Cycle-by-cycle AFR measurement of a cold start using an NDIR500 and HFR500.

Abstract

The cold starting of IC engines remains a significant source of emissions. A gasoline fuelled, passenger vehicle using a EURO IV calibration will produce up to 90% of its drive cycle emissions during the cold start (1). It is therefore important to be able to understand and analyse the cold start in detail. An engine calibrator can use cycle-by-cycle HC, CO, CO2 and AFR to analyse a cold start and make suitable changes to the ECU parameters to minimise emissions.

The document examines the cold start of a 1.8 litre PFI engine using Cambustion NDIR500 and HFR500. From this data λ (AFR normalised to stoichiometry) is calculated. This calculated λ is then compared to the value measured by a UEGO. Recommendations are given on possible changes to ECU parameters that will result in reduced emissions.

Introduction

This application uses fast response gas analysers to analyse a cold start of a gasoline engine. Fast analysers are necessary to fully analyse this part of the drive cycle. The crank and run-up of the engine occurs within 2-3 seconds and during this period the conditions in the engine are changing rapidly and significantly and consequently the instrumentation should be able to respond within fractions of a second.

Real time HC emissions have been measured since the 1990's but these are the result of the cold start transient and give little information about the cause of high HC emissions (eg: whether their origins were from partial burns or misfires that were too rich or too lean). The more recent introduction of the NDIR500 (Non-Dispersive Infra Red) for measuring CO&CO2 with a time response a T90-10 of less than 8ms has allowed a deeper understanding of the cold start process. The CO and CO2 data can be related to combustion AFR as Figure 1 shows.

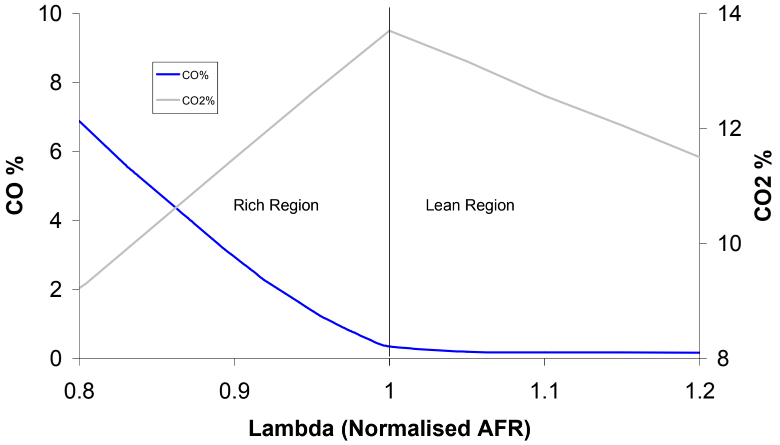


Figure 1: Variation of CO and CO2 with λ.

The traditional method of measuring AFR is to use a UEGO but this has two disadvantages for cold start work:

- The UEGO has a response time of around 100ms in normal use.
- High HC concentrations can cause an error on the UEGO output.

Experiment

The experiment uses a 1.8 litre PFI engine mounted on a cold start frame. The engine is instrumented with:

- Pressure transducer in the intake manifold.
- Pressure transducer mounted in cyl#3 through an offset spark plug.
- HFR500 and NDIR500 measuring from the same place 40mm downstream of the exhaust valve of cyl#3 (see Figure 2)
- An aspirated UEGO (Universal Exhaust Gas Oxygen; measures λ). Exhaust gas is ducted down a 400mm pipe at 6 l/min from a location within 10mm of the Cambustion analysers sample probes. (see Figure 2)
- The drive to the injector for cylinder #3 was logged.

A schematic for the instrumentation is shown in Figure 3.

Further apparatus included an 8-channel data acquisition system and an Excel macro written by Cambustion to calculate λ. Details of the calculation for λ are shown in Appendix A; the calculation takes into account the HC ratio of the fuel as well as oxygen content. The calculation used in this document takes into account unburned hydrocarbons to give a $\lambda_{exhaust}$ but can also be used to give $\lambda_{combustion}$ using only CO and CO_2.

The experiment consisted of starting the engine the taking 10 seconds of data. Five starts were conducted at an ambient temperature of 15°C±1°C. In order to give repeatable data the engine was run for 10 minutes after the cold start to condition the engine. Before the cold start the engine was manually cranked to TDC firing on cylinder #1.

