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IMPCO Technologies
Seattle, Washington

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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

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Prepared under Subcontract No. ZCI-8-17110-01

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1.0 Introduction

This report describes the last in a series of three projects designed to develop a commercially competitive liquefied petroleum gas (LPG) light-duty passenger car that meets the California ultra-low emission vehicle (ULEV) standards and corporate average fuel economy (CAFE) energy efficiency guidelines for such a vehicle. In the first project, we converted a 1994 port-injected gasoline-fueled Chrysler Intrepid to a dedicated LPG vehicle (Figure 1), and completed a 10,000-mile vehicle demonstration program. In the second project, we subjected the vehicle to a series of cold weather tests to validate cold ambient starting and the drive-away capability of the IMPCO LPG vapor fuel injection system.

IMPCO Technologies, Inc., performed this project under subcontract to the National Renewable Energy Laboratory (No. ZCI-8-17110-01, *Additional Development of a Dedicated LPG Ultra-Low Emission Vehicle* [ULEV]). We upgraded the vehicle's LPG vapor fuel injection system to the latest model of production-intent gaseous LPG injectors (Figure 2) from IMPCO. The objective of this project was to demonstrate that compliance with the ULEV 50,000-mile emission standards is feasible with a commercially viable dedicated LPG vehicle.

2.0 Background

This section summarizes the key activities and results from the previous two subcontracts. The first subcontract required 2 years of development and the merging of several technologies to get the vehicle ready for emissions testing. On March 27, 1996, we subjected the vehicle to a complete Federal Test Procedure (FTP) for ULEV emissions testing to determine if it was in compliance with the California ULEV emissions standards. The vehicle met the ULEV standard with emissions of hydrocarbons (HC) = 0.067, carbon monoxide (CO) = 0.335, and oxides of nitrogen (NO_x) = 0.175. Shortly thereafter, the vehicle, now called the ULEV, was subjected to a 10,000-mile vehicle demonstration to test the ULEV gaseous fuel management system for durability. We encountered no major mechanical problems with the fuel system, other than the disintegration of a third-party low-pressure fuel filter, which probably failed near the end of the test program. Fragments from this filter probably entered the injectors and accounted for the erratic emissions performance of the vehicle. In some of the emissions tests conducted at the end of the demonstration, we were able to achieve ULEV emissions levels for NO_x and CO, but not for HC.

Although this result was disappointing, we were generally very encouraged with the overall emissions results, especially because a number of changes to the system were implemented in the production design that we expected would improve performance and reduce emissions. These changes and the impacts we anticipated are outlined below:

1. The injector-to-injector reproducibility was expected to be much better in the production-intent unit because it was designed to be mass-produced rather than as a hand-built prototype. We anticipated that this would necessitate no “software tuning” of the individual injectors, and that the temperature sensitivity of the injectors would be reduced as a result of changes in material selection.

2. All of the commercial applications for the IMPCO injector would be developed with vehicle original equipment manufacturers (OEMs), which would then be responsible for developing a fully optimized engine calibration. Because we achieved ULEV emission levels without a fully optimized calibration, we fully expect much better emissions performance when we work directly with the OEM.

3. The injector size would be fully optimized for each application so that driveability, especially idle stability, would be improved.

4. Optimized algorithms to ensure minimum catalyst "light-off" times and maximum catalyst conversion efficiency would be used with any OEM calibration. We expected this to improve emissions performance.

When the first subcontract was complete, a follow-up contract was placed to test the system for performance in cold weather. The ULEV was driven to Alaska during the winter for cold weather testing. The ULEV demonstrated very good starting and drive-away characteristics at temperatures as low as -15°C without any auxiliary heating or starting assistance. However, when temperatures dropped below -15°C, the fuel management system failed. We identified the prototype LPG fuel vaporizer/regulator as the cause of the failure. This was obviously the weak link in the system. After applying auxiliary heat to the regulator, the system recovered and continued to perform as designed.

We added a block heater and performed additional tests at temperatures below -15°C. This system continued to perform as designed without any further degradation in performance. At the end of the first subcontract, we noted that one of the prototype injectors had become unstable, displaying an inability to close completely. Ultimately, we identified this as a major contributor to the ULEV's idle instability and mild surging at light throttle operation. Overall driveability continued to be very acceptable to all project participants.

3.0 Vehicle Preparation and Testing

In the rest of this report, we will discuss the activities and results associated with the final subcontract.

3.1 Injection System Upgrade

3.1.1 Injector Installation

We ordered a new set of production-intent Mark IV gaseous LPG injectors, which arrived at our facility at the end of the first week in January. We reviewed the data received (Table A) with the seven injectors to determine the best match of three injectors for each bank of the V6 engine. The ULEV's LPG fuel management system software algorithm corrects for minor differences of flow for each injector individually at low RPM. However, this is not possible at medium and high RPM because of the limited central processing unit (CPU) time available to address the slow signal response time needed by the HEGO sensor to differentiate individual cylinder air-fuel ratios. Software corrections for air-fuel ratio control of each bank of three injectors collectively at medium and high RPM is possible; therefore, each of the three injectors in a bank must have closely matching flow characteristics at these higher speeds. Also, the calibration data received with the injectors was based on air as the flow medium, meaning that the injectors had to be recalibrated for use with propane vapor.

We cleaned the ULEV and stripped it of the extraneous sensors and cables used during its development and cold testing. We removed the engine's intake manifold, fuel rail, fuel lines, and other items hampering the injector removal process, taking proper care not to damage or contaminate any of the engine components. Next, we removed the injectors, and plugged the intake ports and the injector ports with cloth to prevent foreign matter from falling into the ports. Then we procured all the basic items for the installation of the new injector set, such as gaskets, sealant, hose clamps, and wire ties.

