

ELECTRONIC IGNITION & FUEL INJECTION SYSTEMS

LE3 AND MOTRONIC SYSTEM TESTING

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Abstract

The goal of this report is to outline the main differences between two Engine Control Systems from the late 80's/early 90's. The report has a detailed background into both systems along with a detailed methodology and list of equipment. An analysis of the ECU Pin Voltage, Scope Patterns and Component Resistance is done. Finally one of the systems was chosen to be modified with any modifications applied being justified.

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1. Introduction

This report details the findings of an investigation into 2 different engines based in the University's Engine Workshop. One engine had the LE3 Jetronic control system while the other engine featured the Motronic control system. Each engine was tested vigorously to determine the main system operational differences. Background Research was done on the history and introduction of the LE3 and Motronic System.

A complete methodology and list of equipment used in the task is document along with the reasons behind using certain tools.

The first test carried out was a voltage test on each pin of the ECU. This was done to determine and analyze what voltages were being supplied to each component and why. This was then interpreted by the use of graphs and tables to gain a deeper understanding into the differences between the 2 control systems.

The second test was testing various control measures of the engines throughout the warmup process to firstly to see how injection on-time is addressed to meet the following operating conditions; Engine cranking (from cold); Engine warm-up; Acceleration.; Idle speed (engine at operating temperature). The test was also used to measure and gain an understanding into the NTC2; Throttle Switch/Potentiometer; Rotary Idle Valve; Lambda and Tank Valve operation throughout the warmup phases of both engines.

In addition to this a Workshop manual (AutoData) was used to cross reference certain control systems' resistive values to the factory specs to gain a deeper understanding into the inner workings as well as to see if there were any discrepancies in the values which could then explain some of the potential anomalies seen in the other data set.

Various scope patters from both engines were interpreted an analyzed to gain a better understanding into the operation and differences between both systems.

Finally, the LE3 system was chosen to list some improvements to the system that would help the running, efficiency and emission output of the engine.

2. Background

In this section is a brief history and introduction of the LE3 and Motronic System.

2.1 LE3

The L-Jetronic series was invented and used by Bosch and the LE3 variant between the years of 1974 and 1989. The L stands for 'Luft' meaning air in German. It is an electronically controlled fuel injection system. One of its main advantages is its ability to sense direct air flow. The system has 3 main functions:

- Fuel Pressurization: The L-Jetronic System supplies fuel to the cylinders through injectors which pressurize the fuel to aid in combustion

Metering: The system features various sensors such as air-flow sensor, throttle valve sensor, engine speed sensor and an engine temperature sensor. It also features an auxiliary air device which features a bimetallic plate which flexes to allow extra air into the engine during warmup. (Bauer, H, 1995)

- Its main disadvantages are its 2 ECU's which require extra pins and communication lines which slow down its processing speed as well as increase clutter in the engine bay. Another disadvantage is that the system is analog and does not store any faults in memory. It has no fault lamp for the injection system. (LE-Jetronic, n.d)

2.2 Motronic v1.1

The Motronic system was also invented and developed by Bosch in the early 1980's. Motronic 1.1 was introduced in 1987 and was originally fitted to BMW cars. Motronic systems feature 1 ECU which control primary ignition, fueling and idle control which is an advantage over the LE3.

The Injection system was based on the earlier L-Jetronic series with some changes being applied, namely sequential injection. Sequential injection allows 2 banks of injectors to be fired every 2 rotations of the crankshaft. This allows for the system to react quicker to changes and fire the exact amount of fuel needed as half the amount is injected per revolution allowing for greater precision. (How a Sequential Fuel Injection Works: Pros and Cons, 2012)

A permanent live is supplied to the Ecu to allow for self-diagnostics. The majority of sensors on the car are supplied with a 5v reference supply. This is seen on NTC1 and NTC2. 5.0v was chosen as this ensures a stable working voltage unaffected by variations in system voltage.

Advantages of the Motronic system

- Motronic cuts off injector operation so limiting the maximum rpm possible.
- When the engine speed is above 1200 RPM with the throttle closed, Motronic cuts off injector operation and retards the ignition timing to aid in economy
- Motronic features sequential injection meaning that the injectors are arranged in two banks with injectors 1 and 3, and injectors 2 and 4. Each bank is connected to the ECU via a different ECU pin.

A Vane MAF measures the amount of air passing through the induction pipe by placing the vane in its path. This vane is connected to a spring and a potentiometer. As more air is passed through the vane, its displacement increases which sends a signal to the potentiometer which changes the voltage sent to the ECU allowing the air flow to be metered. (Bosch Motronic 1.1/1.3, n.d)

3. Methodology

This section details the complete methodology of the tasks undertaken as well as a list of equipment and why it was chosen.

As the testing was completed in a working group, each member was assigned a role; a Scribe; Multimeter user; Scope User and Engine cranker.

3.1 Workshop Safety and PPE

Engine testing can be a very dangerous activity if safety procedures aren't followed correctly. Before any testing can be carried out on the engine it needs to be checked over. The fluids of the engine need to be checked as well as any obvious damage to the engine exterior (cracked manifolds etc.).

PPE - Steel toe cap boots and overalls are required when entering any workshop on campus. Failure to do so will result in dismissal from the workshop. In addition to this everyone entering the workshops are required to complete a Workshop Induction on Moodle which outline all of the general safety risk of the workshop as well as the fire safety routine. In addition to this an extraction fan and pipe was connected to the exhaust to vent out any dangerous gasses such as Carbon Monoxide. Carbon Monoxide is especially dangerous as it is odorless and tasteless. (Mayo Clinic Staff, 2018)

3.2 Equipment

Digital Multimeter – A multimeter was used to help determine the voltages of the ECU pins as well as the resistive values of the engine components. A digital Multimeter was used over an analog multimeter due to their increased accuracy. The main disadvantage of a multimeter is that its unable to show values overtime, only the current value. It also cannot respond quick enough to voltage changes for the task needed. (Sanguri, S, 2012).

Oscilloscope – An oscilloscope was used to gain scope patterns and voltages of components that the multimeter was unable to. Th advantage of an oscilloscope is its able to see how a signal changes over time or in response to stimuli. The Oscilloscope software is able to produce freezeframe waveforms which can be printed and analyzed and a later date. The scale and axis of the waveform can be adjusted with great precision to allow better visualization of the waveform. (Charles, T, n.d)

3.3 ECU Voltage Testing

This testing was done in 2 stages. Once with the Ignition off and once with the Ignition on.

1 of the wires was attached to a ground point on the engine and ensured that it was connected securely.

With the ignition feed off, each pin on the ECU was tested individually, ensuring that the multimeter pin was placed fully into the socket to gain a good connection. The value was then noted.

The engines ignition was then switched, and each ECU pin was tested again in the same manner.

3.4 Engine Component Testing

After the ECU pin testing was complete, the Engine component testing was completed. This required completing voltage, resistance and injector on time tests at various engine temperatures throughout the warmup phase. The voltage testing was completed in the same manner as section 3.3 by using a multimeter. Resistance and injector on time tests were carried out using the oscilloscope.

The oil dipstick was removed, and the temperature gauge of the oscilloscope was placed into the oil sump. This was needed to gain the engine temperature as the testing points were carried out at specific temperatures; 20°C, 40°C, 60°C and 80°C. Before any testing was carried out the engine was ran until the correct temperature was displayed on the screen.

Once the correct temperature was met the following test were carried out on each vehicle.

Temperature	20°C	40°C	60°C
Voltage	NTC2	NTC2	NTC2
Resistance	NTC2	NTC2	NTC2
On Time	Injector Bank	Injector Bank	Injector Bank

Table 1: Testing criteria for the LE3 System

Temperature	20°C	40°C	60°C	80°C
Voltage	NTC1, NTC2	NTC1, NTC2	NTC1, NTC2	NTC1, NTC2
Resistance	NTC2	NTC2	NTC2	NTC2
On Time	Injector Bank	Injector Bank	Injector Bank	Injector Bank
Open Percentage	Rotary Idle Valve	Rotary Idle Valve	Rotary Idle Valve	Rotary Idle Valve

Table 2: Testing criteria for the Motronic System

Voltage - The voltage testing was completed in the same manner as section 3.3 by using a multimeter.

Resistance – Resistance was gained by placing the multimeter on the 2 output pins of the NTC2 sensor.

Open Percentage – Open Percentage was gained via the oscilloscope.

Injector on Time – This was taken via the oscilloscope. To do this, a pair of clamps were used, and one was placed onto the HT lead of and injector and 1 was placed on a grounding point. The oscilloscope software was loaded, and the correct scale was chosen based on the component being tested. This ensured that the full waveform could be seen on one screen. The correct scales can be seen in Table 3.

Component	Y (Volts)	X (m/s)
NTC2	20	50
Injector Bank	200	100
Rotary Idle Valve	20	50
Tank Valve	200	50
Lambda	2	200

Table 3: Oscilloscope Scales for Waveform Analysis

Once the oscilloscope had been correctly setup and the waveform was present, the freeze frame button was pressed and cursors were applied to get an accurate reading to be scribed.

3.5 Resistance Testing

The resistance testing was done via the following process.

An AutoData Workshop Manual was used to gain the Factory Resistance Values for the components listed in Table 4. The components were then tested by placing a multimeter on the pins of the component or either end of the wire (if applicable). These were then scribed into a table for further analysis.

LE3 Components	Motronic Components
Throttle Switch	Throttle Potentiometer
NTC2	NTC2
Auxiliary Air Valve	Air Flow Sensor
Injector	NTC1
HT Leads	Rotary Idle Valve
Ignition Coil	Injector
	HT Leads
	Ignition Coil

Table 4: Components Selected for Resistance Testing

4. Analysis

In this section of the report an in-depth analysis into the results of the testing is produced, with a focus on the actual test readings and signal waveforms recorded as compared to manufacturer's specifications.

4.1 LE3 ECU Voltage (Ignition off vs Ignition on)

LE3 Ignition ECU

Pin Number	What it does	Ignition off (V)	Ignition on (V)
1	Ground	0	0
2	Coolant Temp	0	0
3	12v Supply	0	12.03
4	Not Used		
5	Fuel Ecu Com	0	0
6	Throttle Switch	0	0
7	Coolant Temp	0	2.5
8	Octane Loop	0	0.95
9	Not Used		
10	Octane Loop	0	0
11	Crank Angle Sensor	0	0
12	Crank Angle Sensor	0	0.06
13	Amplifier Input	0	0.13
14	Throttle Switch	0	4.98
15	Fuel Ecu Com	0	0.15

Table 5: LE3 Ignition ECU Pin Voltage (Ignition off vs Ignition on)

The LE3 system has two separate ECU's an Ignition ECU and a Fuel ECU. Each ECU has a maximum of 15 pins of which not all are used depending on the vehicle's specification.