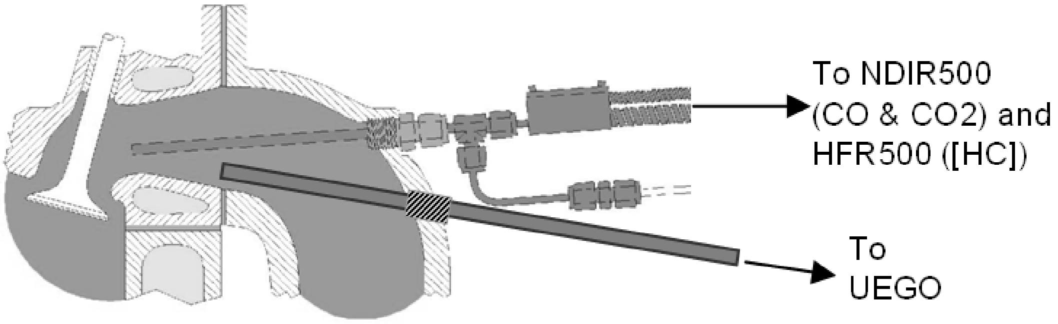


Fig 2: Positions of the sample probes in the exhaust port.

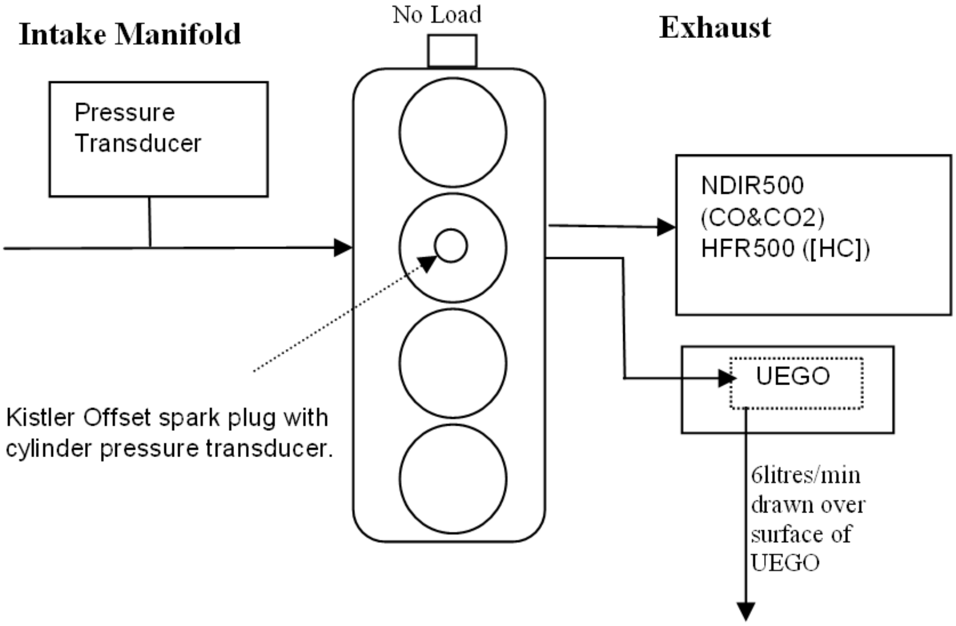


Fig 3: Engine and Instrumentation.

Results

Cold start #1 will be examined in detail in this document. The remaining starts are shown in Appendix B.

Analysis using engine instrumentation

The following analysis uses only cylinder pressure, inlet pressure and injector timing.

The results are presented on separate charts to ease analysis. Figure 4 shows the inlet manifold pressure, cylinder pressure and fuel injector for cold start #1.

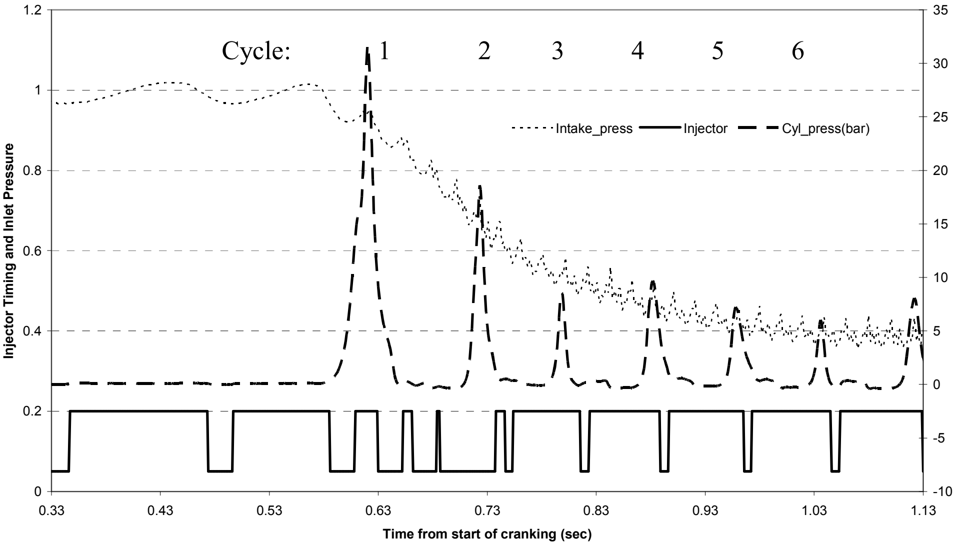


Fig: 4 Inlet Pressure, Cylinder pressure and injector timing for cold start #1.