We installed the new set of injectors into their respective ports in the order determined by the accompanying data (Table A). Then we reinstalled the fuel rail, attaching fuel lines, engine intake manifold, and other related items, and inspected all components of the system carefully to verify that all were properly connected. All electrical wires and connections in the immediate area were also visually inspected for chafing, fraying, or any other apparent damage. At this time, we applied battery power to the ULEV's electrical system, leaving the ignition key in the "Off" position. After verifying that all subsystems appeared to be electrically functional and normal, we slowly allowed the LPG pressure to increase from 0 to a full tank pressure of approximately 200 psi. We observed no leaks, so we turned the ignition key to "On," but not to the cranking position. This allowed the main fuel solenoid to activate, letting pressurized LPG flow through the system and ultimately to the injectors. After waiting a minute, we used a methane fuel sensing meter and detected no fuel leaks. The system was then shut down so that the systems software engineer could review the injector calibration data and the required testing of the ULEV's fuel management system for basic operation.

Table A. Mark IV Injector Baseline Flow Data

Injector ID	#1	#2	#3	#4	#5	#6	#7
PW (msec)							
3.5	0.2201	0.1536	0.2032	0.2079	0.1698	0.1736	0.1757
5	0.3112	0.2590	0.2896	0.2838	0.2605	0.2663	0.2816
10	0.6489	0.6141	0.6691	0.6110	0.6167	0.6509	0.6543
17	1.1377	1.1555	1.1732	1.0873	1.1022	1.1469	1.2101

Note: Air Flow (g/s), 70°F, @ 18 psig, Cycles 50 Hz

3.1.2 System Test for Basic Operation

Using a portable PC, we installed generic operating calibration software into the ULEV's fuel management system software. This enabled the ULEV's engine to be run using the new uncharacterized injectors at low RPM. It took less than 5 seconds to start the ULEV's engine. The engine continued to operate at idle while we inspected the system components. The inspection was a precaution to check for any possible fuel leaks as a result of increased operating temperatures or vibration on the system components during previous running of the ULEV's engine. We used the Datalogger for real-time monitoring at this time to verify proper communication with the ULEV fuel management system's electronic control unit (ECU) and to verify the ability to monitor real-time system sensory data. After we inspected everything and the checked the various test equipment or proper operation, we shut the system down.

3.1.3 System Calibration for Driveability

To calibrate the new injectors, we began by reviewing the flow data to determine what additional injector flow testing would be needed to generate the required calibration data and flow tables. We made some minor software changes to the old injector calibration algorithm, which allowed us to use the new, more efficient, user friendly “Gas VI” software. This enhanced the calibration and data gathering process of the injectors and reduced the anticipated length of time required for their proper integration into the ULEV’s fuel management system.

During early February, we began work on the characterization of key dynamic electrical parameters of the Mark IV injector. Here are the primary electrical parameters required to be characterized before actual fuel flow characterization testing of the injector could be performed:

- “Peak high,” the initial time of power being applied to the injector until the pintle of the injector is fully pulled open to allow fuel to flow.

- “Peak low,” the time period where power is removed from the injector. This allows the energy to dissipate down to a holding level (as determined by the pulse width hold parameter) where the pintle of the injector is continued to be held completely open so that fuel can continue to flow.

- “Pulse width hold,” the on time of the duty cycle of the holding frequency, which enables the injector pintle to continue to be held completely open so that fuel can continue to flow.

During the initial testing for the peak high parameter of the injectors, we received information on the latest durability testing of the Mark IV injector. The injector's life expectancy for repeatable accuracy was downgraded to an approximate 15,000 miles of over-the-road operation. The bearing material used in the Mark IV design was exhibiting a high amount of wear resulting from dynamic friction at elevated temperatures, typically seen in underhood operation over extended driving periods. This was not acceptable for ULEV operation. We then confirmed the availability of the next generation production injector, Mark V, being produced by AMBAC corporation. This unit was designed to reduce production costs and improve the durability of the Mark IV design. The Mark V design was being fabricated for production with a scheduled delivery of the first production intent Mark V injectors to IMPCO engineering for review in late February.

On March 6, we received the new Mark V injectors. A preliminary review of the flow data supplied with them (Table B) revealed acceptable accuracy. However, they required electrical dynamic characterization, flow dynamics characterization, and dynamic flow matching in sets of three to make them usable for ULEV operation, similar to what was done with the Mark IV injectors.

Table B. Mark V Injector Flow (g/sec)

Injector ID	31	32	33	37	44	41	45
PW (msec)							
2	0.211	0.211	0.219	0.204	0.234	0.227	0.234
3	0.340	0.340	0.347	0.302	0.347	0.347	0.385
5	0.642	0.612	0.649	0.589	0.634	0.657	0.627
7	0.997	0.997	1.004	0.921	1.027	1.042	0..966
9	1.465	1.412	1.472	1.336	1.412	1.472	1.450

Initial testing of the injectors for impedance showed that all seven injectors measured 1.36 +/- .01 ohms in resistance (Table C). Testing for inductance showed that all seven injectors measured 2.98 +/- .05 millihenrys (Table D). We were encouraged by these results, which demonstrated that the manufacturing process of controlling fabrication and assembly of the injector coil was very consistent. Next, we characterized the primary dynamic electrical parameters. This step, completed prior to actual fuel flow characterization testing of the injector, enabled the software creation of the proper electrical drive signal to the injector preventing inadvertent overpowering of the injector during testing and possible permanent damage. While testing for these parameters, the injector was configured for operation having the same electrical interface and hookup as that used in the test vehicle. Also, a standard pressure of 18 PSI of air was used as the simulated fuel pressure source. The injectors were tested for Peak High, Peak Low, and Peak Width dynamic electrical parameters, as was done for the Mark IV injectors.