While the Engine is off there is no voltage running to any of the pins, which is to be expected as nothing needs to be powered while the engine is off. However, when the ignition is switched a number of pins' voltage changes. The battery voltage at the time of testing was 12.26.

Pin 3 has a voltage of 12.03v as it is the power supply for the ECU.

Pin 7 has a voltage of 2.5v as the coolant temperature sensor works on the principle of a resistor. The resistance changes with temperature and at room temperature (~20°C) a typical resistance value would be ~3v. The reference voltage supplied is 5v. (Engine Coolant Temperature Sensor (ECT), 2016)

Pin 8 works on a similar principle to a lambda sensor as it's a closed loop system. A reference voltage of 5v is supplied. The 0.95v supplied is based on the current octane rating of the fuel.

Pin 14 has a voltage of 4.98v which is to be expected as similarly to the Coolant Temperature Sensor the Throttle switch works on resistance with a 5v reference. As the resistance of the switch changes, the voltage will change which signals to the ECU along Pin 6, the position of the throttle. However, as it is a digital switch it only has 2 methods of output. Fully Open or fully closed which seriously restricts the ability to meter accurately. (Hella Tech World, n.d)

The small voltage changes (<0.2v) are attributed to a less than perfect grounding. (Heath, 2016)

LE3 Fuel ECU

Pin Number	What it does	Ignition off (V)	Ignition on (V)
1	Ignition ECU Coms	0	0.06
2	Air Flow Sensor	0	11.96
3	Injector Bank	0	0
4	Ground	0	0.02
5	Ground	0	0.03
6	Not Used		
7	Not Used		
8	Ntc2 water	0	1.97
9	Not Used		
10	Ignition ECU Coms	0	0.16
11	Not Used		
12	Air Flow Sensor	0	12.03
13	Not Used		
14	Throttle Switch	0	4.99
15	Throttle Switch	0	0.02

Table 6: LE3 Fuel ECU Pin Voltage (Ignition off vs Ignition on)

Again, while the ignition is off there is no power flowing to any of the pins. Once the ignition is turned on a number of pins' voltage changes.

Pins 1 and 10 have a small voltage due to resistance on the wires as it is connected to the Ignition ECU.

There is 4.99v on Pin 14 as it is a spliced with Pin 14 from the Ignition ECU and is connected to the Throttle Switch.

Pins 2 and 12 are the airflow sensor input return signal. As the sensor is fully closed the 12v supply is being returned unaffected.

Pin 8 has a voltage of 1.97v as the air temperature sensor works on the same principle as the coolant temperature sensor on the Ignition ECU. (Engine Coolant Temperature Sensor (ECT), 2016)

LE3 Amplification Unit

Pin Number	What it does	Ignition off (V)	Ignition on (V)
1	Amp output	0	11.95
2	Ground	0	0.02
3	12v supply	0	11.93
4	Input from ECU	0	0.13

Table 7: LE3 Amplification Unit Pin Voltage (Ignition off vs Ignition on)

The amplification unit amplifies the voltage supplied to it in preparation for ignition. As the engine hasn't been started, the input supply and output supply are the same as no amplification is required.

4.2 Motronic ECU Voltage Comparison (Ignition off vs Ignition on)

The LE3 system has 3 separate ECU's controlling the ignition system and the fuel system. In the later Motronic system, bot ECU's have been combined into 1 ECU.

Motronic ECU

Pin Number	What it does	Engine off (V)	Ignition on (V)
1	Negative side of coil	0	12.2
2	Earth	0	0.03
3	Control circuit for fuel pump	0	12.06
4	Pulsed side of Rotary Idle Valve	0	9.74
5	Pulsed side of Tank Vent Valve	0	12.03
6	4WD ECU - A/T ECU -Fuel tell-tale lamp	0	11.33
7	Load signal output from air-flow meter	0	0.31
10	Earth	0	0
12	5V Supply to air-flow meter & throttle potentiometer	0	5.05
13	Diagnostic socket supply	0	10.11
14	Earth	0	0.02
16	Pulsed side of Injectors (1)	0	12.03
17	Pulsed side of Injectors (2)	0	12.02
18	Permanent live (memory)	12.38	12.01
19	Earth	0	0.03
22	Engine tell-tale warning light	0	0.93
24	Earth	0	0.03
26	Earth	0	0.06
27	Ignition feed	0	12.15
28	Output from Lambda Sensor	0	0.45
32	Output to onboard computer	0	11.3
36	Control circuit for supply to auxiliaries and ECU	12.06	0.3
37	Supply to ECU and onboard computer	0	12.03
40	Air Con	0	0.06
41	Air Con	0	0.06
42	Earth for manual transmission	0	0.02
44	Output from NTC 1	0	3.76
45	Output from NTC 2	0	3.73
46	Octane Plug input	0	5.05
48	Output from crankshaft sensor	0	0.06
49	Output from crankshaft sensor	0	0.09
53	Output from throttle potentiometer	0	0.62
55	Earth for diagnostic socket	0	10.9

Table 8: Motronic ECU Pin Voltage (Ignition off vs Ignition on)

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The ECU has a total of 55 pins of which 33 are used on the tested system. For clarity the unused pins are not displayed in Table 8.

While the ignition is off, unlike the LE3 system the Motronic system has 2 pins with constant 12v. Pins 18 and 36 have permanent live as they supply power to the memory of the ECU. As the ECU is technically a computer it possess ROM (Read only Memory) and RAM (Random Access memory) ROM is non-volatile meaning that it keeps its memory without having a power source whereas RAM is volatile meaning it need a constant 12v to keep its memory. The LE3 ECU doesn't have RAM and therefore does not need a constant 12v. (Papiewski, J, n.d)

When the ignition is switched nearly all the pins have a change in voltage. Similarly, to the LE3 systems any voltage <0.2 is attributed to a non-perfect ground.

Pins 1 and 27 have ~12v each as that is the potential voltage for the ignition system.

Pin 3 supplies power to the Fuel Pump, when the ignition is on the fuel pump will start to prime before the engine is started, hence the 12v.

Pin 4 and Pin 5 supply power to the Rotary Idle Valve and the Tank Vent Valve. The voltage for the Rotary Idle valve is less than battery voltage, meaning that there is some sort of resistance on the line. The LE3 does not feature any of these.

Pin 6 has voltage as it is for a light that must illuminate before the engine is started. The light must illuminate to ensure that the tell-tale is working. The light should deactivate once then engine is started.

Pin 7 states that there is a 0.31v output coming from the Air Flow meter. The Mass Air-flow meter on the engine tested is a Vane type. A Vane MAF measures the amount of air passing through the induction pipe by placing the vane in its path. This vane is connected to a spring and a potentiometer. As more air is passed through the vane, its displacement increases which sends a signal to the potentiometer which changes the voltage sent to the ECU allowing the air flow to be metered. (Measuring a vane type mass air flow sensor, n.d)

In this case as a voltage is seen it suggests that the vane isn't 100% closed. This could be down to the age of the vehicle, meaning that the spring on the vane has worn or it could be dirty meaning a tight seal hasn't been made.

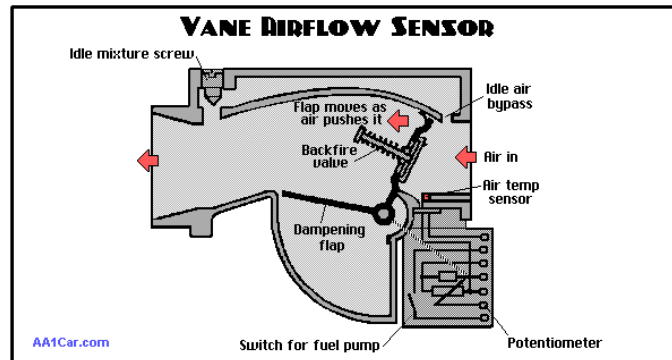


Figure 1: Example of Vane Airflow Sensor (abworks, 2016)
 The throttle potentiometer output on pin 55 has a value of 0.62. This works on the exact same principle as the Air Flow Sensor so a reading of 0.62 suggests that the throttle isn't closed all the way.

Pin 12 supplies 5v to the Throttle potentiometer and the Airflow Meter. The Throttle potentiometer works on the same principle as the airflow sensor with a few differences. The Throttle Position Sensor (TPS) has 3 wires, the 1st wire has a 5v input (Pin 12) with the 2nd wire being the ground and the 3rd wire is connected to the potentiometer which changes the voltage being sent to the ECU. (THROTTLE POSITION SENSOR (TPS), n.d)

Pins 13 and 55 supply voltage to the Diagnostic Socket. This engine was produced pre 1996 so does not have OBD2 but the predecessor OBD1. (Does My Car Have OBD-II?, 2012)

Pins 17 and 18 send 12v to the Injector banks in preparation for ignition.

The Lambda Sensor Output resides on Pin 28. It is showing a voltage of 0.45. Lambda is a feedback control loop, meaning that it produces its own voltage once it gets hot. The input is supplied by Pin 48 at 5v.

“An oxygen sensor will typically generate up to about 0.9 volts when the fuel mixture is rich and there is little unburned oxygen in the exhaust. When the mixture is lean, the sensor's output voltage will drop down to about 0.1 volts. When the air/fuel mixture is balanced or at the equilibrium point of about 14.7 to 1, the sensor will read around 0.45 volts.” (What the Home Mechanic Needs to Know about O2 Sensors, 2012)

NTC1 and NTC2 Outputs have a reading of around 3.5v sensor again work on the principle of a resistor. The resistance changes with temperature and at room temperature (~20°C) a typical resistance value would be ~3v. (Engine Coolant Temperature Sensor (ECT), 2016).

4.3 Engine Testing

During the testing process various pins on both ECU's were tested in depth to gain a better understanding of the Control Systems present on each engine. The number of pins varied between the LE3 system and the Motronic system as the Motronic is a newer system and has more Control Measures in place.

4.3.1 NTC2 Comparison

“Negative Temperature Coefficient is a process of decrease in resistance value with the increase in temperature” (Negative Temperature Coefficient, n.d). The NTC2 sensor is the Coolant Temperature sensor that is used on both engines. The Motronic's sensor is placed into the water jacket, however on the LE3 the sensor is placed into the oil pan.