The injector timing is displayed so that when the signal is low the injector is firing. The time axis is aligned so that t=0seconds occurs at the start of cranking.

Cycle # 1 combustion occurs at about 0.63 seconds. At this time the fuel injector is open for long periods to build up a fuel puddle in the inlet runner. Since the engine needs to reach idle speed a load is seen on this first cycle to increase the speed.

Cycle #2 also has a load above the idle load since the engine is still accelerating and the inlet manifold pressure is relatively high allowing charge into the cylinder. By this time the injector begins operating in a synchronous manner since the fuel puddle has been established.

Cycle #3. At the end of the power stroke the cylinder pressure is lower than during the exhaust stroke. This suggests that there has been a misfire or partial burn. Also the peak pressure for this cycle is lower than that of the subsequent cycle also suggesting poor combustion. There will be significant hydrocarbons resulting from this cycle.

Cycles #4+5. The cylinder pressure indicates that steady running.

Cycle #6. Again, there is a misfire or partial burn indicated by the cylinder pressure trace (peak pressure and pre-exhaust pressure). The following cycle has a higher peak pressure indicating that the engine has slowed as a result of this event.

An engine calibrator can take a guess at the causes of the misfires, since there is insufficient information to know if the flame has been extinguished on its rich or lean limit of flammability. Also there is no information about the overall emissions resulting from this cold start, so it is unknown what effect this will have on total cycle emissions. For a more detailed analysis the fast gas analysers are used.

Analysis using fast gas analysers

The results from the fast gas analysers are shown in figure 5. Each exhaust is clearly distinguished. Each time the exhaust valve opens there is a step change in gas concentration caused by the burnt gas from the previous burning cycle emerging from the cylinder.

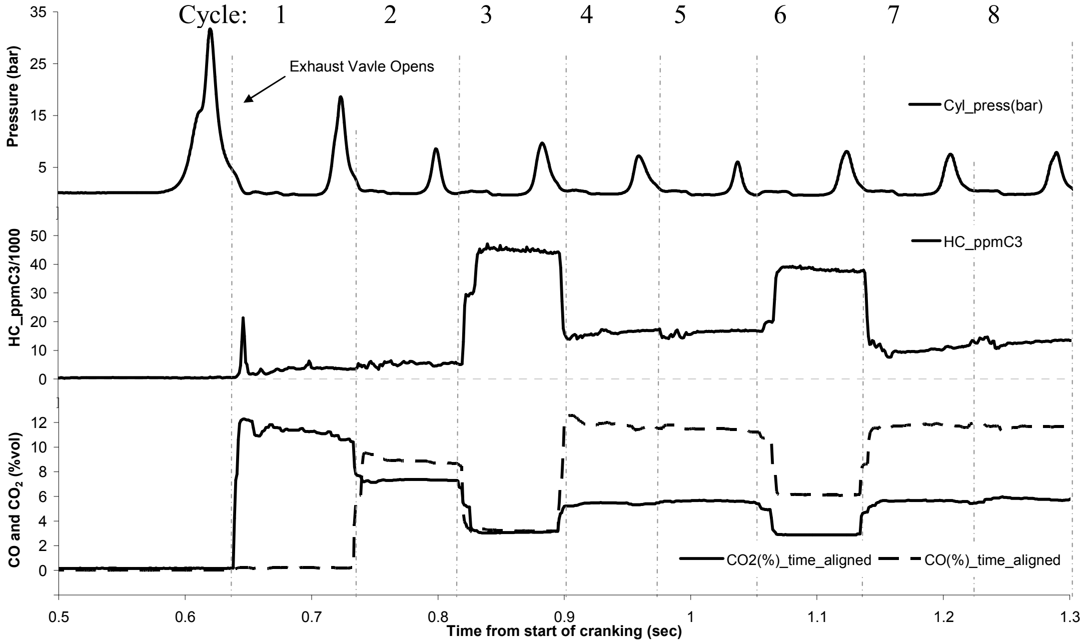


Fig 5: Inlet Pressure, Cylinder pressure and injector timing for cold start #1.

