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New Technology Research & Development Program
Grant Contract 582-5-70807-0004

Task 1 Deliverable Report

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22 August 2006

Task 1 Report:

MODIFY HEAVY DUTY VEHICLES WITH BAYTECH MPFI LPG SYSTEM

Prepared for:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

NTRD Grant 582-5-70807-0004

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1.0 PROJECT OBJECTIVES

The objective of this project is to develop, emissions test, and emissions certify with EPA and CARB a low NOx LPG and Low NOx CNG fueling system for GM heavy duty 8.1L and 6.0L engines. The technology is based upon Baytech's Compressed Natural Gas (CNG) sequential Multi-Port Fuel Injection (MPFI) system, which will be modified to operate on LPG. Emissions testing will be conducted on both fuels. The NOx emission goal for both engines is 0.1 g/bhp-hr.

The project consists of four tasks:

Task 1: Modify Heavy Duty Vehicles with Baytech MPFI LPG System

Task 2: EPA and CARB Certification Applications

Task 3: Perform Heavy Duty Engine Emission Testing

Task 4: Program Management and Reporting

This task report documents the work performed on Task 1 of the project.

2.0 MODIFY HEAVY DUTY VEHICLES WITH BAYTECH MPFI LPG SYSTEM

2.1 Modify MPFI System for LPG Operation

The baseline technology for this project is Baytech's sequential Multi-Port Fuel Injection system for gaseous fules. The system was originally developed by Baytech for Compressed Natural Gas (CNG), and was modified in this project task to operate on propane. Hardware components were specified and selected to meet the operating requirements. Key hardware modifications were:

- Higher flow gaseous fuel injector for propane. The MPFI system requires one injector per cylinder, or eight injectors total for both the 6.0 and 8.1L engines.
- Modified fuel injector block to accommodate the dimensions of the propane injectors.
- Propane vaporizer that vaporizes the liquid propane fuel and maintains a very stable output pressure. (The CNG system utilizes a gas pressure regulator.)
- Addition of a cooling fan to Baytech's injector driver module to mitigate the additional heat generated by driving the larger propane injectors.
- Liquid propane filter and a vapor propane filter (with a custom designed filter element housing) to reduce fuel contaminants that can effect system performance. (The CNG system utilizes a coalescing filter to eliminate any oil in the CNG.)

Baytech's propane engine control calibration software is implemented in the GM Powertrain Control Module (PCM). Baytech modified the engine control calibration software originally developed for CNG to optimize engine performance with propane fuel. Initial engine calibrations were developed for the 8.1L and 6.0L propane engines using strategies similar to Baytech's CNG system.

The system is a closed loop control system, maintaining stoichiometric air/fuel ratio via feedback from oxygen sensors in the exhaust system. Parameters modified included spark advance, air/fuel ratio control, idle speed, crank fuel, deceleration fuel, acceleration fuel, and diagnostics. The initial propane engine calibration software developed for each engine was modified during performance evaluations described in Section 2.3.

A block diagram of Baytech's propane sequential MPFI system is shown in Figure 1.

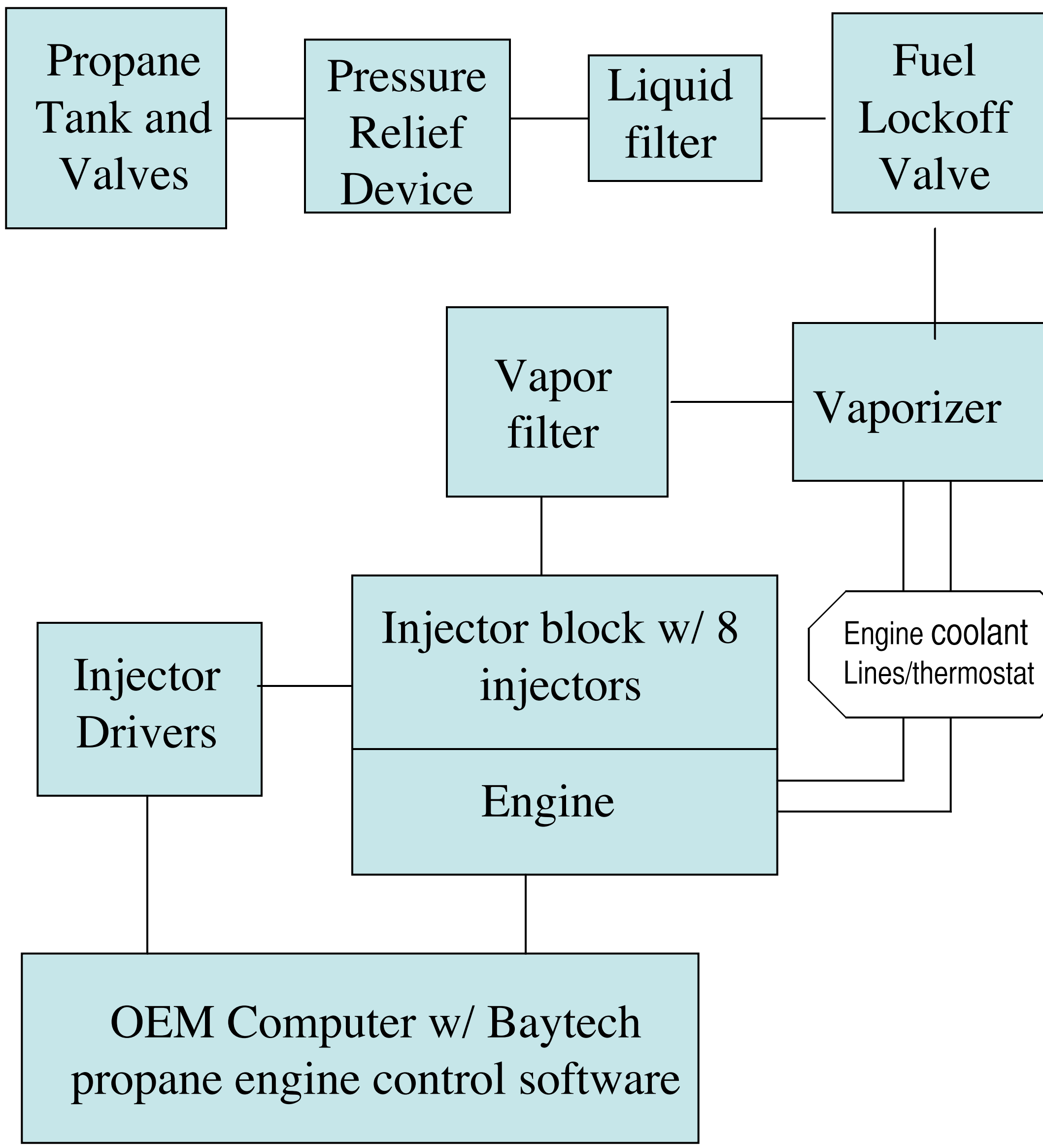


Figure 1 Baytech Propane System Block Diagram

2.2 Install LPG MPFI system on Development Vehicles

2.2.1 8.1L Development Vehicle

Baytech's GMC C4500 8.1L development vehicle, shown in Figure 2, was utilized to develop the 8.1L heavy duty propane engine MPFI system. Baytech installed the prototype propane MPFI system, and an 80 gallon propane tank on the flatbed. The vehicle was already equipped with CNG tanks. The propane tank is mounted behind the CNG tanks, which are covered.

Figure 2 8.0L Development Vehicle

The engine intake manifold cover was removed from the engine, and intake ports were drilled and tapped to insert the tubes that deliver the gaseous fuel to each cylinder port from the respective injector in the injector block assembly. A closeup picture of one intake port is shown in Figure 3.

Figure 4, taken from inside the vehicle with the engine cover removed, shows the injector block mounted on top of the engine manifold. The vapor filter is mounted to the front (vapor input side) of the injector block,, with the vapor hose from the vaporizer leading to the vapor filter. The injector driver wire harness is located to the left of the injector block.

Figure 5, also taken from inside the vehicle with the engine cover removed, shows the vaporizer mounted on the lower right hand side of the engine. The picture also shows the vapor outlet hose from the vaporizer to the injector block, and the engine coolant lines from the engine to the vaporizer with in-line thermostat.