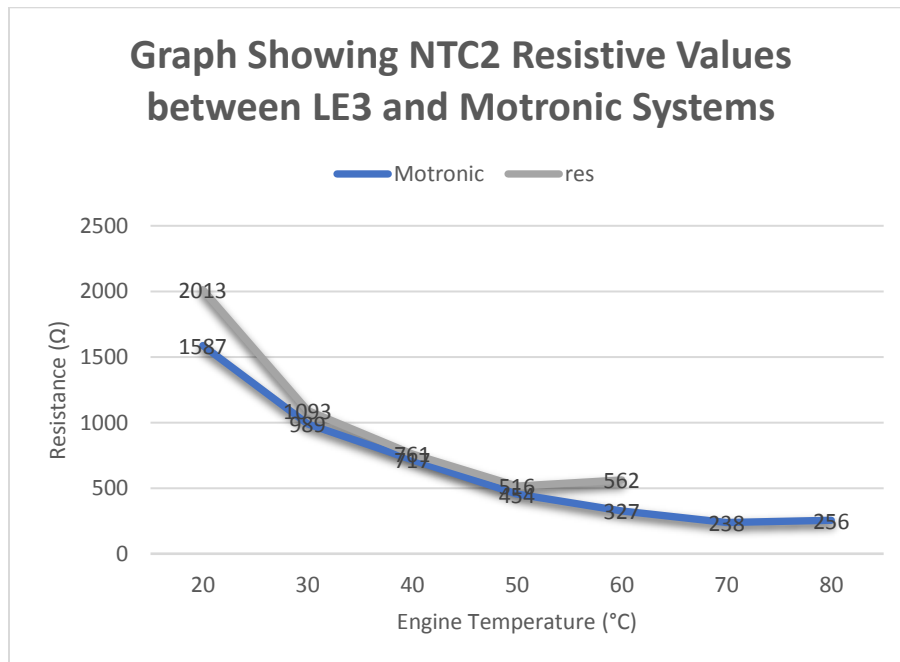


Figure 2: Graph Showing NTC2 Resistive Values between LE3 and Motronic Systems

Both Engines have a similar trendline, with the Motronic system being longer due to its higher operating temperature. The starting resistive value (2013 Ω) for the LE3 system is a lot higher than the Motronic system (1587 Ω). However, if the data is cross referenced with the Factory Data gained from the AutoData Workshop Manual seen in figure.... The LE3 data is close with the Resistive values at all the data points, whereas the Motronic system is out by a few 100 Ω on each data point.

Temperature °C	Factory Resistance Ω (LE3)	Factory Resistance Ω (Motronic)
20	2100 to 2900	2200 to 2800
40	1000 to 1400	1000 to 1400
80	270 to 330	270 to 360

Table 9: Factory Resistance of NTC2 Sensors (LE3 & Motronic)

“Negative temperature coefficient of resistance thermistors, or NTC thermistors for short, reduce or decrease their resistive value as the operating temperature around them increases.” “NTC temperature thermistors have a negative electrical resistance versus temperature (R/T) relationship. The relatively large negative response of an NTC thermistor means that even small changes in temperature can cause significant changes in its electrical resistance” (Thermistors, 2018). With this in mind, a likely cause for the variance in resistance could be a dirty sensor. If the sensor were to be dirty or damaged then its reading could be compromised. However, a more likely answer for the difference in Resistance is that the sensor was replaced with an aftermarket or uprated part, meaning that the resistive values are different.

As NTC sensors work by converting a resistive value to a voltage value, in the case of the Motronic system, the voltage would be at a different value that the ECU would be programmed for so the temperature reading of the coolant would be off by a few degrees. This could lead to various issues such as, poor fuel economy and long cranking times due to over fueling as the ECU thinks the engine is colder than what it is resulting in more fuel being used to heat the engine up. (S, J, 2018)

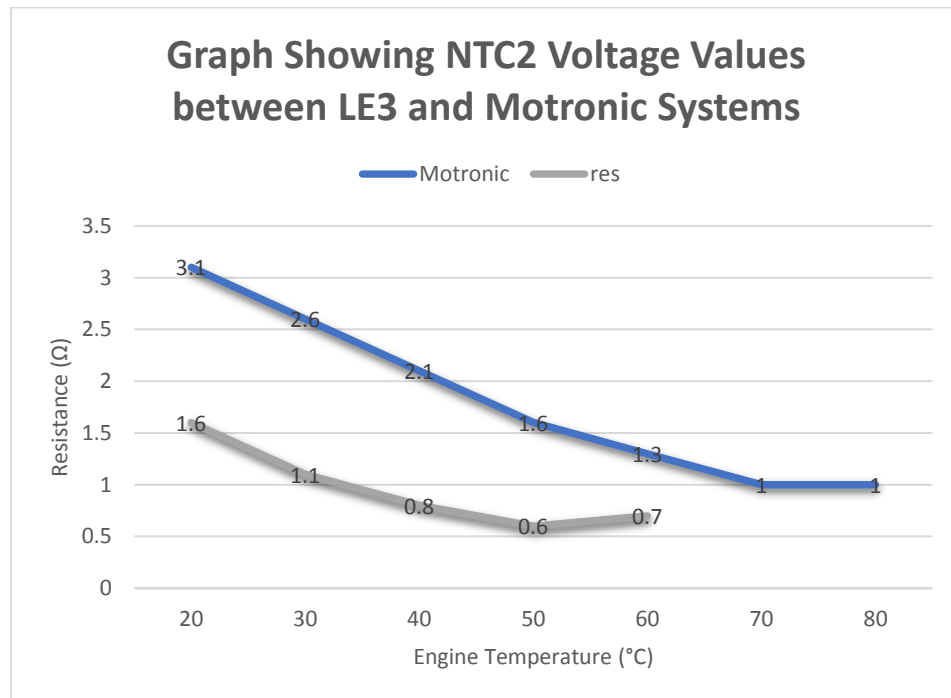


Figure 3: Graph Showing NTC2 Voltage Values between LE3 and Motronic Systems

As seen in Figure 3, the voltage values follow the same trend which is what is expected due to the working of an NTC sensor, however the values have a significant difference between them. This further backs up the case that the Sensor on the Motronic system is either faulty or a replacement non-OEM part.

4.3.2 Injector on Time Comparison

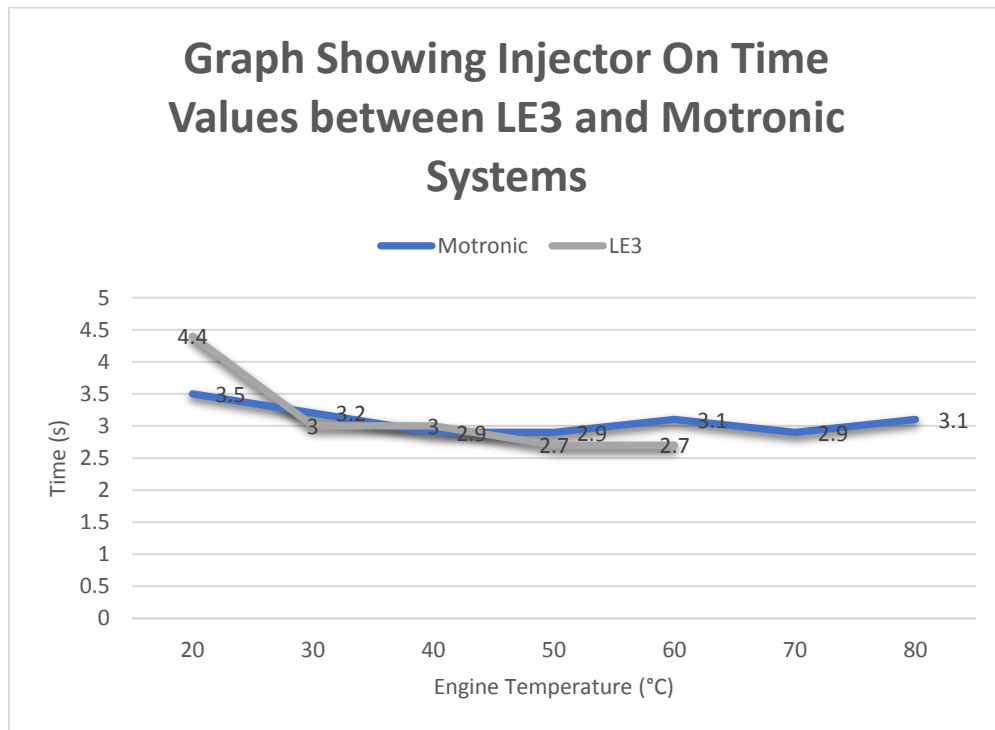


Figure 4: Graph Showing Injector on Time Values between LE3 and Motronic Systems

At 20°C the injection on time is at its highest for both engines with the LE3 at 4.4 m/s and Motronic at 3.5 m/s. The reason that both engines have a high injection on time is due to the fact that the engine requires a richer fuel mixture. This is because cold air is denser than hot air so less air is taken into the engine when cold than hot. Therefore, more fuel is needed to keep a good air to fuel ratio. (Why does hot air rise, n.d)

The LE3 injection time is 0.9 m/s more than the Motronic system at 20°C. This is due to the Rotary Idle Valve on the Motronic System. The Rotary Idle Valve allows for better metering of the air being used vs the bimetallic plate on the LE3 system. This allows for a better air/fuel ratio resulting in less enrichment.

At 30°C enrichment has more or less stopped on both engines as Lambda has switched on the Motronic Engine and the auxiliary air valve has opened fully on the LE3. Injection on time has settled at ~3 m/s on both engines.

~3 m/s is around the maximum time injectors can stay open to ensure atomization. When accelerating the Injector on time will stay at ~3 m/s while the frequency of the opening will increase.

4.4 Lambda and Tank Valve Analysis

Temperature °C	Lambda Status
20	off
30	on
40	on
50	on
60	on
70	on
80	on

Temperature °C	Tank Valve Status
20	off
30	off
40	off
50	on
60	on
70	on
80	on

Table 10: Lambda Status throughout temperature range Table 11: Tank Valve Status throughout temperature range

Figures 10 and 11 show the Lambda Status and Tank Valve Status of the Motronic system. The LE3 System isn't fitted with a Catalytic Converter or a Tank Valve so this analysis is just on the Motronic System.

The ECU on the car uses the Lambda or Oxygen Sensor to help determine the air fuel ratio that the car needs. It does this by using a closed loop operation. This results in a constant switch between rich fuel mixture and lean fuel mixture around a ratio of 14.7:1 which allows the Catalytic Converter to operate at its best.

When the car is cold started there is no signal from the O2 Sensor as the car requires a rich fuel mixture. This is known as an open loop operation as the Ecu is receiving no input from the O2 sensor to regulate the fuel. (What the Home Mechanic Needs to Know about O2 Sensors, 2012)

This is seen in the in the data gathered. At 20 °C Lambda hasn't switched as the engine had just started and is requiring a rich fuel ratio. At 30 °C lambda has switch on and stays on throughout the warmup process as the fuel ratio needs to be regulated from then on.