Table C. Mark V Injector Resistance

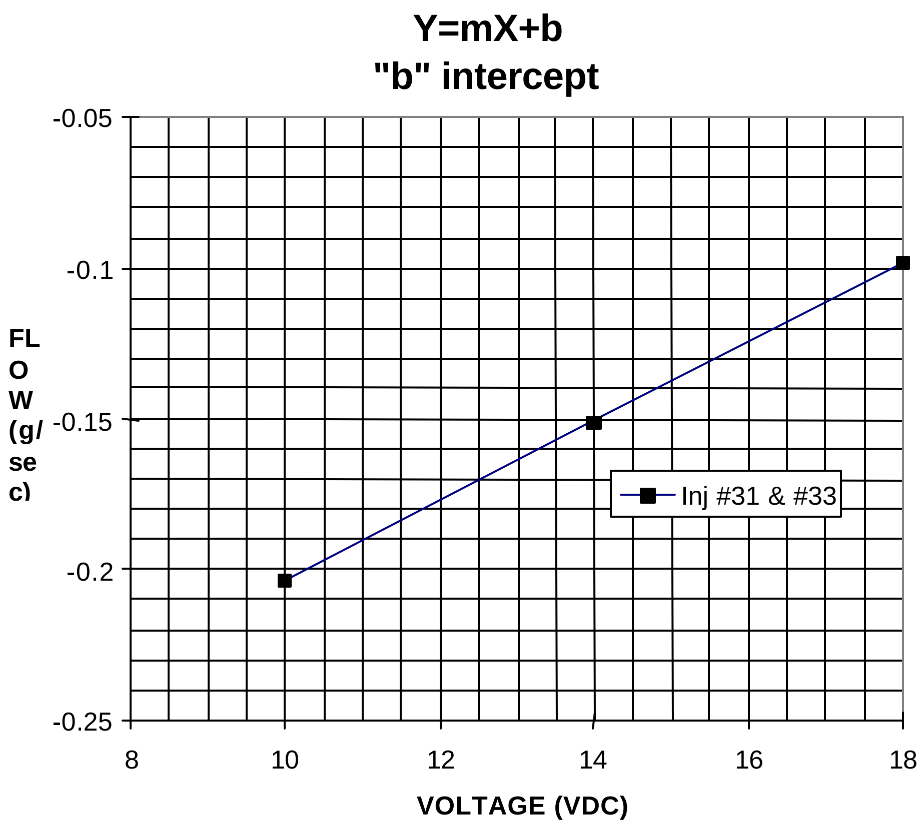
Injector ID	31	32	33	37	41	44	45
Resistance (ohms)	1.36	1.35	1.36	1.37	1.36	1.35	1.37

Table D. Mark V Injector Inductance

Injector ID	31	32	33	37	41	44	45
Inductance (milliHenrys)	2.93	2.97	2.96	3.04	3.01	3.02	2.97

All three of these parameters were characterized for battery voltages from 8 volts dc to 18 volts dc. Although all three parameters affect the flow through the injector, peak high time is the one parameter that has a major linear effect on injector flow time versus battery voltage. Unlike peak high, the peak low time has no linear effect on injector flow time, and pulse width hold duty cycle time has a very minor linear effect on the overall flow time of the injector. Accordingly, we integrated a specific software reference table for peak high time versus battery voltage into the system software to compensate for variations in injector pintle pull-in time caused by battery voltage variations.

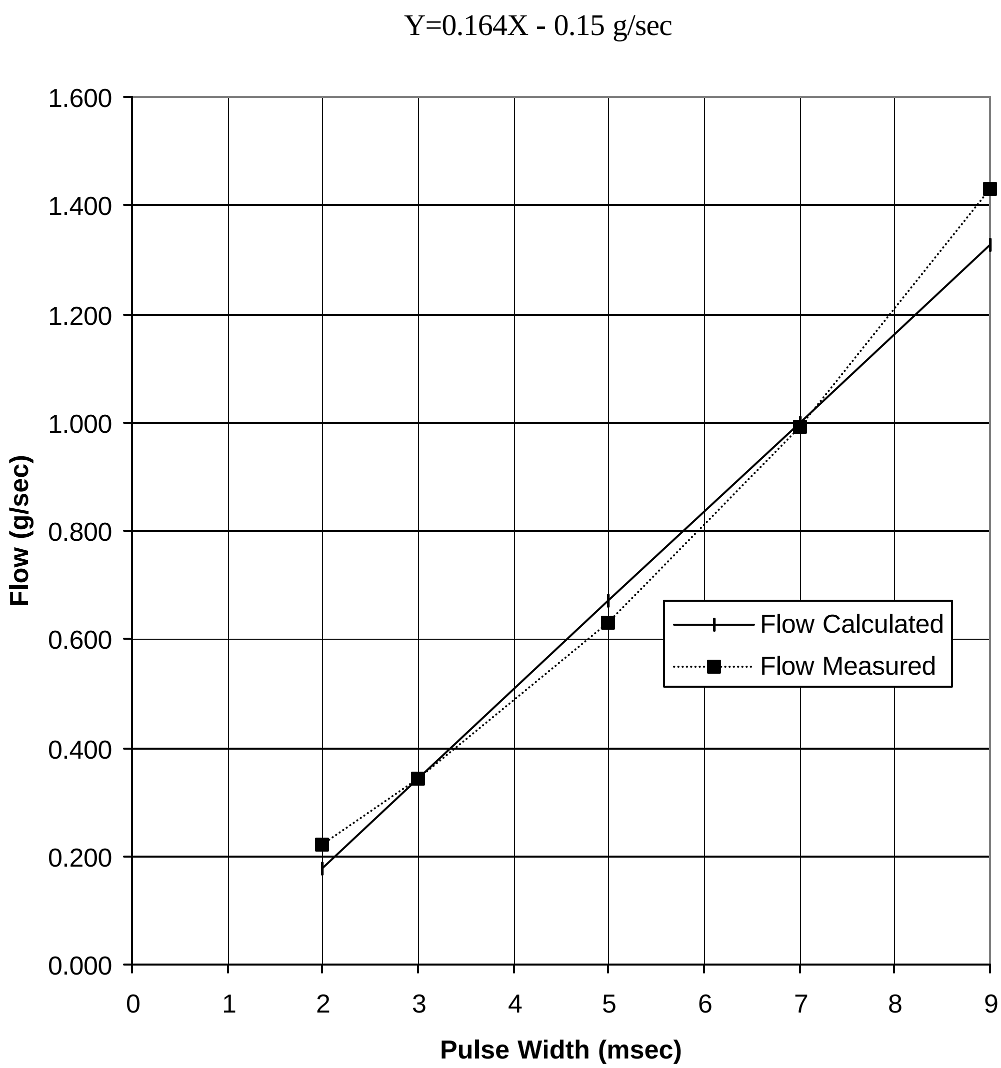
After we finished the electrical dynamics characterization, we started the flow dynamics characterization. Each injector was again mounted on the injector flow bench and subjected to an air pressure of 18 psi, similar to that used during actual operation in the test vehicle. The