Cycle #1. The exhaust from this cycle shows the CO2 reaching 11% while the CO concentration remains very low. With reference to Figure 1 it is clear that this is a slightly lean combustion cycle. There is a spike of HC emissions that occurs on the first exhaust event. This is likely to originate from deposits that accumulated in the crevice of the exhaust valve. This could include unburned fuel, and deposited artefacts from the previous shut down of the engine.

Cycle#2. High CO levels appear in this cycle indicating a very rich burn. We already know that the injector has deposited a large quantity fuel into the intake runner by this time. For the intake stroke of cycle#2 the injector has been firing while the inlet valve is open. This will result in a large quantity of fuel directly entering the cylinder. This large amount fuel is the cause of the rich combustion.

Cycle#3. With reference to figure 4 it has been established that there was a poor burn for this cycle. It is clear to see with the gas analysers that much of the fuel that has entered the cylinder never got burned as shown by the high HC concentrations emerging from this cycle. Both the CO and CO2 levels are reduced. However, it is interesting to note that the levels are not reduced by the same ratio. A complete misfire would result in dilution of CO and CO2 with the fresh charge. This dilution would reduce the concentrations by the same factor. Therefore, there has been some combustion during this cycle.

A closer examination indicates that the CO being more diluted than the CO2. Therefore during the burn the concentration of CO2 was higher than the concentration of CO. Referring to figure 1 we can see that this indicates a $\lambda>0.8$. Cycle #4 shows a condition where $\lambda<0.8$ (CO produced higher than CO2) and there is full ignition in this regime. The conclusion that can be now be drawn is that the flame for cycle #3 was extinguished due to the charge being too lean. This is not the conclusion that would be drawn based on HC alone, as this would suggest the charge being too rich.

It is possible that this lean combustion is due to the injector for cycle#3 firing for a much shorter time than for cycle#2, and furthermore it is no longer firing when the inlet valve is open. This could result in poor charge preparation for this cycle.

Cycles #4 & #5. Both of these cycles are very rich with CO being higher than CO2. This richness is likely to be a result of the lower intake pressure providing better vapourisation of the fuel and causing a larger quantity of fuel to be delivered due to a larger delta P across the injector.

Cycle #6. This cycle is a complete misfire since the CO and CO2 concentrations are reduced by the same ratio (about 50%). This is also indicated by the cylinder pressure trace. However, it is likely that this is a **rich** misfire. The inlet pressure is continuing to fall, the engine is warming up and more fuel is entering the cylinder in vapour form. The hydrocarbon levels are increasing during cycles #4 and #5 and by cycle #6 the mixture is too rich for combustion. The fuel injected from cycles#1 and #2 may have been residing in the intake manifold and only when the pressures were adequate has it vapourised and been taken into the cylinder.

Cycle #7 and beyond. This cycle is a firing cycle that again is very rich. However, for this cycles the inlet pressure is more stable and much of the liquid fuel in the inlet manifold will have been cleared, allowing for more stable operation. The trend from cycle #7 onwards is for rich combustion becoming less rich as the engine stabalises.

λ Comparison.

The data for CO, CO2 and HC was now processed to calculate $\lambda_{exhaust}$ for this start. The equations account for the HC ratio of the fuel as well the oxygen content. This value of λ is a measurement of what is presented to the catalyst.