The Fuel Tank Vent Valve is there to prevent fuel vapors from escaping from the fuel tank to the atmosphere. The Evaporative Emission Control (EVAP) stores the fuel vapors in a charcoal cannister. The canister is filled with activated carbon pellets which absorb the fuel vapors. When the engine is running the vapor is purged from the carbon and burned in the combustion process. (Vent valve (solenoid): how it works, symptoms, problems, testing, 2015)

“The requirements for running the EVAP monitor vary depending on the year, make and model of your vehicle. Generally speaking, the fuel tank must be 1/4 to 3/4 full because a near empty tank or a full tank can affect the accuracy of the EVAP self-test. The ambient outside temperature must not be too hot (above 95 degrees) or too cold (below 30 degrees) because this affects fuel volatility and the amount of vapor inside the tank.” (EVAP System Monitor, n.d)

In the Motronic Systems case the Purge Valve doesn't open until 50 °C and stays open throughout the warmup process.

4.5 Rotary Idle Valve

Temperature °C	Open Percentage
20	45
30	46
40	44
50	45
60	47
70	46
80	48

Table 12: Rotary Idle Valve throughout temperature range

The Rotary Idle Valve or Idle Air Control Valve (IAC) bypasses air from the closed throttle plate to the engine so that it can receive air even though the throttle is 100% closed. Before the invention of IAC's idle speed was adjust via an idle speed screw which determined how much the throttle plate would be open during hot and cold phases.

Before a modern engine is started, the ECU checks the NTC1 and NTC2 sensors to determine the fuel ratio to start the engine. It is important on Fuel Injected vehicles not to have an open throttle when starting as the ECU expects the air volume of the IAC. (Muscoplat, R, 2012)

In the Motronic's Systems case, as the engine was tested at base idle throughout the temperature range, the IAC didn't change its open position very much as the engine wasn't under load. It did open a slight bit more as the temperature went up. One explanation for this could be that warmer air from around the engine is being sucked into the intake manifold. Warm air less dense than colder air, so for the same mass of air to be taken into the engine, the volume of it would need to increase. (Why does hot air rise?, 2013). To do this the Rotary Idle Valve open 3% more throughout the test.

The LE3 system is fitted with an auxiliary air device which is a bimetallic plate that allows extra air into the engine during warmup. The plate works by having 2 different metals that will flex at certain temperatures, closing or opening the auxiliary air valve. The issue with this is that it cannot be metered so the amount of airflow coming through it is unknown. (Bauer, H, 1995)

4.6 Tested Resistance vs Factory Resistance

As part of the testing process, the resistive values of various control systems were tested and compared against their factory counterparts. The purpose of this was to see if there were any discrepancies in the values which could then explain some of the potential anomalies seen in the other data set. All of the results can be found in Appendix H and I Only the results that are vastly different to factory specification are analyzed below. A small difference either side of the factory specification could be due to a number of factors such as frayed wires or dirty connections.

LE3 Throttle Switch and Motronic Throttle Potentiometer

Throttle Position	Manufacturer	Tested
Throttle Closed	0	000.2kv
Throttle Open	Infinity	Infinity

Throttle Position	Manufacturer	Tested
Throttle Closed	1900 to 2000	2107
Throttle Open	1000 to 2000	2702

Table 13: LE3 Throttle Switch Resistance Comparison

Table 14: Motronic Throttle Potentiometer Resistance Comparison

The LE3 Throttle Switch was in Manufacture Spec. However, the Motronic's Throttle Potentiometer was not, this is because the Throttle Body was changed from the OEM one and the resistive values for the newer part are different.

LE3 NTC2 and Motronic NTC2

Pins	Manufacturer	Tested
4 & 2	2100 to 2900	2013
4 & 3	1000 to 1400	761
4 & 1	270 to 330	562

Pins	Manufacturer	Tested
4 & 2	2200 to 2800	1587
4 & 3	1000 to 1400	717
4 & 1	270 to 360	256

Table 15: LE3 NTC2 Resistance Comparison

Table 16: Motronic NTC2 Resistance Comparison

Both systems' resistive values are not in spec with the Motronic System being wildly different to what was expected. The reasons for that were discussed in section 4.2. Another reason behind the false could be due to the fact that the current of the resistor needs to be kept quite low as a resistor has self-heating effects. If a current that is too high is passed through the resistor it can create more heat than can be quickly dissipated from the thermistor. (Thermistors, 2018)

LE3 HT Leads and Motronic HT Leads

Lead Number	Resistance
1	8500
2	8720
3	7270
4	5420
King lead	5515

Lead Number	Resistance
1	19600
2	18440
3	14950
4	21300
King lead	Faulty

Table 17: LE3 HT Leads Resistance Comparison

Table 18: Motronic HT Leads Resistance Comparison

Resistance is defined by the following formula:

$$Resistance = Resistivity\ of\ material \times \frac{Length}{Area}$$

The longer the wire the higher resistance it will have. This is due to the fact that the electrons collide with more atoms in a longer wire than it does with a shorter wire which causes friction and therefore heat which is defined as resistance. (Luno, 2016)

In the case of both engines, lead 4 was the closest to the coil pack and therefore had the shortest wire and Lead 1 was the furthest away. It would be expected that Lead 1 would have the highest resistance; Lead 2 would be lower and Lead 3 slightly lower again etc. However, on the LE3 system Lead 2 was slightly higher than Lead 1 by 220Ω. This isn't a lot so it could be related to a dirty or bad connection or a slightly frayed wire.

The Motronic System has around 2x the resistance of the LE3 system.

LE3 and Motronic Ignition Coils

Coil	Resistance
Primary	0.6
Secondary	7760

Coil	Resistance
Primary	0.8
Secondary	7450

Table 19: LE3 Ignition Coil Resistance Comparison

Table 20: Motronic Ignition Coil Resistance Comparison

Each coil has an extremely long amount of wire, so it's expected to have an extremely high resistance. The Secondary Winding is normally hundreds of times longer than the Primary. (Nice, K, n.d) The resistance is seen on the Secondary Winding as the Primary has been switched and the Secondary Winding is carrying the current to the HT Leads.

4.7 Scope Pattern Analysis

In this section of the report various Scope Patterns from both Engines will be discussed and analysed.

Motronic Primary Wave

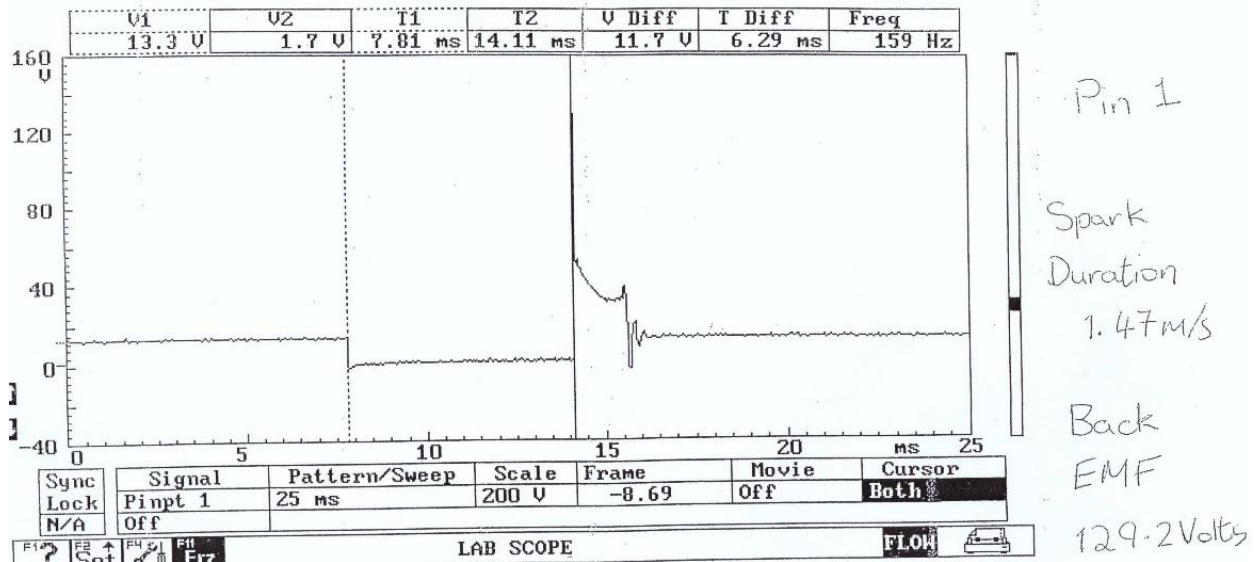


Figure 5: Motronic Primary Wave Scope Pattern

Between 0 and 7 m/s Battery or Potential voltage is seen. It then gets instantly grounded; this is where the secondary winding is activated. At around 14 m/s a huge voltage spike to 129.2 Volts is seen. This is Back EMF. Back EMF occurs whenever and Voltage is applied to a coil winding. (Electromagnetic Induction, AC Circuits, and Electrical Technologies, n.d) Between ~14 m/s and ~16 m/s the spark duration of 1.47 m/s is seen and then a short amount of coil oscillation afterwards. An identical wave form is seen on the LE3 system, and can be seen in Appendix A

Motronic Secondary Wave

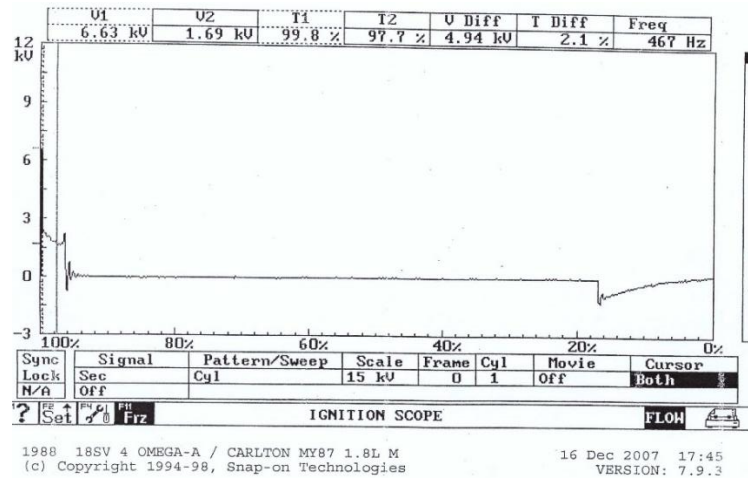


Figure 6: Motronic Secondary Wave Scope Pattern

The secondary winding is switched once a spark is required. The Primary Winding gets grounded and the Secondary Winding is switched. This is what is displayed in Figure 6. At the very beginning Back EMF of around 6,000v is seen then the spark duration as well as a short amount of coil oscillation afterwards. The Secondary is then grounded as the primary has switched on. An identical wave form is seen on the LE3 system, and can be seen in Appendix B.