Graph 1. Injector flow versus battery voltage

injector-driver electronics were again identical of those used in the test vehicle. We varied the duty cycle to the injector from 0 to 9 milliseconds, while maintaining the period of the test frequency to the injector of 10 milliseconds. The supply voltage of 13.5 VDC was held constant while data was recorded for flow rates ranging from 0 to 1.5 gm/sec. We measured the airflow with a very accurate mass flow meter made by Micro Motion Corporation. We also recorded flows through the injectors while we varied the battery voltage from 8 to 18 volts dc (Graph 1) to determine battery voltage effects (intercept “b”).

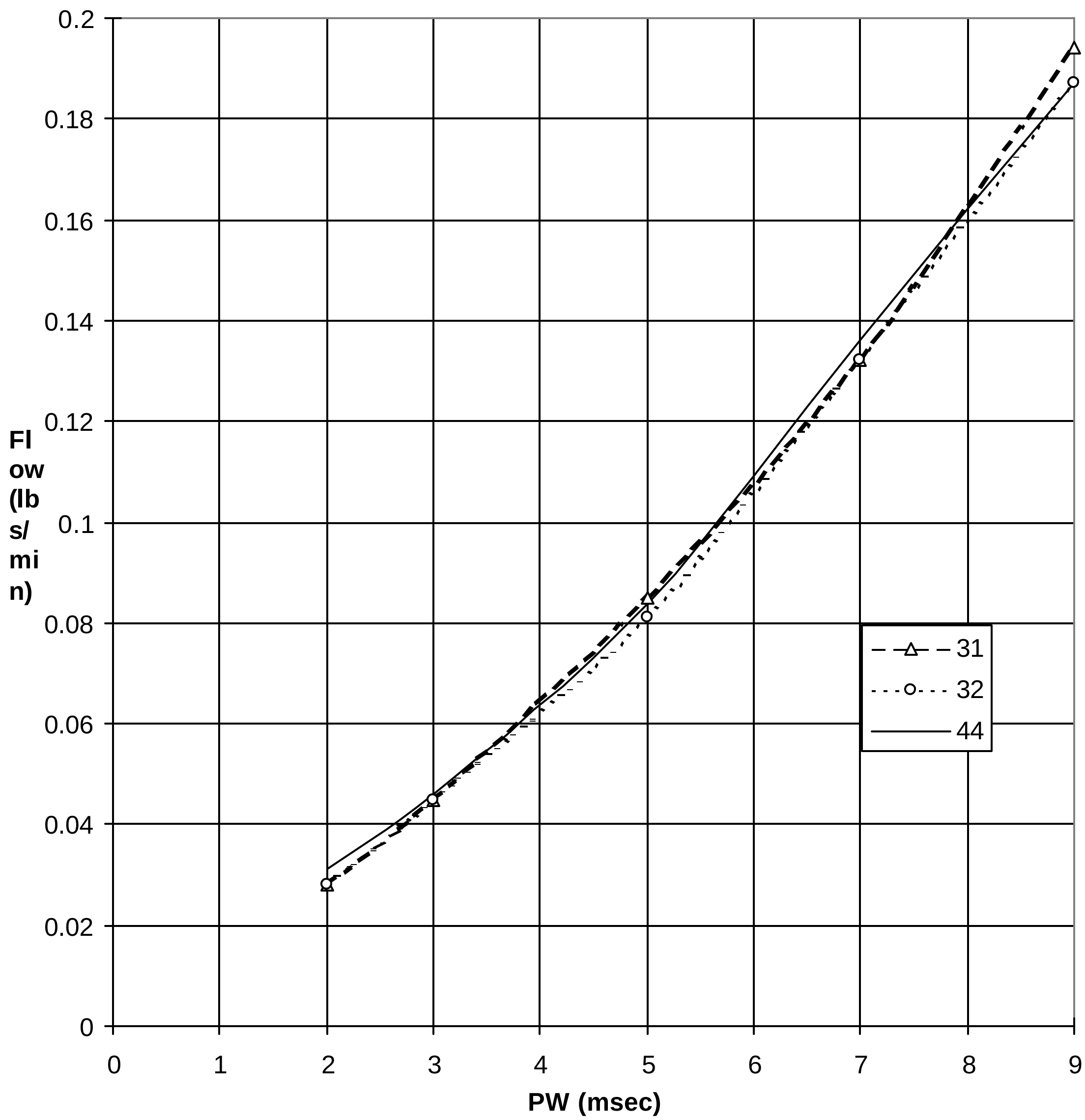
After gathering the data, we reviewed and analyzed the information to determine the mathematical equivalent of the injector flow characteristics so that the information could be modified for use in the ULEV’s fuel management system software algorithm. The flow through the injector versus the pulse width to which the injector was subjected was characterized by using the equation for a straight line, y=mx+b. The intercept, b in the equation, is the key parameter that is most affected by battery voltage variations and short injector on-times. The resulting mathematical formula that best quantifies the dynamic flow characteristics (Graph 2) of the new Mark V injector is Y=0.164 X - 0.15 (gm/sec), where Y is the mass of air flowing through the injector, and **X** is the time period in milliseconds of the pulse width driving the injector. This formula was transposed into “C” computer language and converted for use in the ULEV’s fuel management system software code. We set the new injector flow characterization



