

Electronic Ignition and Fuel Injection Systems

Jakub Kot

Student Number: 1701919

BSc Motorsport Engineering – Year 1

University of Wales Trinity Saint David

Abstract

During this assignment two engines were tested, and their electronic systems compared. The collected data, including resistance and voltage values were compared to manufacturer specifications and explained, along with the collected scope patterns. The LE3 system was chosen over the Motronic to modify and improve, and the modifications were justified. The whole test was also evaluated and suggestions for improvements were made.

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1. Introduction

In this assignment, two separate engine control systems will be studied and tested to find out how they operate. Both systems are Bosch fuel injection systems, controlling GM (Vauxhall) engines. One of the systems is the LE3 system, operating an 18SEH engine, while the other is the Motronic system of a C20NE unit. Both of these are early electronic fuel injection engines with very outdated sensors and actuators, and very little emission control.

The aims of the assignment will be to carry out multiple systematic tests using a multi-meter and oscilloscope, compare the results with circuit diagrams and manufacturer's data, work effectively as part of a team during the testing process, and decide on any improvements that would be beneficial for one of the systems.

The tests carried out will include static voltages with both the ignition on and off, as well as dynamic tests with the engine running through a warm up phase and then at operating temperature. The results of these test should allow for evaluating and comparing both systems as well as determining exactly how they operate.

2. Methodology

The testing will consist of static and dynamic live engine tests on a specially prepared engine rig. This provides easy access to all the sensors, actuators, control units and connections which will be tested. This should not affect the results significantly compared to a car fitted with the appropriate control system, although temperatures may be slightly affected due to not having the confined space of an engine bay.

The equipment used will be a digital multi-meter and a Bosch oscilloscope. Digital equipment will provide very good accuracy of the results and is well suited to the task, as analogue equipment could potentially damage more sensitive electronic components. The multi-meter is quick and easy to use for measuring voltage and resistance values and therefore well suited to the static tests. For dynamic testing however, a multi-meter is not quick enough to capture the fast changes in voltage values and is unable to provide scope patterns. The Bosch oscilloscope also allows the accurate monitoring of engine temperature and battery voltage correction.

There are several health and safety to consider during testing. All team members taking part in the testing should be aware of the health and safety at work act and take reasonable steps to ensure the safety of everyone present. An exhaust fume extractor hose should be attached securely to the exhaust and the extractor fan switched on at all times when the engine is running. The main garage door to the workshop should be kept open during the test – this will impact on the results as the engine is not in a fully controlled cell, however this is necessary to maintain good ventilation and a healthy working environment. The PPE required will be protective boots and lab coats in case of any potential spillages. The engines will not be running at high load, so ear and eye/face protection will not be required. The final considerations for health and safety will be to avoid touching hot areas of the engine and stay clear of moving parts. Before starting the engine, the starter must make sure that everyone is clear of the rig and give a clear signal that the engine is about to be cranked over.

The testing procedures will begin with static testing with the ignition off. The battery voltage should be measured first for comparison, following by each pin of the ECU(s). This should then be repeated with the ignition switched on. Resistance values will be collected for the throttle position sensor, air flow sensor, coolant and air temperature sensors, idle valve, injectors, and HT leads. The dynamic testing will begin with cold cranking. The oil temperature and injector pulse width should be noted. During the warm up phase, both systems will be monitored for coolant temperature sensor resistance and voltage, as well as the injector pulse width. The Motronic system will also be monitored for air temperature sensor (NTC1) voltage, rotary idle valve keying ratio, charcoal canister purge valve activity, and lambda

sensor switching. These tests should be carried out for every 10°C until operating temperature is reached.

3. Results

The following voltage reading were collected from the static tests of the LE3 system:

Pin Number	Fuel ECU		Ignition ECU		Amplifier	
	Ign. OFF	Ign. ON	Ign. OFF	Ign. ON	Ign. OFF	Ign. ON
1	0	0.11	0	0.8	0	12.28
2	0	12.41	0	0.28	0	0.02
3	0	0	0	12.11	0	12.28
4	0	0.02	-	-	0	0.35
5	0	0.03	0	0.18		
6	-	-	0	0.02		
7	-	-	0	1.49		
8	0	0.81	0	1.08		
9	-	-	-	-		
10	0	0.15	0	0.33		
11	-	-	0	0.21		
12	0	12.44	0	0.24		
13	0	4.64	0	0.28		
14	0	5	0	5.02		
15	0	0.02	0	0.16		

The static battery voltage was measured as 12.57V. The cold cranking temperature was 16.9°C and the injector pulse width 195ms. The following table was generated during the warm up phase:

Oil Temp. (°C)	NTC2 Ω	NTC2 V	Injector time (ms)
20	1786	1.5	3.8
30	973	1	2.9
40	743	0.8	2.9
50	493	0.6	2.6
60	382	0.5	2.5

Finally, the following table shows the resistance values:

Component	Resistance Ω	Notes
HT lead 1	8570	
HT lead 2	8490	
HT lead 3	7330	
HT lead 4	5440	
HT lead - king	5620	
throttle switch	0	pin 2&18
throttle switch	∞	pin 3&18
aux air valve	46.2	
injector values 1	16	
injector values 2	16	
injector values 3	16	
injector values 4	16.1	

The following table shows the static voltage results for the Motronic system ECU. This system uses a single ECU to control both fuel and ignition.

Pin Number	Voltage (V)	
	Ign. OFF	Ign. ON
1	0	12.3
2	0	0.04
3	0	12.18
4	0	9.86
5	0	12.15
6	0	11.41
7	0	0.34
10	0	0
12	0	5.09
13	0	10.2
14	0	0.03
16	0	12.1
17	0	12.1
18	12.4	12.1
19	0	0.01
22	0	0.95
24	0	0.04
26	0	0.09
27	0	12.2
28	0	0.42
32	0	11.4
36	12.1	0.34
37	0	12.1
40	0	0.07
41	0	0.07
42	0	0.03
44	0	3.75
45	0	3.7
46	0	0.2
48	0	0.07
49	0	0.11
53	0	0.65
55	0	11.05

The battery voltage was measured as 12.45V. Cold cranking temperature was 17.9°C and the injector time was 19.4ms. The next table shows the resistance values:

Component	Resistance Ω	Notes
Throttle Position	2000	pins 1&2
Throttle Position	2560	pins 1&3
Air Flow	30	pins 2&4
Air Flow	560	pins 3&4
NTC2	2650	at room temp.
NTC1	2810	at room temp.
Idle valve	7.9	
Injector 1	15.9	
Injector 2	15.8	
Injector 3	15.9	
Injector 4	15.9	
HT Lead 1	18.7k	
HT Lead 2	17.7k	
HT Lead 3	14.7k	
HT Lead 4	20k	
HT Lead - King	Faulty	
Coil Primary	0.6	
Coil Secondary	7500	

The final table shows the results collected during the warm up phase testing:

Oil Temp. (°C)	NTC2 Ω	NTC2 V	NTC1 V	Injector time (ms)	Keying Ratio	EVAP	Lambda
20	1660	3.1	3.7	3.5	46%	off	off
30	1090	2.6	n/a	3.6	44%	off	on 36°C
40	650	2	n/a	3.1	43%	off	n/a
50	440	1.6	n/a	3	42%	off	n/a
60	300	1.2	n/a	3	44%	on 62°C	n/a
70	240	1	n/a	2.9	44%	n/a	n/a
80	250	1	3.4	3.1	45%	n/a	n/a

4. Analysis

During the static testing of the LE3 system, there were no live feeds found with the ignition off. This shows that there is no keep alive memory function for this system. With the ignition on, there is only one pin where the voltage reads zero. This is pin 3 of the fuel ECU, which is the injectors. These have a live feed via the fuel relay and are earth switched within the ECU. The resistance values are mostly within range in comparison to the manufacturer specified figures. The auxiliary air valve however has a resistance 6 Ohms higher than the specified figure – this could indicate a fault within the valve which could potentially affect the results of the whole test.

During the cold cranking test, the injector time was noted as 195ms. This must be an error, as this would be almost two full revolutions of the engine at 600rpm. This value should not be used for analysis without repeating the test.