Motronic Rotary Idle Valve

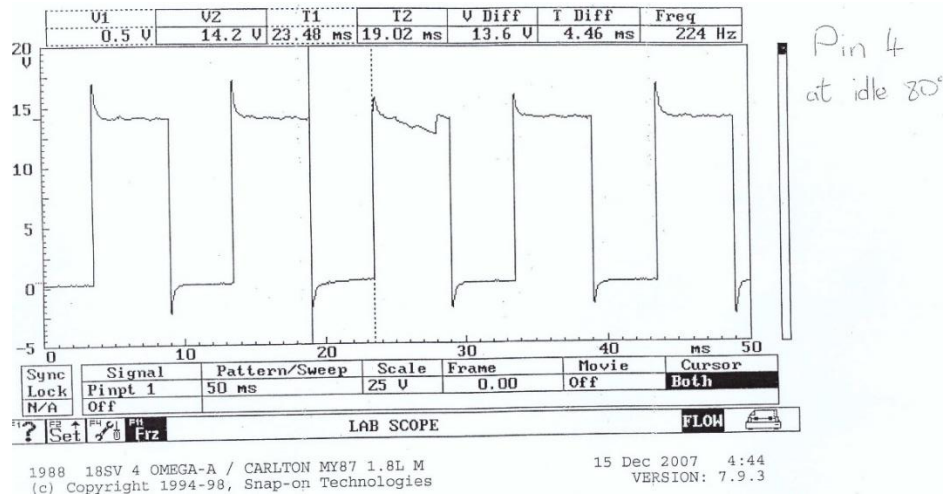


Figure 7: Motronic Rotary Idle Valve Scope Pattern

Rotary Idle Valves are normally solenoid based. The Rotary Idle valve has an analogue signal as when the ECU needs to change the angle of the valve it grounds the solenoid with a cycle signal which in turn creates a magnetic field that moves the valve into the required position. (Measuring an idle air control valve, n.d)

Motronic 12v Supply and Earth

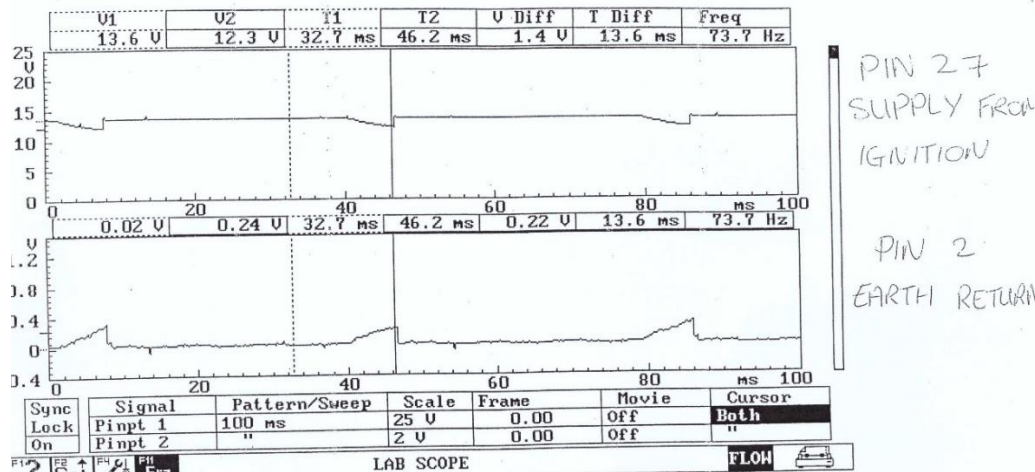


Figure 8: Motronic 12v Supply and Earth Scope Pattern

The voltage on both pins change at the exact same time. This is due to the switching of the primary. The switching of the primary has a big power draw and a huge grounding. This is seen as a drop of ~1v at the supply and a spike in the ground pin at the same time. An identical wave form is seen on the LE3 system, and can be seen in Appendix C.

Motronic Throttle Potentiometer

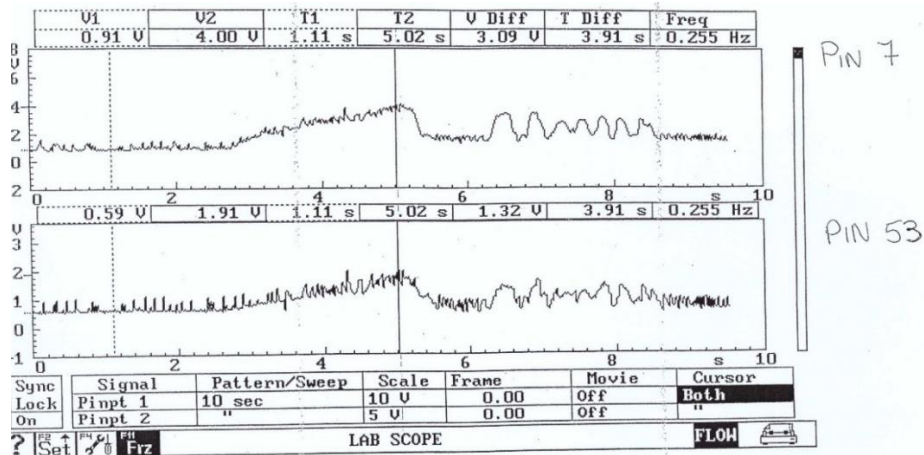


Figure 9: Motronic Throttle Potentiometer Scope Pattern

On 1st glance the scope patterns look the same. However, the scale on the scope is different, this is because of the resistive potentiometer discussed in section The Throttle Position Sensor (TPS) has 3 wires, the 1st wire has a 5v input (Pin 12) with the 2nd wire being the ground and the 3rd wire is connected to the potentiometer which changes the voltage being sent to the ECU. (THROTTLE POSITION SENSOR (TPS), n.d)

Motronic Injector Banks

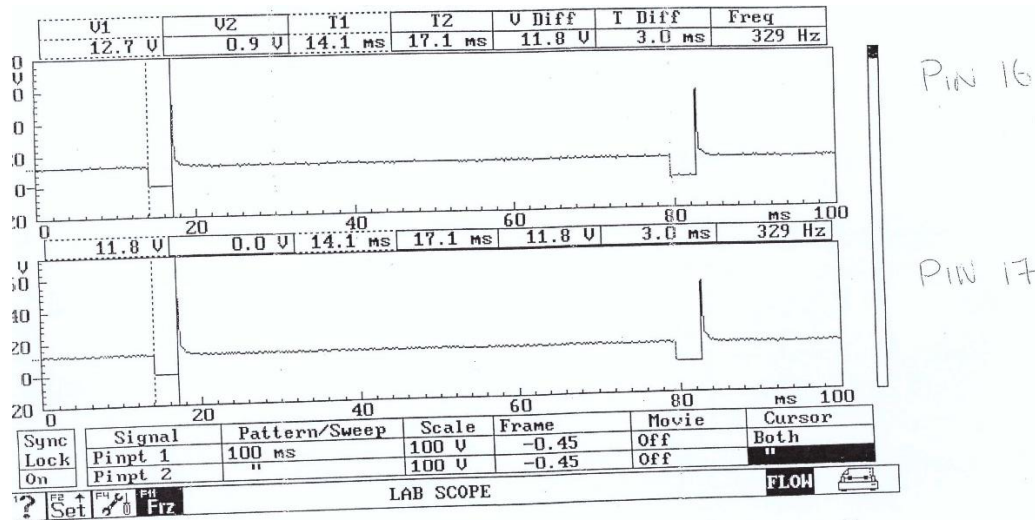


Figure 10: Motronic Injector Banks Scope Pattern

Pin 16 and Pin 17 are the Injector Banks. There are 2 different Injector Banks as the Motronic ECU supports Sequential Injection. This is seen on the Scope Pattern as 2 Injectors activate at around 18 m/s and the other 2 activate at ~79 m/s. (Gosheto, n.d) “Most injectors use 12 volts to energize the coil, and the driver energizes the circuit by pulling it to ground. When the injector is energized, the voltage drops to almost zero. If it does not, it could mean an open or weak connection in the wiring harness or open coils inside the injector. When the voltage is turned off, the needle starts to close. When it closes, it generates a voltage spike known as the inductive kick. This is a generated magnetic field collapsing in the coils.” (Markel, A, 2017)

Motronic Injection on Time (Idle)

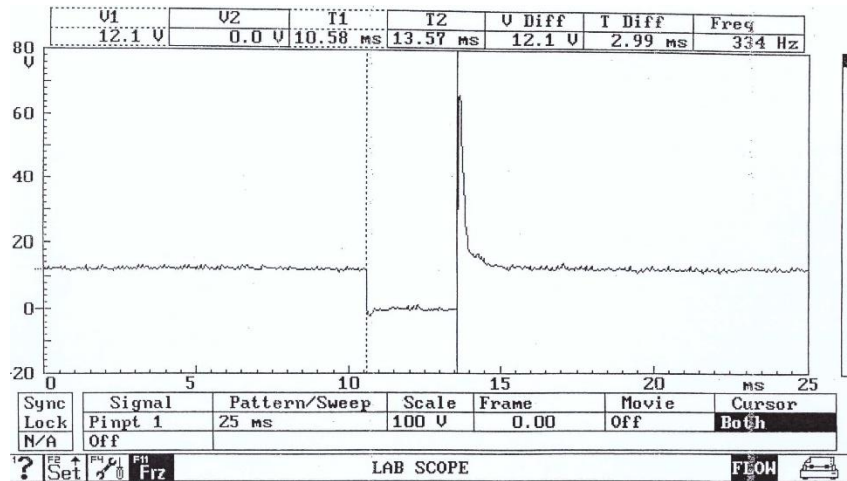


Figure 11: Motronic Injection on Time Scope Pattern (Idle)

Motronic Injection on Time (Accelerating)

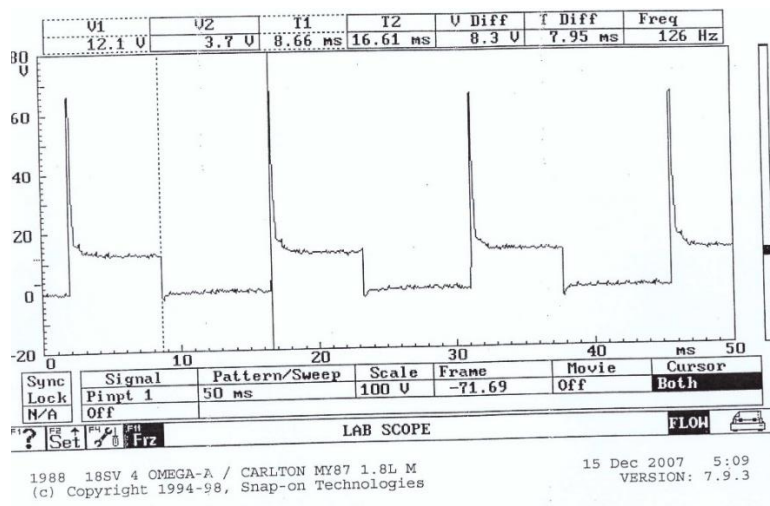


Figure 12: Motronic Injection on Time Scope Pattern (Accelerating)