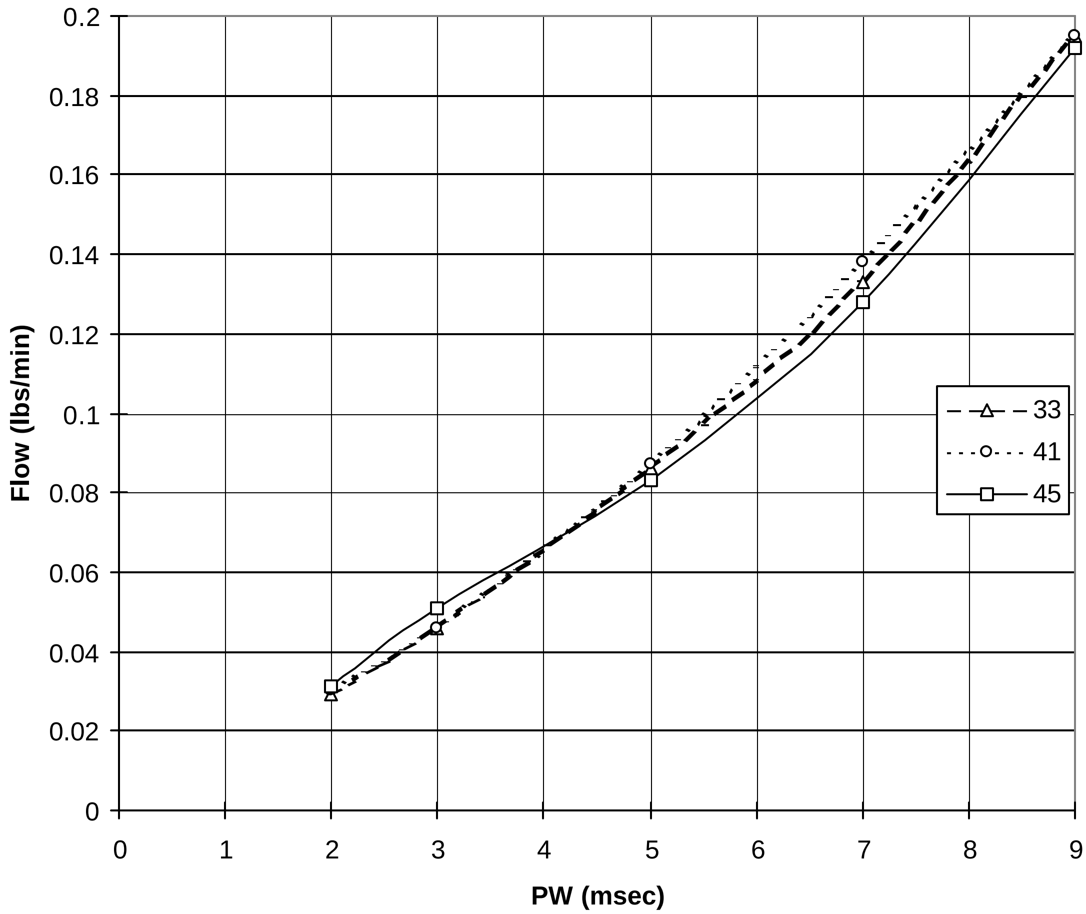
Graph 2. Injector flow versus pulse width

algorithm as the baseline for the new air-fuel ratio tables used in the ULEV's fuel management system software and resulting ULEV emissions calibration.

The ULEV's engine was then stripped of the Mark IV injectors and prepared for the installation of the new Mark V injectors. Prior to the installation of the new injectors, the flow data for each of the new Mark V injectors were compared for matching injector flow characteristics. The injectors were labeled and installed in sets of three (Graphs 3 and 4), one set for each bank of the V6 engine. While the Mark V injectors were being installed, the ULEV's fuel management system software was updated using the new database algorithm generated from the previous tests. The ULEV was then checked for any fuel pressure leaks and mechanical soundness. The engine was started and run for less than a minute as a quick check for proper functioning. Monitoring of the engine compartment and the engine's idling stability were done visually by the driver and the accompanying test engineer. The Datalogger Interface computer was also used to review in real time the system sensor data reflecting the operation of the engine. When all was



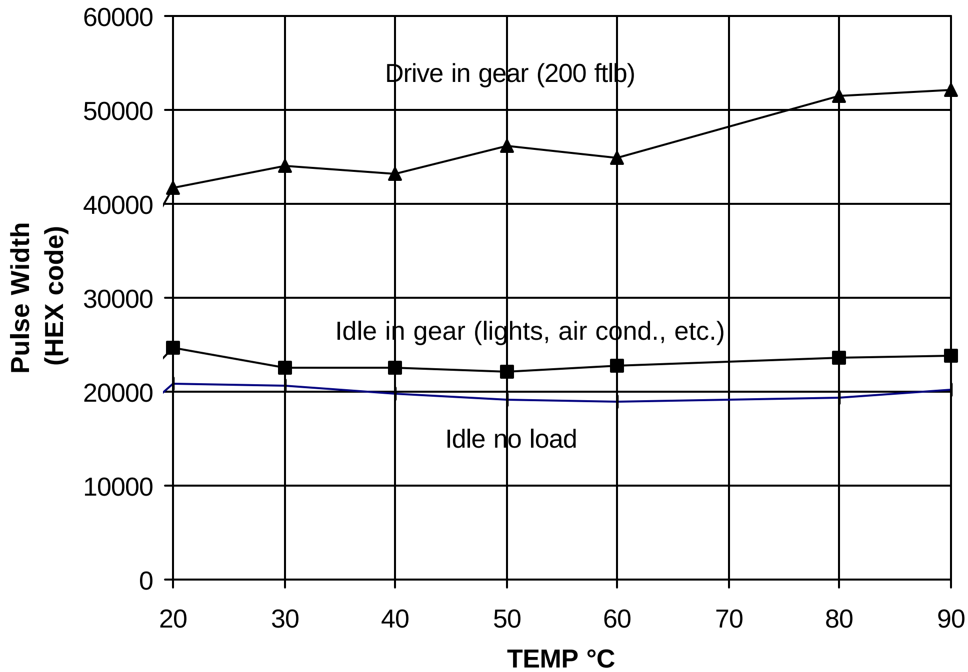
Graph 3. Mark V injector flow curve for Bank 0



Graph 4. Mark V injector flow curve for Bank 1

determined to be functioning normally, the ULEV was shut down in preparation for injector temperature calibration compensation versus fuel flow testing the following week.