This engine does not have a catalytic converter fitted, so it has a lower operating temperature of 60°C. The NTC2 ranges from around 1800 to 400 Ohms, and 1.5 to 0.5 volts. The injector pulse width ranges from 3.8 to 2.5ms. All three values reduce progressively with temperature as would be expected. Looking at the NTC2 vs Oil Temperature graph below (fig. 1) the curve almost plateaus at operating temperature. This suggests that this specific NTC2 sensor would not be suitable for an engine operating at higher temperatures. A resistance graph is much more accurate due to the high level of rounding in the voltage figures.

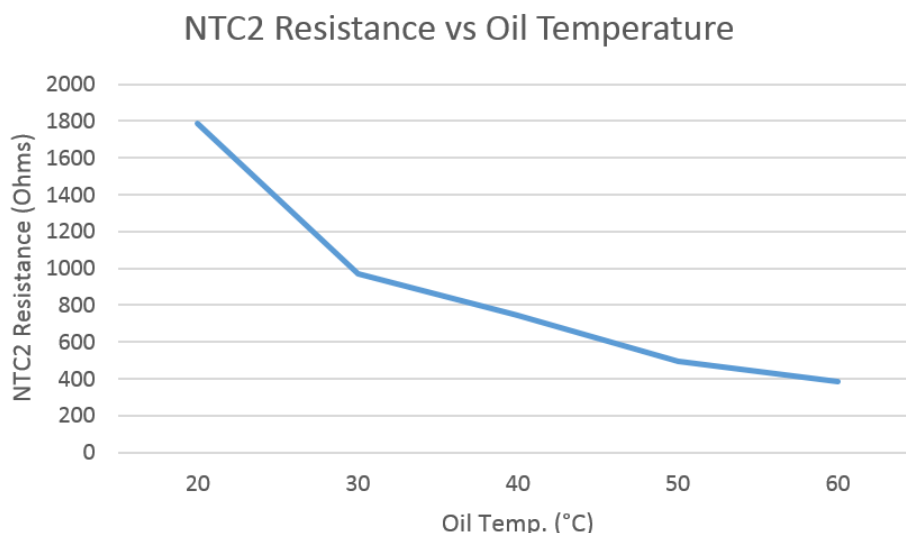


Figure 1: NTC2 Resistance vs Oil Temperature graph.

During the static testing of the Motronic system, two pins showed battery voltage with the ignition off. As the Motronic is one of the first systems with diagnostic capabilities, it requires a feed for the keep alive memory function (pin 18). Pin 36 also shows battery voltage, being the auxiliary supply. With the ignition on, pin 10 is the only pin showing strictly zero voltage – this is an earth connection.

During the resistance checks, it was found that most values were within, or very close to the manufacturer specified ranges. The throttle position sensor was an exception to this, as for pins 1 and 3 the resistance was 500 Ohms out of range, which could potentially affect the results of the tests. The Motronic system uses a potentiometer sensor compared to the LE3's throttle switch. This allows for varying load figures to be accounted for.

During cold cranking, the temperature was 1°C higher than that for the LE3. This must be taken into consideration when comparing to the LE3 figures. The injector pulse width was noted as 19.4ms – a far more realistic figure than that of the LE3. The injector pulse width cannot be ten times greater on one engine than another with such a small difference in temperature. This further proves that there must be an error in the reading for the LE3 system. During cold cranking, the ECU(s) takes into consideration values given by the coolant temperature sensor (NTC2) and air temperature sensor (NTC1) to give a longer injector pulse width for enrichment.

The Motronic engine uses a catalytic converter for emission control, and therefore has a higher operating temperature of 80°C. Looking at the NTC2 figures (and fig. 2) it can be noticed that the coolant temperature drops very slightly at an oil temperature of 80°C. This is possibly due to the cooling fan being in operation at this point. Looking at the NTC1 figures at 20°C and 80°C, there is a slight difference of 0.3V as would be expected. This is due to the air surrounding the engine warming up from the engine's heat – however I would expect a bigger difference if the engine was fitted in a car, due to the enclosed engine bay keeping more heat in. At 30°C, the injector pulse width increased by 0.1ms, indicating a possible error as it should be decreased. This could be that the pulse used for the measurement was too early and still involved some start up enrichment. At 60-70°C, the pulse width should theoretically increase due to the additional load from the cooling fan. This again, could indicate errors in the measurements. Looking at the keying ratio figures, this can be seen as an increase in keying ratio to maintain idle speed with a higher load. The evaporative emissions valve was witnessed to start operating at 62°C but this is not an accurate representation of when it actually begins operating. The lambda sensor signal was first witnessed at 36°C, and again this is not an accurate representation of operating temperature. The lambda sensor will also be more dependant on exhaust gas temperature, rather than engine temperature. The engine operates in open loop – meaning that it uses pre-programmed figures and cannot adjust the air fuel ratio. Once the lambda sensor is up to temperature, the system starts operating in closed loop, taking oxygen readings from the sensor into account and adjusting the fuelling accordingly to the exhaust oxygen content.

Figure 2 below shows the NTC2 vs Oil temperature graph for the Motronic system. The range in this case is between around 1700 and 250 Ohms, slightly lower than the LE3. The curve shape is very similar to the LE3 systems, but can actually be seen to plateau and rise again slightly at 80°C. For a more useful comparison, the coolant temperature itself should be measured separately to see how it differs from the oil temperature.

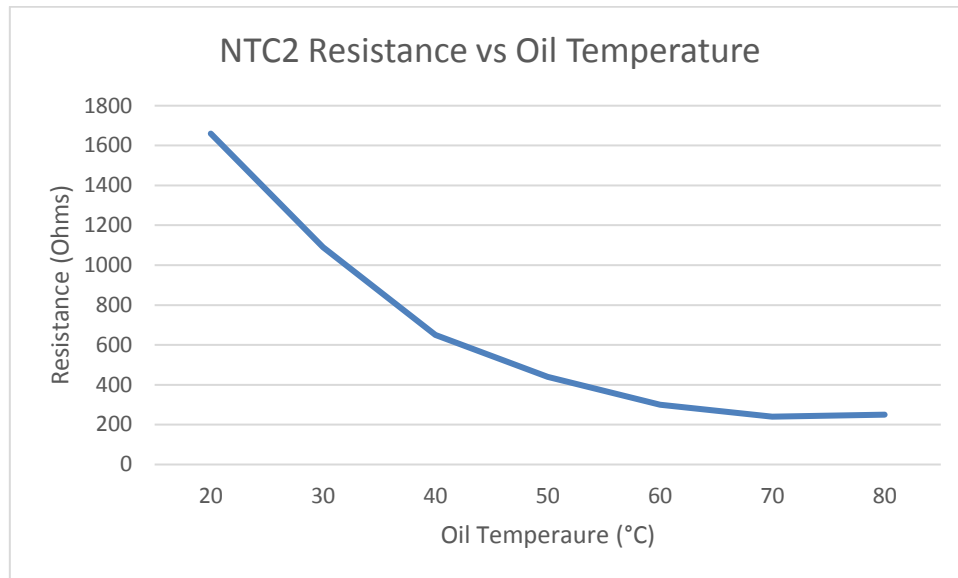


Figure 2: NTC2 Resistance vs Oil Temperature graph for the Motronic system.

All scope patterns can be found in the appendices (pg 17). Appendix 1 shows the scope pattern for the Motronic injectors at 80°C and idle speed. There is a potential voltage of around 12V until the injectors are switched, at which point the voltage drops to 0V. The pulse width of the injectors is measured over the 0V time, in this case 2.99ms. Back EMF is then seen as the injector closes – this is due to the very high frequency at which the injector is pulsed. The same pattern can be seen in appendix 12, which is the injector pattern for the LE3 system.

Appendix 2 shows the scope patterns for pins 16 and 17 of the Motronic ECU. Both of those pins are used to control the injectors – this could suggest batch injection. Looking at the scope patterns however, it is clear that both pins are switched at the same time, proving that the system operated in simultaneous injection. In comparison, the LE3 system also operates using simultaneous injection, but using only one pin connection.