When at idle the injection on time is 2.99 m/s and the frequency is low with 1 injection happening in 25 m/s. However, when accelerating the Injection on time increases to ~7 m/s but the frequency also increase. The frequency of injection happens as having the injectors open for a long period of time increases the risk of atomization of the fuel happening. So, the injection frequency increases giving a lot more fuel in a short amount of time without compromising atomization. (Magdi, K, (2013)

Motronic Injection on Time (Decelerating)

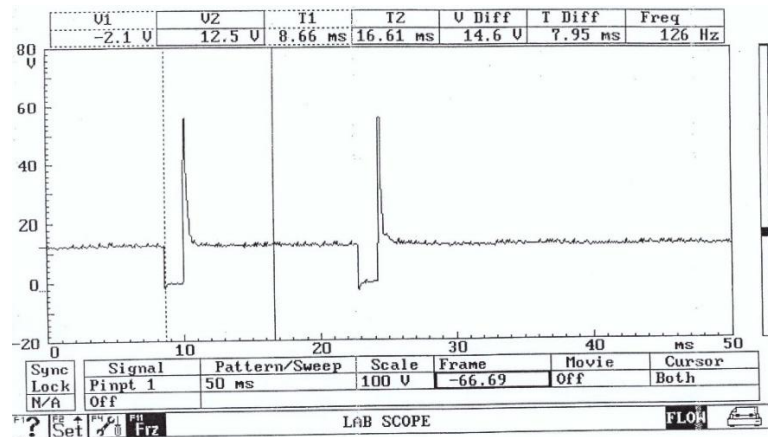


Figure 13: Motronic Injection on Time Scope Pattern (Decelerating)

The Injection on time has decreased as the ECU has seen received a signal from the throttle position sensor stating it has started to close. Once the ECU realises that the throttle has fully closed it switches the injectors off to save fuel. (Allen, M, 2009)

Identical Scope Patterns for Injector Idle, Acceleration and Deceleration for the LE3 Engine can be found in Appendix E, F and G.

Motronic Lambda Sensor

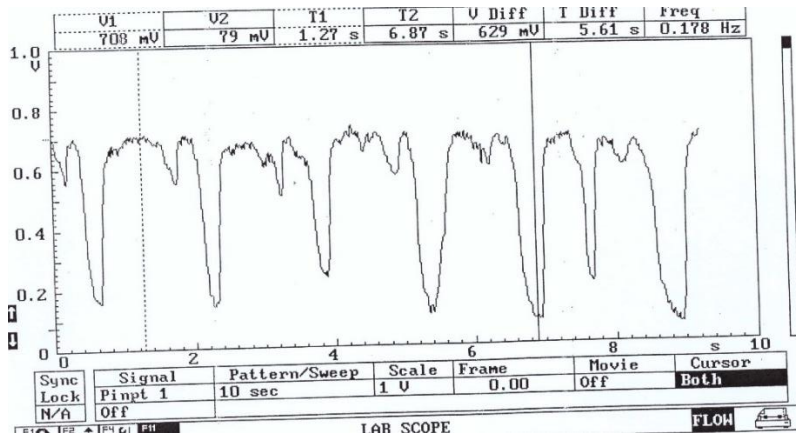


Figure 14: Motronic Lambda Sensor Scope Pattern

The waveform shows the O2 sensors voltages switching from ~0.7v to ~1.5v. The ECU on the car uses the Lambda or Oxygen Sensor to help determine the air fuel ratio that the car needs. It does this by using a closed loop operation. This results in a constant switch between rich fuel mixture and lean fuel mixture around a ratio of 14.7:1 which allows the Catalytic Converter to operate at its best. (What the Home Mechanic Needs to Know about O2 Sensors, 2012)

Motronic Crankshaft Sensor

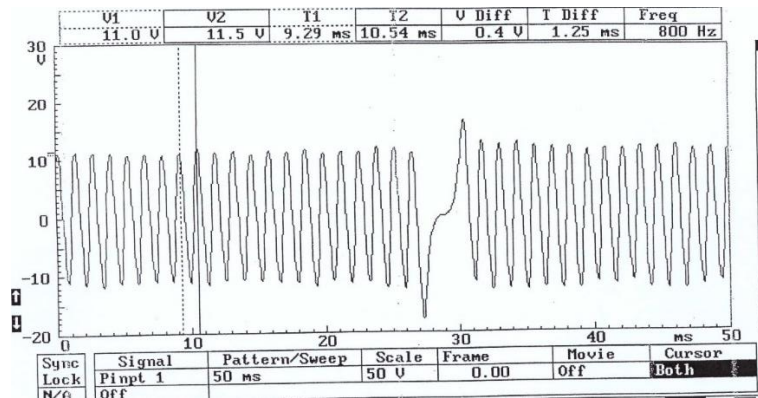


Figure 15: Motronic Crankshaft Sensor Scope Pattern

The Type of Sensor on this system is a magnetic effect. This means that it does not need a power supply and generates its own voltage by capturing the magnetic field produced by the crankshaft. A minimum of 2v is required for it to be recognized by the ECU. (ADPTraining, 2008)

In this case, the voltage range is between -10v and 10v.

LE3 Crankshaft Sensor

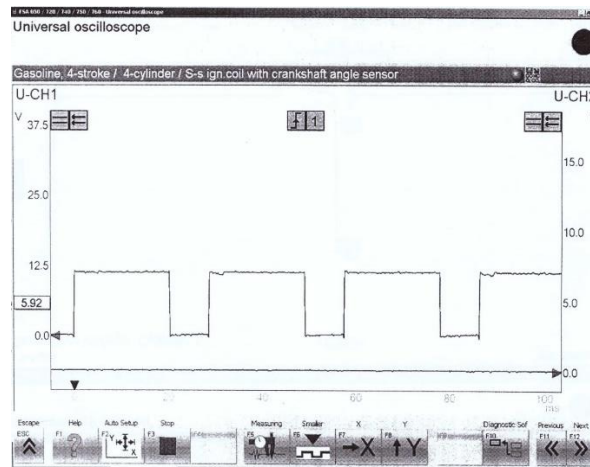


Figure 16: LE3 Crankshaft Sensor Scope Pattern

The waveform seen on the Crank Sensor for the LE3 System indicate that it is a Digital Hall Effect sensor. This is because it is a digital signal ranging from 0 to 12v. “Hall Effect Digital output sensors have a Schmitt-trigger with built in hysteresis connected When the magnetic flux passing through the Hall sensor exceeds a pre-set value the output from the device switches quickly between its “OFF” condition to an “ON” condition without any type of contact bounce.” The digital Signal is received on Pin 5 of the Ignition Ecu and is converted to analog before being sent to the Fuel ECU via pin 10. (Dejan, 2017)

Primary Waveform and Spark Advance Signal

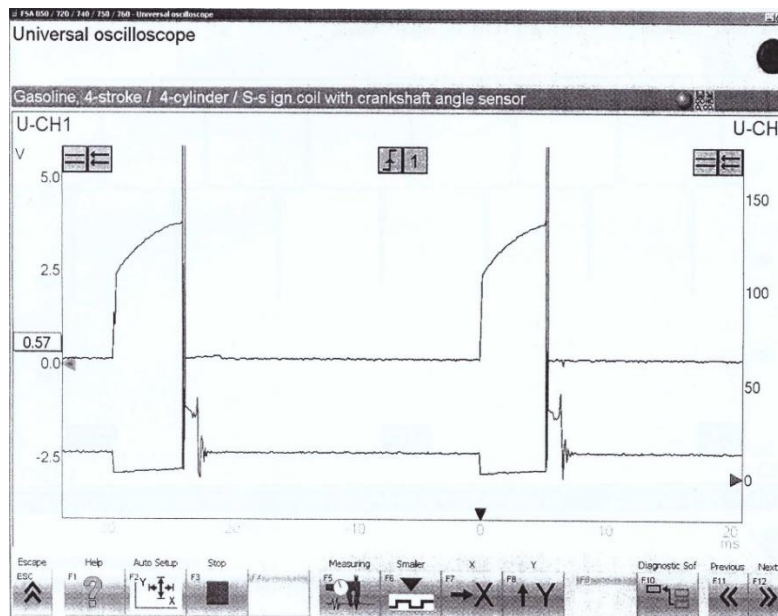


Figure 16: Primary Waveform and Spark Advance Signal Scope Patterns

In figure 16 the bottom waveform is the Primary waveform where the peak of the waveform is the Back EMF and the point where the spark occurs. The top waveform is spark advance signal. The arch that is seen when the primary is grounded is the dwell period, just before the cylinder is at top dead center (the optimal time for spark) (Ribbens, W, 2017)

5. Modifications to the LE3 System

Hot Wire Mass Air Flow Sensor

A Hot wire mass meter is superior to the Air Potentiometer as it can measure the mass of air instead of its volume. This is important as the mass of air changes with density (Why does hot air rise?, n.d) so just measuring the volume does not give an accurate representation of the amount of fuel being sucked in. The Mass Air Flow Sensor (MAF) consists of a thermistor, platinum hot wire and electronic control circuit. The thermistor measures incoming air temperature while the Hot Wire is kept at a constant temperature. When air flow increases the Hot Wire loses some of its heat, this is then replaced by voltage being added by the Control Circuit. The Control Circuit then measures the current flow and sends a voltage to the ECU which deciphers it into a temperature. (Mass airflow sensor basics | MAF sensor working, n.d)

Throttle Potentiometer

Replacing the throttle switch with a throttle potentiometer improves the system as it helps with metering. A throttle switch only has two known states. Fully open and closed, a throttle potentiometer has metering through 100% of its cycle. A potentiometer allows for the correct load reference to be given to the engine. Which could help with going into Limp Mode if required. (THROTTLE POSITION SENSOR (TPS), n.d)

Rotary Idle Valve

The Rotary idle valve is superior to the auxiliary air valve in the same way a throttle potentiometer is superior to the switch. The bimetallic only has 2 states. Fully open and closed, a Rotary Idle Valve has metering through 100% of its cycle allowing for a better air to fuel ratio when at base idle. (Vent valve (solenoid): how it works, symptoms, problems, testing, 2015)

Knock Sensor

Modern cars have replaced the Octane Loop with a Knock Sensor. It is normally located on the engine block or cylinder head. It is a piezoelectric sensor that contains a piezoelectric sensing crystal and a resistor. The piezoelectric crystal generates a small voltage when shaken and thus can detect any change in vibration in the engine that would suggest detonation (pinging or knocking). It will retard the ignition if it detects detonation. This is advantageous over the Octane Loop as it can react to changes quicker while on the fly. (Knock Sensor, n.d)

Sequential Injection

The main advantage of Sequential Injection over Simultaneous is the ability to make a change to the fuel amount in a short amount of time compared to sequential. As sequential fuels 100% of the fuel every 720° if a change happens in that period the fueling has already happened. Sequential Injection only supplies 50% of the fuel required over 360°, meaning that the injectors can react to any change in speed or load quicker and increasing economy. (How a Sequential Fuel Injection Works: Pros and Cons, 2012)

Lambda Sensor and Catalytic Converter

Fitting a Lambda Sensor along with a Catalytic Converter to the system would be beneficial as it would ensure that the fuel/air ratio would be kept at 14.7:1. Not only would this help with fuel economy but is a requirement in the current UK MOT laws. (NEED REF)

Wasted Spark & Coil on Plug

Wasted spark is superior to direct spark as it removes the need for a High-Tension Distributor. This improves reliability as the HT Distributor is susceptible to condensation, dirt and degradation of insulating materials with time. This is replaced with Coil on plugs which not only improve reliability but are easier to replace as if one is faulty only 1 must be changed instead of the whole unit.