During the first week of April, testing of injector temperature calibration compensation versus fuel flow was performed. During this sequence of tests, the body of the injector was monitored for temperatures ranging from 25°C to 90°C. As the engine was warmed up to a normal operating engine temperature of 95°C, recording of the apparent injector pulse widths were performed. This was done at three levels of torque loading applied to the engine; "Idle" out of gear, "Idle" in gear, and "Drive". This was done while maintaining a constant load to the rear wheels of near 100 ft lbs of torque. It was apparent in the analysis of the recorded data (see Graph 5) that the present base line temperature compensation would be adequate. During the testing sequence for heavy torque loading of the engine, it was noted the fuel pressure of the fuel rail was degrading below 10 PSI where 18 PSI was expected. Although the system was performing smoothly at light and medium loads, it was apparent that a fuel restriction in the fuel



Graph 5. Injector flow versus temperature

delivery system was being experienced. The system was shut down at this time for additional instrumenting to enable conclusive diagnostics to be performed.

Further testing determined that the prototype fuel regulator/vaporizer was no longer providing proper regulation of vaporized LPG fuel at 18 psi. We found the problem: a loose retaining screw from the vaporizer coils of the fuel regulator (Figure 3). The vaporizer, used during the ULEV's cold testing phase and no longer needed, was removed, returning the regulator to normal operation. Shortly thereafter, we ran the ULEV on the chassis dynamometer for several hours at various loads and speeds to allow software calibration adjustments while monitoring real time system software data for any abnormalities.

3.2 Emissions Testing

The vehicle was calibrated on a chassis dynamometer for dynamic operation while simulating FTP parameters and measuring emission levels. After completing the calibration on the chassis dynamometer, we performed a series of FTPs to verify compliance with ULEV standards.

3.2.1 System Calibration for ULEV Emissions

Before the systems software engineer arrived, we ran the ULEV through several simulated FTPs to ensure that the Heuristic software had adequately updated the air-fuel ratio tables for the best emissions performance. When the engineer arrived, we ran several partial FTPs and recorded emissions data to establish a preliminary emissions baseline for the ULEV. After reviewing the recorded data it was noted that HC was very low and NO_x was high. In comparing the real time air-fuel ratio for each bank that the system was maintaining and the EGO feedback biasing that was being used, it was decided that the air-fuel ratio ramp excursion rate used by the fuel management software required a faster rate of change on the rich side of stoichiometry. This would theoretically result in the fuel management system software closed loop algorithm to maintain a slightly richer mixture as the algorithm continues to cycle the air-fuel ratio constantly from rich to lean and back to rich at an approximate rate of 4 times a second. After making the software adjustments to increase the excursion rate, an additional partial FTP (LA4) was run, resulting in the very high NO_x and HC emissions. The software ramp excursion rate was again adjusted and the emissions were measured. The result appeared to be adequate, and the ULEV was prepared for a full emissions FTP for the following morning.

3.2.2 Federal Test Procedure Results

We planned to run at least three FTPs. The first, on May 12, 1998, resulted in emissions of 0.091 g HC/mile, 0.654 g CO/mile, and 0.064 g NO_x /mile (Table E). The ULEV had passed the CO and NO_x ULEV emissions standard, but failed the HC ULEV emissions standard of 0.080 maximum. We adjusted the software ramp excursion rate toward the lean side and ran another unofficial FTP LA4 for verification of acceptable results. After the ULEV had run a sufficient time to give us reasonable assurance that the heuristic software had updated the air-fuel ratio tables, we ran a partial FTP while we monitored raw emissions to determine the approximate effect of the new calibration. Because the data looked encouraging, we prepared the ULEV for a complete FTP to be performed the next morning.

We tested the ULEV again on the morning of May 13, 1998, and it achieved ULEV compliance with the following results: 0.076 g HC/mile, 0.310 g CO/mile, and 0.174 g NO_x /mile. These results were very close to those achieved on the same ULEV on March 27, 1996, during the first subcontract. This was achieved despite the possibility that other major system components may have degraded similar to the original prototype Mark IV injectors, such as the prototype three way catalyst, during the 10,000-mile durability testing in the first subcontract. Based on these results, we decided to add more spark retard to further reduce the ULEV HC emissions during the initial start of the FTP. Accordingly, an additional 3 to 5 degrees of spark retard was added, and the ULEV was again prepared to run a complete FTP. This approach is similar to that used by automotive OEMs, an approach that uses spark retard algorithms to control emissions. For example, during cold start for the first few seconds the closed couple catalyst can be activated much earlier in the running cycle by both enriching and retarding the spark to produce heat to the catalyst for early light off.

The following morning, May 14, the emission tests were run, and the ULEV failed to meet ULEV emissions standards because of slightly high HC emissions. The spark table was reset to the previous setting used on May 13 when the ULEV had met the ULEV emissions standard. We ran the final FTP on May 15, and the ULEV once again met ULEV standards with emissions of 0.075 g HC/mile, 0.265 g CO/mile, and 0.169 g NO_x /mile. These results were very close to that achieved on the same ULEV on March 27, 1996, and on May 13, 1998.