Appendix 3 shows the injector pattern for the Motronic under snap acceleration conditions. The injector pulse width increases dramatically to 7.95ms to overcome the expected higher load. The frequency of injections increases with the increasing engine speed. Appendix 13 shows the same pattern, but for the LE3 system.

Appendix 4 shows the Motronic's injector pattern under deceleration. The ECU recognises that the high engine speed and lack of load do not require fuel to be injected and puts the engine into overrun mode. The injectors remain closed until the engine speed drops down to idle and fuel is required to maintain the engine at idle. Again, the same can be seen in appendix 14 for the LE3 system.

Appendix 5 shows the lambda sensor scope pattern for the Motronic. This can be seen to vary as the engine adjusts the air/fuel mixture. Normally, this will give an average ratio of 14.7:1 (which is the ideal stoichiometric ratio) with the exception of mainly cold starts and wide-open throttle. The LE3 system does not monitor the exhaust oxygen content.

Appendix 6 shows the speed sensor scope pattern for the Motronic. A sinusoidal waveform can be seen, with a missing tooth to indicate crankshaft position. This allows the ECU to inject at the correct times and adjust injector pulse width to the engine speed. As this system uses a single ECU, this analogue signal is the only engine speed signal required. The LE3 system has a similar crank signal (appendix 16) but also sends a digitised, square wave speed signal from the ignition ECU to the fuel ECU (appendix 15).

Appendix 7 shows the patterns for both of the load sensors found on the Motronic system – the air flow meter (pin 7) and the throttle position sensor (pin 53). Both patterns are very similar and show that the sensors work in unison. The ECU will use both figures to calculate the engine load and adjust the fuelling accordingly. The LE3 system uses a throttle switch, which can only have two settings – low or high load.

While the LE3 uses an auxiliary air valve, mainly for cold starts, the Motronic system has a rotary idle valve. This uses a keying ratio (appendix 8) to adjust the idle air. This can be used not only to help with cold starts, but also to maintain the idle speed with load changes (such as cooling fans). The Motronic applies the keying ratio over a time of 10ms. The time spent switched on (0V) is the keying ratio, as a percentage. A higher keying ratio allows more air to pass through into the intake.

Appendix 9 shows the live feed and earth for the ECU, simply to show that the patterns are opposite to each other. This can be seen in appendix 14 for the LE3 system.

Appendix 10 shows the secondary pattern for the ignition coil on the Motronic system. There is a high jump in voltage to start with, which is the actual voltage sent to the spark plugs. The section where the voltage stays at around 2kV is the spark duration, after which some coil oscillations can be seen. Further along the scope pattern where the voltage drops again, the dwell time starts for the next spark. Older systems had a fixed dwell time, which caused overcharging at low rpm and a weak spark at higher rpm. Both the systems tested use a constant energy system – the dwell time is adjusted to provide the correct amount of energy for the engine speed. This can also be seen in appendix 18 for the LE3 system.

Appendix 11 shows the primary waveform for the Motronic. This is a very similar pattern to the secondary. The dwell time is seen where the voltage shows 0V. This time, the spike in voltage is back EMF. This can be seen in appendices 19 and 20 for the LE3 system.

Looking at the LE3 systems, many different modifications could be made to improve the system. This system relies on three main electronic components – fuel ECU, ignition ECU and the amplifier. An improvement would be to have these three components combined into one, like on the Motronic system. This means that multiple control units do not have to communicate – there is less wiring, complexity and potentially faster reaction from the system to changing conditions. From a maintenance point of view however, amplifiers can often fail, and replacing an ECU with an amplifier built in would be a waste of customer's money, and a waste of resources with a bigger negative impact on the environment. My suggestion would be to combine the fuel and ignition ECU's with a separate amplifier.

In terms of air metering, an improvement on both systems would be a hot film air flow sensor. This type of sensor still has its disadvantages with maintenance and reliability, and therefore my suggestion would be to fit a piezo crystal manifold absolute pressure sensor. This would require the ECU to calculate the airflow, but these sensors are generally reliable, and an additional advantage is the removal of a restriction from the intake.

The auxiliary air valve could be replaced by a rotary idle valve, like that of the Motronic system. A further improvement from that would be a solenoid type idle control valve. This is more accurate as the duty cycle hold the plunger in the correct position and does not require any rotating parts.

A good modification for the fuelling would be sequential injection instead of simultaneous. Rather than injecting twice per revolution, the injector would inject the correct amount of fuel just before the inlet valve opens for its cylinder. This means there is less time for fuel to condense on the back of the valve and on the port walls, giving better fuel economy, reduced hydrocarbon emissions and potentially more performance. This will require the introduction of a camshaft position sensor to allow the ECU to know which cylinder is on its intake stroke. A hall effect sensor would be well suited to this task due to the lack of signal distortion.

In relation to the ignition system, there are many restrictions of the system used on the LE3. The distributor could be replaced with a coil pack, eliminating the mechanical disadvantage of the spinning rotor. This would then use a wasted spark system. My suggestion however, would be to go a step further and introduce coil-on-plug. This would eliminate the HT leads which have a high resistance and are prone to interferences. The spark plugs would also not be subjected to accelerated wear

like they would in a wasted spark system. Again, this would require a camshaft position sensor as explained above.

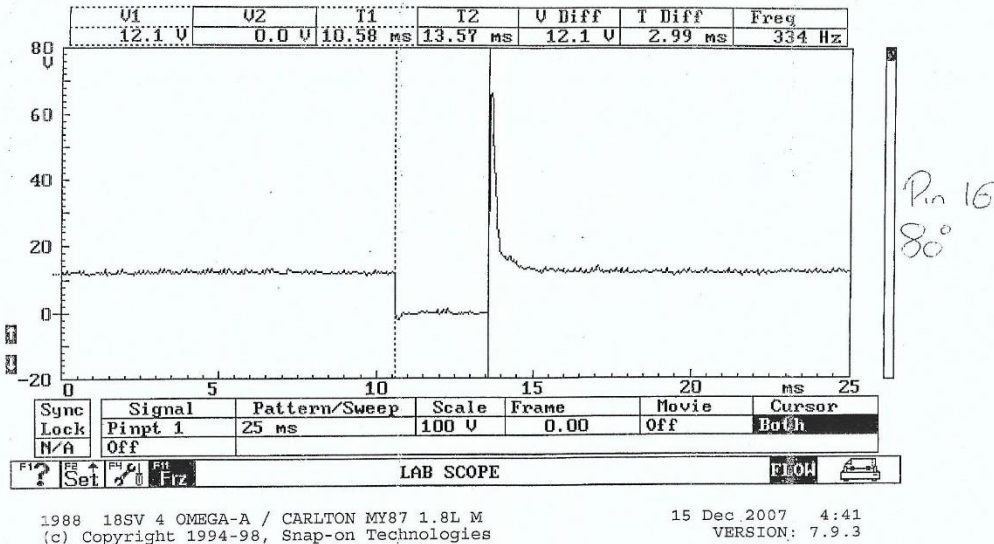
The final modification I would make is to introduce adaptive control measures. This includes a lambda sensor, as found on the Motronic system, and a knock sensor. The lambda sensor would allow the ECU to adapt to the oxygen content level in the exhaust and maintain the desired air/fuel ratio. The knock sensor would allow the ignition timing to be adjusted automatically and advanced much closer to knock without the risk of damaging the engine.

