Development of a Closed Loop Fuel Management System for a Lean Burn Natural Gas Engine

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ABSTRACT

Concern over the adverse health and environmental effects of air pollution has resulted in increasingly stringent medium and heavy duty vehicle emissions standards. To maintain performance specifications while meeting federal emissions regulations, optimal closed loop feedback control, achieved through measuring the oxygen concentration in the exhaust, is becoming increasingly important for heavy duty spark ignited natural gas engines. Natural gas powered engines that operate at a stoichiometric air/fuel ratio can readily adapt a standard stoichiometric exhaust gas oxygen (EGO) sensor for use in light duty vehicles, whereas a lean burn engine would need a special sensor and/or strategy to accomplish the same feat. Compressed natural gas (CNG) composition varies geographically as well as seasonally, and there exists a need to provide a method or strategy to compensate for significant or even subtle changes in gas quality.

The objective of the proposed closed loop lean burn feedback system is to develop a strategy to compensate for variations in fuel composition and also long term engine wear. Several types of EGOs have been researched and hardware and software development is in the preliminary stages. Knock sensing is being addressed through the use of accelerometers and in-cylinder pressure transducers to determine if and what changes need to be made to the ignition timing to prevent damage through knock. The completed system will then be tested on different compositions of natural gas in both transient and steady state tests to demonstrate the efficacy of this strategy.

A Hercules 3.7 liter lean burn natural gas engine with a Gaseous Fuel Injection Incorporated (GFI) solenoid based fuel metering system has been chosen as the engine on which this research will be based.

INTRODUCTION

Natural gas has shown the ability to produce very low emissions in heavy duty vehicle applications [1][*] . In addition, the widespread availability of natural gas has made it a leading alternative fuel. The usage of natural gas not only reduces engine-out emissions [2], including oxides of nitrogen (NO_X), hydrocarbons (HC) and carbon monoxide (CO), but also eliminates the need for linehaul trucks for fuel transportation. A large and growing refueling infrastructure is already in place and the pipelines that would be needed to transport the fuel from the well to the consumer refueling station are currently in use.

Natural gas is primarily 85 to 99 percent methane with the remainder made up of other heavier hydrocarbons such as propane, hexane, ethane and inert gases [2]. Additives such as propane and air are sometimes added to keep the energy value of the fuel as consistent as possible when the fuel finally reaches the consumer. Contaminants such as compressor oil from the pumping stations, water from condensation and the odorant ethyl mercaptan also have a direct impact on the fuel energy value.

Natural gas engines that operate at a stoichiometric air/fuel ratio while using a standard exhaust gas oxygen sensor (EGO) for closed loop fuel control and a three-way exhaust catalyst show a reduction in emissions but rely on the hope that significant catalyst degradation will not occur. Lean burn engines operate at an excess air/fuel ratio and, without an exhaust catalyst, are able to produce lower engine-out emissions than stoichiometric natural gas engines. The only drawback is that a lean burn engine requires a special wide range or universal exhaust gas oxygen (UEGO) sensor and control algorithm to compensate for fuel composition variations.

In stoichiometric and lean burn versions, natural gas engines are currently being employed in automobiles, school buses and light trucks while the lean burn versions are being used industrially in forklifts and natural gas compressors and commercially for linehaul trucks, school and transit buses and delivery trucks. Manufacturers such as Cummins, Detroit

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[*] Numbers in brackets designate references at end of paper.

Diesel, Hercules and Caterpillar are currently producing and further developing lean burn natural gas engines with various types of induction and control systems.

The objective of the research reported in this paper is to develop a closed loop fueling operation system for lean burn natural gas engines.

LITERATURE REVIEW

This review addresses aspects of both natural gas engine operation and knock. Current light duty natural gas engines are mostly converted from gasoline operation with aftermarket induction and control systems added on. The most popular configuration is the carburetor type system, which uses the pressure change in the mixer to meter incoming fuel and normally operates without any exhaust gas feedback. However, some manufacturers are using an extra valve to trim the mixture with an EGO sensor, which is essential for low exhaust emissions. In the future, NG engine configurations will most likely utilize some form of fuel injection. There are two variations of fuel injection currently used: "throttle-body" injection, which injects the fuel upstream of the throttle to take advantage of mixing effects, and "port" injection, which injects the fuel directly at the intake valve [3]. Fuel injection offers the advantage of more accurate fuel/air ratio control and more effective closed loop engine control around a desired λ, a unitless variable representing the actual air/fuel ratio divided by the stoichiometric air/fuel ratio. However, fuel injection does not necessarily imply precise fueling as most available systems use an open loop strategy via a "map" of load and speed [2].

Stoichiometric engine operation is highly susceptible to variations in the gas composition [3]. Previous studies have shown the wide variation of natural gas composition from region to region and day to day throughout the United States [4]. The sources of these variations range from supply origins to the practice of "propane/air peak shaving" in which propane and air are added to the pipeline to produce a larger volume of gas with the same effective heating value [4]. Commonly, the same supplies of natural gas which heat homes are also used as fuel supplies for natural gas vehicles. Consequently, engines which rely on "open-loop" engine control strategies will produce unnecessarily high levels of federally regulated emissions if the gas composition differs from that which was used to optimize the engine. Closed loop engine control is recognized as a solution to fuel variation problems. With stoichiometric engines, exhaust gas oxygen sensors are used with a closed loop controller. Lean burn engines, however, must utilize a λ-type oxygen sensor under closed loop control to account for gas composition variability for operation at a specified air/fuel ratio [4].