Table E. FTP Emissions Summary

	Date	HC (gm/mi)	NO_x (gm/mi)	CO (gm/mi)
1998 EPA ULEV Emission Standards		0.08 (1)	0.200	1.700
Test #1	5/12/98	0.091	0.064	0.654
Test #2	5/13/98	0.076	0.174	0.310
Test #3	5/14/98	0.106	0.190	0.260
Test #4	5/15/98	0.075	0.169	0.265
Test #2 and #4 Average		0.076	0.172	0.288

(1) ULEV standard of 0.04 gm/mi adjusted for reactivity of LPG emissions relative to gasoline. The ULEV emission standard is actually 0.04 gm/mi non-methane organic gases (NMOG). Based on earlier discussions with the California Air Resources Board and extensive data collected at IMPCO Technologies over the past several years, a correction factor of 2 was used to convert HC emissions to NMOG emissions, and to account for the lower reactivity of LPG emissions. This correction factor changes the standard to 0.08 gm/mi HC, as shown in the table.

As shown in Table E, the vehicle met the ULEV 50,000-mile standard when the calibration was set properly as was done in Tests #2 and #4. Table E presents the average emissions of these two tests.. This successfully demonstrates the feasibility of meeting ULEV 50,000-mile standards with a dedicated LPG vehicle. Actual checking of the emissions performance for deterioration by re-testing the vehicle after it accumulated 50,000 miles was beyond the scope of this project.

3.2.3 Driveability and Performance

The emissions driving technician thought that the ULEV was one of the smoothest and most responsive vehicles that he had driven on a full FTP driving cycle. He also noted that the starting of the engine was consistently in the 1-second range. The apparent superior driveability of the ULEV had been retained through the system upgrading process.

4.0 Commercialization of the IMPCO Injector

As a result of this program, IMPCO Technologies has greatly accelerated the commercialization of its injector technology. Currently, our injectors are being tested by two OEM manufacturers who have achieved very promising emission and performance results. Both of these manufacturers are continuing plans to introduce low emissions alternative fuel vehicles in the 1999–2001 time frame.

Recently, IMPCO signed an agreement with AMBAC to manufacture IMPCO LPG and natural gas injectors. AMBAC has extensive experience in manufacturing precision mechanical systems, including diesel injectors. As part of this work, we conducted a detailed design review and modified the injector design to improve durability and reduce manufacturing costs. As we observed in the project, the Mark III injector design exhibited some premature wear characteristics that degraded the emissions performance. The newer Mark V has replaced the Mark III and continues to be reviewed for further manufacturing and durability design improvements. AMBAC is in the process of producing production-intent units of the latest Mark V design in quantity. They are now available for engineering testing and evaluation and are scheduled for limited customer evaluation by the latter part of 1998.

IMPCO is also pursuing the development of a heavy-duty (HD) version of its injector technology for lean burn engines. This is in response to several OEM customers who are developing low emission alternative fuel HD engines. Prototype units have been produced and are now being tested for performance and durability.

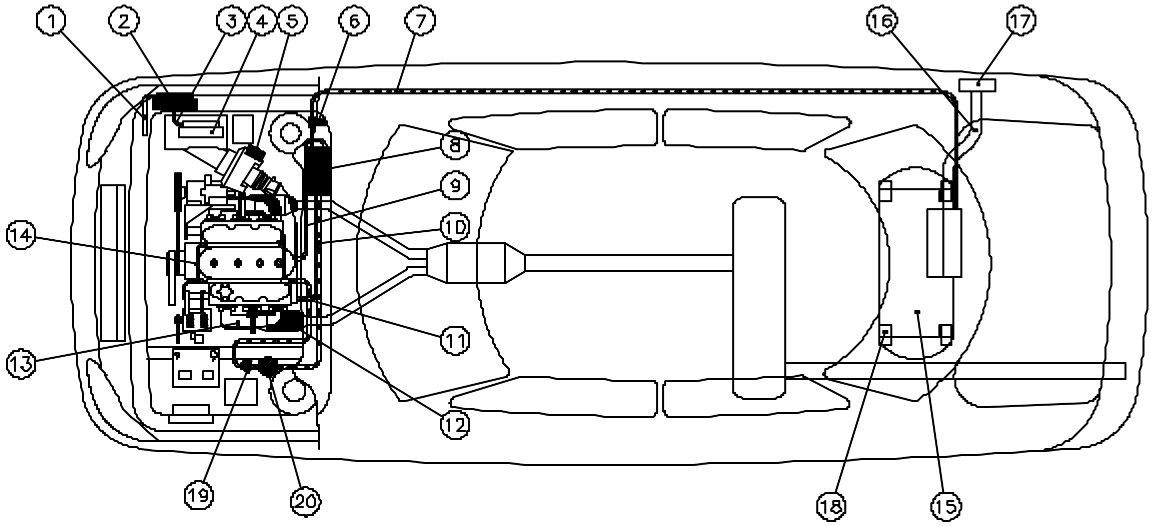
5.0 Summary

During January of 1998 we started to upgrade the ULEV's system to replace the worn out prototype Mark III injectors with the improved Mark IV injectors. During the lengthy process of testing and calibrating the new set of injectors, durability testing of the Mark IV injectors revealed that their life expectancy was estimated to be approximately 15,000 miles of over-the-road equivalent miles of operation because of internal bearing wear of the injector. Although this was an improvement over the Mark III injector, it was still not acceptable for ULEV operation. Accordingly, we ordered the new Mark V injectors with improved durability attributes, originally scheduled for engineering use at the end of February, to replace the Mark IV injectors. On receipt, we characterized them for electrical and flow characteristics. Once they were installed into the ULEV, we performed driveability calibrations and limited steady state emissions calibrations.