5. Evaluation

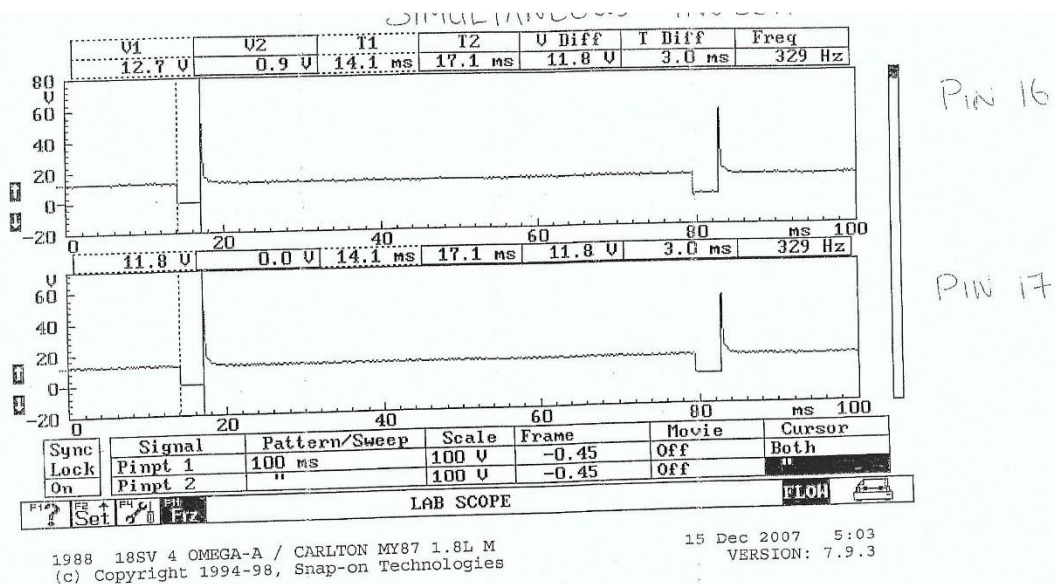
In conclusion, the aims of the assignment were successfully met, however the testing carried out on the two systems is not reliable enough to draw accurate conclusions. Each test should be repeated at least three times with the average being used for analysis. This would eliminate any errors made during testing and would validate the collected data. Many other improvements could be made to the testing procedures. The two engines were tested on different days with different weather conditions. One of the days had mixed weather, which would affect the atmospheric humidity levels throughout the test, especially with the door being open. For more valid results, the tests would have to be carried out in a closed, controlled cell. Unfortunately, this would require a lot more resources – firstly to have a controlled cell to test in, and secondly to have a remote data collection system installed on the engines as well as a remote-control system to operate the starter, ignition switch, and throttle. This would ensure that the collected data is valid without any health and safety compromises. The results collected can only be used to form a basic comparison.

6. Appendices

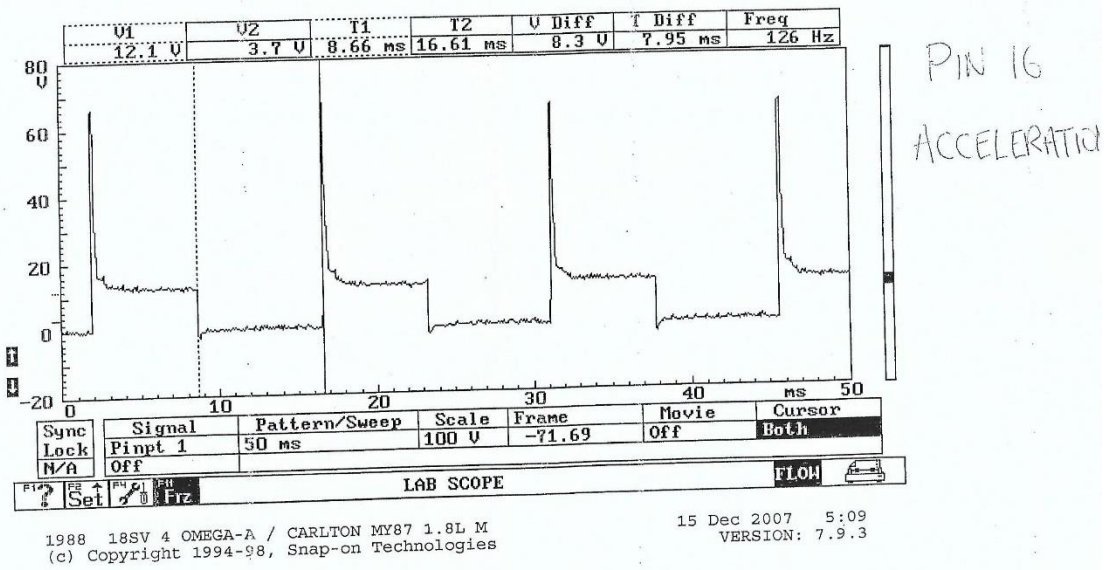
Appendix 1: Motronic injector scope pattern (pin 16).



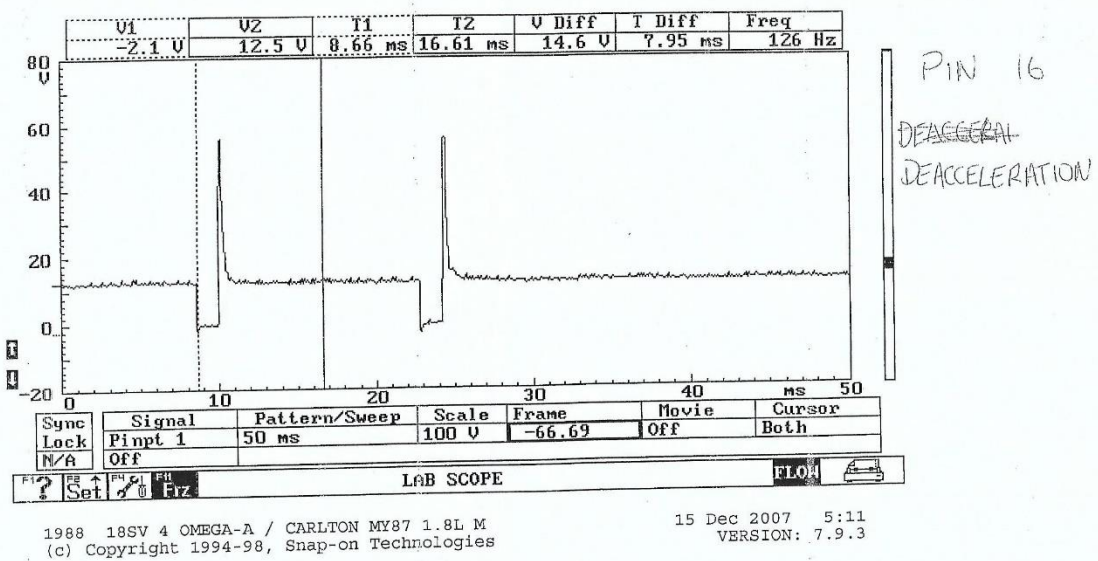
Appendix 2: Motronic injector scope patterns for both pins (16&17).



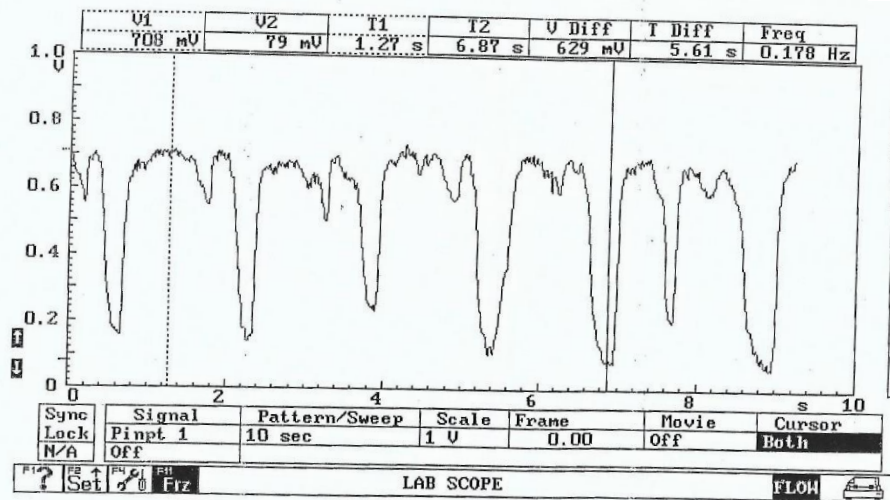
Appendix 3: Motronic injectors under acceleration (pin 16).



Appendix 4: Motronic injectors under deceleration (pin 16).