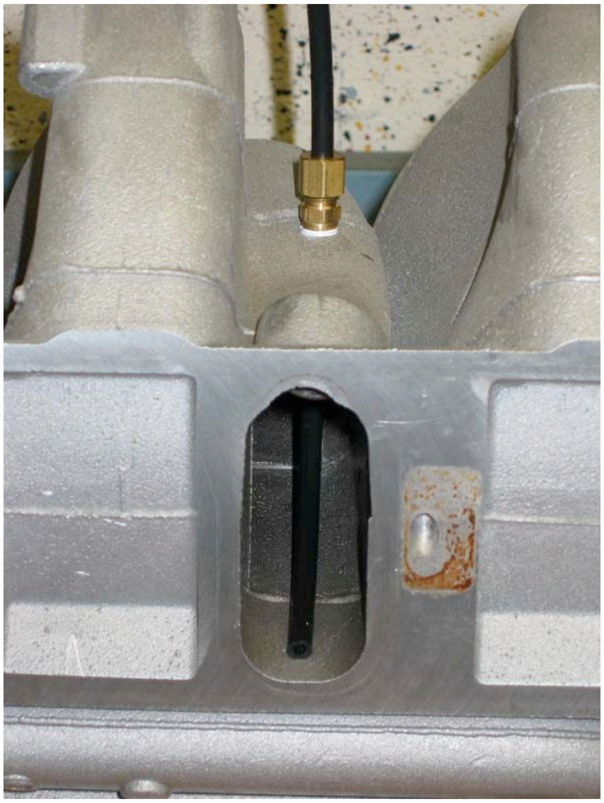


Figure 3 Fuel Delivery to Intake Port

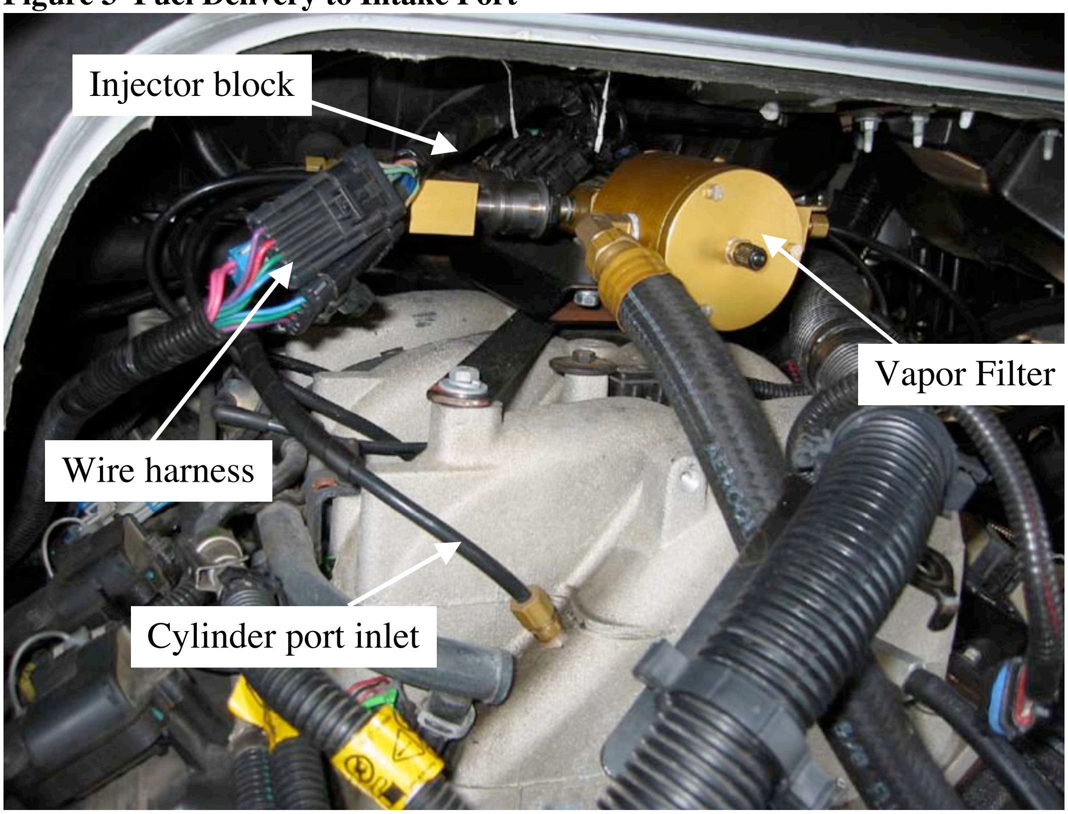


Figure 4 -- 8.1L Injector Block

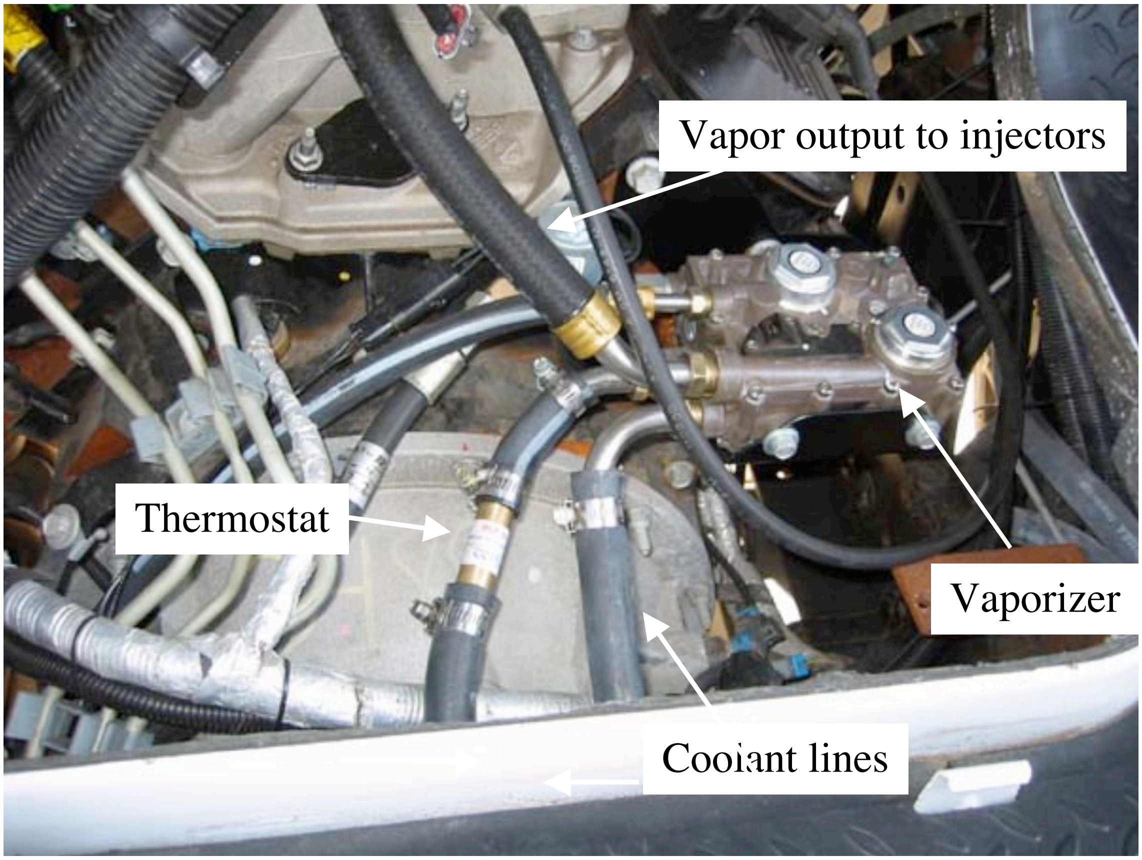


Figure 5 -- 8.1L Vaporizer

2.2.2 6.0L Development Vehicle

For development of the 6.0L heavy duty propane engine MPFI system, Baytech utilized a Chevrolet Silverado C2500HD pickup truck, shown in Figure 6. A 60 gallon propane tank was mounted in the truck bed against the cab, shown in Figure 7.

Figure 6 6.0L Development Vehicle

Figure 7 60 Gallon Propane Tank Mounted in 6.0L Vehicle Pick-Up Bed

The same hardware component configuration is used in the 6.0L vehicle as is used in the 8.1L vehicle, except for the fuel injectors. Modifications were made to the propane fuel injectors to meet the idle and full throttle fuel requirements of the 6.0L engine. Figure 8 shows the injector block mounted on top of the 6.0L engine manifold, and the tubes going from each injector to a cylinder port. The engine manifold was drilled and tapped for each fuel tube from the injectors as it was for the 8.1L engine.

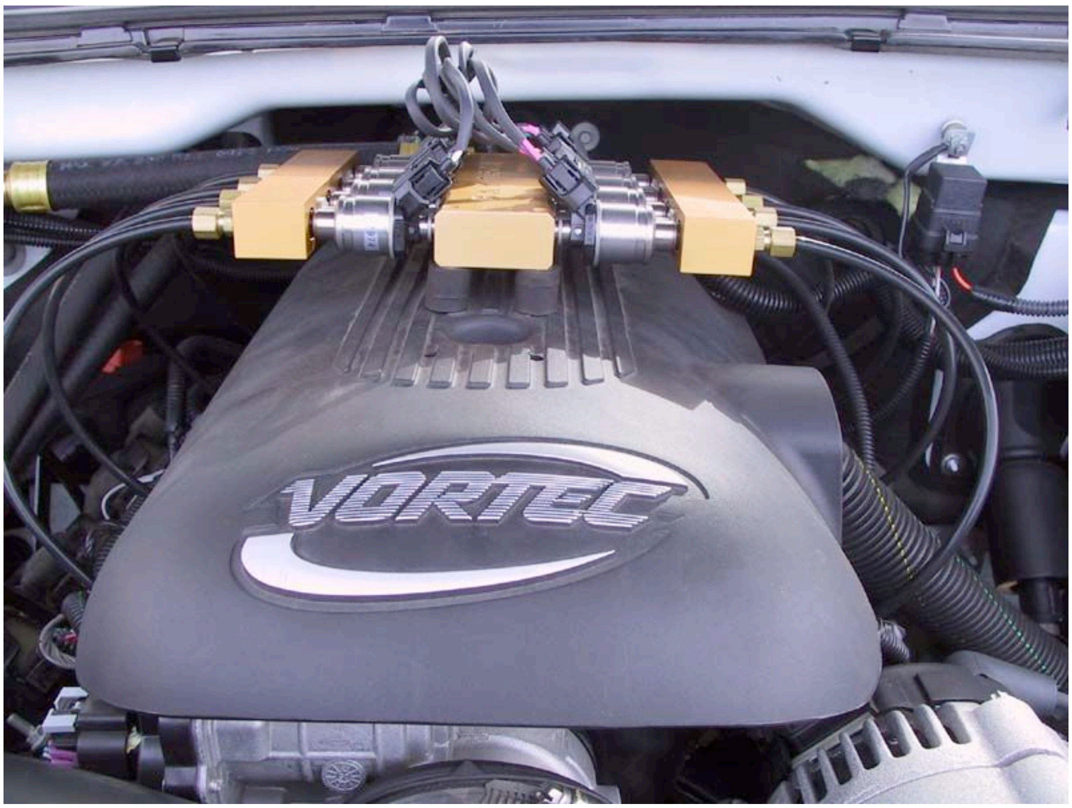


Figure 8 Propane Fuel Injector Block Mounted on 6.0L Engine

Figure 9 shows the vaporizer and vapor filter mounted on the back left hand side of the engine compartment. Unlike the 8.1L configuration, the vapor filter is not mounted directly on the injector block. Also visible in the picture is the lock-off valve, which is closed when the ignition is off.

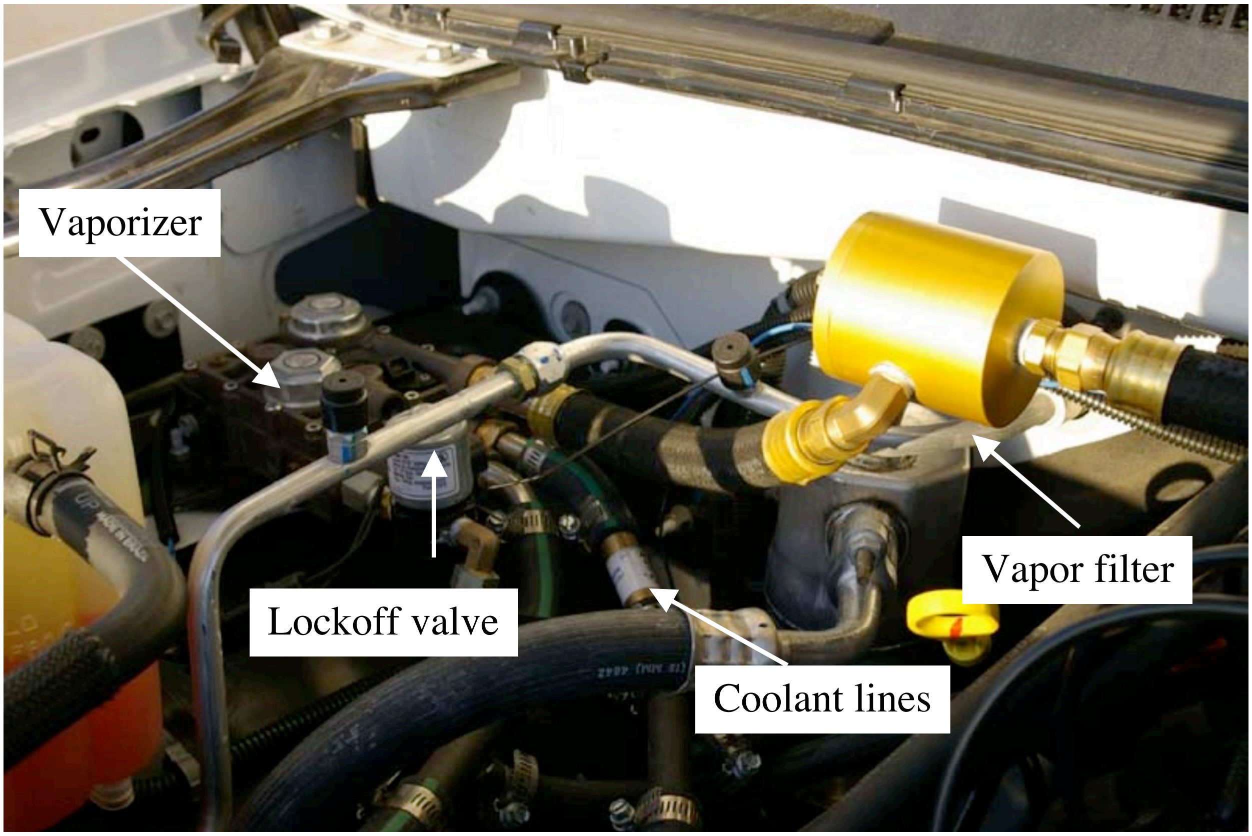


Figure 9 -- 6.0L Vaporizer

2.3 Data Collection and Performance Evaluation

Baytech conducted extensive driveability and performance evaluations of both the 8.1L GMC C4500 and 6.0L Chevrolet Silverado C2500HD propane development vehicles.. Test instrumentation was utilized to monitor engine parameters during these evaluations, and the engine calibration software was optimized for propane. This process was conducted at Baytech's California facility; 8.1L performance evaluations were also performed during the 1200 mile trip to Southwest Research Institute (SwRI) in San Antonio under a wide variety of driving conditions.

