiport LPG Fuel Injection

Wet Bulb	49	°F	Vp	0.95	kPa
Dry Bulb	57	°F	13.9	°C	
Baro	30.2	in Hg	Comp	-0.09	103 kPa
Baro Temp	62	°F	Corr	0.95	

RPM	A/F Ratio	Spark Adv.	Pulse Width	BV	AMS	Torque	Corr Torque	Corr HP	Fuel Cons.
	(LBT)	(MBT)	ms	volts	#/hr	ft-lbs	ft-lbs	HP	lbs/HP-hr
2000	15.17	29 deg BTDC	14	14.6	405	180	173.24	65.97	0.405
2400	15	28 deg BTDC	13.76	14.6	484	182	175.17	80.05	0.403
2800	14.8	26 deg BTDC	14.3	14.6	550	182	175.17	93.39	0.398
3200	14.45	24 deg BTDC	14.82	14.6	652	186	179.02	109.07	0.414
3600	14.2	24 deg BTDC	14.96	14.6	725	184	177.09	121.39	0.421
4000	14.15	24 deg BTDC	15.04	14.6	894	188	180.94	137.81	0.458
4400	14.25	24 deg BTDC	15.32	14.6	970	182	175.17	146.75	0.464

Appendix G

Chrysler 3.3l Intrepid V6 Cylinder-to-Cylinder Air Fuel Distribution

Multiport Gasoline Injection
Synchronized to Cylinder 2

Speed	Load	Overall	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 5	Cyl 6	Overall
rpm	ft-lbs	AFR	AFR	AFR	AFR	AFR	AFR	AFR	AFR
1000	Idle	15.4	15.3	15.9	15.1	15.4	15.55	15.8	15.4
1600	60	15.2	14.75	15.5	14.9	15.8	15.1	16.4	15.25
2400	WOT	14.5	14.65	14.8	14.4	14.5	14.5	14.5	14.5

Multiport LPG Injection
Synchronized to Cylinder 2

Speed	Load	Overall	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 5	Cyl 6	Overall
rpm	ft-lbs	AFR	AFR	AFR	AFR	AFR	AFR	AFR	AFR
1000	Idle	13.75	13.1	13.5	14.6	14.1	14.5	14.4	13.75
1600	60	14.3	13.85	14.2	14.2	14.7	14.3	14.6	14.1
2400	WOT	14.1	14.13	14.2	14.1	14.1	14.18	14.18	14.13

Multiport Gasoline Injection
1600 rpm 60 ft-lbs load

	Sync.	Overall	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 5	Cyl 6	Overall
		AFR	AFR	AFR	AFR	AFR	AFR	AFR	AFR
	1	14.75	14.25	14.9	14.6	15.4	14.65	15.5	14.85
	2	14.70	14.52	14.54	14.62	15.05	14.68	15.00	14.65
	3	14.8	14.5	14.7	14.6	15.3	14.75	15.15	14.75
	4	14.75	14.45	14.7	14.8	15.2	14.9	15.1	14.8
	5	14.8	14.5	14.6	14.9	15.2	15	15.1	14.9
	6	14.75	14.4	14.8	14.7	15.3	14.75	15.4	14.85