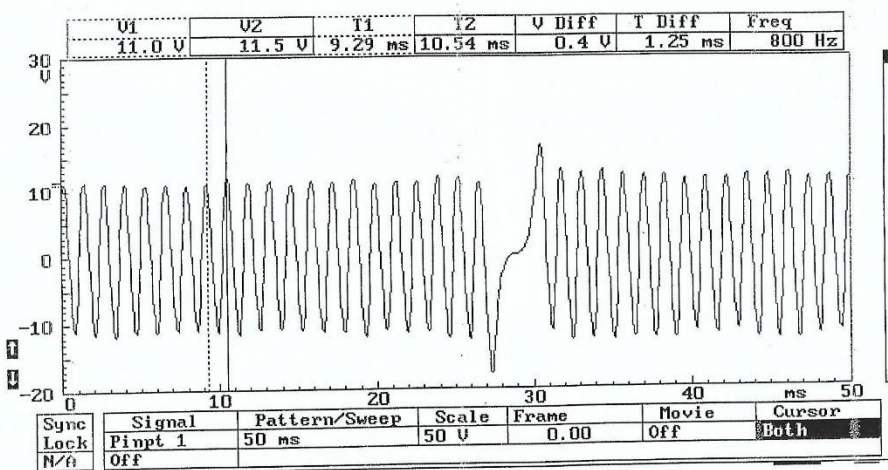
Appendix 5: Motronic lambda sensor scope pattern (pin 28).



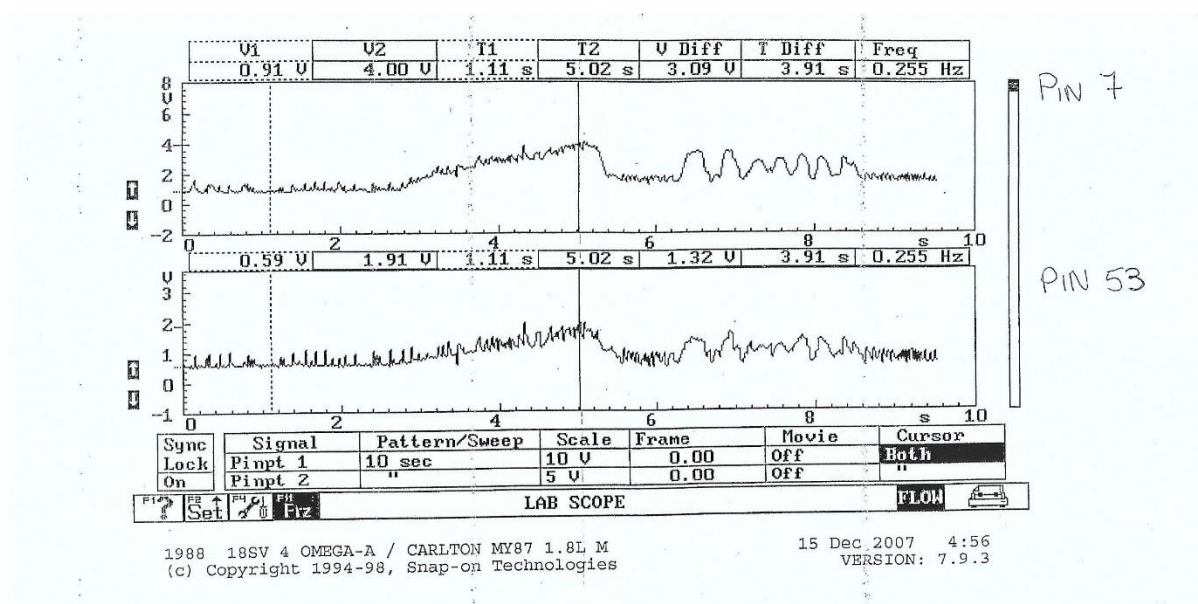
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(c) Copyright 1994-98, Snap-on Technologies

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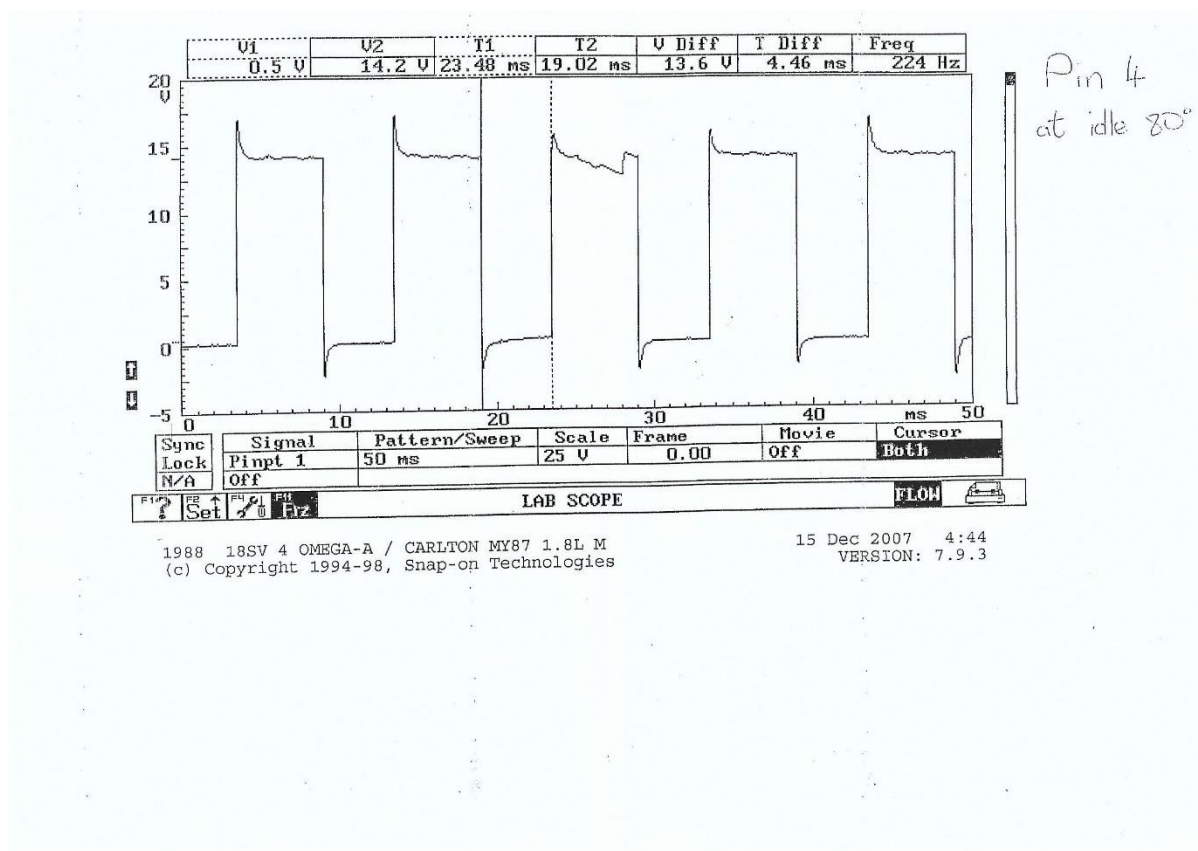
Appendix 6: Motronic speed sensor signal (pin 49).



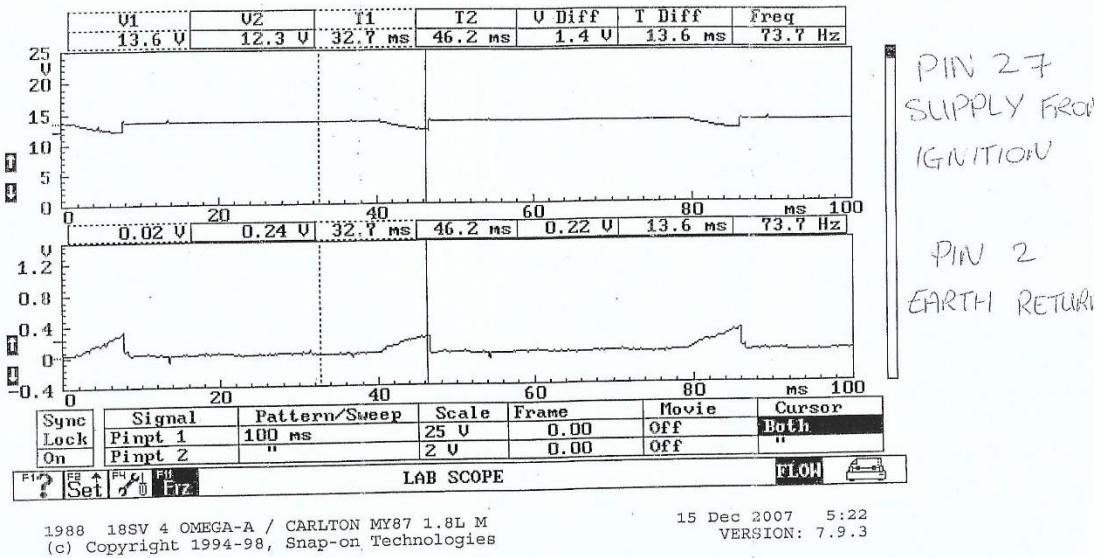
Appendix 7: Motronic airflow (pin 7) and throttle position (pin 53) scope patterns.