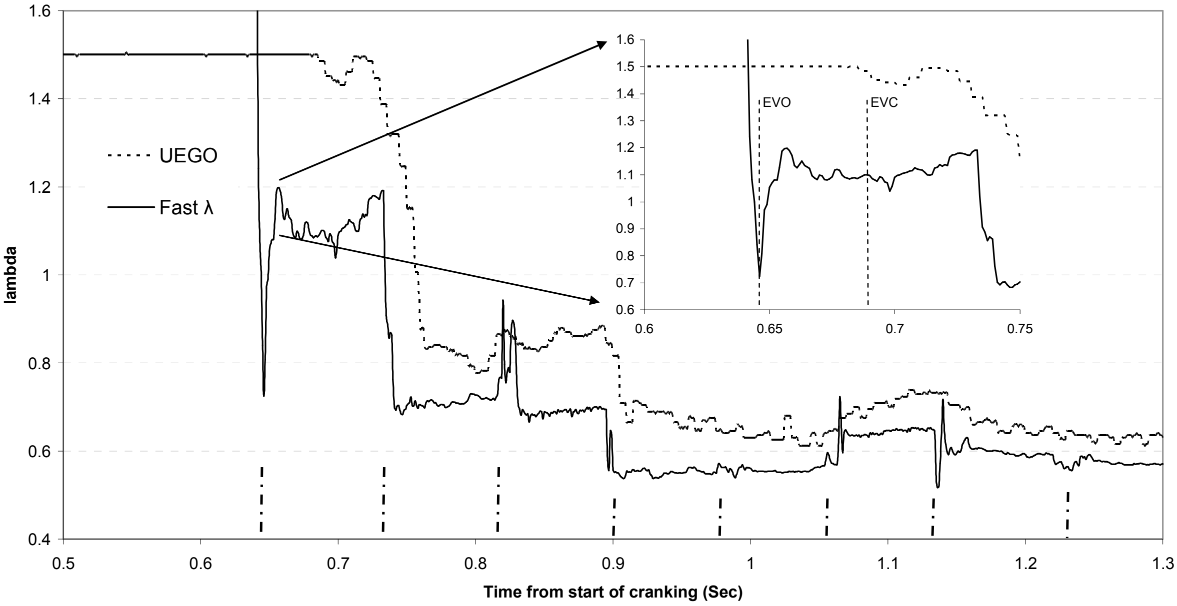


Fig 6: Calculated λ and UEGO for start #1.

It is again easy to see the step-response of the fast analysers each time the exhaust valve opens. There are some spikes that can be seen on the fast λ data and these are due to slight misalignment of the HC and CO&CO2 traces.

It can be seen that the general trend is for rich operation during these first few seconds. The fast λ responds to very first exhaust stroke. The UEGO is still in saturation at this time and takes a time to recover and it does not resolve the first exhaust stroke. The fast λ shows that this stroke is indeed lean although not far from stoichiometric combustion. There is unevenness in the λ throughout this stroke suggesting that the combustion was not very uniform. This is to be expected during the first few strokes where the cylinder contents may not mix well due to the lower air-flow and also due to the poor fuel vapourisation.

The next firing cycles (#2, #3, #4, #5, #6, #7) are rich. It can be seen that during this period there are differences in the λ calculated by the fast analysers and the λ measured by the UEGO. The UEGO is measuring λ to be more lean than the fast λ. This difference can be attributed to a lean shift in the UEGO due to the large amount of HC present in the exhaust. This is a well-known effect and caused by the HC changing the characteristics of the diffusion layer within the UEGO.

From about 2.8 seconds the UEGO and the fast λ are in better agreement due to the lower concentration of HC in the exhaust. This is shown in Fig 7.

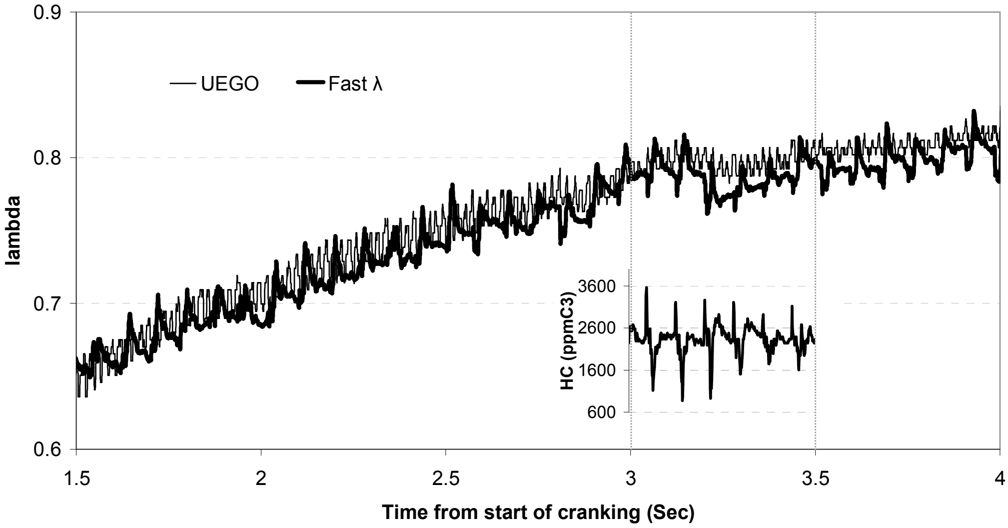


Fig 7: Comparison between UEGO and fast λ some time after the cold start.

There is still some high frequency detail shown on the fast λ. This is due to the rapidly changing HC output which changes as the exhaust is expelled from the cylinder. This is due to such as effects as valve crevice HC appearing as the exhaust valve opens and scroll-up (from the cylinder wall being pushed up by the piston) hydrocarbons appearing at the end of the stroke. This is shown by the inset on Fig 7.

Repeatability

The five cold starts show good repeatability. Fig 8 shows the cylinder pressures for the start and Table 1 shows the λ achieved on each of the starts. It can be seen that start #2 actually fired on the 6th cycle where all the other starts misfired. Cycle#2 was leaner for all the preceding cycles and this is what has prevented the rich misfire for cycle 6 (the reasons for the cycle 6 misfire for start #1 are given above).