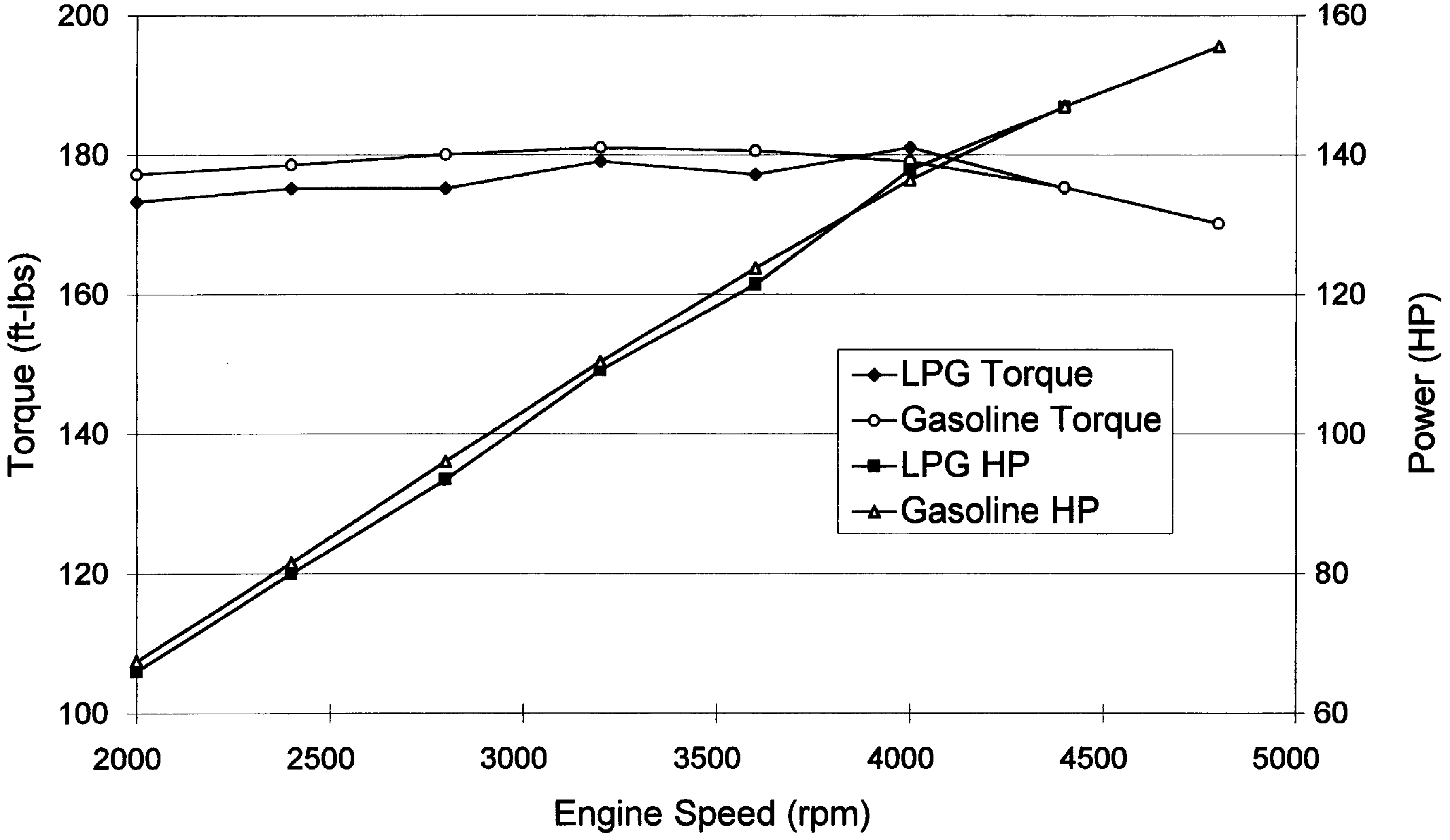
Multiport LPG Injection
1600 rpm 60 ft-lbs load

	Sync	Overall	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 5	Cyl 6	Overall
		AFR	AFR	AFR	AFR	AFR	AFR	AFR	AFR
	1	15.5	14.8	16.2	15.3	16.5	15.3	17.3	15.5
	2	15.65	15.4	15.9	15.4	16.1	15.4	16.5	15.55
	3	15.65	15.65	15.8	15.5	16.1	15.5	16.2	15.65
	4	15.7	15.75	15.6	15.6	15.6	15.95	15.85	15.65
	5	15.8	15.8	15.3	16	15.5	16.35	15.55	15.65
	6	15.55	15.5	15.5	15.5	15.7	15.6	16.25	15.6