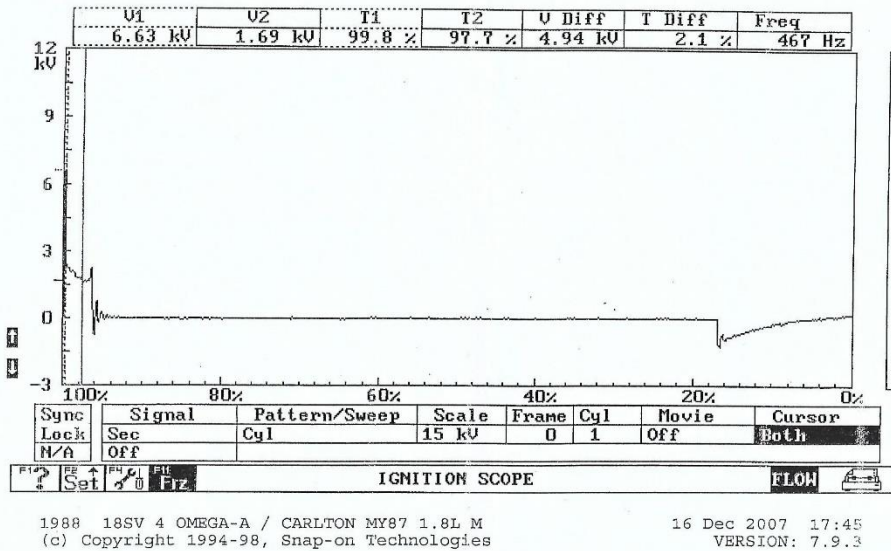
Appendix 8: Motronic rotary idle valve scope pattern (pin 4).



Appendix 9: Motronic live feed and earth to ECU (pins 27&2).

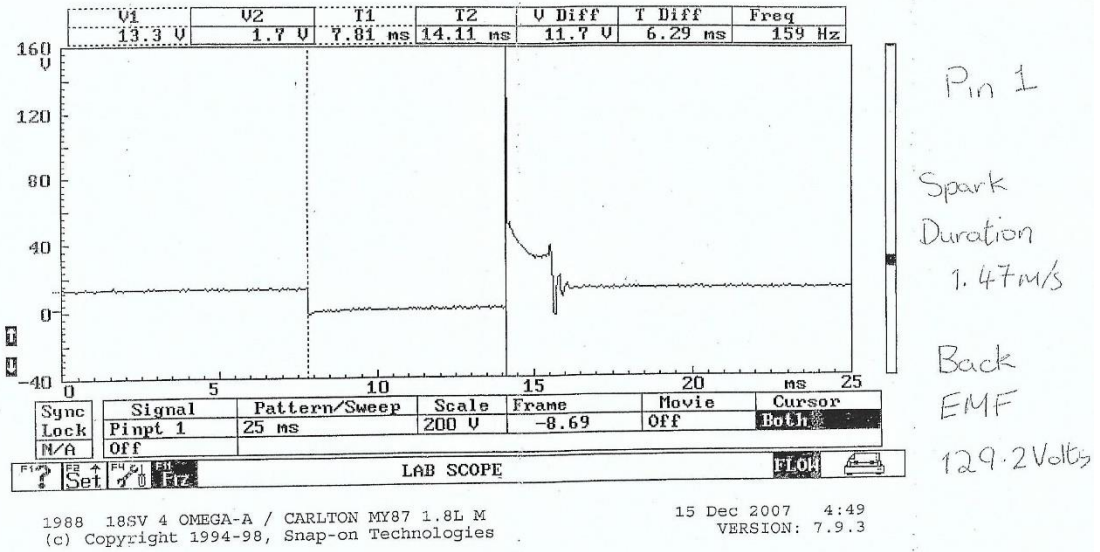


Appendix 10: Motronic ignition coil secondary waveform.

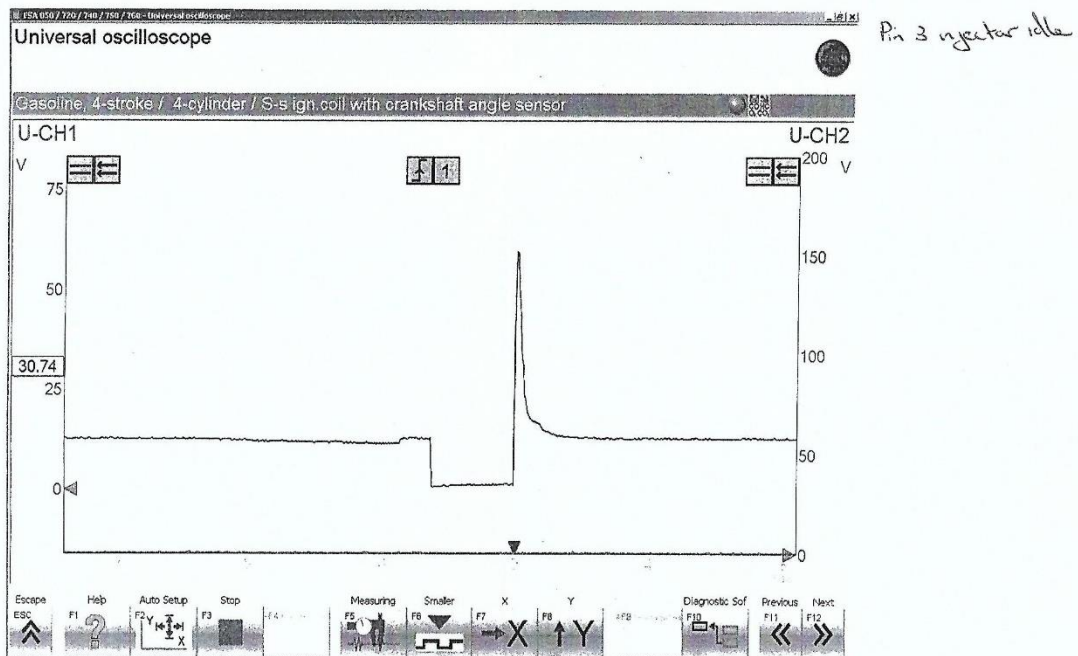


Secondary Wave Pattern

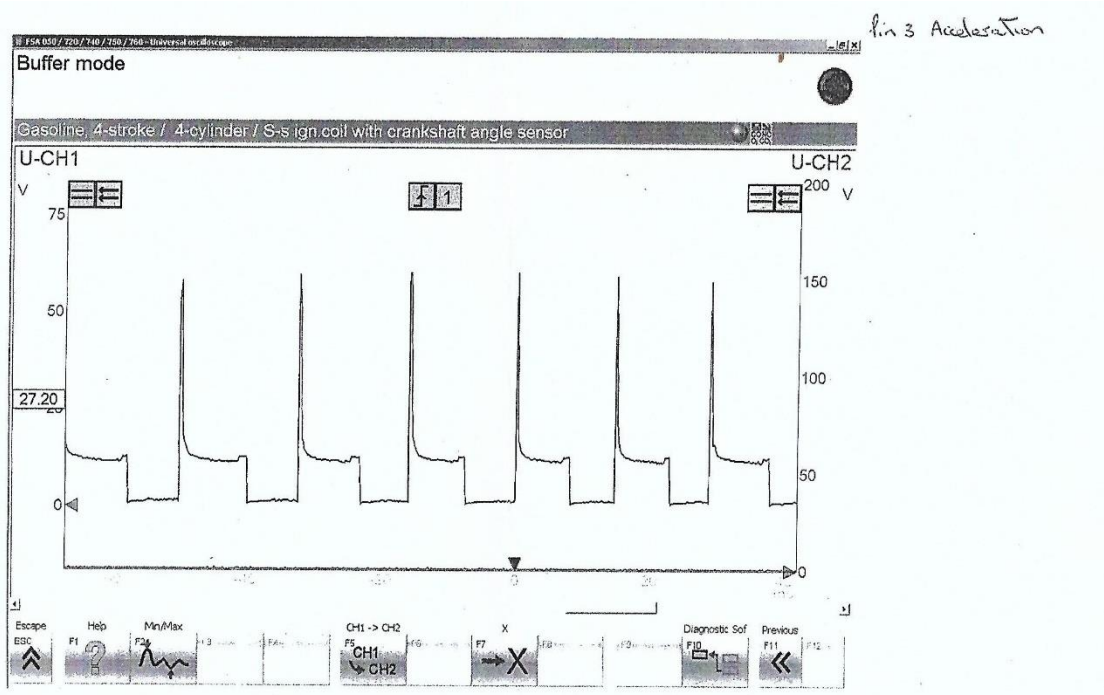
Appendix 11: Motronic ignition coil primary waveform.