Wasted Spark works by firing in pairs, one on its compression stroke and the other on its exhaust stroke. The extra spark during the exhaust stroke has no effect and is thus "wasted". (The Audiopedia, 2018)

“This design halves the number of components necessary in a typical ignition system, while the extra spark, against much reduced dielectric resistance, barely impacts the lifespan of modern ignition components. In a typical engine, it requires only about 2–3 kV to fire the cylinder on its exhaust stroke. The remaining coil energy is available to fire the spark plug in the cylinder on its compression stroke (typically about 8 to 12 kV).” (The Audiopedia, 2018)

Combining both ECUS

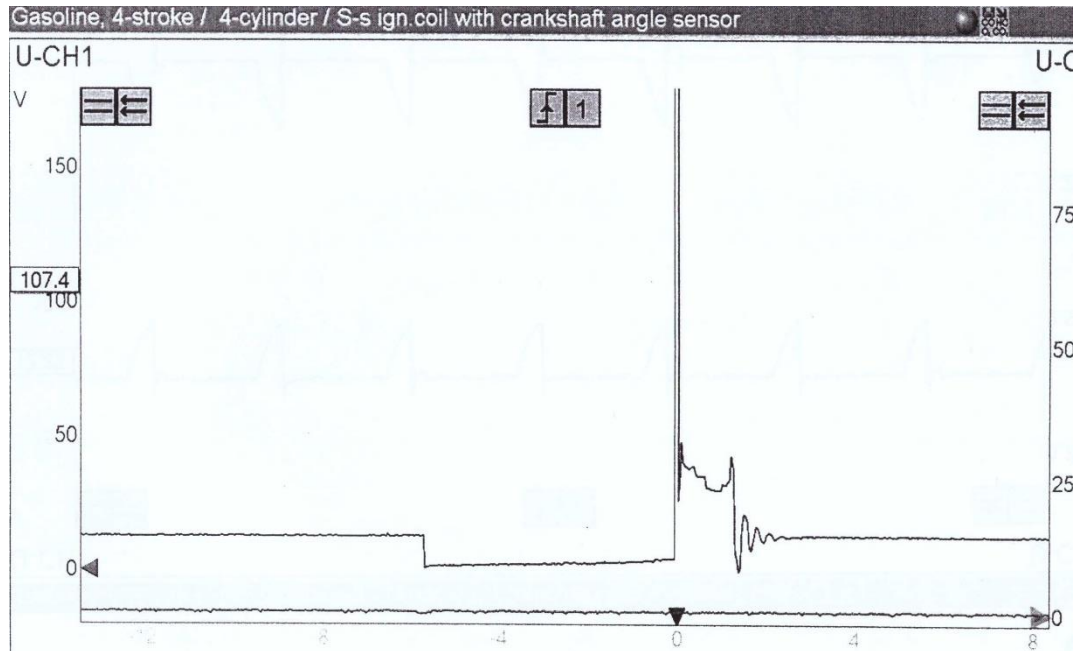
By combining both ECU's into one it can help speed the communication process up as there is no need for communication lines between the ECU's.

6. Conclusion

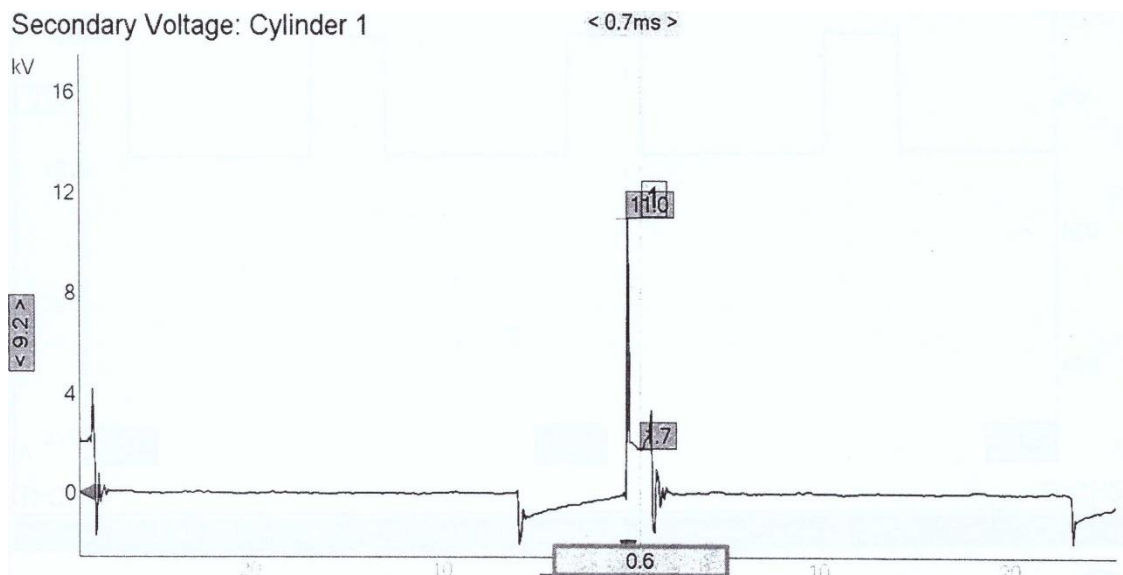
To conclude, both ECU's have various control measures in place to help meter fuel as well as adjust the ignition timing to enhance fuel economy. However, the Motronic system has major advantages to the LE3 system, with its 1 Ecu instead of the 2 featured on the LE3. It has various control measures on the system that the LE3 hasn't such as, a throttle potentiometer, lambda sensor, catalytic converter sequential injection and a rotary idle valve which is a sure upgrade of the auxiliary air valve featured on the LE3. All of the control measures listed above, help the Motronic system outperform the LE3 system in all phases of operating; Engine cranking (from cold); Engine warm-up; Acceleration.; Idle speed (engine at operating temperature). The Motronic system isn't perfect as there are modification that could be made to it to improve it further such as, a Wasted Spark and Coil on Plug system, replacing the Octane Loop with a Knock Sensor and upgrading the Air Flow Sensor to an Air Mass Meter.

7. Appendices

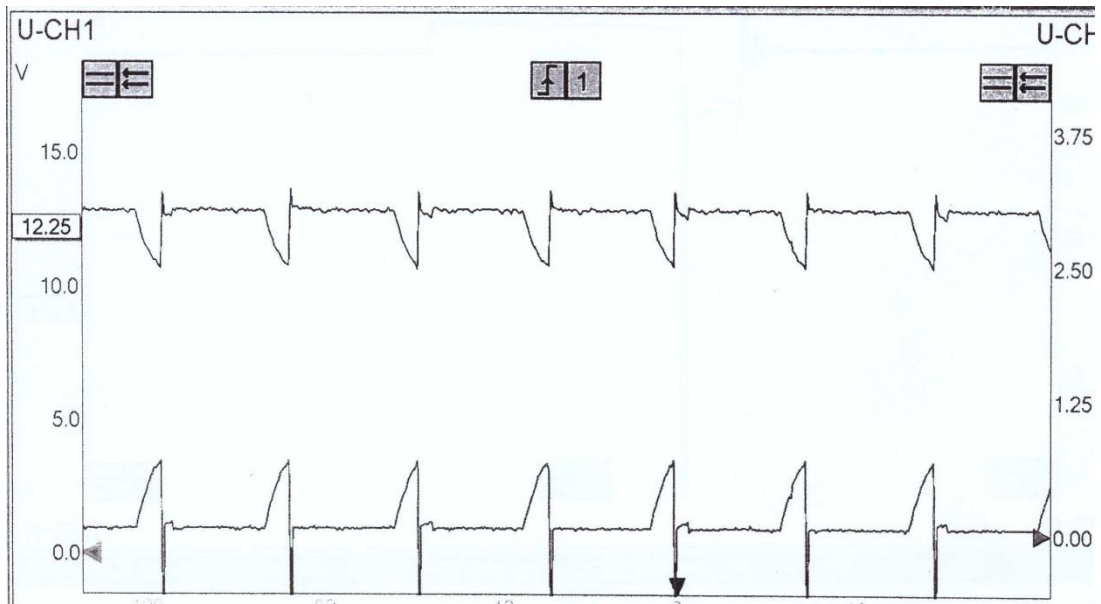
Appendix A: LE3 Primary Waveform Scope Pattern