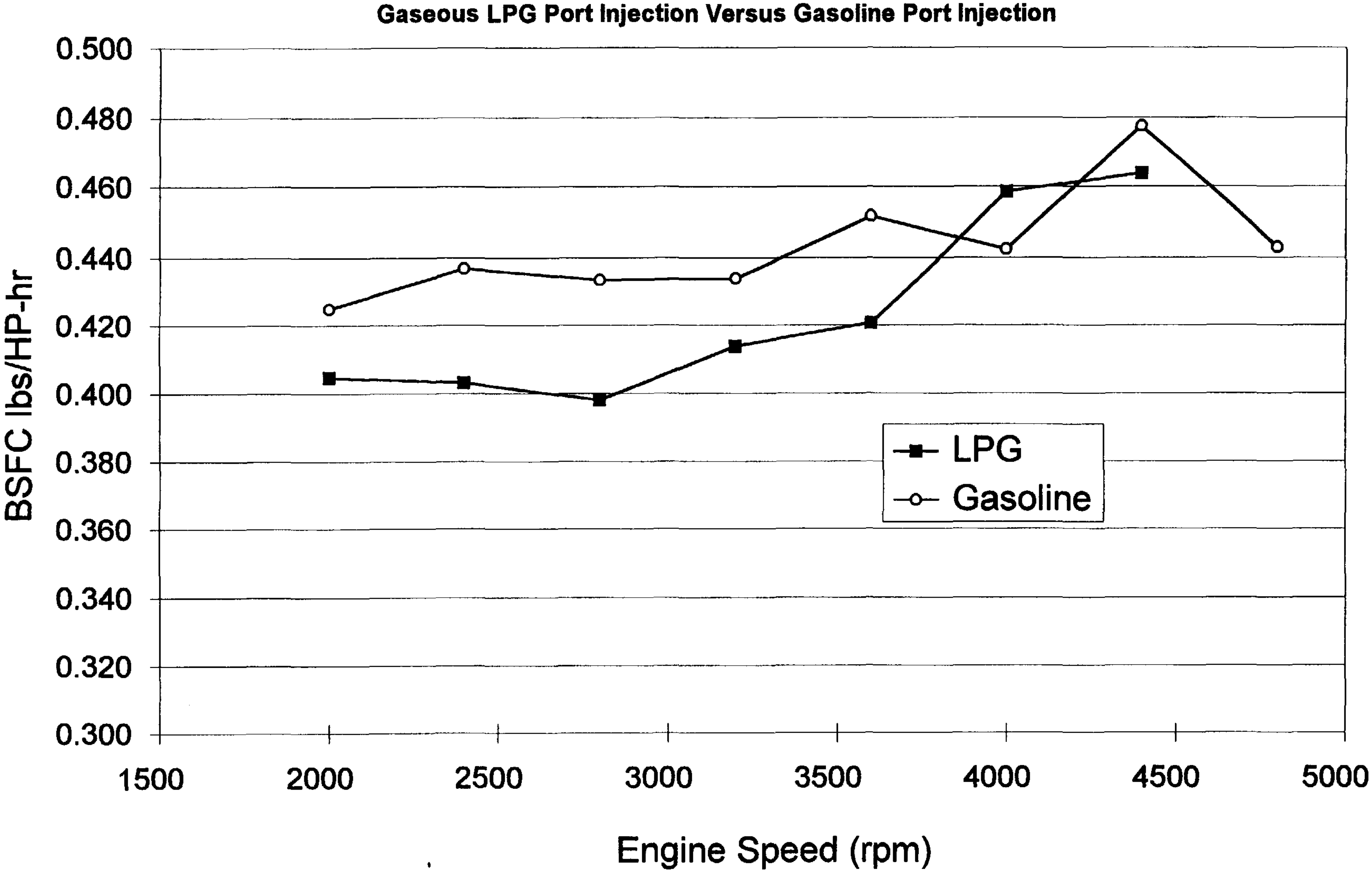
Appendix G

1994 CHRYSLER 3.3 L WIDE OPEN THROTTLE OUTPUT

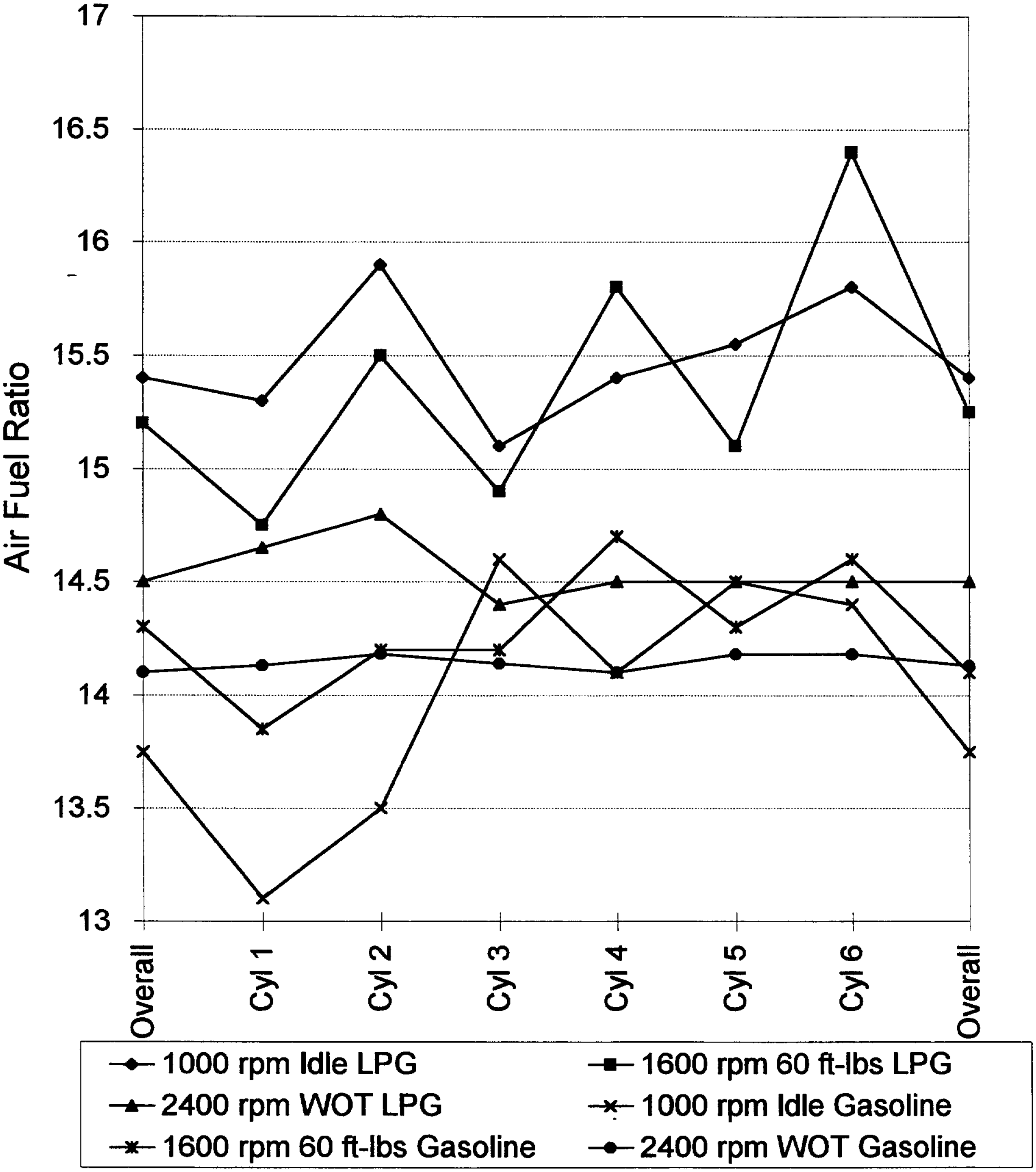
Gaseous LPG Port Injection Versus Gasoline Port Injection