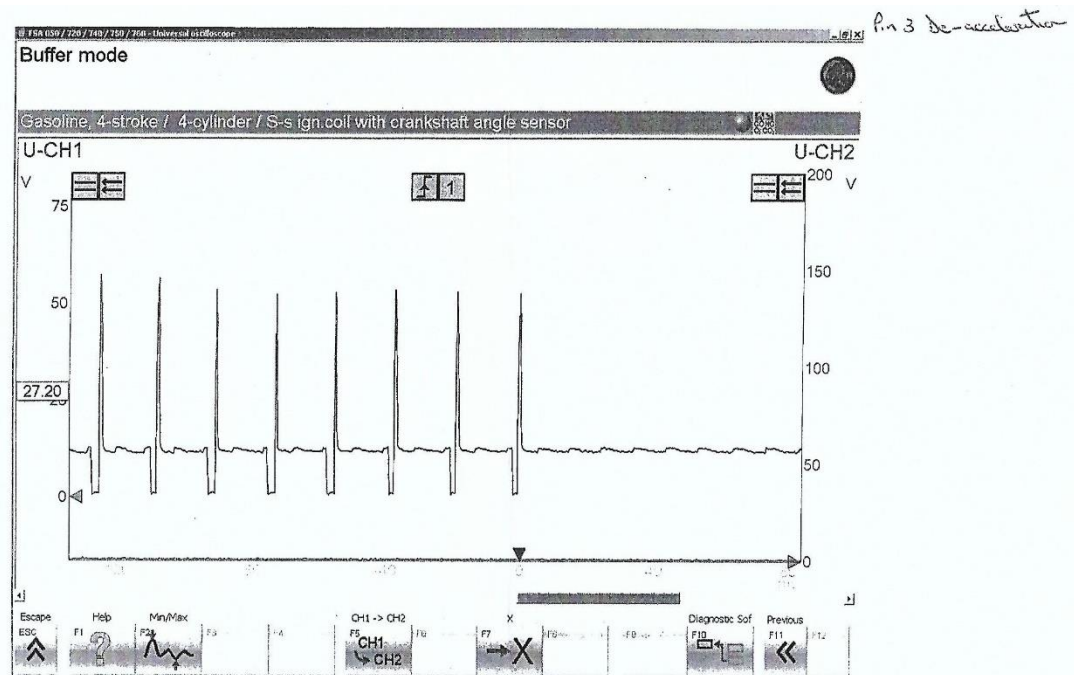
Appendix 12: LE3 injector scope pattern (pin 3).



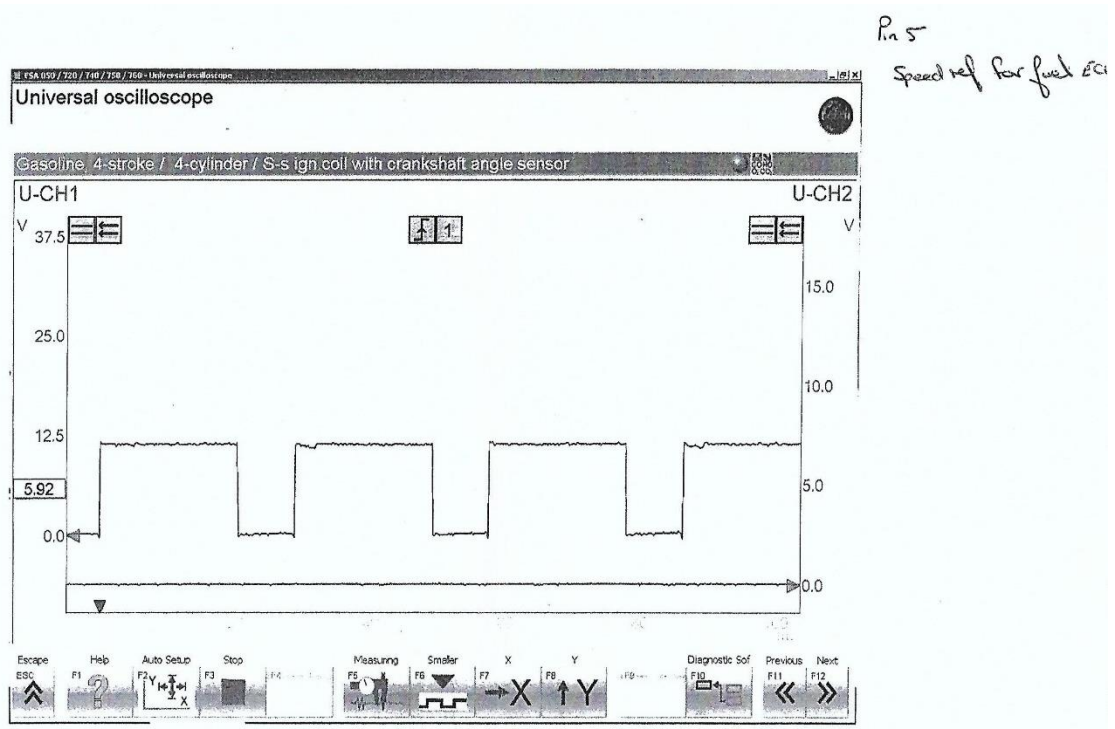
Appendix 13: LE3 injectors under acceleration (pin 3).



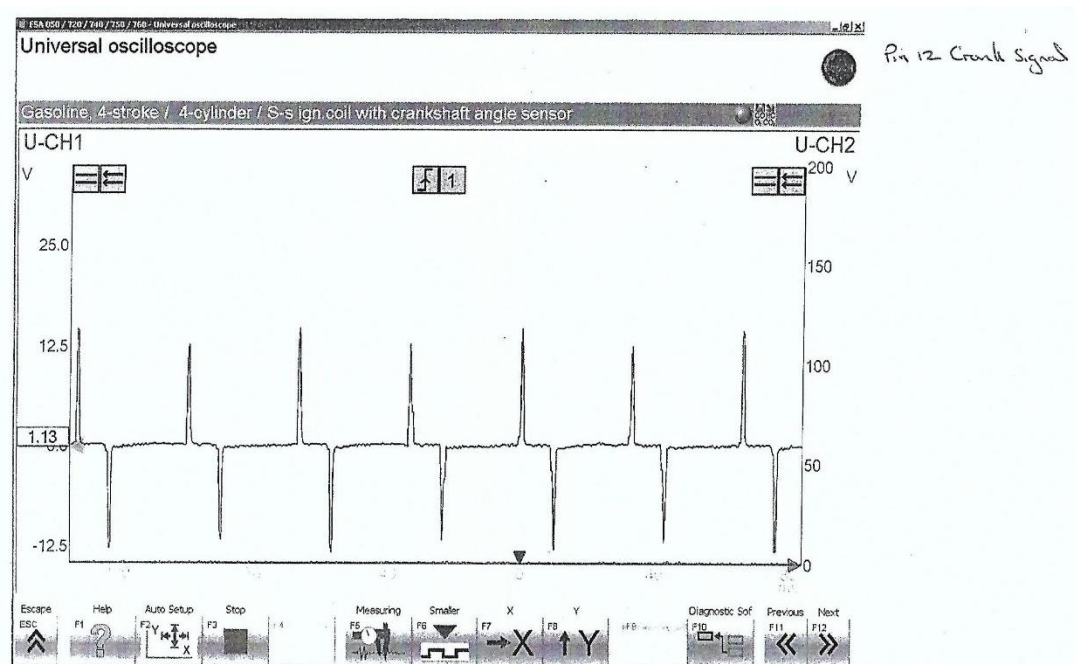
Appendix 14: LE3 injectors under deceleration (pin 3).