2.3.1 Instrument Development Vehicles

Baytech's engine calibration software is implemented in the OEM Powertrain Control Module (PCM). Therefore, Baytech's propane (and CNG) sequential MPFI systems are fully compatible with the OEM on-board diagnostic systems. Baytech used two engine scanning devices, connected to the diagnostic ports of each vehicle, to monitor engine performance during on-road evaluations. These devices were the GM Tech 2 scanning tool and the MasterTech scanning tool. These devices can be used to capture snapshots of engine parameters versus time during on-road evaluations under different operating conditions. Selected engine parameter time history data can be downloaded to a PC for evaluation.

Baytech also instrumented the exhaust system of the 8.1L development vehicle with thermocouples to measure exhaust temperatures upstream and downstream of the catalytic converters.

2.3.2 Performance Evaluations

Baytech conducted extensive performance and driveability evaluations of the 8.1L and 6.0L propane engines. These evaluations covered a wide range of operating conditions, including cold/hot start, cold/hot idle, cruise, acceleration, full throttle acceleration from a stop, full throttle hill climbs, and high altitude. Engine parameters were monitored during each of these operating conditions, and numerous iterative changes to the engine control calibration software were made until Baytech was satisfied with the overall performance.

The 8.1L propane MPFI system was developed first, and received the most extensive performance testing and updating of the engine calibration software. The engine calibration developed for the 8.1L engine was then used as the baseline calibration for the 6.0L engine.

Initially, Baytech implemented the same propane fuel injectors on the 6.0L propane development vehicle that were used on the 8.1L propane engine. Idle instability performance problems were encountered, which were solved by changing the propane fuel to lower flow injectors. Significant changes to the engine calibration software were required to accommodate the new injectors, as they affected engine performance throughout the engine operating range (idle through full throttle under load).

The following sections present on-road test data for the 8.1L and 6.0L propane engines under different test conditions. Engine parameters are presented in a series of charts that show the value of the particular parameter versus time for the test period. The x-axis (time) on each chart is labeled to show the driving conditions represented by segments of the chart. The key to the labels is:

A = Wide open throttle acceleration

D = Deceleration

C = Cruise

I = Idle

B = Brake Torque

PA = Partial Throttle Acceleration

O/L = Open loop fuel control

C/L = Closed loop fuel control

2.3.2.1 8.1L Propane Engine Performance Evaluation

Charts 1 through 7 represent a set of test data collected during an on-road test drive on an expressway. The data cover a 9min:35 sec test period. Charts 1 though 5 show various engine operating conditions. Charts 6 and 7 show the high frequency oxygen sensor signals during idle, accelerations, and cruise conditions The oxygen sensor signal output is a direct indication of the precision of the air-to- uel ratio control. High frequency oxygen sensor signal perturbations from low to high voltage (lean to rich) are representative of high precision fuel control about the stoichiometric air to fuel ratio. During prolonged decelerations the fuel injectors are shut off to greatly reduce exhaust emissions and increase fuel economy. The oxygen sensor indicates a lean condition (low voltage) during deceleration fuel cut-off.

Chart 1 'Vehicle Speed Sensor' mph'

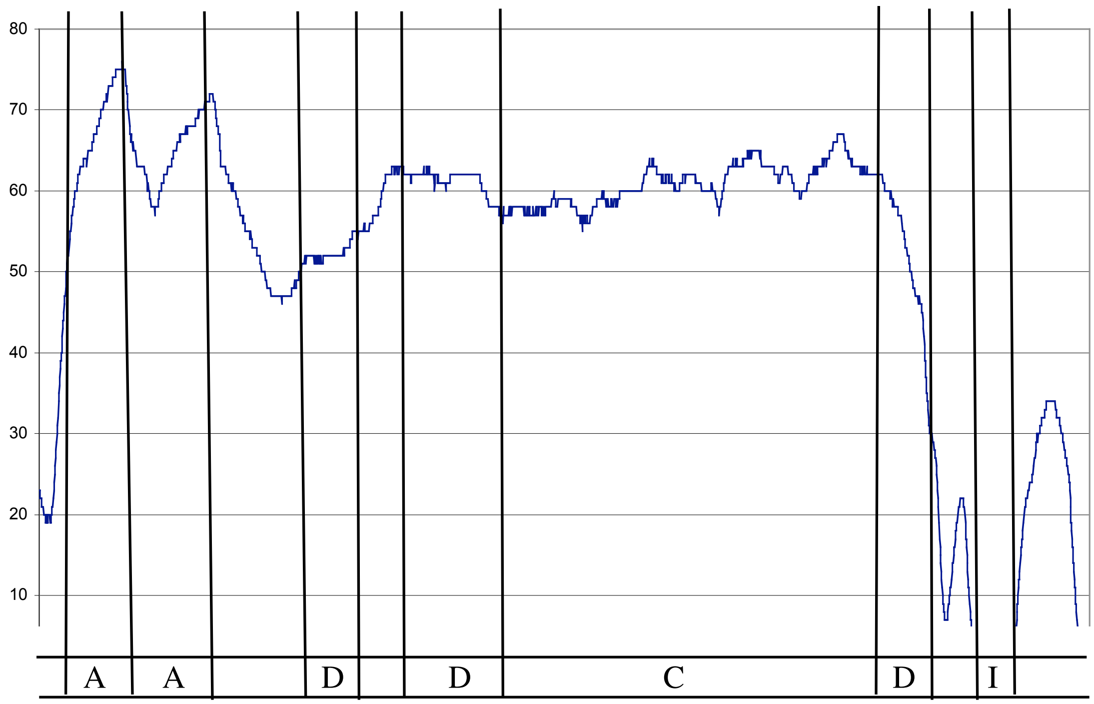


Chart 2 'Engine Speed' 'RPM'

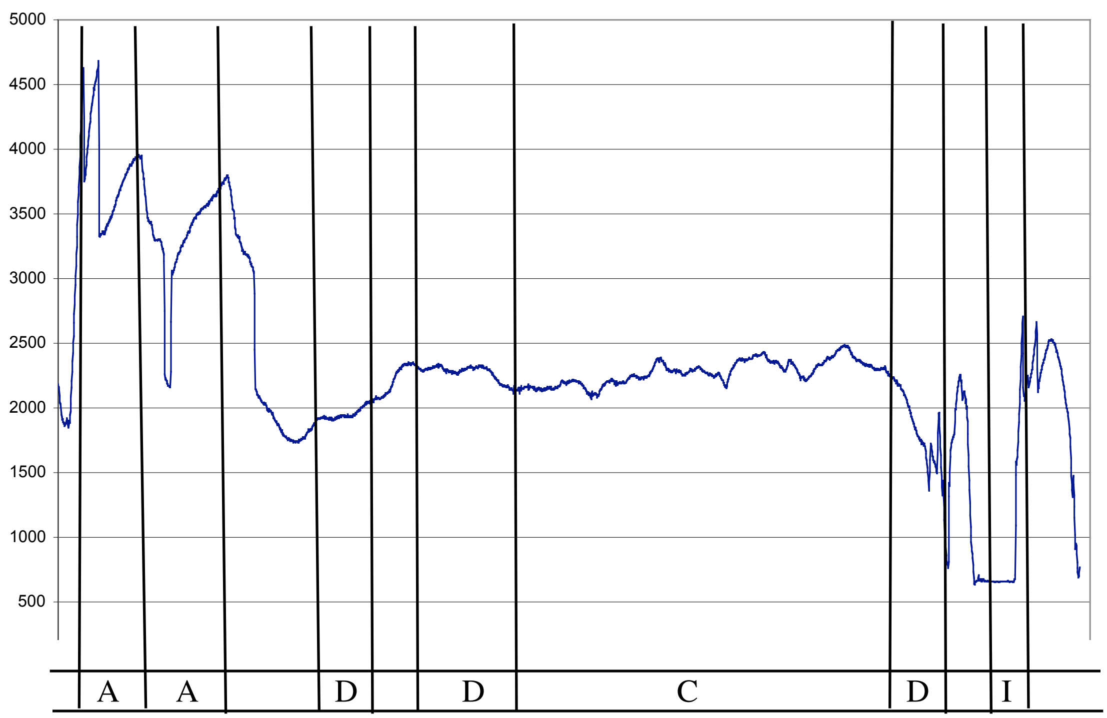


Chart 3 Manifold Absolute Pressure Sensor' 'kPa'