Dedicated natural gas engines are generally spark ignited and operate at or near stoichiometric conditions. At slightly rich operation, levels of NO_X are less than those at the lean peak as shown in Figure 1 [5]. This is, unfortunately, at the cost of increased CO emissions. Lean burn operation could solve this problem as CO emissions at λ values greater than 1.1 are reduced significantly. If the engine can operate at a λ of greater than 1.1, NO_X emissions are also decreased [2]. This occurs because a leaner mixture decreases the flame temperature in the cylinder, since the energy from the combustion of the fuel must raise the temperature of a larger mass of air [2]. Reduction of these emissions comes at a price, however, as an engine operating in the lean burn region requires a higher amount of energy to ignite the mixture and has a reduced power density unless it is turbocharged. There are also limits to lean burn operation due to a decrease in combustion stability. As fuel represents less and less of the mixture on a mass basis, ignition delays and combustion durations both increase until excessive misfiring occurs, causing an increase in HC emissions [2]. Consequently, there is an optimum effective operating area in the lean burn regime between high levels of NO_X and HC emissions.

An advantage of natural gas as a fuel is its improved resistance over gasoline to engine "knock". With an octane rating generally supposed to be at 130, the compression ratio of natural gas engines can be raised to increase overall thermal efficiency [2]. With these higher compression ratios, knock on natural gas operation is still a problem that must be dealt with, although current thought holds that the onset of knock is accelerated with the addition of contaminant hydrocarbons. These contaminants are introduced by the compressor oil during high pressure refueling [6]. However, knock can be controlled through a feedback system using a knock sensor to alter ignition timing. Knock resonant frequency is strongly related to the cylinder bore diameter of the engine, and for most automotive or light-duty engines, the knock frequency lies in the range of 5 - 12 kHz [7,8].

EXPERIMENTAL SETUP

The current experimental setup consists of a Hercules GTA 3.7 liter 4 cylinder engine (Table 1) with a GFI fuel metering valve with integrated ignition controller. An Altronics capacitor discharge ignition module reads a signal from the GFI ignition controller and fires the spark plugs. A dedicated test bed was constructed for the research, which included the requisite water and charge air cooling systems. A Mustang eddy current dynamometer with both load cell and in-line torque cell was installed to absorb power from the engine.

Fuel management system control and monitoring, as well as engine monitoring through the GFI controller, are accomplished using a dedicated computer-based data acquisition and control system as shown in Figures 2 and 3. The engine has been fitted with manifold air pressure, mass air flow, mass fuel flow, temperature, in-cylinder pressure, speed and in-line load cell sensors which are listed in Table 2. Exhaust from the engine is routed through insulated stainless steel exhaust pipe into a full scale dilution tunnel from which dilute exhaust is sent to the analyzers. Exhaust emissions are quantified using a non-dispersive infrared detector (NDIR) for carbon monoxide and carbon dioxide (CO_2), a chemiluminescent detector (CLD) for oxides of nitrogen, and a heated flame ionization detector (FID) for total hydrocarbon emissions as listed in Table 3.

Feedback equivalence ratio control can be obtained by sensing relative exhaust gas oxygen content and then by increasing or decreasing the fuel input until the desired equivalence ratio is obtained. Oxygen content information is currently being obtained using a NGK universal exhaust gas oxygen sensor with its proprietary controller. The UEGO controller outputs a voltage proportional to the equivalence ratio and can operate from 0% up to 22% oxygen content. Additional exhaust gas oxygen sensors including a Bosch wide range sensor and an AC Rochester stoichiometric EGO are currently being evaluated. A Rosemount oxygen analyzer is being used to determine oxygen content from exhaust samples captured at the outlet of the turbocharger that are dried and filtered for comparison with EGO sensor outputs.

To detect the onset of knock, wide range accelerometers and in-cylinder pressure transducers will initially be utilized to determine block resonance and verify the occurrence of knock. Data collected using the wide range accelerometer will be used to determine the optimal location and frequency range for the knock sensor so that a resonant type sensor can be fitted.

ENGINE DATA

For preliminary testing, a twenty-five mode test program, consisting of five torque setpoints at five different engine speeds, was developed to allow analysis over the complete engine operating range. The engine was operated at each mode in the test program to determine both exhaust emissions and the equivalence ratio set by the stock (open loop) fuel management system. Figure 2 shows a schematic of the open loop engine control. Figure 3 shows the torque and equivalence ratio found using the UEGO. Figure 4 shows NO_X and HC emissions during these modes.

Additionally, the engine was operated at 1200 RPM and at a torque of 136 Nm through a wide range of air/fuel ratios from slightly rich through to lean misfire. Figure 5 shows distinctly the NO_X peak associated with slightly lean operation. It is evident that for this engine, λ ratios from approximately 1.25 to 1.45 are desirable since mixtures leaner than this will produce high HC emissions while mixtures less than this will produce high NO_X emissions. Experience with the engine has also shown that power density may be inadequate during very lean operation.

For purposes of demonstrating closed loop operation, the philosophy shown in Figure 6 was employed. In this case the gas metering by the GFI Compuvalve is modified based upon a signal from the UEGO. Converted input from the UEGO can be compared with a target λ table using a PC-based controller, and the difference between actual and desired λ is used to control the GFI unit. Both NGK and Bosch LSM-11 EGOs have been employed. The NGK sensor consists of a pair of cells while the Bosch sensor consists of a single cell doped to provide wider range performance. The Bosch cell is of interest in this application because it involves simpler and less expensive technology than the NGK cell. However, the Bosch cell output offers little sensitivity at the lean exhaust conditions needed in this research. Figure 7 shows a filtered output from the Bosch sensor compared with that from the NGK sensor. This curve has been used to translate the Bosch output into a useful λ signal, and Figure 8 shows a comparison of NGK and processed Bosch signals over the 25 mode test. Figure 8 shows that the Bosch will be suitable for closed loop control purposes.

At this time, closed loop operation is feasible at any single operating point, but before the whole "map" is explored for control purposes, the engine volumetric efficiencies and desirable λ set points for each speed and load must be determined accurately.

A broad range accelerometer has been attached to the engine block between cylinders 1 and 2 to investigate knock. Figure 9 shows a trace which illustrates the firing of cylinders 3, 4, 2 and 1 while Figure 9 shows the power-spectral density of this signal. It is evident from Figure 10 that a resonant sensor operating slightly above 4 kHz could be expected to function well if located in this position. Since the knock detection will be used for engine protection rather than spark timing control, the detection threshold is not too critical. Nevertheless, the head of the engine has been drilled to receive and has been fitted with 4 flush mounted PCB piezoelectric in-cylinder pressure transducers. The in-cylinder pressure traces can be processed to yield a plethora of information including knock threshold [9,10]. This in-cylinder data will be used to verify the effectiveness of the engine-mounted knock sensor.

RESULTS

Preliminary testing has shown that open-loop operation of a lean burn natural gas engine is far from optimal when gas composition varies. The stock GFI controller currently supplied with Hercules 3.7 L engine is not equipped for feedback during lean burn operation. In open loop mode, NO_x emissions exceeded 5.0 g/bhp-hr during 8 modes of the 25 mode test when the engine was operated on a gas different from that used for the controller calibration. It was also observed that during several other modes, NO_x emissions were only slightly below this level. The use of feedback control will overcome the effects of varying fuel composition and allow more precise control over the engine fueling. Besides reducing engine emissions, the feedback system will help maintain emissions levels by compensating for component wear over the life of the engine.

Closed loop control has been demonstrated and will be implemented over the whole engine operating range following accurate volumetric efficiency and optimal λ mapping. In addition, the engine will receive knock protection through the incorporation of a knock sensor in the engine control system.

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REFERENCES

[1] Wong, W., Gautam, M., Sung, X., Bata, R., Clark, N., Palmer, M. and Lyons, D., “Emission Comparisons of 26 Heavy Duty Vehicles Operated on Conventional and Alternative Fuels”, SAE Paper 932952, 1993.

[2] Weaver, C. S., “Natural Gas Vehicles - A Review of the State of the Art”, SAE Paper 892133, 1989.

[3] King, S.R., “The Impact of Natural Gas Composition on Fuel Metering and Engine Operational Characteristics”, SAE Paper 920593, 1992.

[4] Liss, W. E. and Thrasher, W. H., “Natural Gas as a Stationary Engine and Vehicular Fuel”, SAE Paper 912364, 1991.

[5] Tennant, C. J., deJong, R. J., Atkinson, R. J., Traver, M. L., Atkinson, C. M., Vincent, C. J., Clark, N. N., and Lyons, D. W., “Performance of a High Speed Engine with Dual Fuel Capability”, SAE Paper 940517, 1994.

APPENDIX

Natural Gas Analysis : This gas was used during dynamometer mapping, 25 mode test and emissions vs. lambda tests.

Component	Molar %
methane	91.891
ethane	4.844
propane	1.131
n-butane	.250
i-butane	.173
n-pentane	.063
i-pentane	.090
hexanes +	.060
nitrogen	1.498
CO_2	0.000
Total	100.00

Analysis performed by Gas Analytical Services, Inc., Bridgeport, WV

[6] Kienzle, Edwin, Personal Communication, Hercules Engine Co., Canton, Ohio, 1994.

[7] Dues, S.M., Adams, J. M. and Shinkle, G. A., “Combustion Knock Sensing: Sensor Selection and Application Issues”, SAE Paper 900488, 1990.

[8] Puzinauskas, P.V., “Examination of Methods Used to Characterize Engine Knock”, SAE Paper 920808, 1992.

[9] Checkel, M.D. and Dale, J.D., “Pressure Trace Knock Measurement in a Current S.I. Production Engine”, SAE Paper 890243, 1989.

[10] Tennant, C. J., Atkinson, R. J., Traver, M. L., Atkinson, C. M. and Clark, N. N., “The Design of a Bi-Fuel Engine which Avoids the Penalties Associated with Natural Gas Operation”, Submitted to SAE Congress, 1995.

TABLE 1: Engine Specifications

Test Engine: Hercules 3.7 Liter Turbocharged Aftercooled
Serial # GTA 3.7 X017

Stock Specifications:

Type	Water cooled 4-cycle
Cylinder Arrangement	4 cylinder Inline, Turbocharged
Bore and Stroke	101.6 mm x 114.3 mm
Compression Ratio	10:1
Displacement	3.7 liter (226 cu. in)
Firing Order	1-2-4-3
Valve Train	2 valves per cylinder
Lubrication System	Pressure Feed
Fuel	Dedicated Natural Gas
Engine Dry Weight	313.9 kg (692 lb.)

Engine Controller

GFI (Gaseous Fuel Injection) System	Stewart And Stevenson Power, Inc. Part 021001009
Manifold Absolute Pressure (MAP)	
Manifold Skin Temperature (MST)	
Fuel Regulated Temperature (FRT)	
Barometric Absolute Pressure (BAP)	
Fuel Absolute Pressure (FAP)	
Intake Air Temperature (IAT)	

TABLE 2 : Experimental Sensors and Instrumentation

Universal Exhaust Gas Oxygen Sensor (UEGO)	NTK: NGK Spark Plug Co., LTD Model TL-7113-A1
Wide Range Oxygen Sensor	Robert Bosch Co. Model LSM11
In-Cylinder Pressure Transducers	PCB Piezoelectronics Model 112A15
Crankshaft Encoder	Sumtak Opticoder Model LEI-292-720
Airflow	Bosch Hot Wire Air Mass Meter Model 0-280-212-016
Fuel Flow	Sierra Hot Wire Fuel Mass Meter Series 730
Thermocouples	Omega: K- and J-type, ungrounded Models TJ36-ICSS and TJ36-CASS
Accelerometers	PCB Piezoelectronics Charge Output Model 357-B02 Quartz Shear Model A353-B17
Load Cell	Lebow In-line Cell Model 6214
Eddy Current Power Absorber	Mustang Model K400

TABLE 3 : Emissions Analysis Equipment

Venturi Pressure	Viatran Model 1042A03AAA20
Venturi Temperature	Tayco RTD Model P/N 68-3839-1
Carbon Dioxide Analyzer	Beckman Industrial Model 868
Carbon Monoxide Analyzer	Beckman Industrial Model 868
Hydrocarbon Analyzer	Rosemount Analytical Model 402
NO_x Analyzer	Rosemount Analytical Model 955
Gas Chromatograph	Varian Model 3600

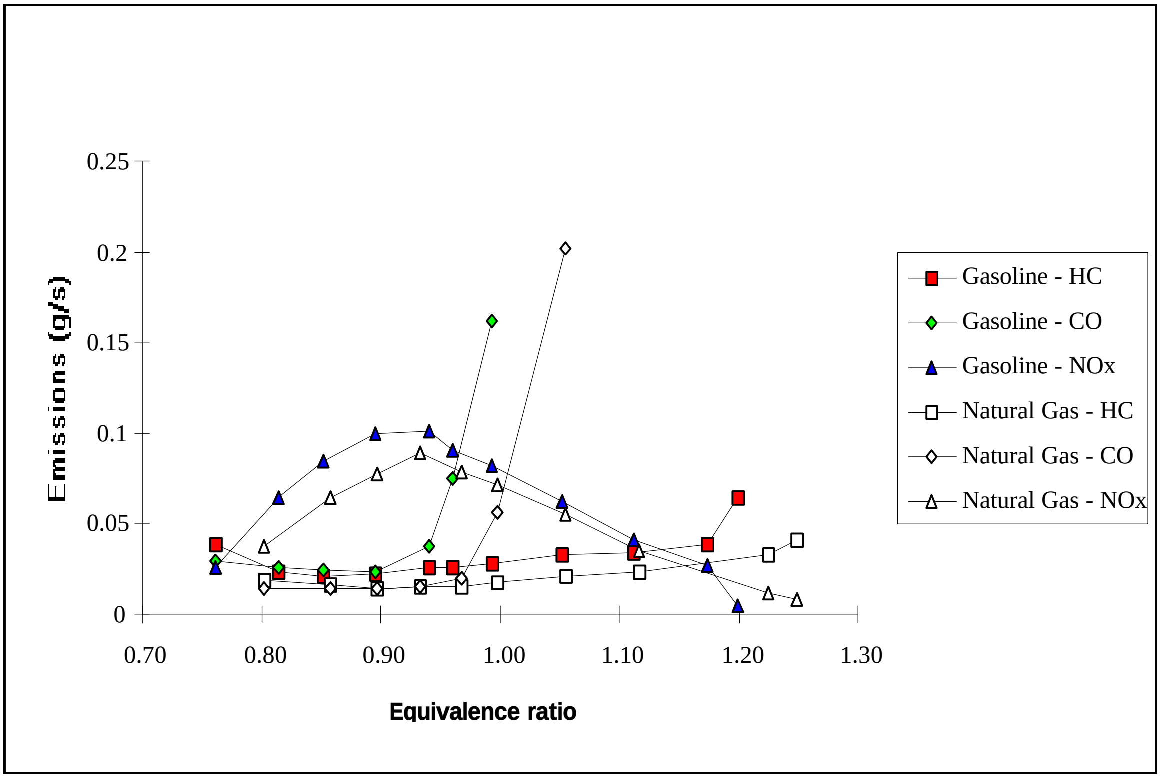

Figure 1: Emissions as a function of Equivalence Ratio, ϕ, defined as $1/\lambda$, obtained from a dual fuel engine (Tennant, et al., 1994).

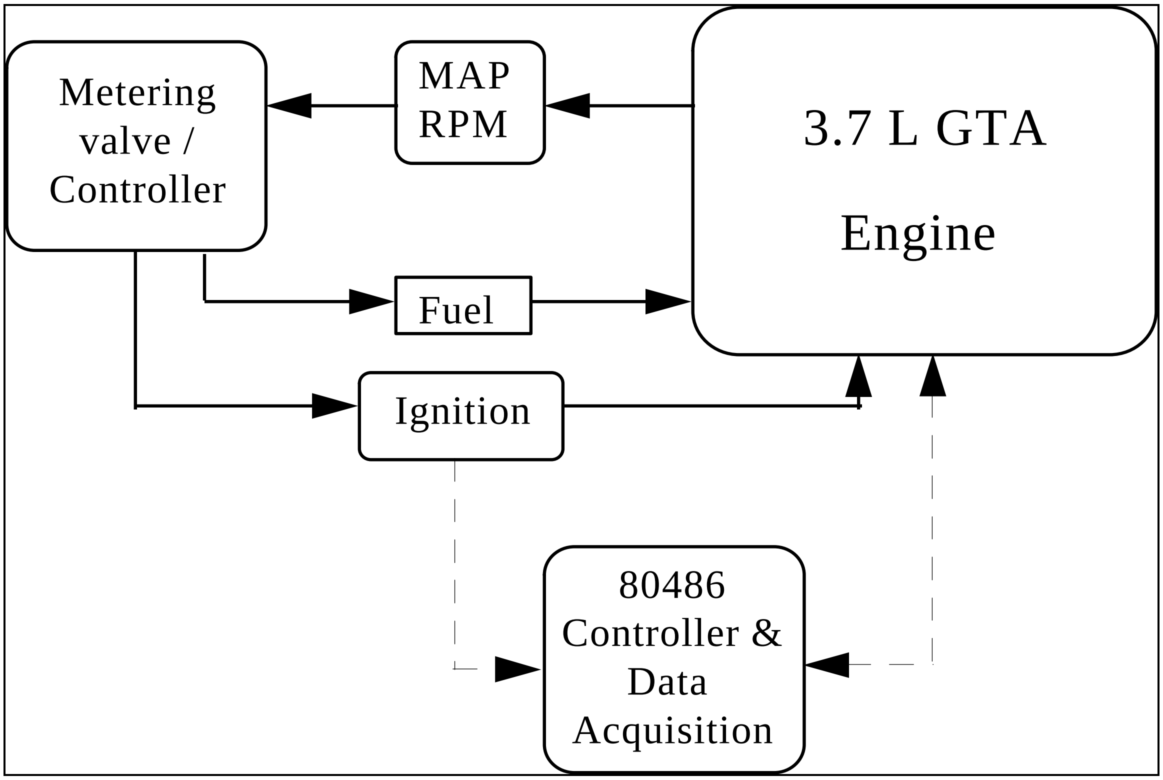

Figure 2: Open loop configuration with data acquisition shown.

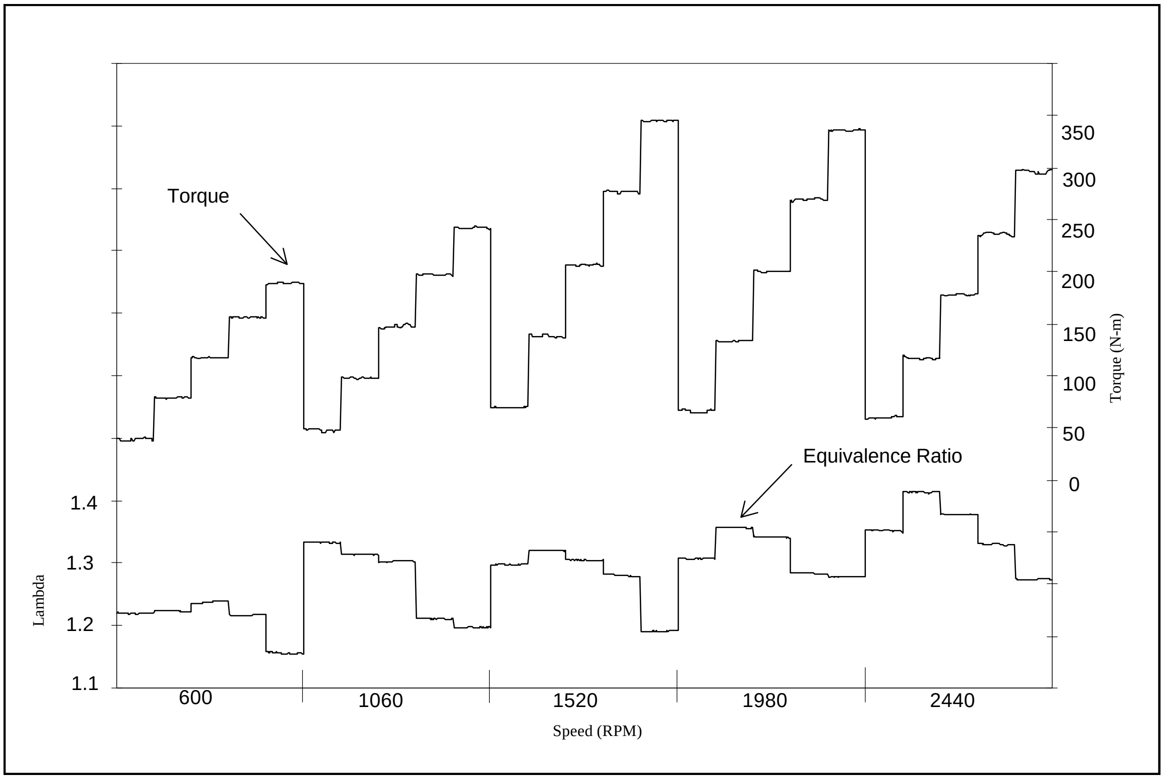

Figure 3: Hercules 3.7 L GTA - Representation of λ and torque vs. speed for 25 mode test.

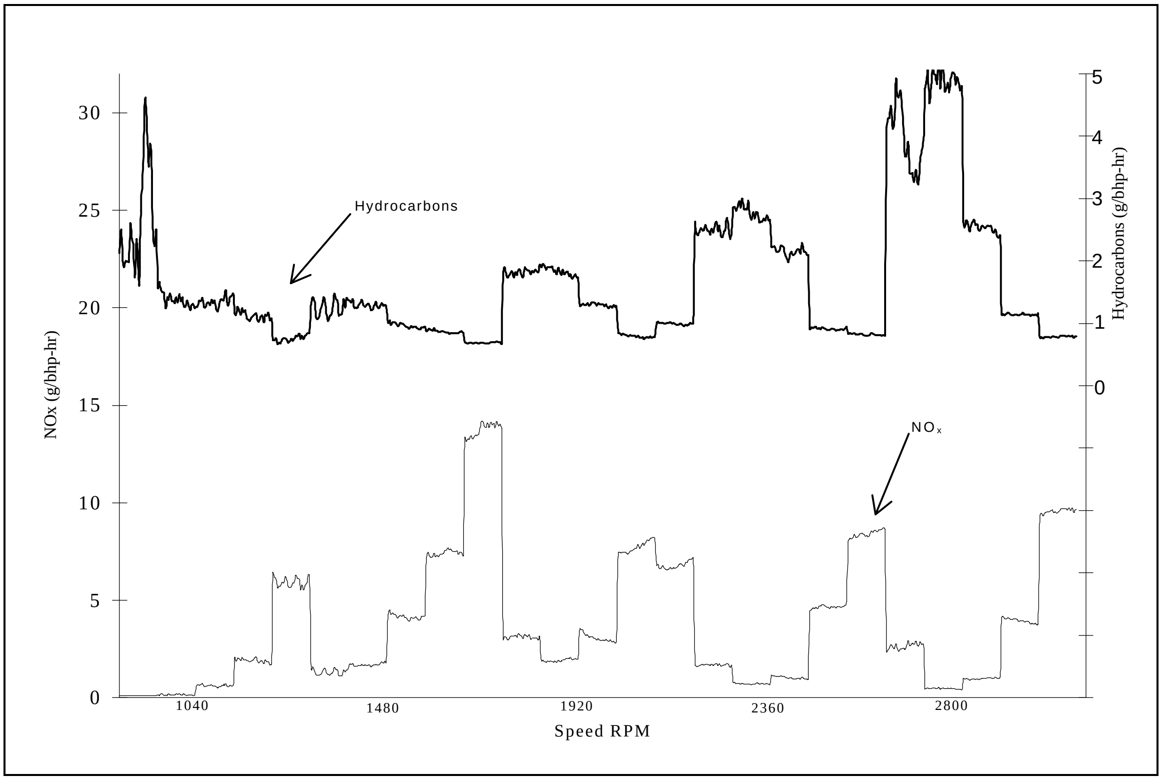

Figure 4: Mode test showing engine-out emissions.

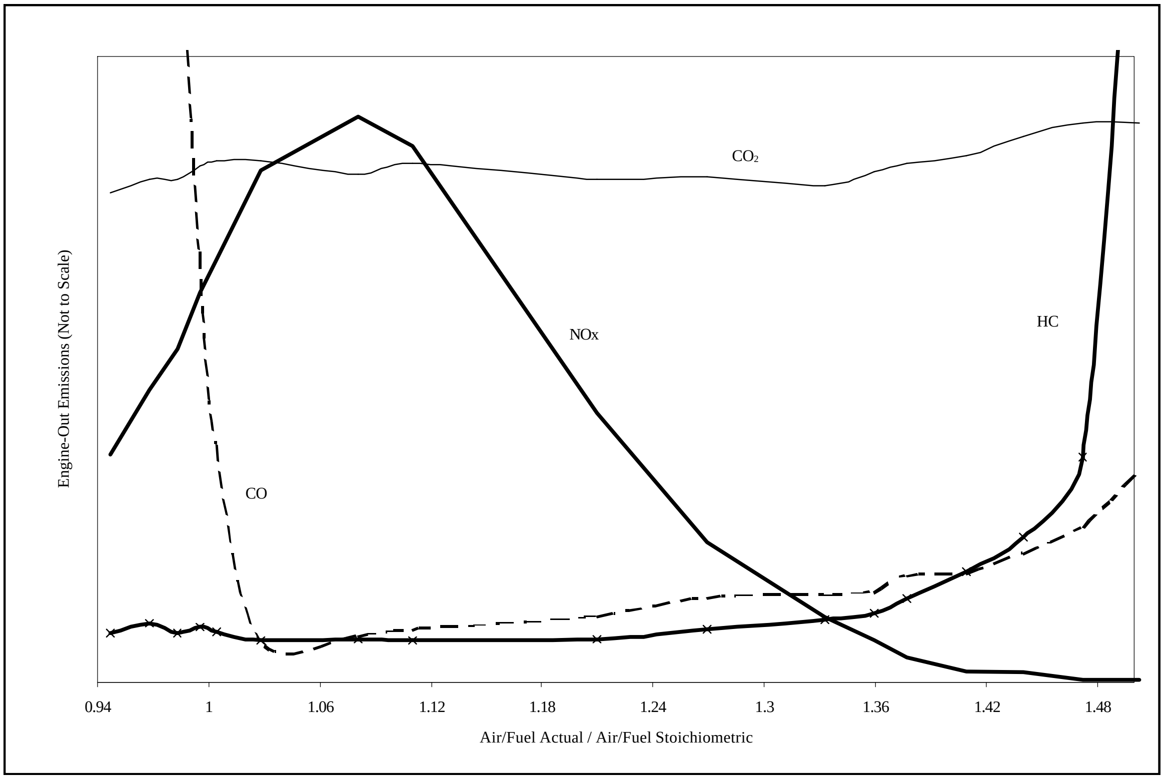

Figure 5: Relative engine emissions vs. λ for the lean burn natural gas engine.

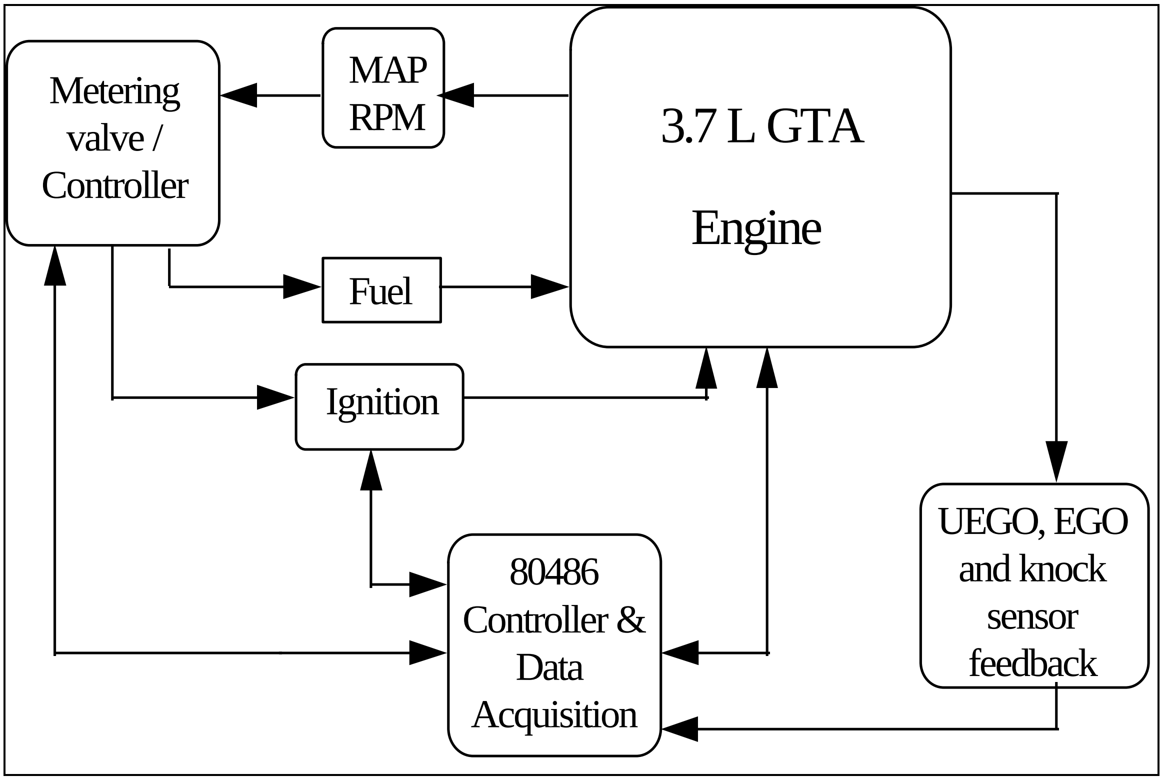

Figure 6: Closed loop configuration shown with added exhaust gas oxygen sensors and knock sensor.

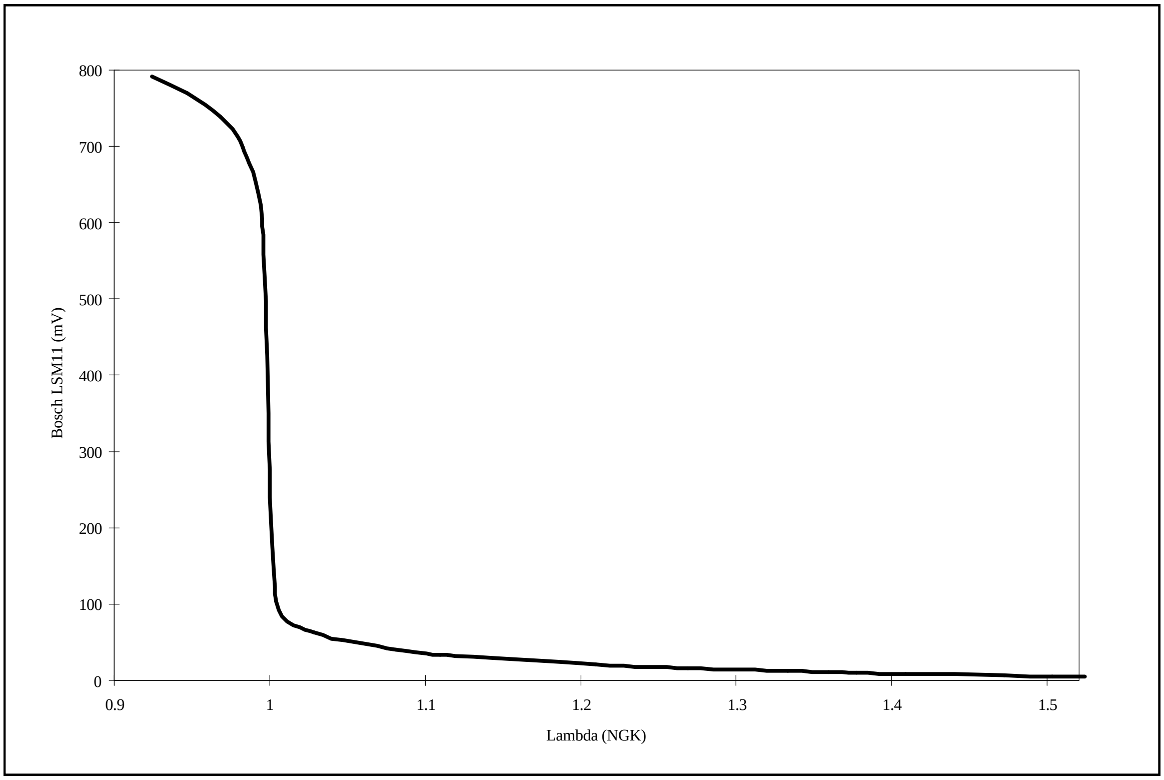

Figure 7: Bosch LSM11 output vs. NGK UEGO output.

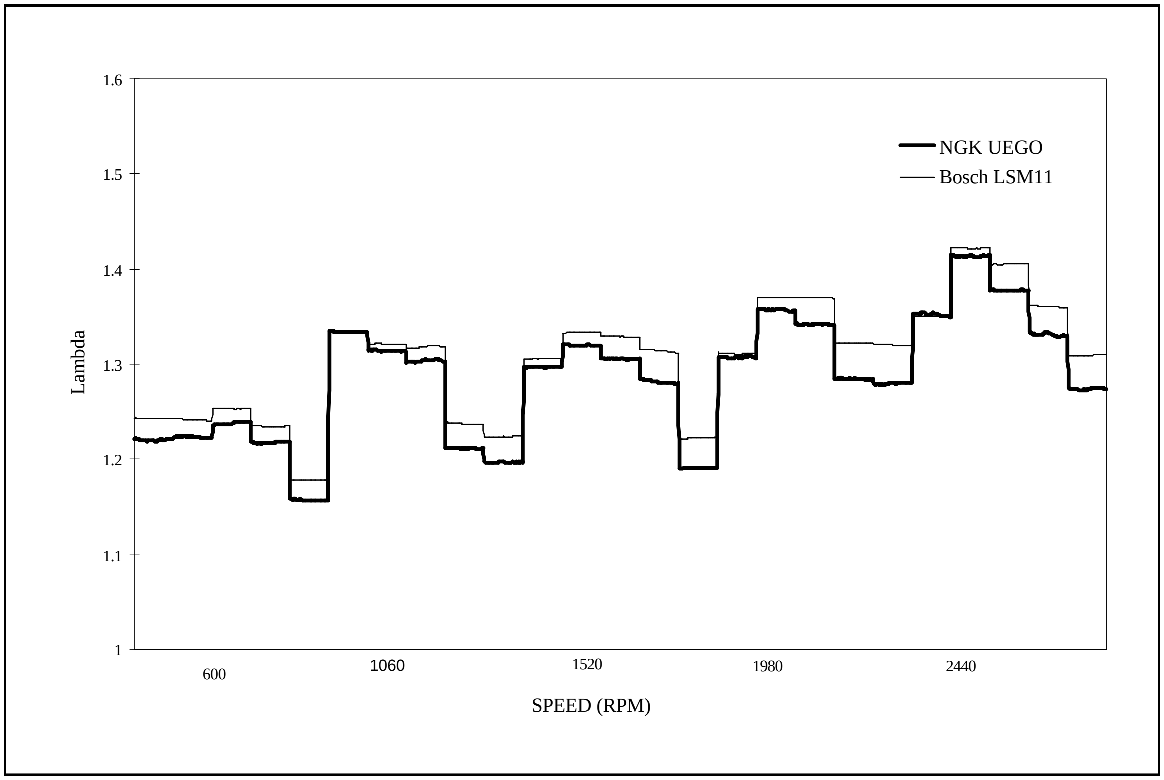

Figure 8: Oxygen sensor outputs during the 25 mode test.