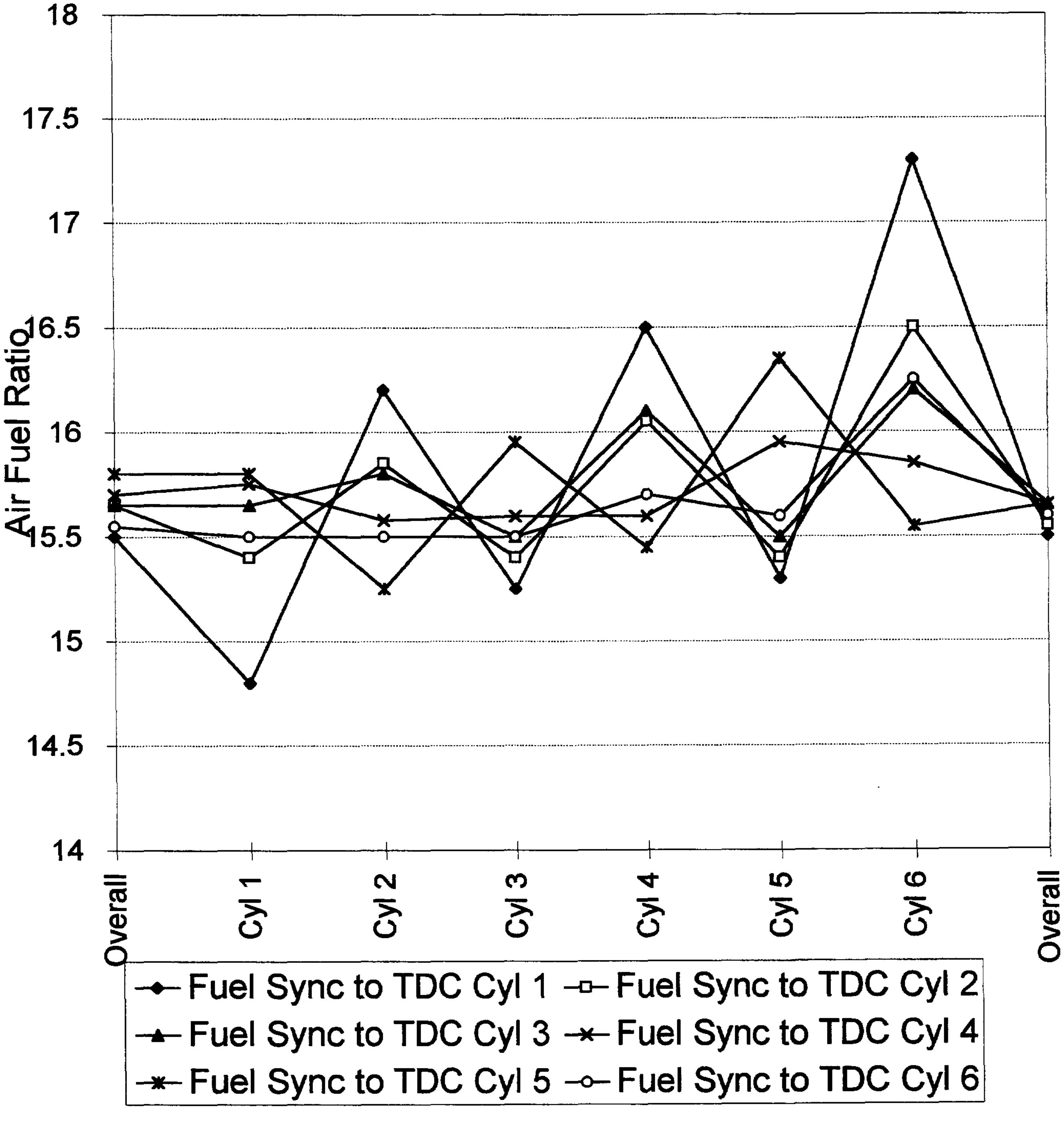
1994 CHRYSLER 3.3 L WIDE OPEN THROTTLE FUEL CONSUMPTION