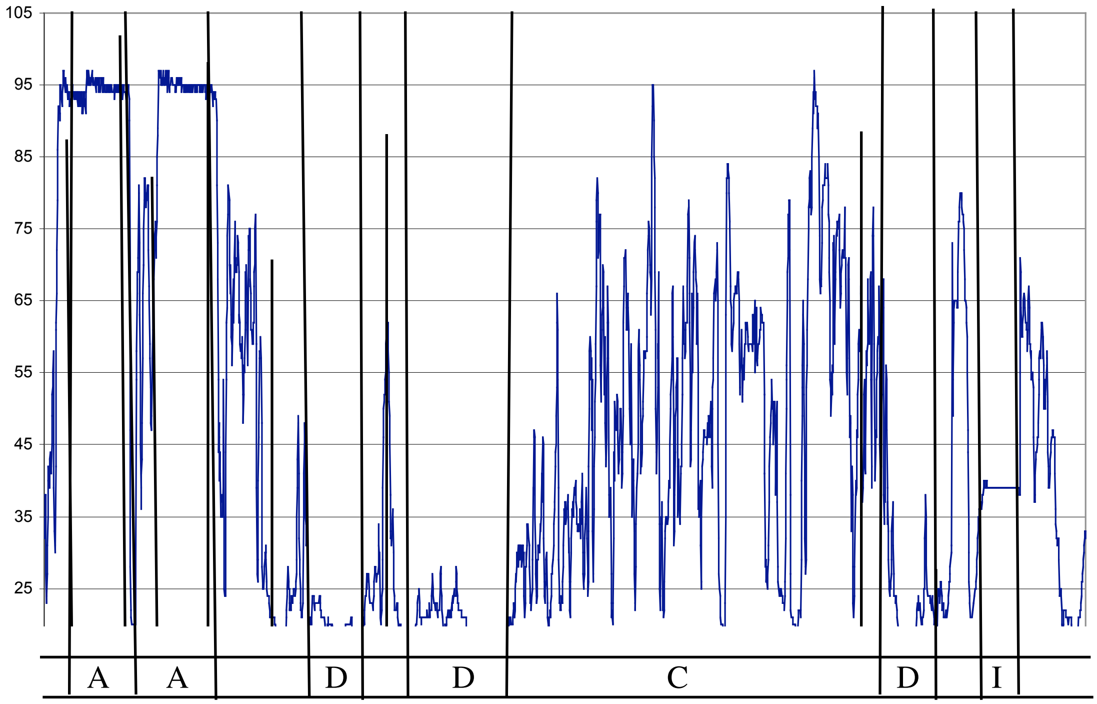


Chart 4 Accelerator Pedal Position Indicated Angle' '%'

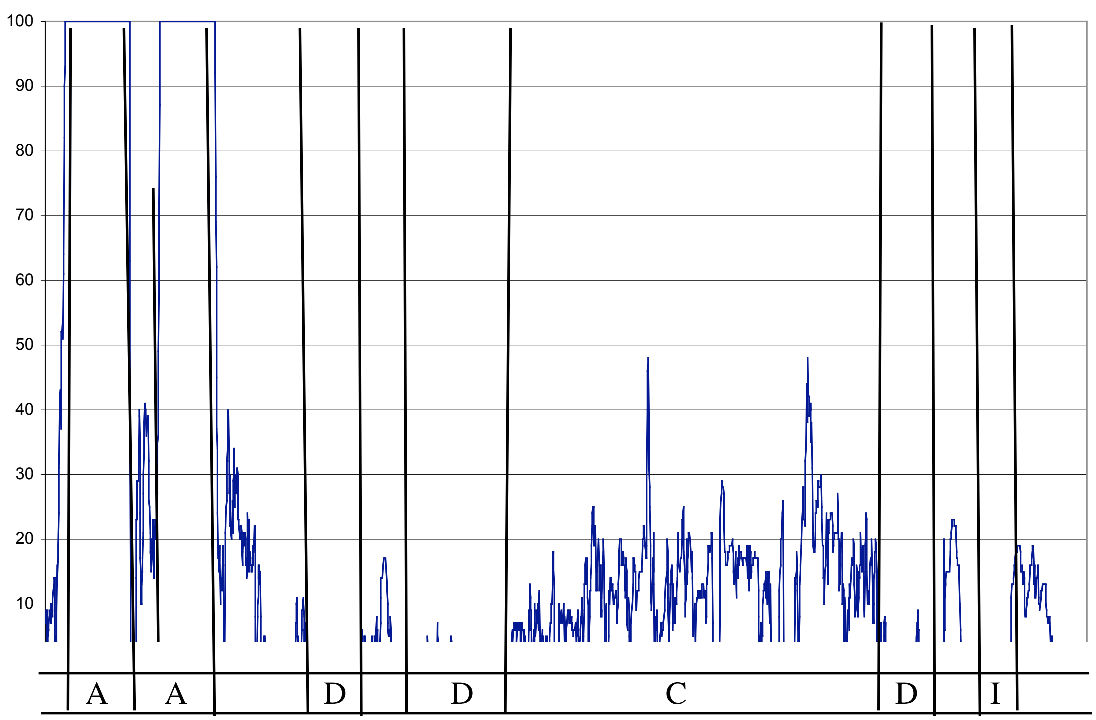


Chart 5 Engine Load' '%'

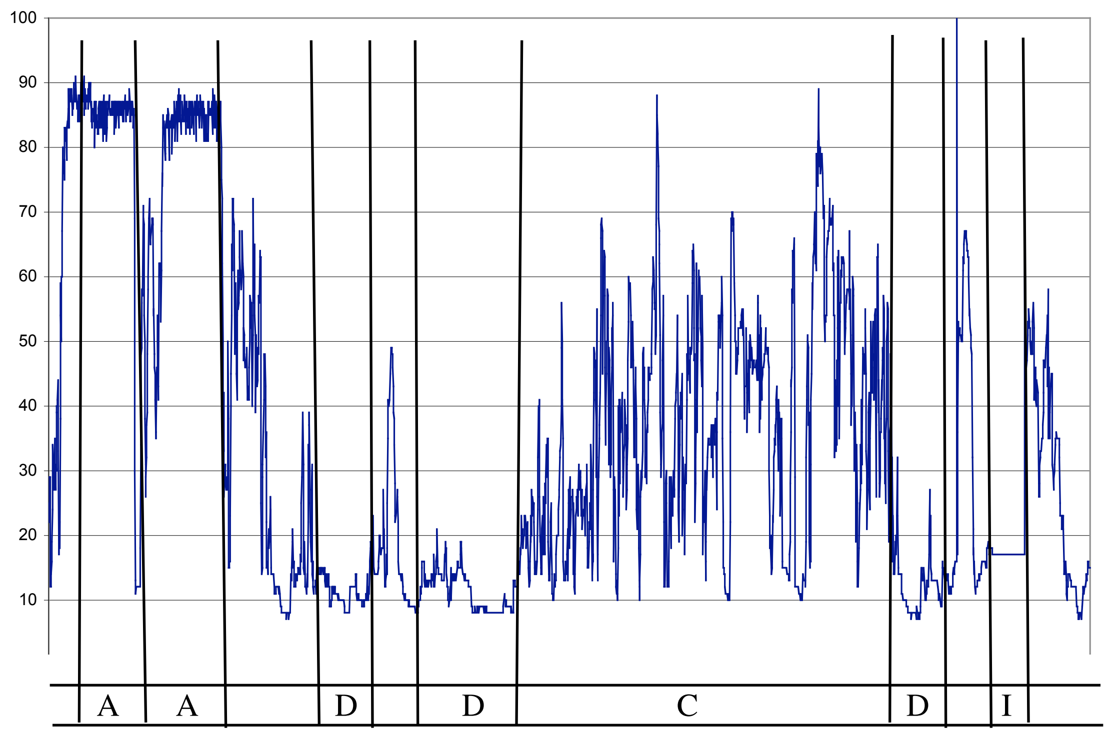


Chart 6 Heated O2 Sensor Bank 1 Sensor 1' 'mV'

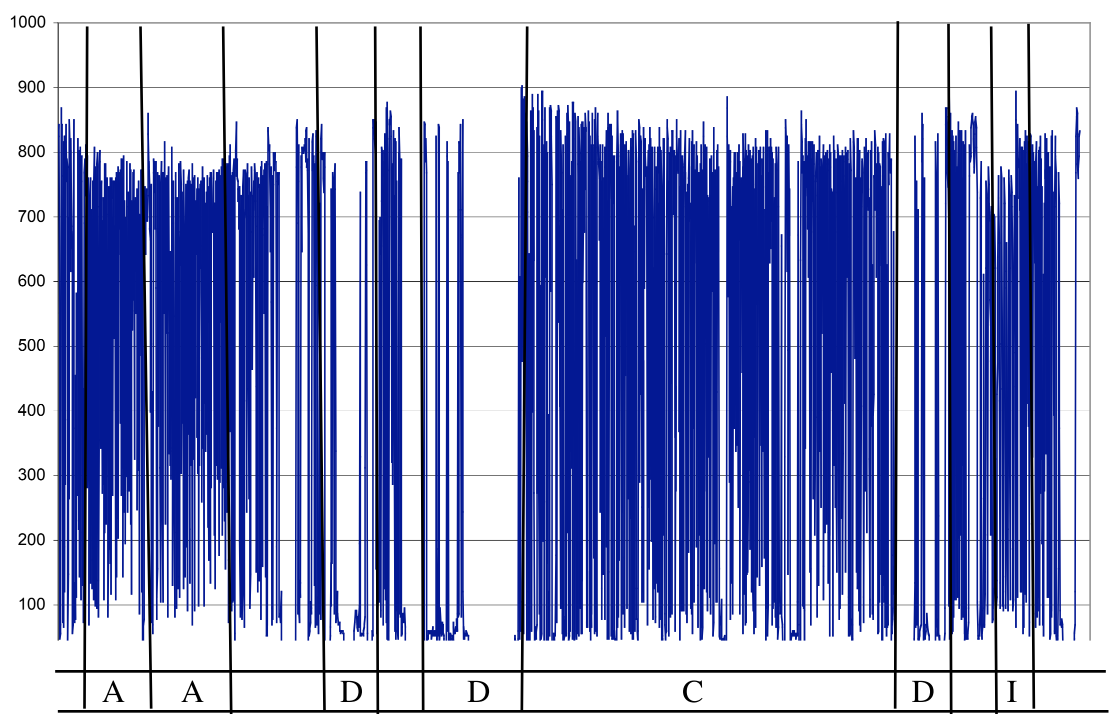
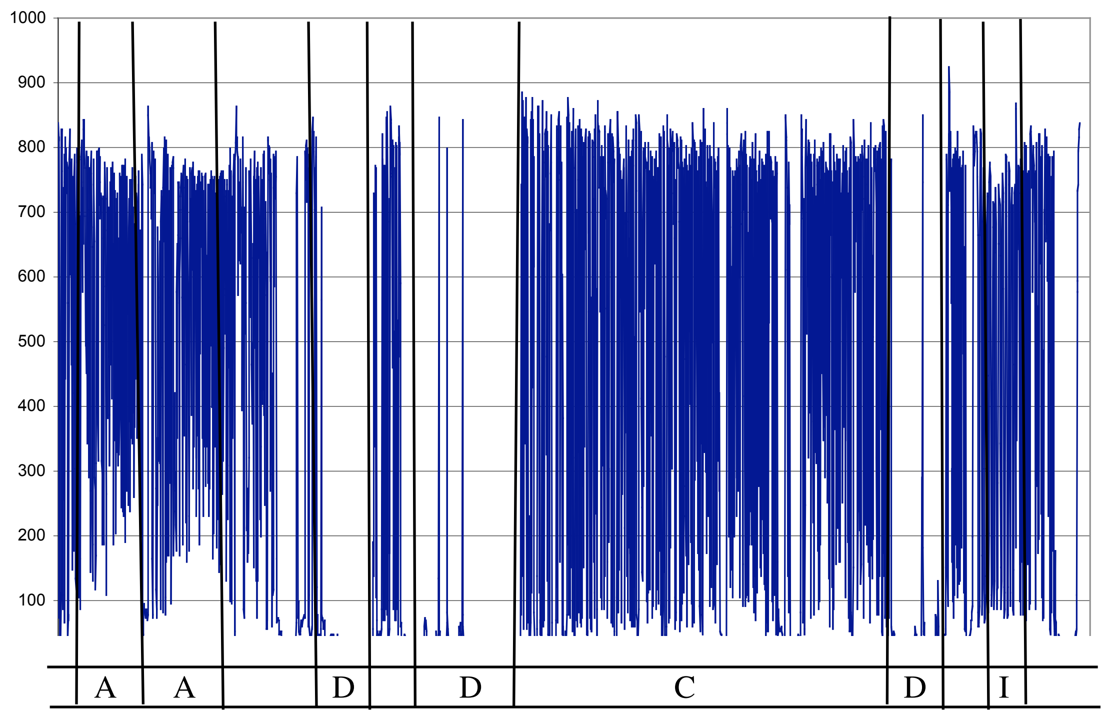


Chart 7 Heated O2 Sensor Bank 2 Sensor 1' 'mV'



2.3.2.2 6.0L Propane Engine Test Data

Two data sets are presented for the 6.0L propane engine. The first set represents an on-road evaluation under warm start-up conditions. The second set represents an on-road evaluation under 20 degree C emission test cold start-up conditions.

2.3..2.2.1 6.0L Warm Start-up Conditions

Charts 8 through 14 present a series of engine parameters for a 4 min:13 sec test sequence beginning with engine start-up after the engine was warm. It includes engine start-up, engine idle, brake torque test maneuvers, and on-road test drive. Charts 8 though 12 show various engine operating conditions. Charts 13 and 14 show the oxygen sensor signals during engine start-up, idle, brake torque maneuvers, accelerations, and cruise conditions. The fuel control system is commanded closed loop shortly after engine start-up, as shown by the oxygen sensor activity shortly after the engine is running. High precision fuel control is shown by the high frequency oxygen sensor activity during brake torque, acceleration, and cruise conditions. Leaner operation is shown during deceleration to reduce emissions and increase fuel economy.

Chart 8 Vehicle Speed Sensor' mph'

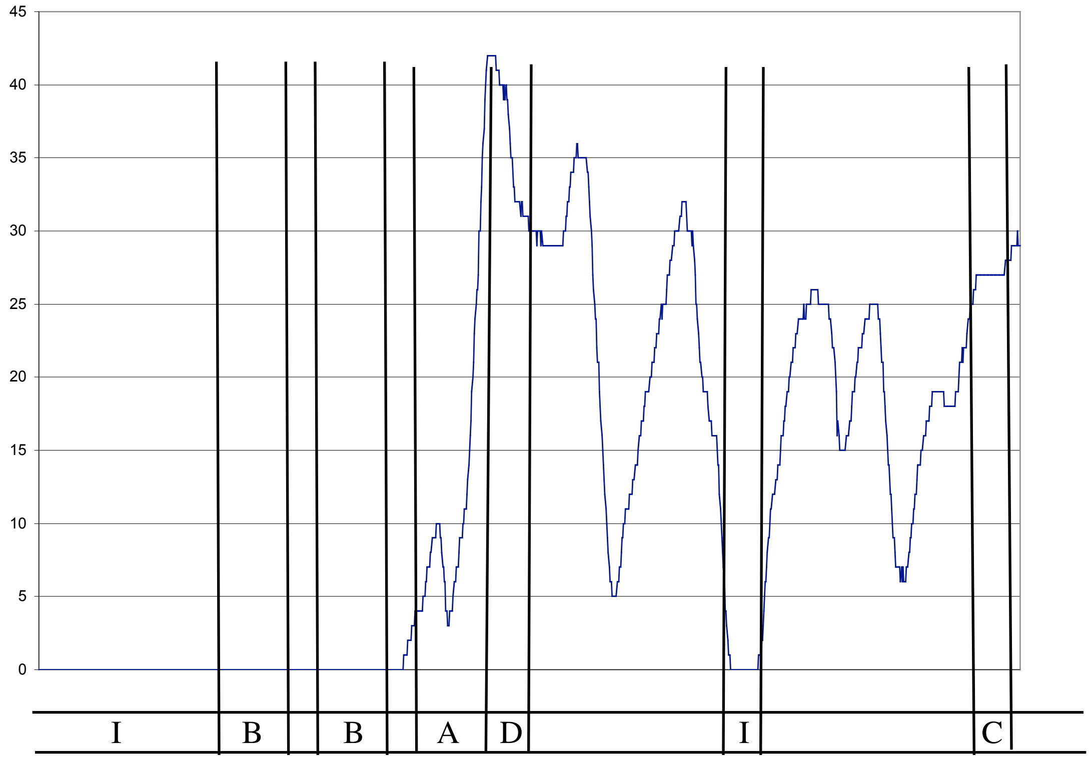


Chart 9 Engine Speed' 'RPM'

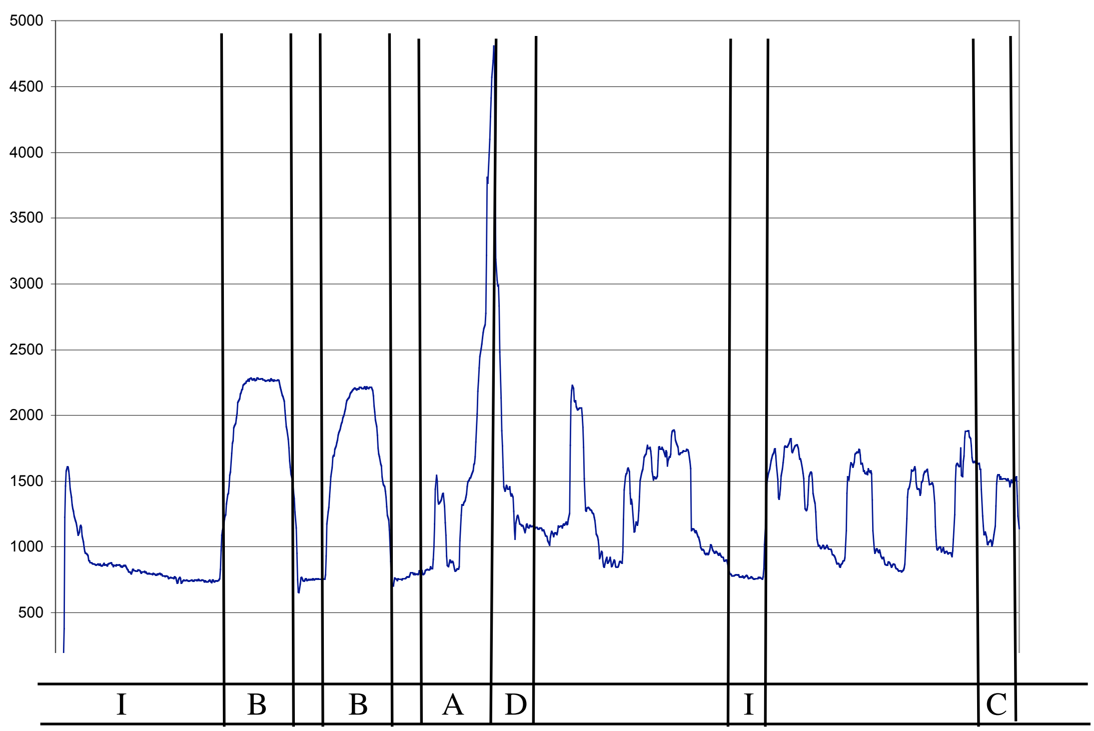


Chart 10 MAP Sensor' 'kPa'

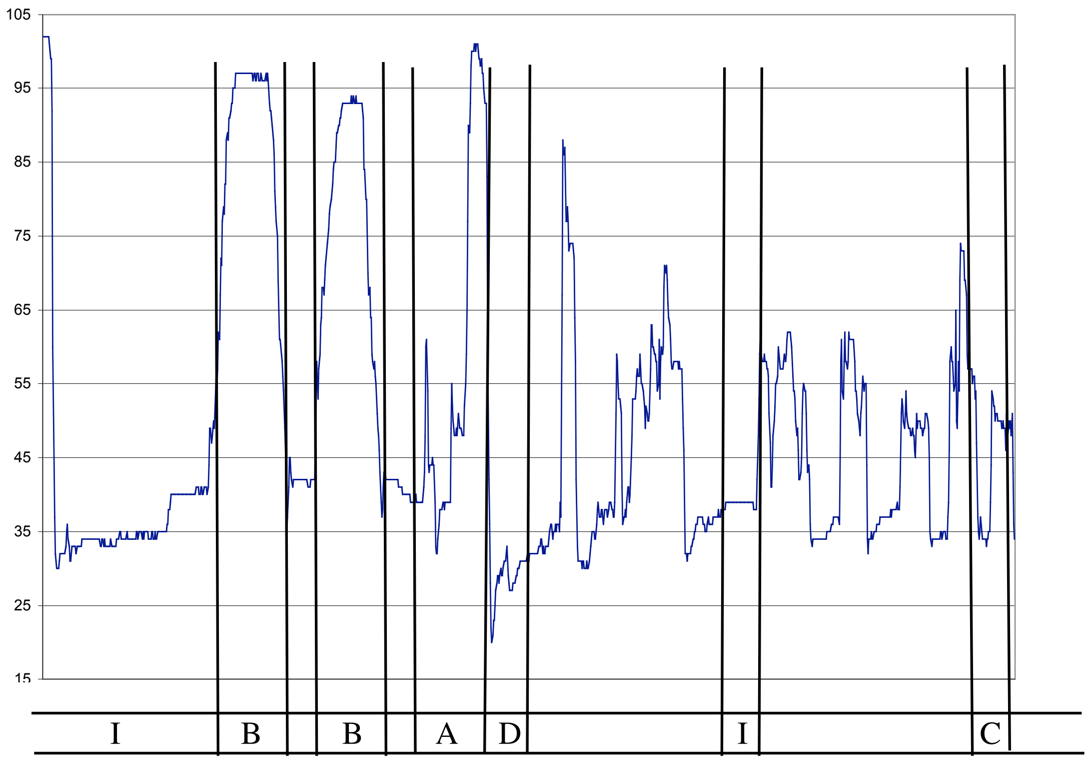


Chart 11 Accelerator Pedal Position Indicated Angle' '%'