During driveability calibration, the ULEV experienced a system failure caused by the prototype fuel vaporizer/regulator no longer providing adequate fuel at medium to high load operation. The prototype fuel vaporizer/regulator was repaired and reinstalled, and the system once again performed to design. The ULEV was then shipped to the IMPCO emissions testing facility in Cerritos, California, where it was subjected to several emissions FTPs for its calibration and to verifiy compliance with the 1998 EPA ULEV emissions standards. Accordingly, on May 12 through May 15, 1998, we performed emissions testing on the ULEV. The data showed that the ULEV was in compliance with the California ULEV emissions standards. This successfully demonstrates the feasibility of meeting ULEV 50,000-mile standards with a dedicated LPG vehicle. Actual checking of the emissions performance for deterioration by re-testing the vehicle after it accumulated 50,000 miles was beyond the scope of this project.

The driveability also improved. The apparent surging and idle instability previously experienced with the Mark III injectors was gone—a direct result of using the Mark V injectors and new software calibration. We are encouraged by the performance of the system to date and are proceeding to commercialize the gaseous LPG injectors with AMBAC Corporation. AMBAC has extensive experience in manufacturing precision mechanical systems including diesel injectors. The ECU design (IMPX) that was developed and used in the fuel management system, was also reviewed for design modifications and improvements. As a result of those findings, they are now being applied to its next generation. The commercialization of the next generation 32-bit ECU for use on future gaseous fuel applications of light- and heavy-duty vehicles, is targeted for late 1998.

Figure 1. Dedicated LPG ULEV component layout



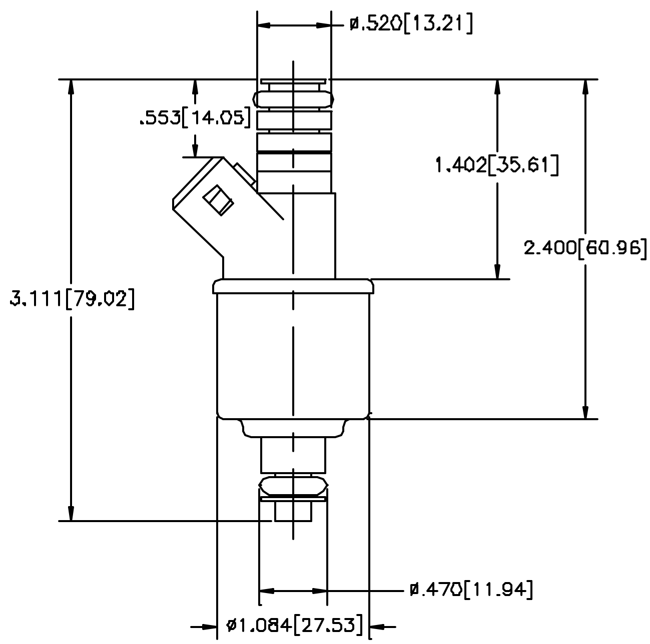


Figure 2. Mark V gaseous LPG injector (note: dimensions are in inches [mm])

Specifications

Maximum Voltage	24 VDC
Maximum Current	4 amps peak, 1 amp continuous
Operating Voltage Range	6 to 24 VDC
Impedance	1.4 ohms typical
Response time	2.2 ms open, .75 ms close at 14.0 VDC
Operating Life	200 million cycles
Maximum Pressure	100 psig
Maximum Leakage	0.2cc/min at 60 psig, 70°C
Suggested Operating Pressure	18 psig (PG), 60 psig (NG)
Dynamic Flow 2.0 g/s	(18 psig)
Operating Temperature	-40 °C to +105 °C
Shock	30 g
Vibration	20 g
Flow Repeatability	Dynamic 2.0%, Static 1.5%

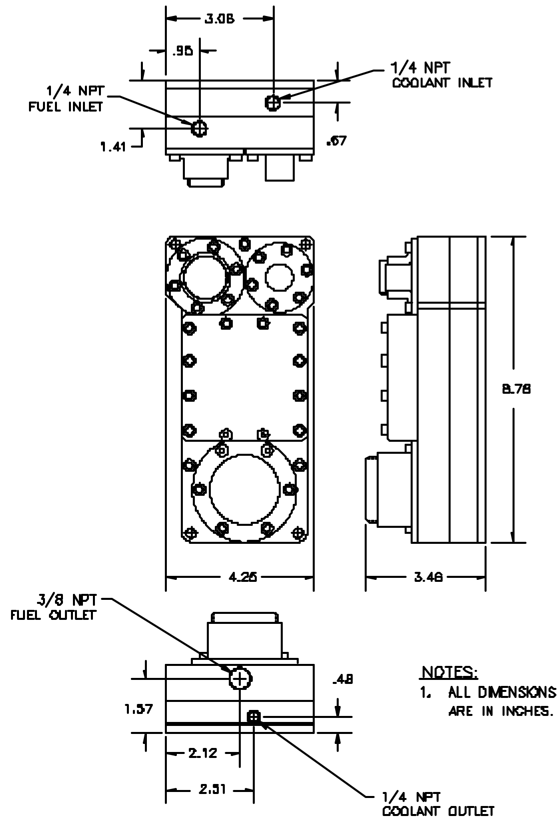


Figure 3. Prototype LPG fuel vaporizer/regulator

Specifications

Dynamic Flow Range	0 to 150 lbs/hour
Outlet Pressure	18 psig
Outlet Pressure Drop	Less than 1%
Flow Pressure Drop	Less than 2%
Cracking Pressure Drop	Less than 5%
Operating Temperature Range	-20°C to +150 °C
Maximum Inlet Pressure	250 psig
Minimum Inlet Pressure	25 psig
Maximum Vibration	10 g
Maximum Shock	20 g
Maintenance	None

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13. ABSTRACT *(Maximum 200 words)* This report describes the last in a series of three projects designed to develop a commercially competitive LPG light-duty passenger car that meets California ULEV standards and corporate average fuel economy (CAFE) energy efficiency guidelines for such a vehicle. In this project, IMPCO upgraded the vehicle's LPG vapor fuel injection system and performed emissions testing. The vehicle met the 1998 ULEV standards successfully, demonstrating the feasibility of meeting ULEV standards with a dedicated LPG vehicle.

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