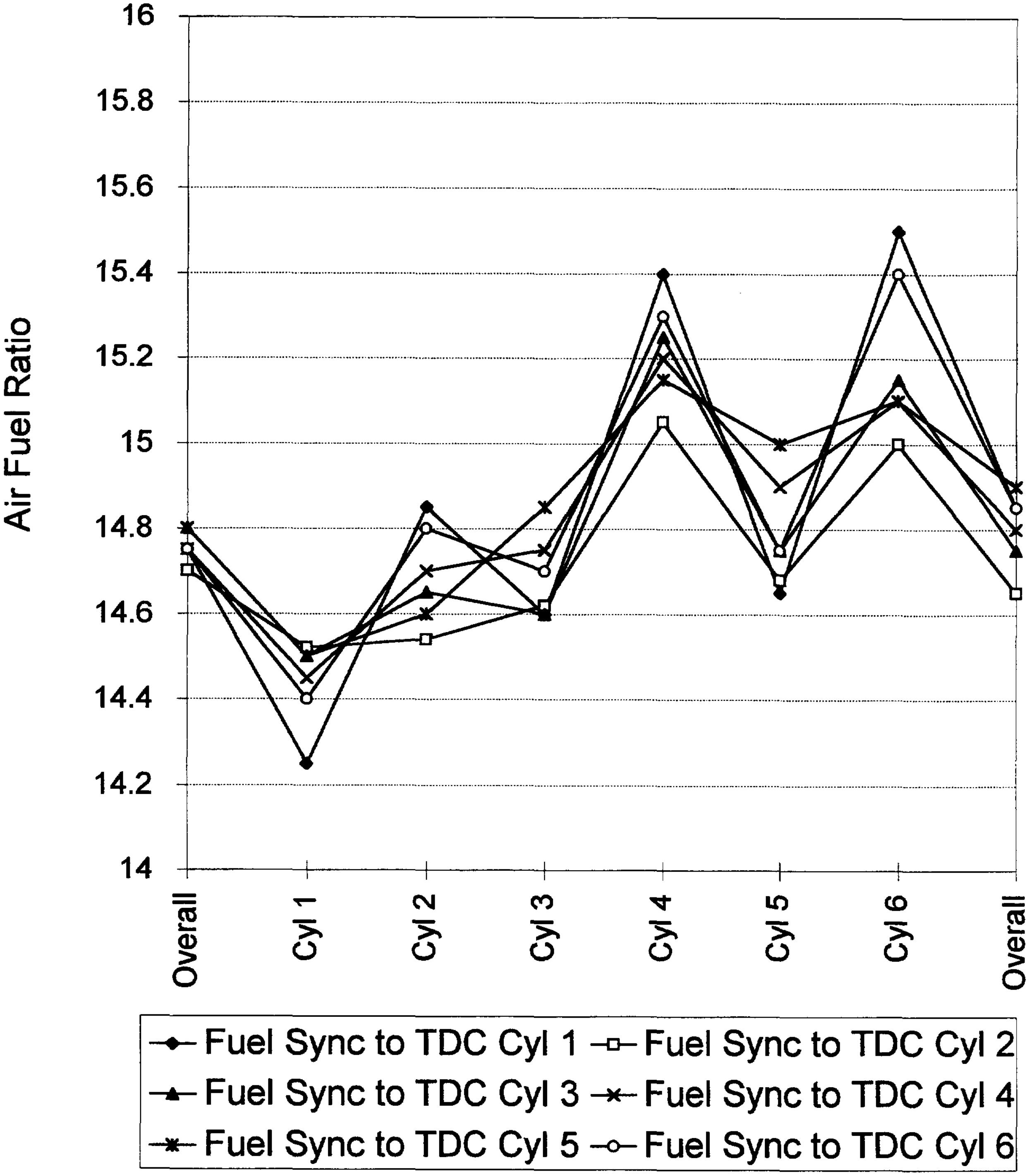
1994 CHRYSLER 3.3L CYLINDER-TO-CYLINDER AIR FUEL DISTRIBUTION



1994 CHRYSLER 3.3L AIR FUEL DISTRIBUTION GASEOUS LPG INJECTION SYSTEM AT 1600 RPM 60 FT-LBS

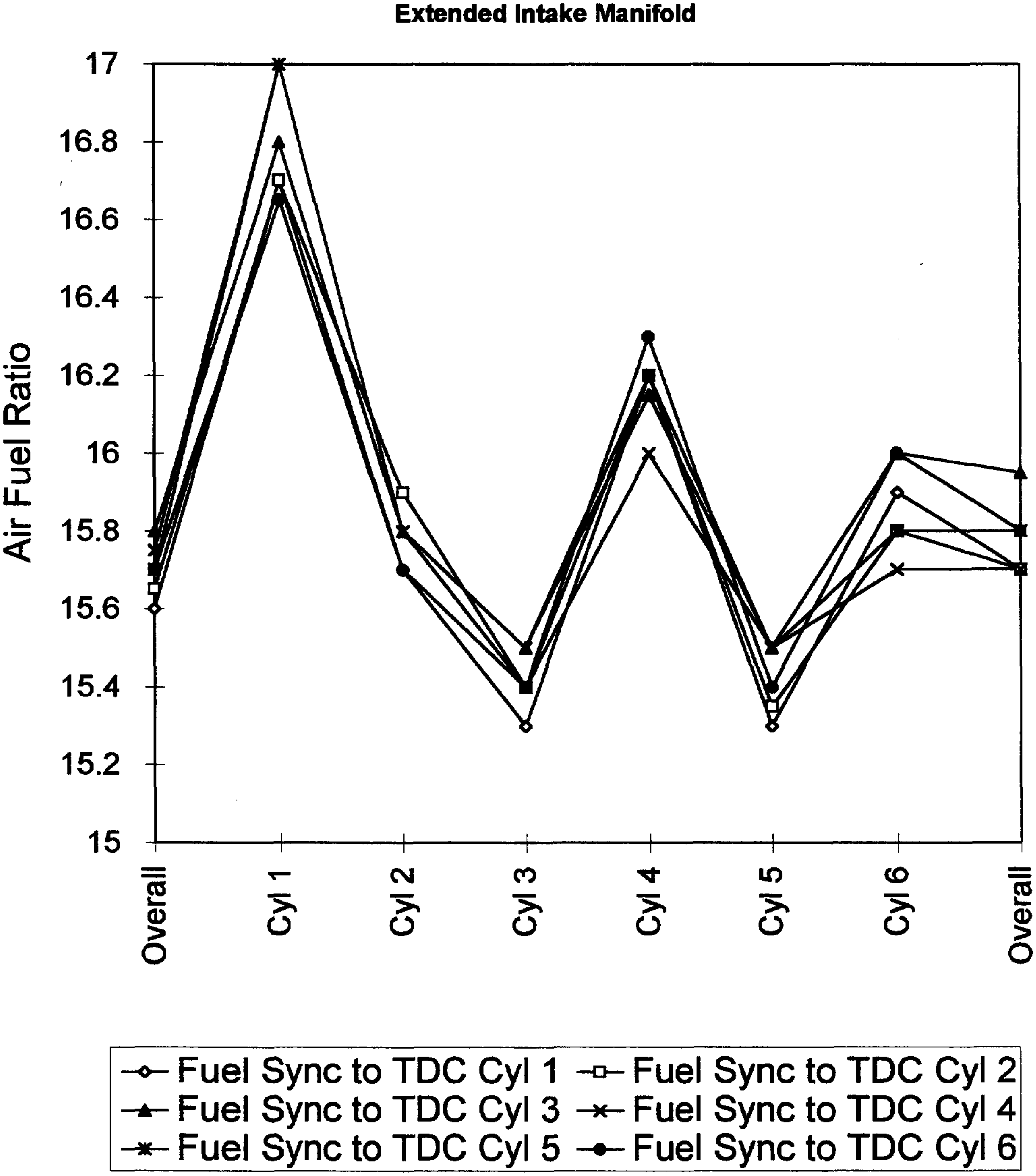


1994 CHRYSLER 3.3L AIR FUEL DISTRIBUTION GASOLINE INJECTION SYSTEM AT 1600 RPM 60 FT-LBS



Appendix I

CHRYSLER 3.3L AIR FUEL DISTRIBUTION AT 1600 RPM 60 FT-LBS



Appendix J

VEHICLE BASE EMISSIONS
Gasoline

	MEASURED EMISSIONS	1994 EPA EMISSIONS STANDARD	
	September 8, 1994		
HC	0.230	0.250	(grams/mile)
CO	1.380	3.400	(grams/mile)
NOx	0.172	0.400	(grams/mile)

FUEL ECONOMY	(GALLONS/MILE)
URBAN CYCLE	16.74

Appendix J

******** AUTO EXHAUST EMISSIONS AND FUEL CONSUMPTION ANALYSIS ********

*********************General Description*********************

Vehicle				Test Environment				Miscellaneous	
Year	94	Make	Dodge Intrepid	Barometer	29.88	Inertia Weight	3750	Test No.	3438
Model	Intrepid	License Number	758FPE	Soak Temp	68	Act HP @ 50 MPH	6.3	Date	9/8/94
Eng Disp	3.3	Transmission	A	Dry Bulb Temp	-75	IND HP @ 50 MPH	5.3	Operator	2
Fuel Type	Gasoline	Carburetor	FI	Wet Bulb Temp	66	Actual Dist Travelled	7.39	Driver	K
Odometer	1017	VIN	1B3HD46T3RF275776					Version	2/2/94
Air Condition	Yes								
Comments	Cold Start Test Stock Gasoloine Baseline								
Remarks	CVSC013								