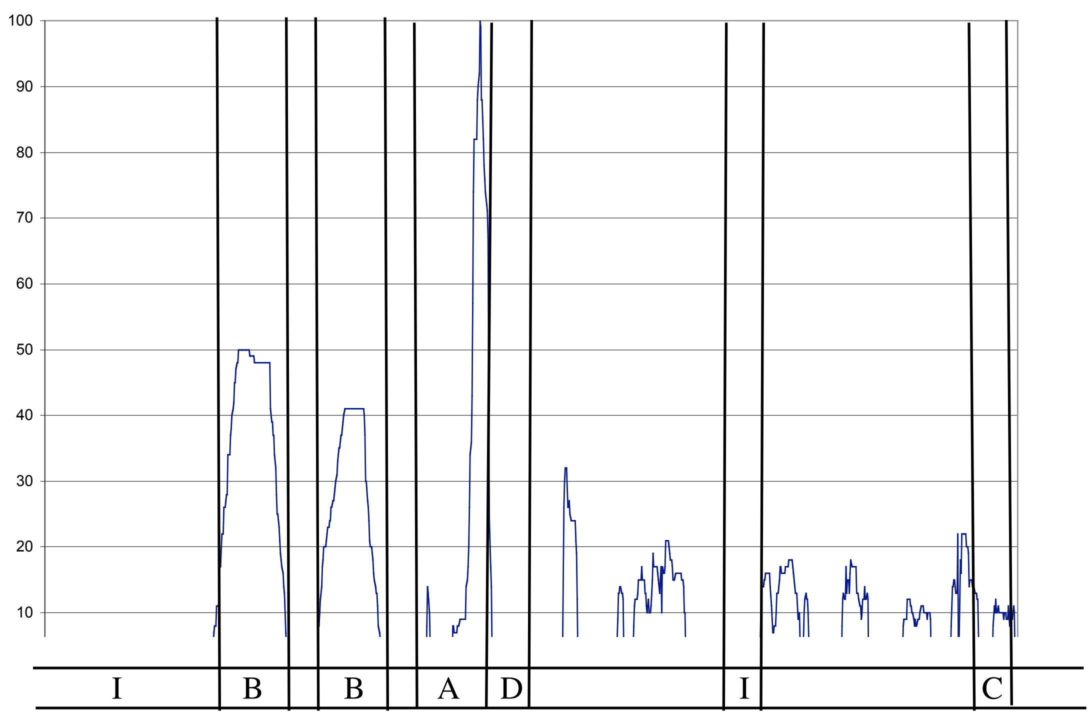


Chart 12 Engine Load' '%'

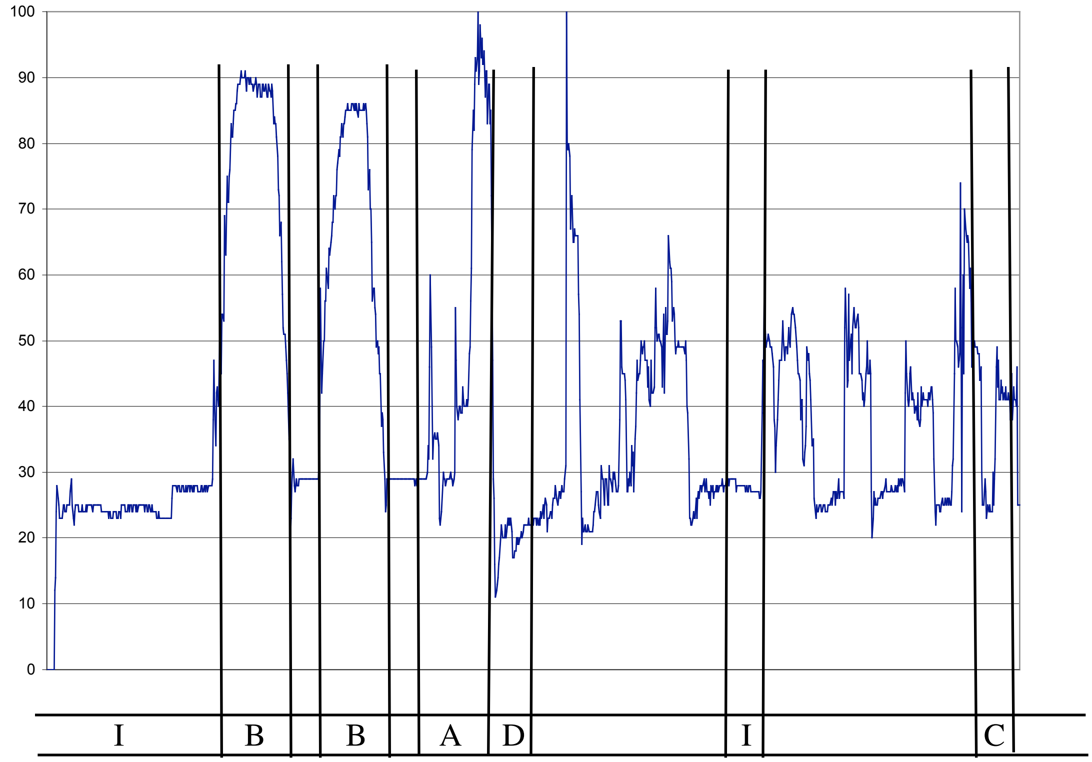
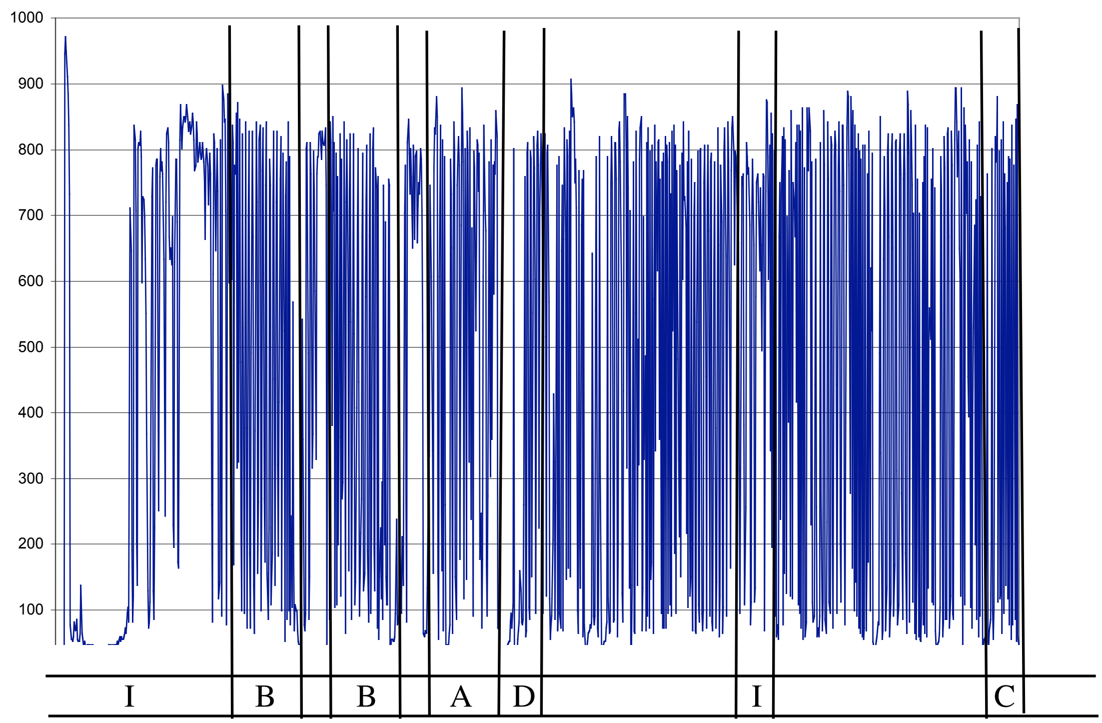
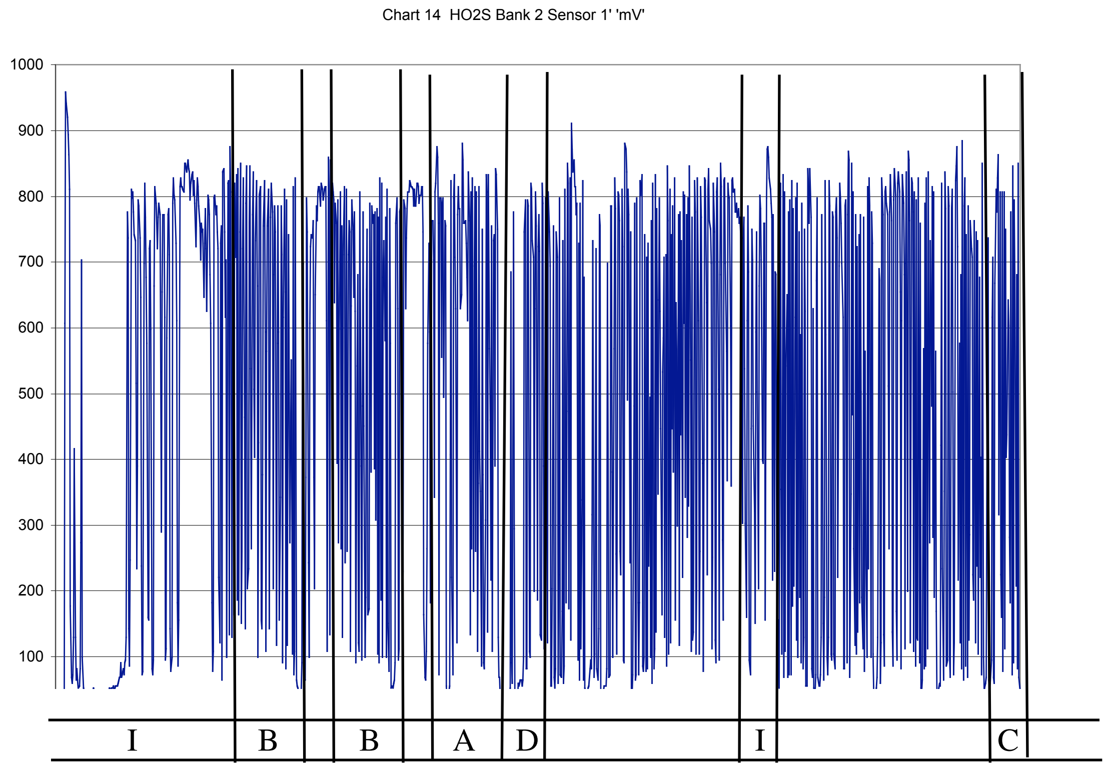


Chart 13 Heated O2 Sensor Bank 1 Sensor 1' 'mV'





2.3.2.2.2 6.0L Cold Start-up Conditions

Charts 15 through 23 present a series of engine parameters for a 1 minute test sequence beginning with cold engine start-up. It includes cold engine start-up, engine idle, and on-road test drive. This data set shows the open-loop fuel control transition to closed-loop fuel control. Charts 22 and 23 show the oxygen sensor signals. After engine start-up the fuel control is open-loop (no oxygen sensor activity). The fuel control is commanded closed-loop as soon as the oxygen sensors are warm enough to properly measure the oxygen content of the exhaust.