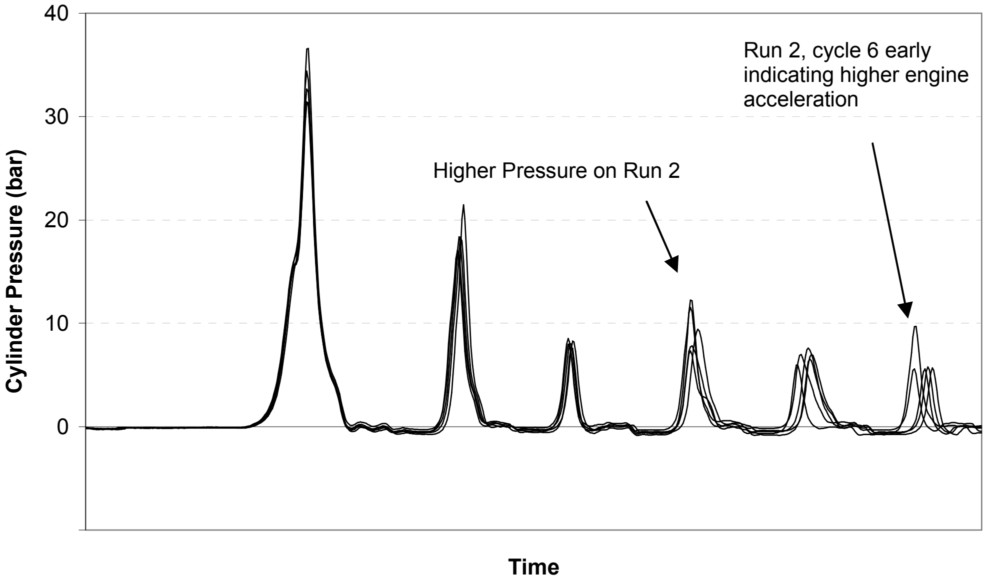


Figure 9: Cylinder Pressure for all cold starts.

Table of first 6 firing cycles.

run	cycle1(λ)	cycle2(λ)	cycle3	cycle4(λ)	cycle5(λ)	cycle6(λ)
1	1.12	0.71	M	0.55	0.55	m
2	1.14	0.75	M	0.56	0.62(m)	0.56
3	1.06	0.67	M	0.54	0.54	m
4	0.98	0.69	M	0.53	0.55	m
5	0.97	0.69	M	0.54	0.54	m

m=misfire

Table 1: summary of data for each of the starts.

Recommendations

Based on the above the analysis the following recommendations would be made with the aim of reducing cold start emissions.

To reduce the HC concentrations the misfires must be avoided. Cycle #3 misfire was shown to be a lean misfire. However, there is already a significant amount of fuel in the intake manifold. For this stroke it is likely to be beneficial to change the injector phase so that the fuel is applied as the inlet valve is open thereby depositing fuel straight into the cylinder.

This change in phase may mean that less fuel needs to be injected. This could result in leaner combustion during the following cycles, and this could prevent the misfire at cycle #6 (the leaner cycles of start#2 show this to be true).

There is a significant amount of CO released due to the richness of the fuelling. As described above a change in the phasing of the injection may result in less fuel being required and therefore leaner combustion. The injector can also be opened for shorter periods during cycle#4 and cycle#5 as there is now an abundance of fuel entering the cylinder. Again, a side effect of this change may be to prevent the misfire at cycle #6.

Conclusions

A technique for measuring λ with a time response of 8ms has been developed that is free from the diffusivity effects and poor equilibration of the mixture on UEGO sensors in the presence of high [HC] concentrations. This technique has been applied to cold start of a gasoline PFI engine and cycle-by-cycle data has been recorded. Good agreement to UEGO data was observed under steady running conditions. The technique has been shown to be repeatable and reliable.

The fast λ data will allow engine calibrators to develop cold start strategies optimized for reduced CO and [HC] emissions. Cycle-by-cycle λ could also be useful for improving fuelling for engine transients as well as steady state measurements.

APPENDIX A: EQUATIONS USED IN EXCEL MACRO

The iteration $(gas)_{wet} = (1-(H_2O)).(gas)_{dry}$ is used by the macro in all cases.