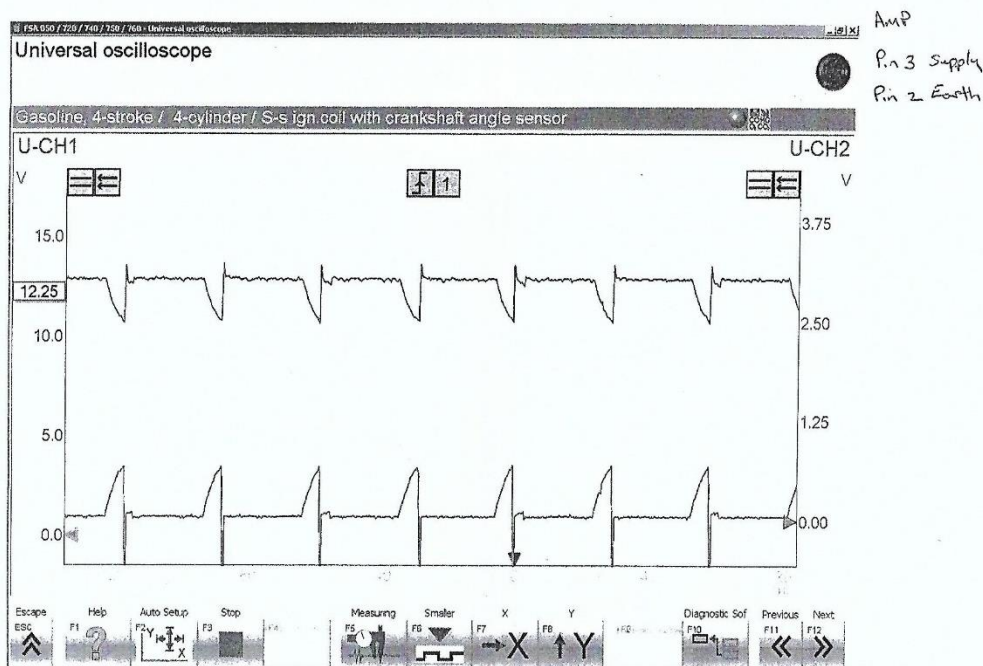
Appendix 15: LE3 speed signal (pin 12).



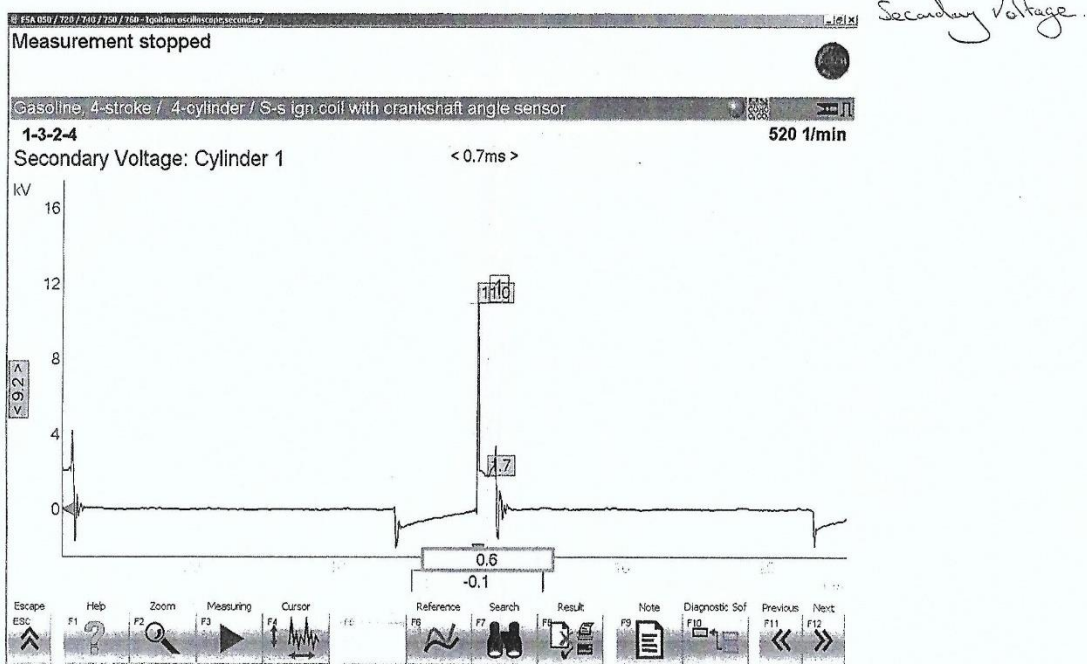
Appendix 16: LE3 digital speed signal for the fuel ECU (pin 5).



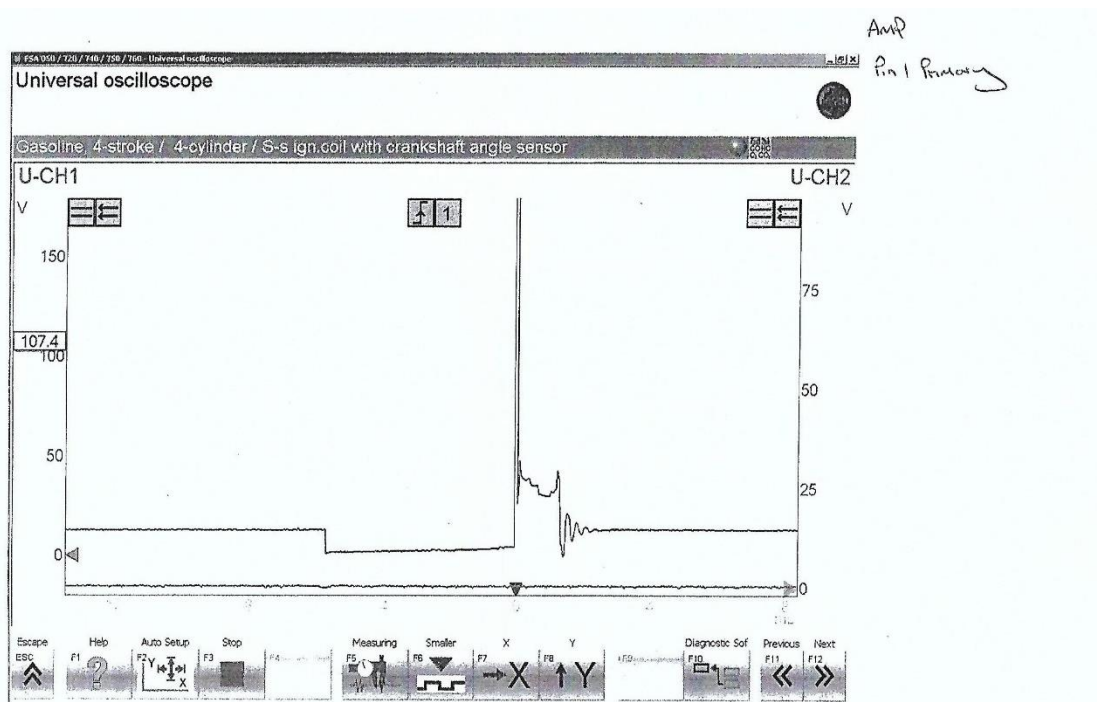
Appendix 17: LE3 live feed and earth to amplifier (pins 3&2).



Appendix 18: LE3 ignition coil secondary waveform.



Appendix 19: LE3 ignition coil primary waveform.



Appendix 20: LE3 spark advance signal and primary waveform (amplifier pins 4&1).