Chart 15 Engine Coolant Temperature Sensor 'degC'

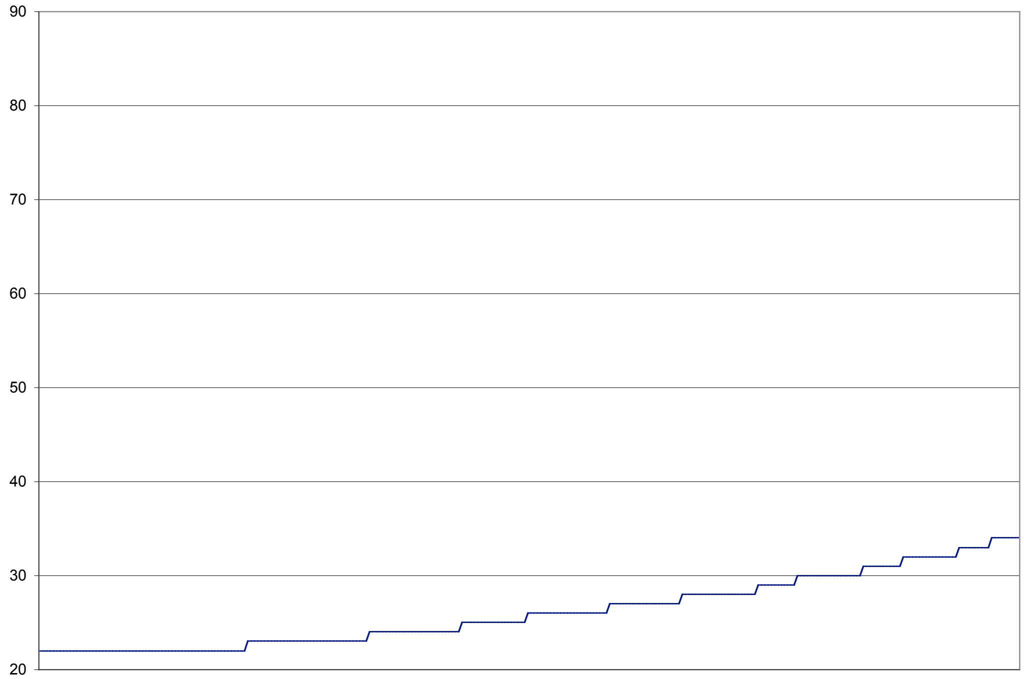


Chart 16 Intake Air Temperature Sensor 'deg C'

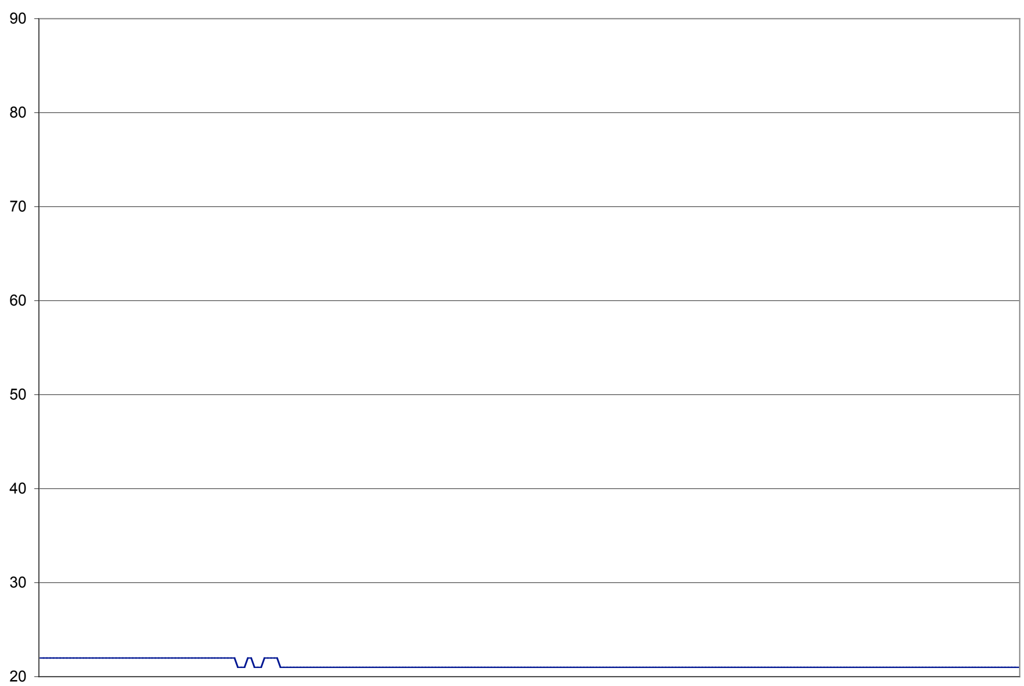


Chart 17 Vehicle Speed Sensor' 'km/h'

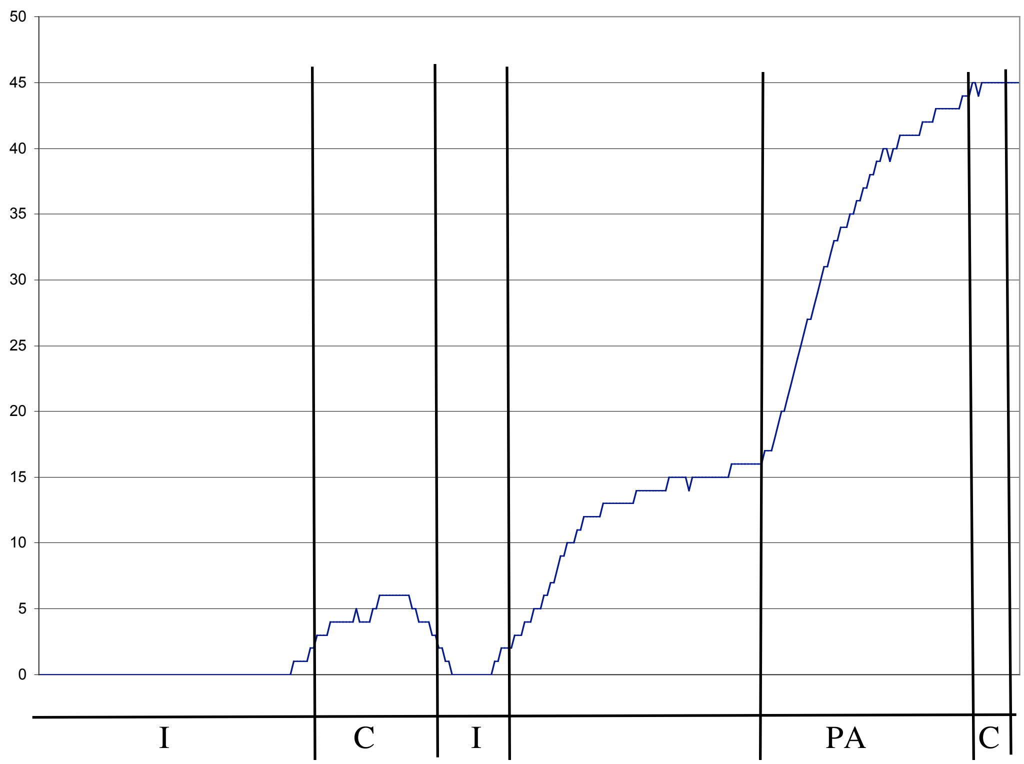


Chart 18 Engine Speed' 'RPM'

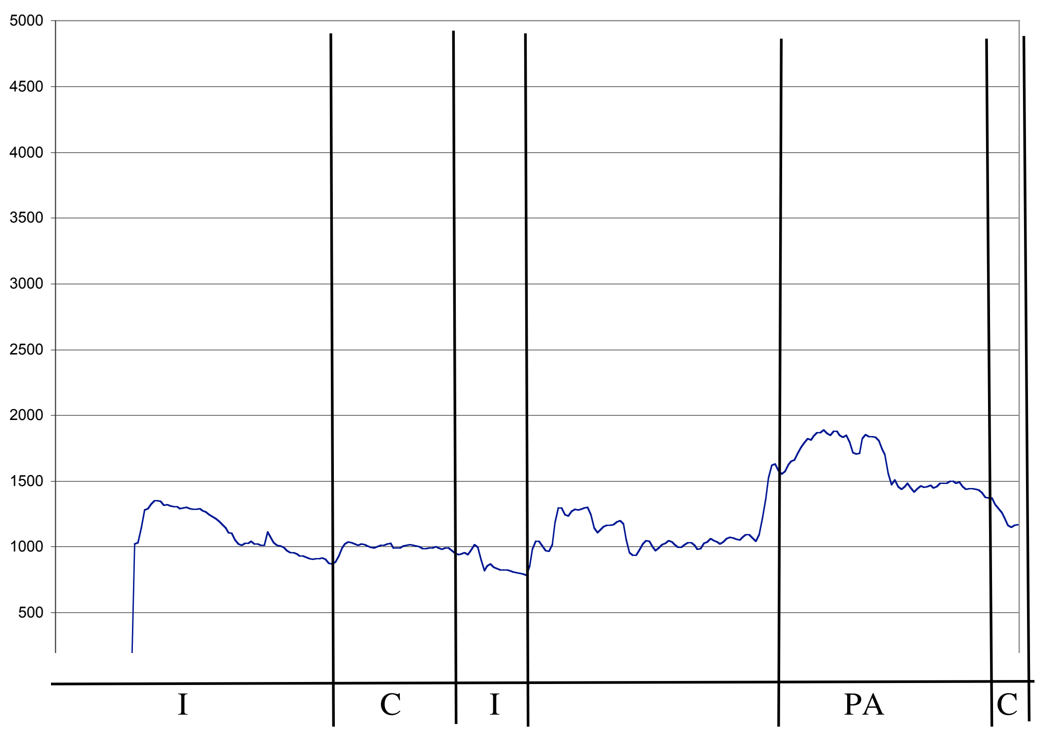


Chart 19 Manifold Absolute Pressure Sensor 'kPa'

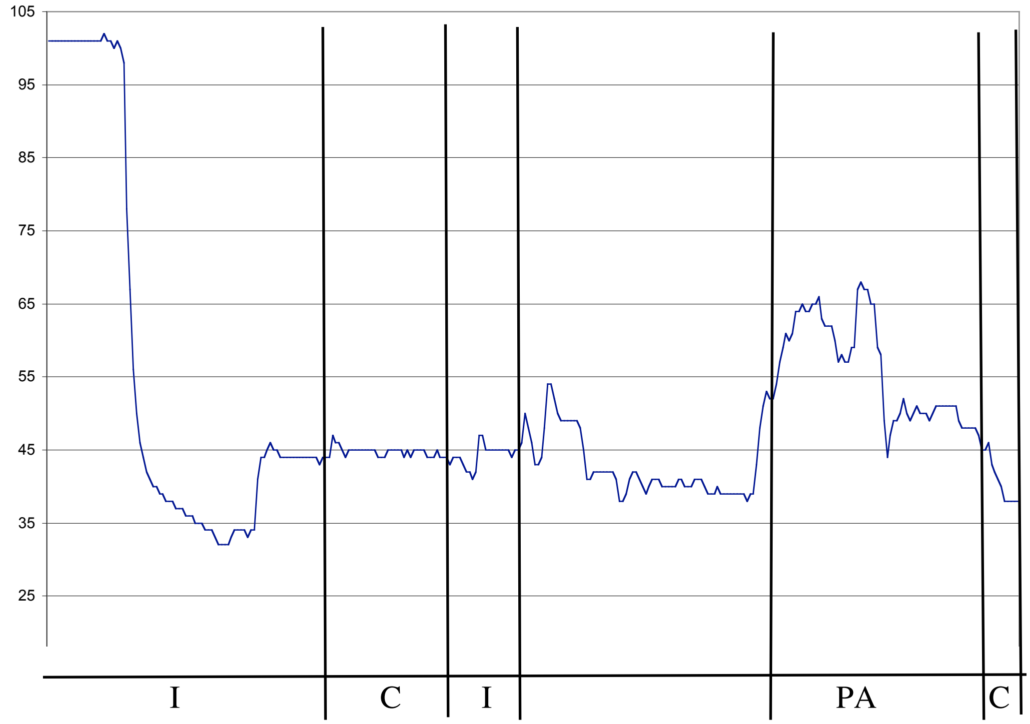


Chart 20 Accerator Pedal Postition Indicated Angle' '%'