TEST VARIABLES		URBAN CYCLE PHASE 1			PHASE 2			PHASE 3			HIGHWAY CYCLE PHASE 4		
Dry Bulb Temp				75			75			75		0	
Wet Bulb Temp				66			66			66		0	
Barometer				29.88			29.88			29.88		29.88	
Inlet Press				30.3			30.3			30.3		0	
Sample Temp				106.00			106.00			106.00		0.00	
Distance				3.59			3.8			3.69		0.00	
		R	DEF	CONC	R	DEF	CONC	R	DEF	CONC	R	DEF	CONC
HC	E	14	43.3	67.026	14	11.6	19.261	14	17.6	28.643	0	0.0	0.000
HC	D	14	9.4	15.692	14	9.3	15.528	14	10.0	16.669	0	0.0	0.000
CO	E	2	80.5	158.753	2	5.9	10.514	2	36.7	70.749	0	0.0	0.000
CO	D	2	2.7	4.749	2	2.3	4.039	2	3.1	50462	0	0.0	0.000
CO2	E	8	58.5	1.360	8	44.7	0.998	8	52.5	1.199	0	0.0	0.000
CO2	D	8	3.7	0.070	8	3.6	0.069	8	3.6	0.069	0	0.0	0.000
NOx	E	20	9.9	9.388	20	1.9	1.758	20	4.7	4.390	0	0.0	0.000
NOx	D	20	0.5	0.460	20	0.4	0.368	20	0.5	0.460	0	0.0	0.000
CH4	E	12	0.0	0.000	12	0.0	0.000	12	0.0	0.000	0	0.0	0.000
CH4	D	12	0.0	0.000	12	0.0	0.000	12	0.0	0.000	0	0.0	0.000
—Calculated Variables—													
Dilution Factor				0.896795			0.925286			0.909749		0	
V Mix (Cu Ft)				2676.62			4586.52			2676.62		0.00	
KH Corr Factor				1.0266			1.0266			1.0266		0.0000	
Relative Hum				62.09426			62.09426			62.09426		0	

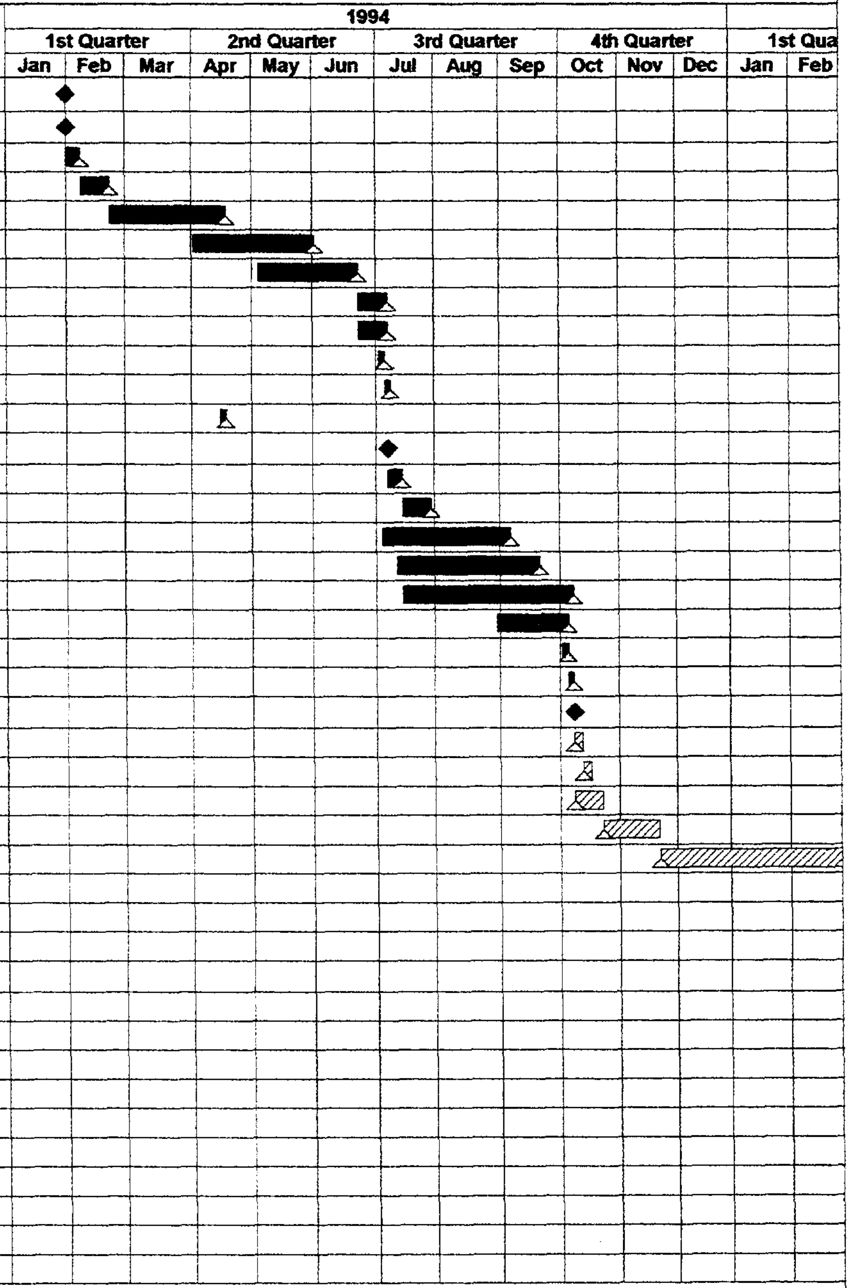
—Dynamometer Test Results—

	Net Concentration			Calculated Emissions						GR/MI	-Net Conc-	-MASS-	GRAMS/MILE
PHASE	-1-	-2-	-3-	-1 MASS	1 G/M	-2 MASS	2 G/M	-3 MASS	3 G/M	-Total-			
HC	52.952	4.893	13.484	2.315	0.645	0.366	0.096	0.589	0.164	0.23	0.000	0.000	0.000
CO	154.494	6.777	65.78	13.634	3.798	1.025	0.27	5.805	1.617	1.38	0.000	0.000	0.000
CO2	12971.57	9347.764	11370.72	1800.228	501.456	2223.002	585.001	1578.059	439.571	527.279	0.000	0.000	0.000
NOx	8.975	1.418	3.971	1.336	0.372	0.362	0.095	0.591	0.165	0.172	0.000	0.000	0.000
CH4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
NMHC	52.952	4.293	13.484	2.315	0.645	0.366	0.096	0.589	0.164	0.230			

Fuel Economy		— Emissions - Grams / Mile —	
Urban Cycle=	16.74	Total Hydrocarbons=	0.23
Highway Cycle=	0	Carbon Monoxide=	1.38
Composit=	0	Oxides of Nitrogen=	0.172

Project Name: NREL # ZAW -4-12244-01 Appendix K

#	Task Name
1	**NREL**
2	**PHASE I SYSTEMS DESIGN**
3	Fuel Formulation & Preparation
4	Fuel Storage Design
5	Engine System Design
6	Emission Control Sys. Design
7	Vehicle System Integr. Design
8	System Design Optimization
9	Install Engine on Dyno
10	Program Review (NREL)
11	Program Review (LEP Partner)
12	Contractor's Coordination Mtg
13	**PHASE II - PROT. ASSEM. & TEST**
14	Fuel Blending & Testing
15	Fuel Storage System Fab.
16	Engine System Development
17	Emissions System Development
18	Test Engine Components
19	Vehicle System Integration
20	Program Review (NREL)
21	Program Review (LEP Partner)
22	**PH. III FULL SC. TEST & INTEG.**
23	Fuel Preparation
24	Install Fuel Storage System
25	Engine System Integration
26	Emission Control System Integ.
27	Vehicle System Integration
28	Vehicle Optimization
29	Program Review (NREL)
30	Program Review (LEP Partner)
31	**PHASE IV VEHICLE DEMO**
32	Fuel Preparation
33	Fuel Storage
34	Engine Performance
35	Emission Performance
36	Vehicle Performance
37	Vehicle Optimization
38	Contractor's Coordination Mtg
39	Program Review (NREL)
40	Program Review (LEP Partner)
41	Project Complete



Project Name: NREL # ZAW -4-12244-01 Appendix K

#	Task Name	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
		1995											
		rter	2nd Quarter			3rd Quarter			4th Quarter			1st Quart	
1	**NREL**												
2	**PHASE I SYSTEMS DESIGN**												
3	Fuel Formulation & Preparation												
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25	Engine System Integration												
26	Emission Control System Integ.												
27	Vehicle System Integration	▨	▨										
28	Vehicle Optimization		▨	▨	▨	▨							
29	Program Review (NREL)				△								
30	Program Review (LEP Partner)				△								
31	**PHASE IV VEHICLE DEMO**					◇							
32	Fuel Preparation					△							
33	Fuel Storage					△							
34	Engine Performance					▨	▨	▨	▨	▨	▨		
35	Emission Performance					▨	▨	▨	▨	▨	▨		
36	Vehicle Performance					▨	▨	▨					
37	Vehicle Optimization									▨	▨	▨	
38	Contractor's Coordination Mtg								△				
39	Program Review (NREL)											△	
40	Program Review (LEP Partner)											△	
41	Project Complete											◇	

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 1995	3. REPORT TYPE AND DATES COVERED Subcontract report

4. TITLE AND SUBTITLE

Hardware Assembly and Prototype Testing for the Development of Dedicated Liquefied Propane Gas Ultra Low Emission Vehicle

5. FUNDING NUMBERS

(C) ZAW-4-12244-01
(TA) FU521010

6. AUTHOR(S)

IMPCO Technologies

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

IMPCO Technologies
708 Industry Drive
Seattle, WA 98188

8. PERFORMING ORGANIZATION REPORT NUMBER

DE95009250

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NREL/TP-425-7618

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

UC 1504

13. ABSTRACT *(Maximum 200 words)*

The objective of this project, which began in February 1994, was to develop a dedicated liquefied propane gas vehicle that would meet or exceed the California ultra low emission vehicle standards. The work was broken into four phases. This report describes the approach taken for the vehicle's development and the work performed through the completion of Phase II dynamometer test results.

14. SUBJECT TERMS

Alternative fuels, liquefied propane gas, ultra low emission vehicles

15. NUMBER OF PAGES
37

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-1
298-10