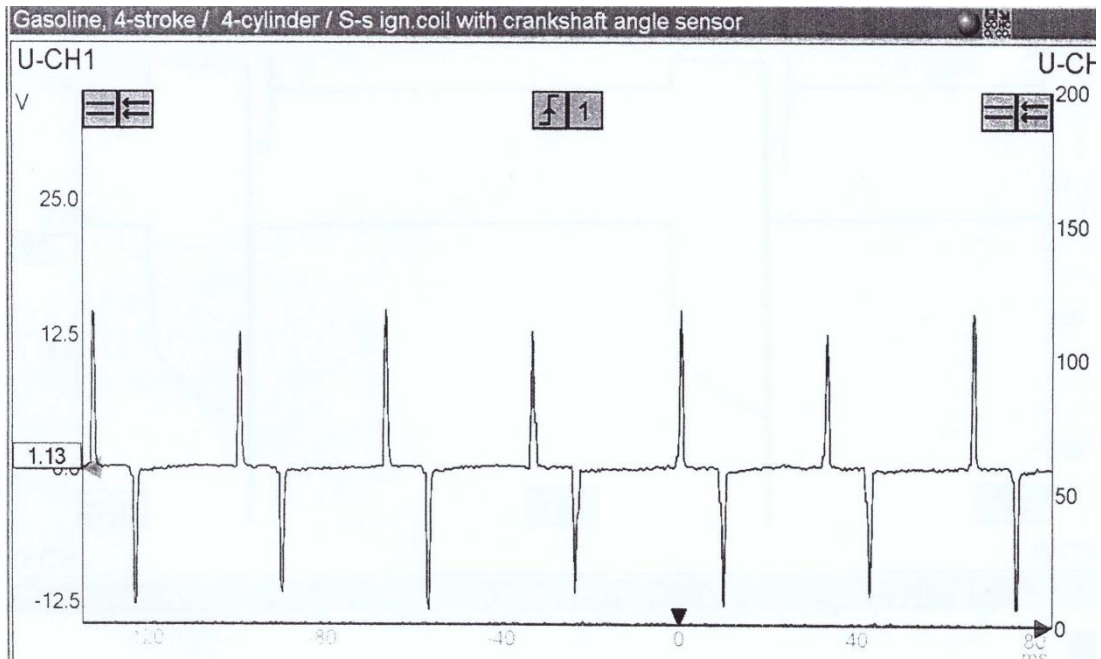
Appendix B: LE3 Secondary Waveform Scope Pattern



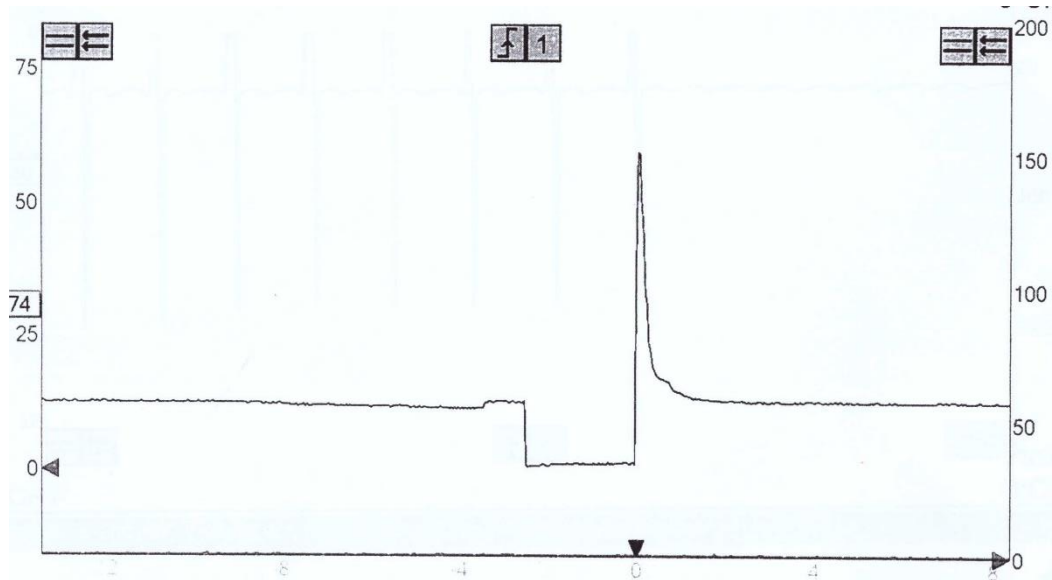
Appendix C: LE3 Amplification Unit Scope Pattern



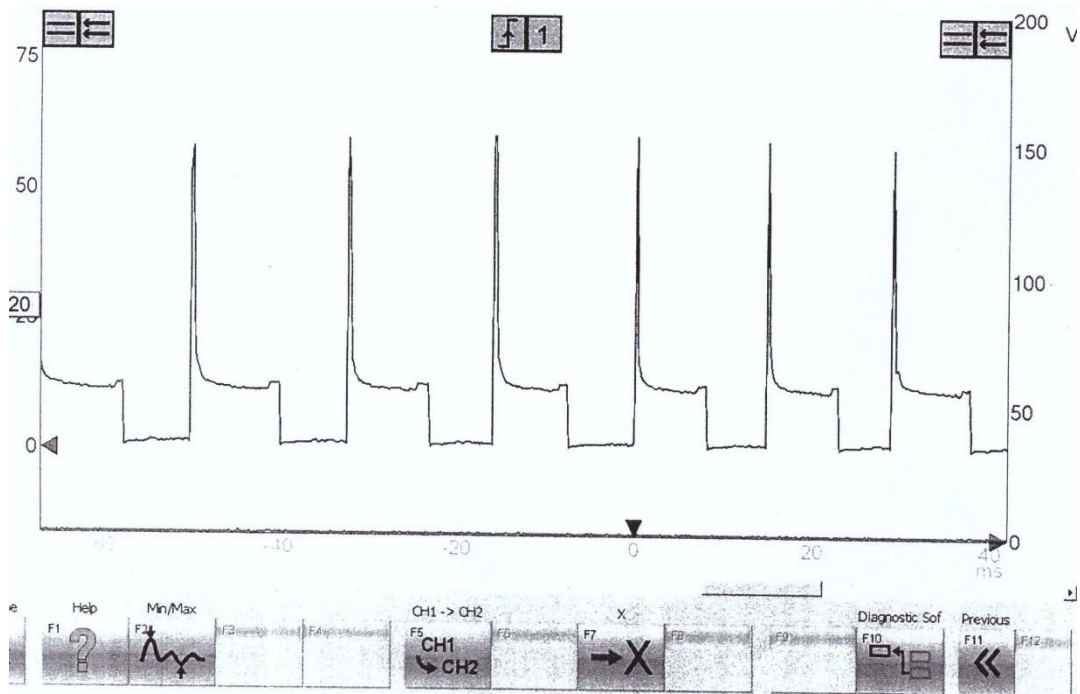
Appendix D: LE3 Crankshaft Sensor Scope Pattern



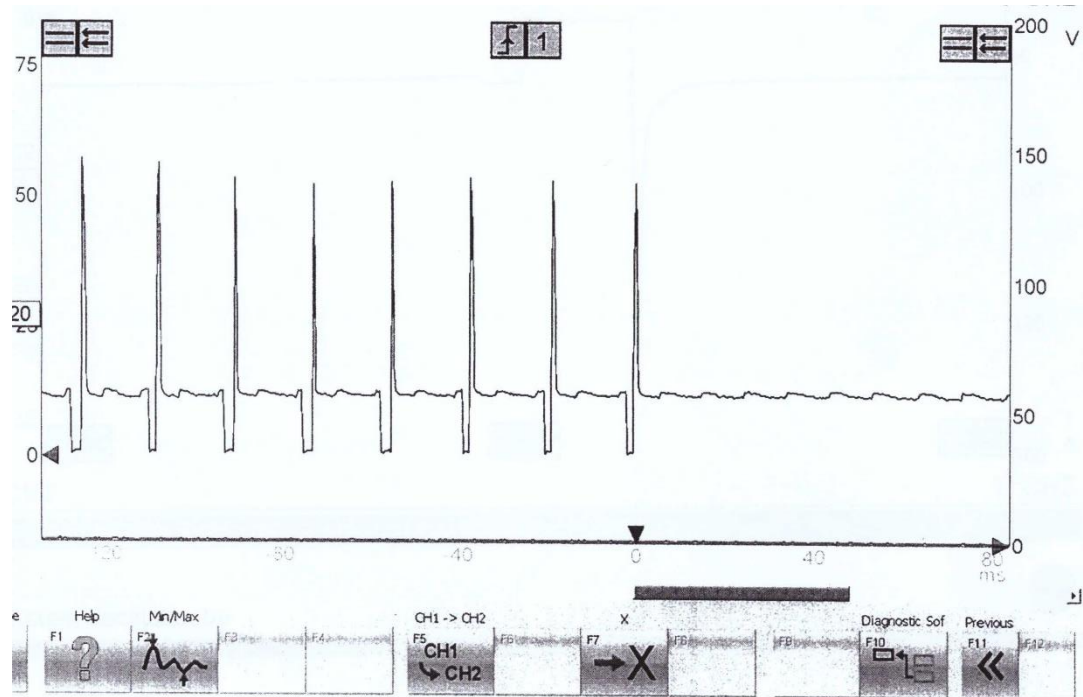
Appendix E: LE3 Injector Idle Scope Pattern



Appendix F: LE3 Injector Accelerating Scope Pattern



Appendix G: LE3 Injector Decelerating Scope Pattern



Appendix H: LE3 Full AutoData Results

Throttle Switch		
Throttle Position	Manufacturer	Tested
Throttle Closed		0 000.2kv
Throttle Closed	infinity	Infinity
Coolant Temp		
Temperature	Manufacturer	Tested
-10	7000-11600	
0		
20	2100-2900	
40	1000 to 1400	
80	270-330	
Auxillary Air Valve		
Resistance between terminals		
	Manufacture	Tested
	40	46.4
Injector Valves		
	Manufacturer	Tested
1	15-17	16.1
2	15-17	16.1
3	15-17	16.1
4	15-17	16.1
HT Leads		
	Resistance	
1	8500	
2	8720	
3	7270	
4	5420	Faulty plug
King lead	5515	
Coil Resistance		
	Resistance	
Primary	0.6	2 - because of air
Secondary	7760	

Appendix I: Motronic Full AutoData Results

Throttle Potentiometer		
Throttle Position	Manufact	Tested
Throttle Closed	1900/2000	2107
Throttle Open	1000/2000	2702
Air flow sensor		
Terminals	Manufact	Tested
4 & 2	8 to 2500	33.6
4 & 3	300 to 550	561
4 & 1	270 to 520	0
Coolant Temp		
Temperature	Manufact	Tested
0	4800 to 6600	
20	2200 to 28	1587
40	1000 to 14	717
80	270 to 360	256
Air Temp Sensor		
Temperature	Manufact	Tested
15-30	1500 to 3300	
80	280 to 360	280
Idle Speed Control		
	Manufact	Tested
Resistance	8	8.1
Injector Valves		
	Manufact	Tested
Resistance		
1	15 to 17	16.3
2	16 to 17	16.3
3	17 to 17	16.4
4	18 to 17	16.3
Lambda		
Voltage	Manufact	Tested
	0.5 to 0.5	0.4 to 0.5
HT Leads		
	Resistance	
1	19600	
2	18440	
3	14950	
4	21300	Faulty plug
King lead	Faulty	

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