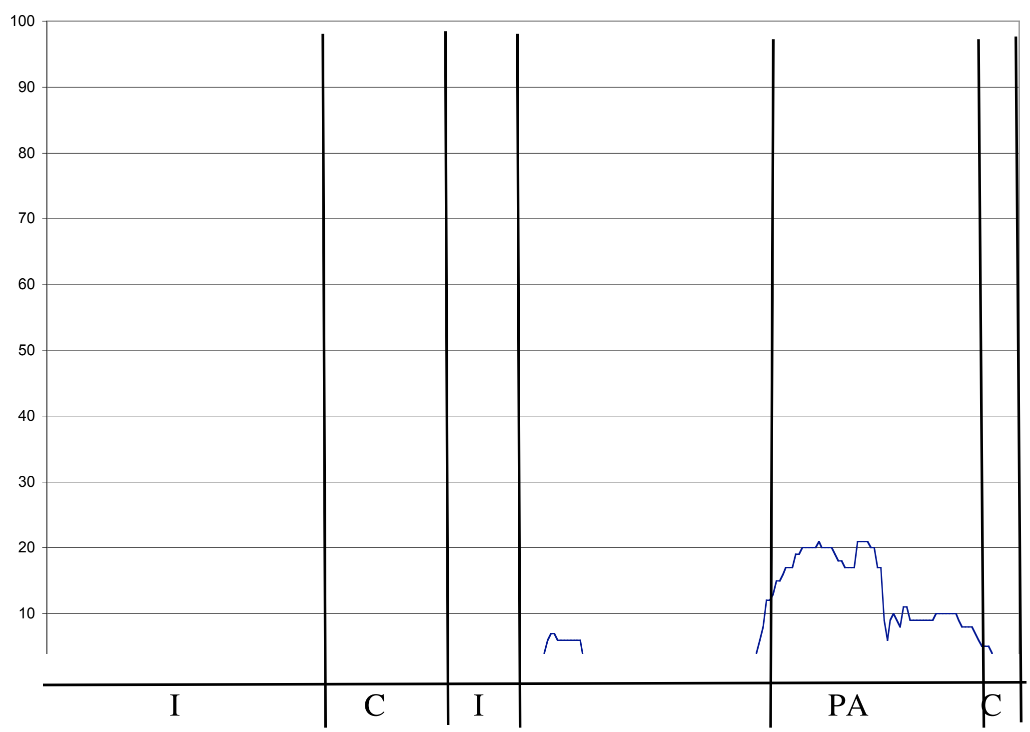


Chart 21 Engine Load '%'

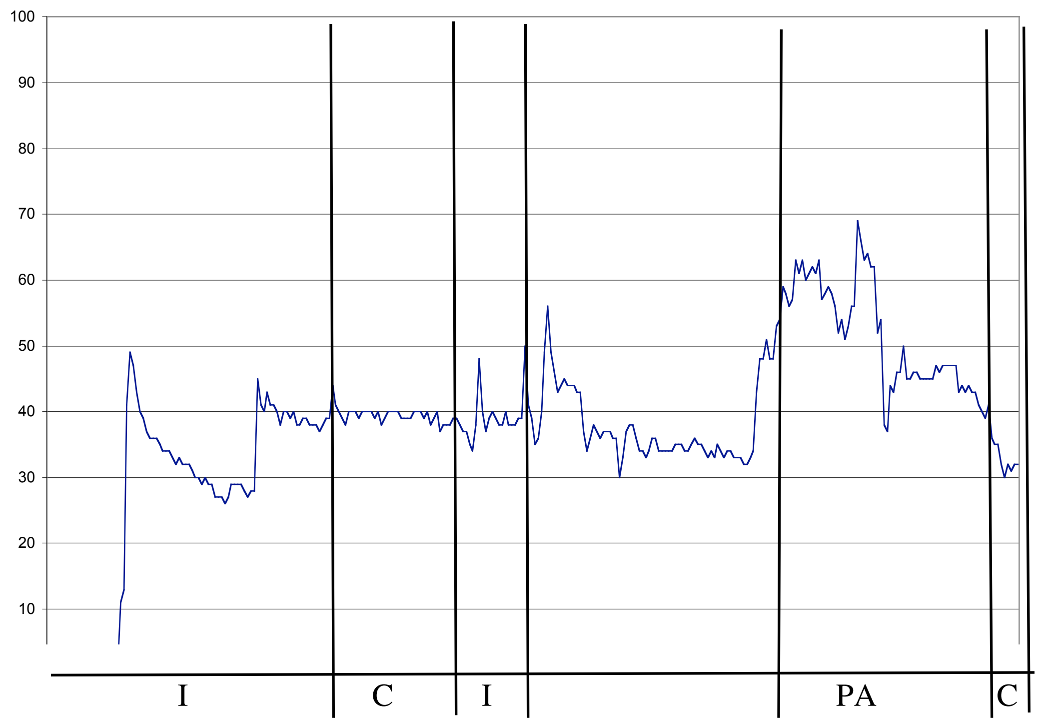
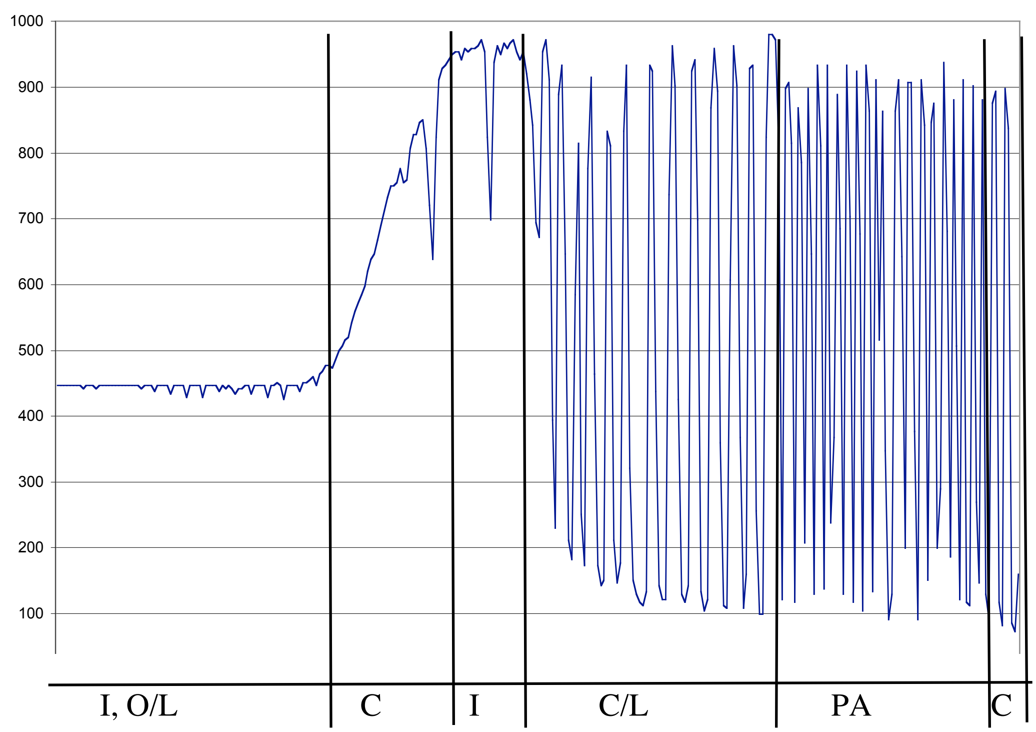
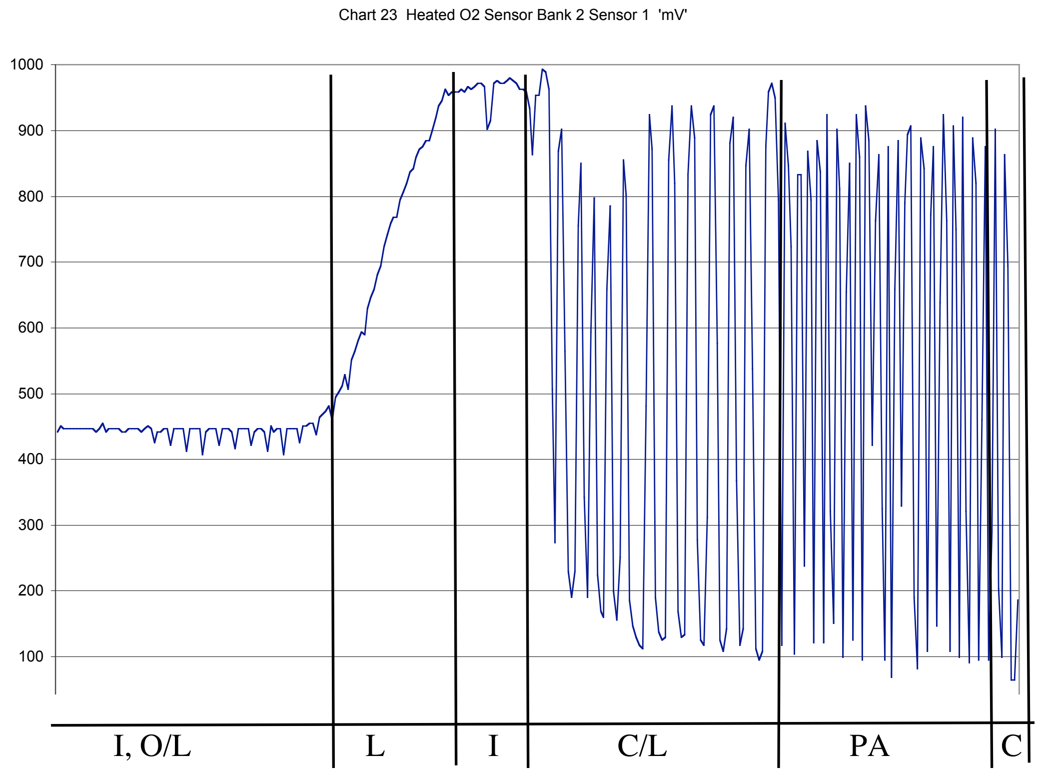


Chart 22 Heated O2 Sensor Bank 1 Sensor 1 'mV'





3.0 Conclusions

Based upon the extensive performance evaluations of the 8.1L and 6.0L propane engines, and numerous iterations of the engine calibration software and hardware adjustments on each engine to optimize engine performance, Baytech determined that the engines were ready for engine dynamometer emissions testing (Task 3 of the project).