Mols O_2 required for complete combustion of one mole of fuel $C_nH_mO_r$.

$$n_{o_2} = n + \frac{m}{4} - \frac{r}{2}$$

(1)

Mols of products; (HC),(CO),(CO_2) mol fractions; hydrocarbons assumed same composition as fuel (C_nH_m).

$$n_p = \frac{n}{\left(n(HC) + (CO) + (CO_2)\right)}$$

(2)

Mol fraction (H_2O). Derived using (4) and H balance.

$$(H_2O) = \frac{m.\left(\frac{1}{n_p} - (HC)\right)}{2\left(1 + \frac{(CO)}{K.(CO_2)}\right)}$$

(3)

Mol fraction (H_2). K=water-gas reaction equilibrium constant also known as water-gas shift constant. Default value of 3.5$^{(3)}$

$$(H_2) = \frac{(CO).(H_2O)}{K.(CO_2)}$$

(4)

Mol fraction O_2;φ=3.773, mols N_2 per mol O_2 in air. Derived from Σmol fractions=1, N balance and O balance. NO assumed negligible.

$$(O_2) = \frac{\left(1 - (HC) - (1 + \frac{\varphi}{2})\left((CO) + (H_2O)\right) - (H_2) - (1+\varphi)(CO_2) + \frac{r\varphi}{2n_p}\right)}{(1+\varphi)}$$

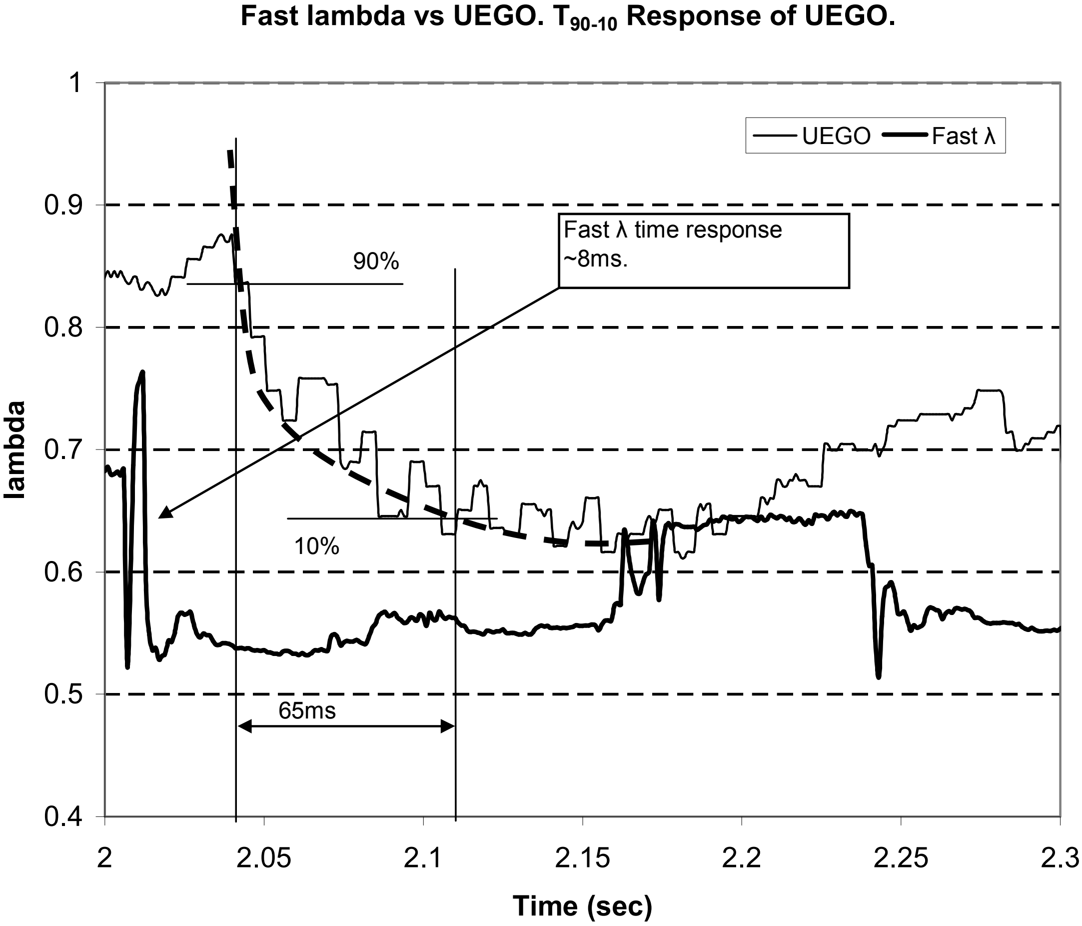
(5)

Ratio of oxygen species in exhaust to oxygen required for stoichiometric combustion.

$$\lambda = \frac{n_p\left((CO) + 2(CO_2) + 2(O_2) + (H_2O)\right) - r}{2n_{o_2}}$$

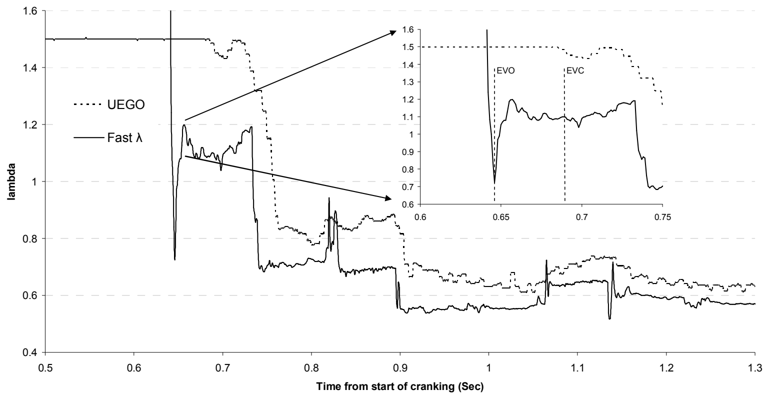
(6)

APPENDIX B: TIME RESPONSE OF ASPIRATED UEGO

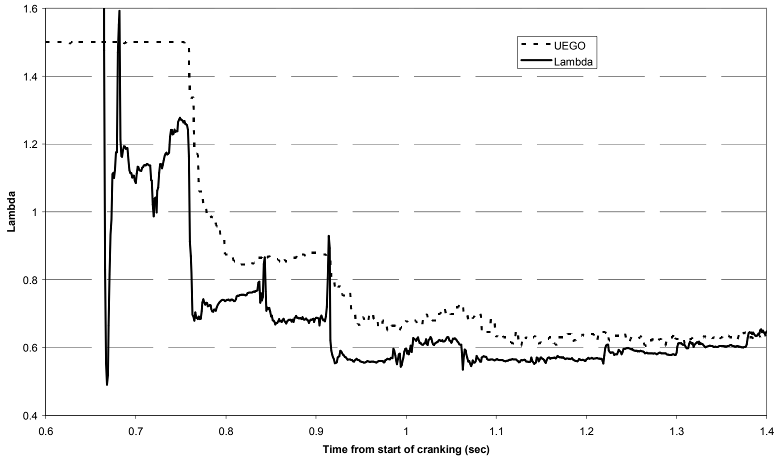


APPENDIX C: FAST LAMBDA VS UEGO FOR ALL 5 STARTS.

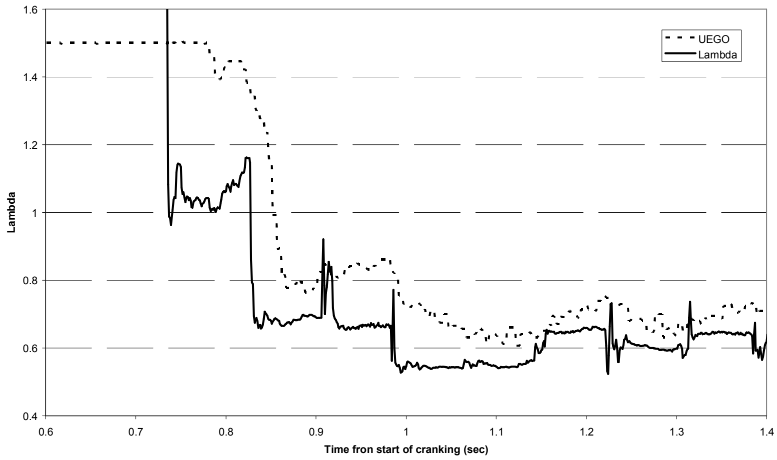
START 1:



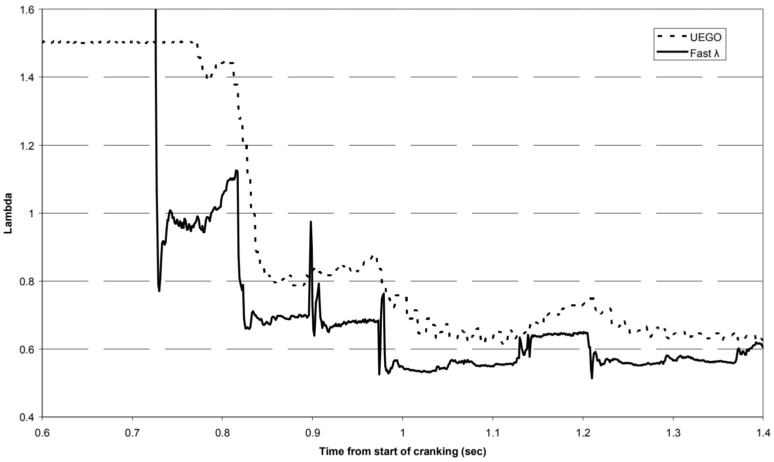
START 2:



START 3:



START 4:



START 5: