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Electronic Ignition & Fuel Injector Systems Report

Electrical Control Systems – ACHA4010

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1 Introduction

This report details a test carried out on two engines, Bosch 1.8l LE3 Jetronic 18SEH (LE3) and General Motors (GM) 2.0l Motronic C20NE (Motronic). Testing procedures consisted of a live test and observation of these engines with the ignition in both off and on positions as well as recording data from both engine during a sweep of temperatures during its warmup phase. The testing is split into two groups on testing the Motronic and the other testing the LE3.

Live engine testing is an essential tool for engine manufactures, as described by Martyr and Plint (2012) live testing ensure that test engineers can diagnose and fix potential performance faults before the end user is aware of them. In addition to this it allows test engineers to simulate the working life span of an engine in order to ensure it meet expectations of longevity. Isermann, Schaffnit and Sinsel (1999) describe the benefits of live testing as including the ability the test dangerous or destructive conditions, enabling repeatable testing, and reducing development cost by allowing faults to be identified earlier.

Prototype testing is another key use of live testing as this provides an environment where new ideas and concepts can be tested physically. In their paper on the testing procedure of a prototype diesel engine Grigoratos *et al.* (2016) states that the transportation sector accounted for over half of the increase in greenhouse gas emissions between 1990 and 2011 in the USA and as such prototype engine testing is becoming increasingly important as manufactures strive for better emissions standards.

The aim of this report is to collect data on the operating condition of the specified engines to compare against manufacture specifications and to suggest improvements that could be made to the engines control systems and sensors.

2 Background Information

The ideal air/fuel ratio for a petrol-powered spark ignition (SI) internal combustion engine (ICE) is 14.7:1, referred to as the stoichiometric ratio (Wang *et al.*, 2006).

Electrical control systems refer the array of sensors that send data to an engines Electrical Control Unit (ECU) to assist in engine operations. As described by Reif and Dietsche (2014) the goal of the control system is to ensure the drivers commands are implemented for example acceleration, deceleration or constant velocity travel.

In its basic form the sensor array of an engines electrical control system consists of the following.

- Throttle position sensor (TPS) – Uses a potentiometer which functions on the effect of moving a wire through an arc where it contacts materials of differing resistances producing a different voltage which can then be interpreted as movement of the throttle plate.
- Mass Airflow Meter (MAF) – In the case of both tested engines the MAF uses a spring-loaded flap that's placed in the intake airflow, the incoming air pushes on this flap and this movement is then extrapolated to calculate the volume of air passing into the cylinder.
- Engine Coolant Temperature Sensor (CT) – Uses a Negative Temperature Coefficient (NTC) Thermistor which functions by placing a conducting element in the flow, the temperature of this flow changes the resistance of the conducting element. The resistance of an NTC thermistor reduces when temperature rises as such the voltage needed to overcome this resistance is reduced and therefore this voltage can be interpreted by the ECU as a temperature reading.
- Exhaust Gas Oxygen Sensor (EGO) or Lambda Sensor – As described by De Souza Sobrinho and De Lima (2012) a lambda sensor uses a Zirconium Oxide element on one side of which is the exhaust gas and on the other is atmospheric gas. The difference in oxygen concentration between these gases causes oxygen to diffuse across the element causing a voltage, this voltage can then be used to interpret the air/fuel ratio in the cylinder. This is known as a narrow band Lambda and can only give information on whether the engine is running rich, lean or stoichiometric.

- Crank Position Sensor - Uses a magnet that register a voltage when its magnetic field is disrupted by a passing object that is used as a reference point, for example a missing tooth on a flywheel or a lug on a rotating component of the engine. This refence point is used to mark one full rotation and as such gives a reading of engine speed that is used to aid ignition timing.
- Air Temperature Sensor (AT) – Uses a NTC sensor to measure the temperature of intake air.
- Fuel Pressure Sensor (FPS) – Both tested engines use a diaphragm type FPS, where fuel pressure is regulated using two chambers separated by a diaphragm. When pressure exceeds the target pressure the diaphragm flexes and excess fuel is returned to the tank.

Information from this array of sensor is feedback to the ECU as a range of voltages, the ECU compares this data against a lookup table and can adjust the engines operations accordingly. The Motronic test engine has a first-generation version of Onboard Diagnostics (OBD) specifically Motronic M1.5. OBD enables adaptive measures to be taken by the ECU depending on the reading from the various sensors. These measures can include the following.

- Adjustment of the air/fuel mixture to maintain complete combustion and stoichiometric ratio. The ECU achieves this by metering the fuel depending on the volume calculated from the data given by the TPS, MAF, and AT sensors, in addition this data is checked against oxygen readings from the EGO sensor.
- Adjustment of dwell time and ignition timing. Dwell time refers to the period in which the ignition coil is being charged. Ignition timing refers to when a spark is sent to the cylinder when compared to the piston being in Top Dead Centre (TDC), for example advancing ignition describes sending the spark to the cylinder before the piston reaches TDC. As described by Wu *et al.* (2010) ignition timing is vital in an ECUs ability to maintain efficiency and improve emissions.

The Motronic system uses a single ECU for all control systems where as the LE3 uses two ECUs, one for the ignition system and one for the fuel system.

Both tested engines use a Kettering ignition system as shown in figure 1. Where a coil stores a charge that is then transferred to the spark plug through a distributor. The distributor is connected to the engine and as such rotates at the same speed. A conductive arm spins within the distributor completing a circuit with separate nodes within the distributor housing sending a current to each spark plug, for example for a 4-cylinder engine there will be four separate nodes in the distributor housing. As such all of the engines spark plugs rely on a single ignition coil. This becomes a limitation at higher engine speeds as the coil has less time to charge the spark between firing and must fire all spark plugs leading to a reduced voltage as the coil struggles to keep up with the engine. This reduced voltage may lead to incomplete combustion within the cylinder.

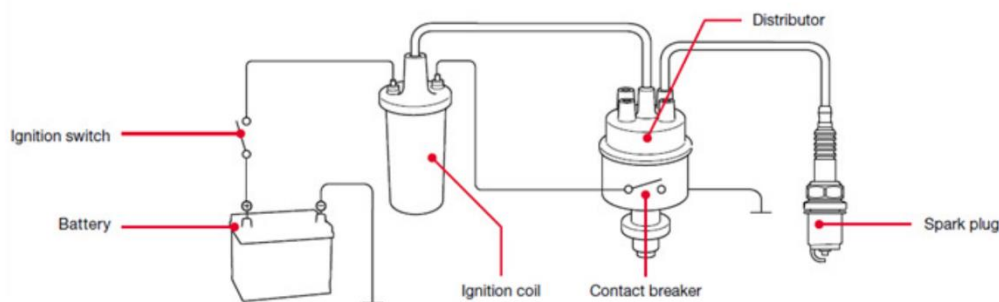


Figure 1 - Example of a Kettering Ignition System (Denso, 2021)

The tested engines both use electronically controlled fuel injection. As described by Bosch (1982) electronically controlled fuel injection allows the ECU to change the air/fuel mixture by extending the duration of the injector pulse depending on operating conditions or data receive from the engines sensors. Both engines use a rotary type of pump that maintains fuel pressure which is then regulated by the fuel pressure sensor.

The Motronic uses a throttle switch for idle control which activates when a high load on the engine is detected with the throttle closed. This load may be produced my electronic in the cabin e.g. A/C, heated seats or the car sound system.

The operating temperature of the Motronic is 80°C, the operating temperature of the LE3 is 60°C.

3 Methodology

3.1 Health and Safety

Being aware of risks involved and minimising the potential for these risks to cause injury or damage the health of those involved is a key aspect of any test, more so during a test of live machinery. The following measures were taken to reduce the risks involved in the test.

- All test participants were required to wear safety shoes and lab coats in order to protect from falling objects and fluid spills respectively.
- All participants were required to remove loose fitting clothing, including hoodies with loose strings attached, to minimise risks associated with rotating machinery.
- Extra care was taken to ensure all participants were standing clear of the engines when starting and running as some rotating parts were exposed.
- Exhaust extraction systems were used in order to comply with COSHH EH40/2005 regulations for workplace exposure limits (HSE, 2020).
- All testing activities were supervised by an experienced technician.

3.2 Testing Equipment

The following equipment was used during the test.

- A digital multimeter – This is a good choice of equipment for this test as it can provide readings on a range of variables, voltage, resistance and current. It provides a clearer reading than an analog multimeter as there is no scale to interpret thus reducing human error. However, the multimeter has an internal resistance of 0.2Ω take must be accounted for during readings of resistance, all data shown in the results section has been adjusted. For all tests the multimeter was grounded to the throttle body of the tested engine.
- Motronic engine contained on a test rig as shown on the next page (Figure 2).
- LE3 engine contained on a test rig.
- A computer was used as an oscilloscope in order to obtain scope patterns.



Figure 2 - Example of engine test rig with 2.0l Motronic

3.3 Motronic Methodology

The Motronic tests were carried out by the other group. The following steps were taken during the test.

- A reference battery voltage was taken using a multimeter.
- A Static ECU pin check was completed.
- Resistance readings of the fuel injectors, throttle potentiometer, coolant temperature sensor and airflow sensor for comparison against manufacturer specs.

The Motronic engine was then started to undergo the next phase of the test where the following steps were completed.

- Cold cranking was initiated at ambient temperature and the injection on time was recorded during this phase
- Idle speed was recorded.
- The engine was warmed to 20°C, measured using a thermometer connected to the oscilloscope in place of the oil dipstick, and allowed to stabilise.
- At 20°C baseline readings were recorded including, readings of the voltage from the air intake sensor (NTC1), resistance and voltage values of NTC2, injection on time, rotary idle valve percentage on time, recordings of the tank vent valve and Lambda switching.
- The process described in the previous two steps was repeated and further readings of all variables from the previous step (except NTC1) were recorded across the temperature range 20 – 80 °C in 10°C increments.
- A reading of NTC1 voltage was taken at 80°C.
- Due to time constraints the test was not repeated.

3.4 LE3 Methodology

The LE3 tests were carried out using guidance from Autodata (Autodata, 1993). The following steps were taken during the static pin test.

- A reference battery voltage was recorded using a digital multimeter.
- A static ECU pin check was completed, where the voltage of all the pins from both ECUs is checked with a multimeter when the ignition is off and again with ignition on.
- Resistance readings of the fuel injectors, throttle switch, coolant temperature sensor, and auxiliary air valve for comparison against manufacture specs. The resistances of components were checked by placing multimeter on the pins of the components.
- The oscilloscope was used in order to record scope patterns of injection on-time during idle, acceleration, and deceleration in addition to ignition primary and secondary wave scope patterns.

The LE3 engine was then started to undergo the warm-up phase test.

- Cold cranking was initiated and the injection on time was observed.
- The engine was warmed to 20°C, measured using a thermometer connected to the oscilloscope in place of the oil dipstick, and allowed to stabilise.
- Baseline readings were taken at 20°C of the resistance and voltage of NTC2, and injection on-time.
- The process described in the previous two steps was repeated at 10° intervals between 20 - 60°C.
- Due to time constraints the test was not repeated.

4 Results and Analysis

Ambient temperature for all tests was 18°C.

4.1 ECU Pin Check

4.1.1 LE3 Pin Check

Battery voltage was 12.23v.

The ignition ECU on the LE3 has 15 pins, unused pins are not shown in Table 1.

Table 1 – LE3 Ignition ECU Test Results

Pin Number	Ignition Off (v)	Ignition On (v)
1	0	0.03
2	0	0.03
3	0	11.57
5	0	0.06
6	0	0.02
7	0	2.42
8	0	0.95
10	0	0.03
11	0	0.03
12	0	0.06
13	0	0.13
14	0	4.98
15	0	0.06

From the table it can be observed that all circuits on the ignition system are complete as they all return a voltage when ignition is on.

The fuel ECU has 15 pins, unused pins are not shown in Table 2.

Table 2 – LE3 Fuel ECU Test Results

Pin Number	Ignition Off (v)	Ignition On (v)
1	0	0.6
2	0	11.67
3	0	0
4	0	0.02
5	0	0.03
8	0	1.94
10	0	0.16
11	0	1
12	0	11.75
14	0	4.98
15	0	0.02

From Table 2 it can be observed that all except one pin are returning a voltage and as such are complete circuits, the pin not returning a voltage may be an earth. From Tables 1 & 2 it can be observed that the LE3 has no permanent live.

4.1.2 Motronic Pin Check

Battery voltage was 12.4v.

The Motronic ECU has 55 pins, unused pins are not shown in Table 3. Components were provided by Gibson (2022b).

Table 3 – Motronic ECU Test Results

Pin Number	Ignition OFF (v)	Ignition ON (v)	Components
1	0	12.15	Negative side of coil
2	0	0.04	Earth
3	0	12.04	Control circuit for fuel pump
4	0	9.74	Pulsed side of Rotary Idle Valve
5	0	12.01	Pulsed side of Tank Vent Valve
6	0	11.31	4WD ECU – A/T ECU – Fuel Tell-Tale lamp
7	0	0.33	Load signal output from air-low meter
10	0	0	Earth
12	0	5.08	5v supply to air-flow meter & throttle potentiometer
13	0	10.1	Diagnostic socket supply
14	0	0	Earth
16	0	12.1	Pulsed side of injectors (bank of two)
17	0	12.1	Pulsed side of injectors (bank of other two)
18	12.4	12.1	Permanent live
19	0	0	Earth
20	0	0	Earth (for catalyser)
21	0	0	Earth (for A/T)
22	0	0.93	Engine tell-tale warning light
24	0	0	Earth
26	0	0	Earth via ECU
27	0	12.09	Ignition feed
28	0	0.45	Output from Lambda sensor
32	0	11.3	Output to on-board computer
36	12.07	0.31	Control circuit for auxiliaries & ECU
37	0	12.03	Supply to ECU & to on-board computer
40	0	0	A/C
41	0	0	A/C
42	0	0	Earth (manual transmission only)
44	0	3.69	Output from NTC 1 (Intake Air Temp)
45	0	3.69	Output from NTC 2 (Coolant Temp)
46	0	0.25	Octane plug input
48	0	0.07	Output from crankshaft sensor
49	0	0.11	Output from crankshaft sensor
53	0	0.66	Output from throttle potentiometer
55	0	10.99	Earth for diagnostic socket

From Table 3 it can be observed that all pins, except earths and A/C pins, are returning a voltage and are therefore complete circuits. The A/C pins are not returning a voltage as the engine is mounted to a test rig and the A/C system is not attached. It can also be observed that the Motronic engine has a permanent live connected to the ECU, the purpose of this is to store electronic data about recent operating conditions of the engine.

4.2 Resistance Check Test

4.2.1 LE3 Resistance Check

All manufacture specifications in this section were provided by Autodata (1993).

Table 4 – LE3 Tested Components

Component
Fuel Injectors
Throttle Switch
Coolant Temperature Sensor
Auxiliary Air Valve

Table 5 – Injector Resistance Test Results

Injector	Manufacture Spec (Ω)	Test Reading (Ω)
1	15 – 17	15.8
2	15 – 17	15.8
3	15 – 17	15.8
4	15 – 17	15.8

From Table 5 it can be observed that all four injectors functioning within manufacturer specifications.

Table 6 – Throttle Switch Resistance Test Results (Throttle Closed)

Pins	Manufacturer Spec (Ω)	Test Reading (Ω)
2 & 18	0	0
3 & 18	∞	∞

From Table 6 it can be observed that the throttle switch is functioning within manufacturer spec.

Table 7 – CT Sensor Resistance Test Results

	Manufacturer Spec (At 20°C)	Test Reading (Ambient)
CT Sensor Resistance (Ω)	2100 – 2900	2690

Results shown in Table 7 are slightly inaccurate as the manufacture specs are given for 20° and the test was conducted at 18°C, however the CT sensor can still be observed to be functioning within manufacturer spec.

Table 8 – Auxiliary Air Valve Resistance Test Results

	Manufacturer Spec	Test Reading
Auxiliary Air Valve Resistance Between Terminals (Ω)	40	45.9

From Table 8 it can be observed that the Auxiliary Air Valve is operating outside of manufacturer spec. This may indicate a potential fault with this device.

4.2.2 Motronic Resistance Check

Manufacturer specifications were provided by Gibson (2022a).

Table 9 – Motronic Tested Components

Component
Fuel Injectors
Throttle Potentiometer
Coolant Temperature Sensor
Airflow Sensor

Table 10 – Injectors Resistance Test Results (2)

Injector	Manufacturer Spec (Ω)	Test Reading (Ω)
1	15 – 17	16.6
2	15 – 17	16.5
3	15 – 17	16.5
4	15 – 17	16.6

From Table 10 it can be observed that all four injectors are functioning within manufacturer spec.

Table 11 – Throttle Potentiometer Resistance Test Results

Throttle Position	Manufacturer Spec (Ω)	Test Reading (Ω)
Open	1000 – 2000	2680
Closed	1900 – 2000	1480

From Table 11 it can be observed that the throttle potentiometer does not meet manufacturer spec, as such it is likely to be malfunctioning. However, this was known prior to the test as the potentiometer is aftermarket and faulty.

Table 12 – CT Sensor Resistance Test Results (2)

	Manufacturer Specs	Test Reading (Ambient Temp)
CT Sensor Resistance (Ω)	4800 – 6600 At 0°C 100 – 1400 At 40°C	2530

Due to the given ranges in the manufacturer specs, it is difficult to assess the test reading. However, given that the reading of 2530 Ω at 18°C falls within the bracket 4800 – 1400 Ω between 0 – 40 °C it can be assumed that the CT sensor is roughly operating within manufacture spec.

Table 13 – Airflow Sensor Resistance Test Readings

Airflow Sensor Pin	Manufacturer Spec (Ω)	Test Reading (Ω)
4 & 2	8 – 2500	320
4 & 3	300 – 550	560

From Table 13 it can be observed that the Airflow sensor is operation slightly outside its manufacturer spec, this has to potential to create a fault.

4.3 Motronic Warm-up Phase Test

During the cold cranking test, at ambient temperature, the following was observed.

Initial injection on-time was 21.3ms, then 18.2ms for the next engine rotation. This trend continued for 300ms. After this period the injection on-time returned to idle condition.

This occurs due to the ECU running the engine at a lower stoichiometric ratios (Rich). To achieve this the injector is pulse for longer allowing more fuel to enter to cylinder. The engine is running rich during cold cranking in order to ensure that combustion occurs within the cylinder.

Idle speed of the engine was measured to vary inconstantly between 700 and 800 RPM, this inconstancy may be due to the faulty potentiometer.

Table 14 -Motronic Warm Up Test Results

Engine Temp (°C)	NTC2 Resistance (Ω)	NTC2 Voltage (v)	Injection On-time (ms)	Rotary Idle Valve (% on-time)	Tank Vent	Lambda Sensor	NTC1 Voltage (v)
20	1900	3.1	3.1	44	Off	Off	3.6
30	1020	2.5	2.8	42	Off	On	-
40	660	2.2	3.2	41	Off	On	-
50	450	1.6	2.9	42	On	On	-
60	340	1.4	2.9	41	On	On	-
70	240	0.9	2.6	40	On	On	-
80	250	1.0	2.8	43	On	On	3.3

The NTCs shown in Table 14 represent the following, NTC1 is the Intake Air Temperature Sensor, NTC2 is the Coolant Temperature Sensor. Then fan on the radiator of the cooling system turned on at 70°C. The following can be observed from Table 14.

- Injection on-time remained relatively consistent over the range of temperatures suggesting that the Air/fuel ratio did not need much adjustment from the ECU to maintain idle across differing temperatures.
- Rotary Idle Valve (RIV) % on-time remained between 40 – 44 % during the test. This is because the Rotary Idle Valve is adjusting the Air/fuel mix to maintain idle.
- The Tank Vent Valve can be observed to have opened after 40°C, this may be explained as the temperature increase of the engine would have heated up the fuel system causing an increase in pressure that would need to be vented.

- NTC1 voltage can be seen to have decreased between 20 and 80°C. This is because the increased heat of the engine is leading to an increase in the heat of the air entering the engine. As such the resistance of NTC1 has reduced resulting in a lower voltage.

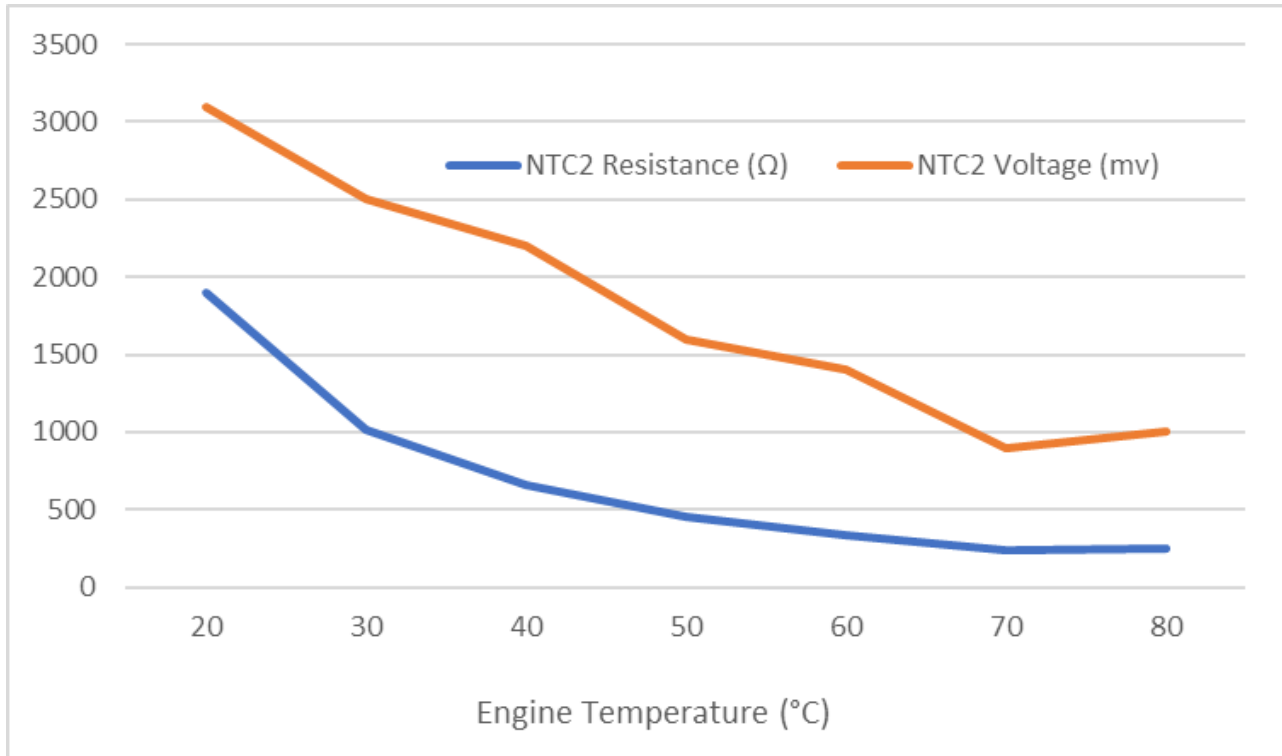


Figure 3 - Graph Showing NTC2 Voltage and Resistance Against Engine Temperature

From the graph (Figure 3) the following can be observed.

- As expected, the resistance of NTC2 reduces as the temperature of the engine increases and as such the coolant temperature increases. Therefore, NTC2 can be observed to be functioning correctly.
- As expected, the voltage at NTC2 reduces as a result of the resistance drop.
- Voltage and resistance values follow a similar trend however they do not follow the exact same trend suggesting that the NTC thermistor system is slightly inaccurate.

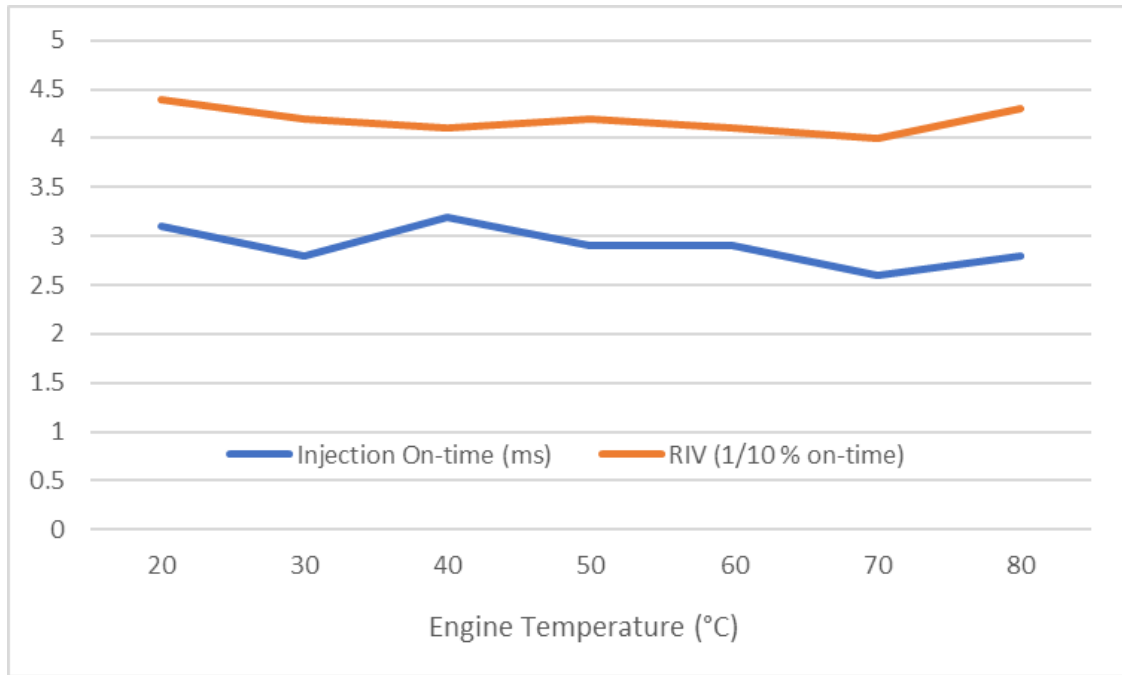


Figure 4 - Graph Showing Injection On-time and RIV On-time Against Engine Temperature

From the graph (Figure 4) it can be observed that injection on-time and RIV on-time follow a similar curve. This is a result of both component working to achieve the same outcome, idle control of the engine. The variables do not correlate directly however as injection on-time shows more variation along the curve, this may be due to false reading from the faulty throttle potentiometer.

4.4 LE3 Warm-up Phase

When cold cranking was initiated, at ambient temperature, it was observed that injection on time increased during this period. As described in the previous section this is to ensure that combustion occurs in the cylinder.

Table 15 - LE3 Warm up Test Results

Temperature (°C)	NTC2 Resistance (Ω)	NTC2 Voltage (v)	Injection On-time
20	1940	1.7	1.42
30	1070	1.1	2.9
40	770	0.9	2.9
50	538	0.7	2.9
60	392	0.5	2.7

NTC 2 is the coolant temperature sensor. From Table 15 the following can be observed that injection on time remained relatively consistent between 30 - 60°C, however at 20 °C the injection on time gave an anomalous result, this may be a result of faulty testing equipment as the expected result would be higher as shown in Table 14.

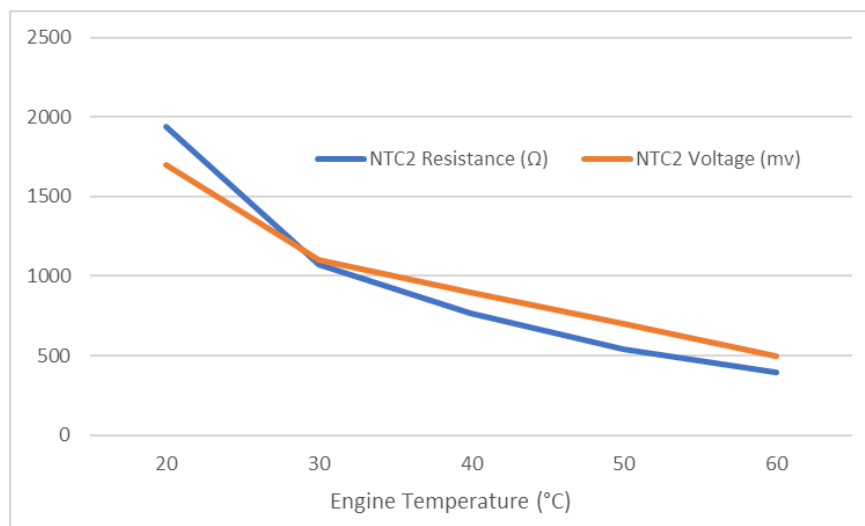


Figure 5 - LE3 NTC2 Voltage and Resistance Against Engine Temperature

From the graph Figure 5 it can be observed that the resistance and voltage of NTC2 follow the same trend much more closely when compared to the results of the Motronic (Figure 3) therefore this shows the coolant temperature sensor is operating more accurately on the LE3.

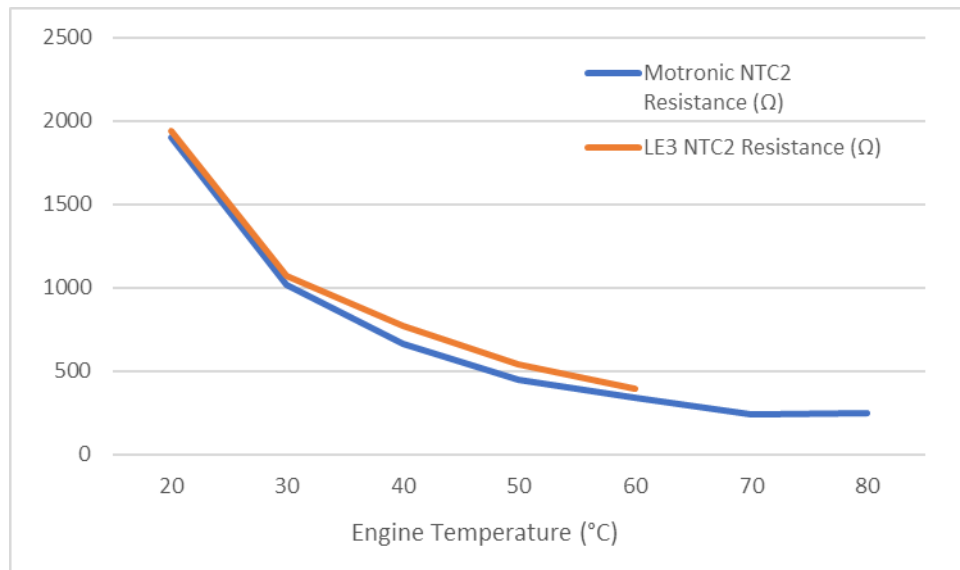


Figure 6 - Motronic and LE3 NTC2 Resistance Against Engine Temperature

From the graph figure 6 it can be observed that not only do the NTC2 results for each engine follow the same trend but have similar resistance values at the tested temperatures.

4.5 LE3 Scope Patterns

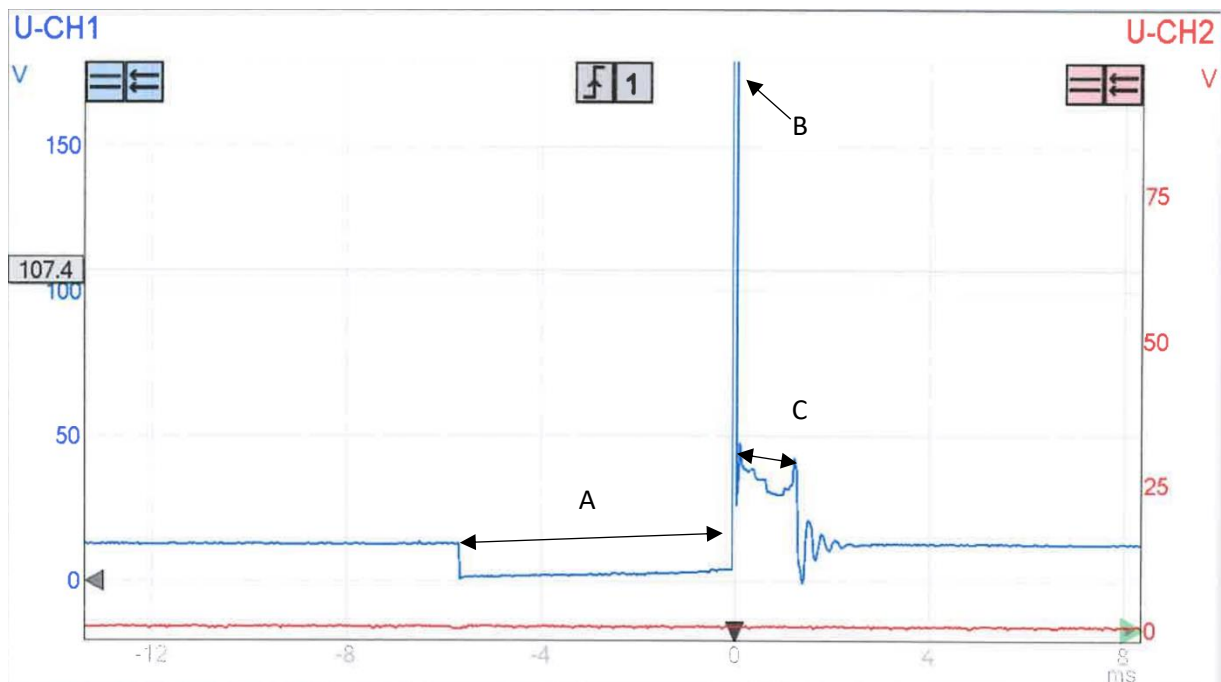


Figure 7 - LE3 Primary Side of Ignition Coil Scope Pattern

Figure 7 shows the scope pattern for the primary side of the ignition coil at idle. Data point A shows the dwell time, effectively the time the coil takes to charge up before a spark is produced. Data point B shows the back EMF produced when the coil begins to discharge. Data point C shows the spark duration.

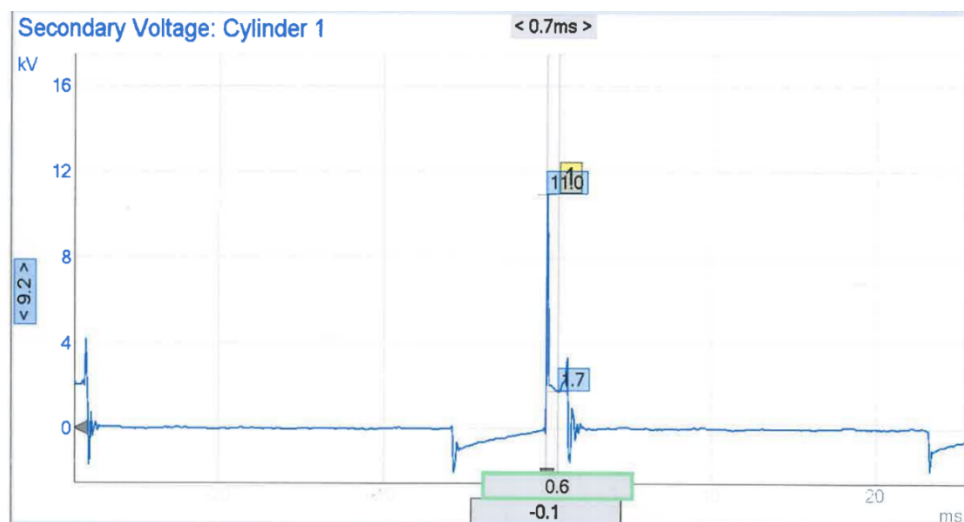


Figure 8 - LE3 Secondary Side of Ignition Coil Scope Pattern

From Figure 8 it can be observed that the secondary side of the ignition coil has a similar scope pattern to the primary, this is because they are connected in the same circuit.

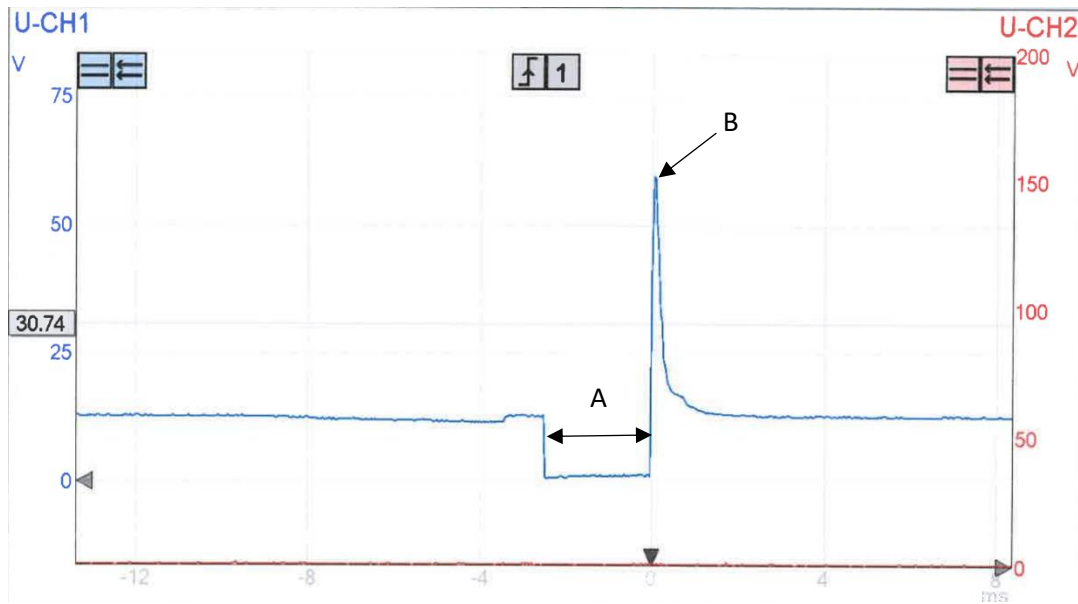


Figure 9 - LE3 Injector Scope Pattern (Idle)

Figure 9 shows the scope pattern for the fuel injectors. Data point A shows the injection on-time. Data point B shows the back EMF. It can be observed that the injection on-time at idle is roughly 3ms.

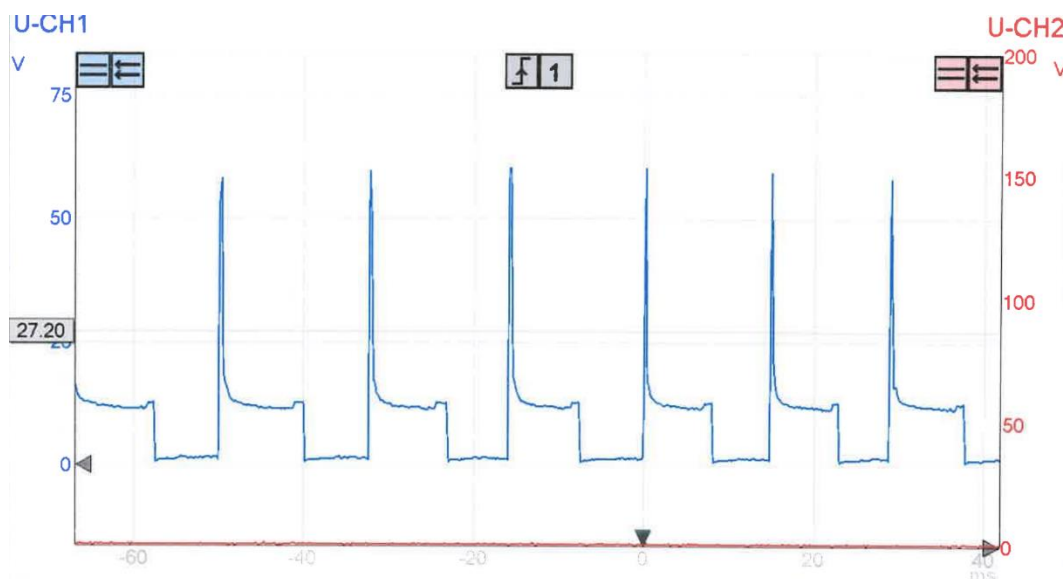


Figure 10 - LE3 Injector Scope Pattern (Acceleration)

From Figure 10 it can be observed that the individual patterns of each injector cycle have increased in frequency and are closer together than at idle (Figure 7). This is due to an increase in engine speed. It can be observed that injection on-time is roughly 8ms during acceleration.

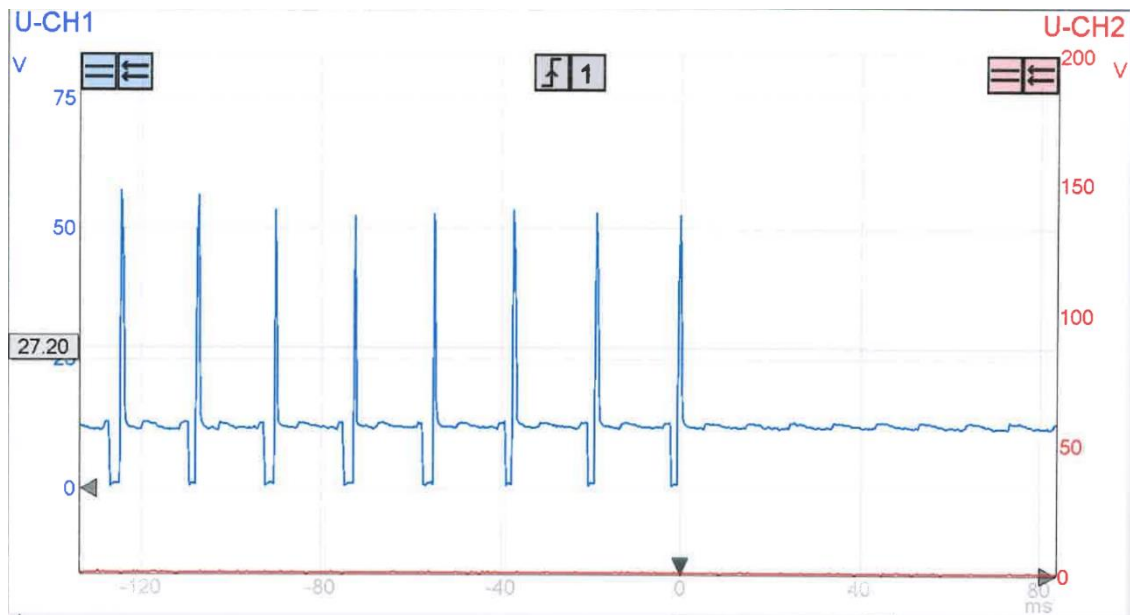


Figure 11 - LE3 Injector Scope Pattern (Deceleration)

From figure 11 it can be observed that, similar to Figure 8, the individual patterns of each injector cycle and increased in frequency and are closer together when compared to idle (Figure 7). This is due to an increase in engine speed. It can be observed that interaction on-time is roughly 2ms.

Table 16 - Data Retrieved from Scope Patterns

Engine State	Injection on-time (ms)
Idle	3
Acceleration	8
Deceleration	2

From Table 16 it can be observed that injection on-time increased while accelerating when compared to idle, this is a result of a greater load placed on the engine. When a load is placed on the engine more fuel must be added to the combustion process in order to produce power. The engine is under little load to maintain idle and as such the amount of fuel needed is less.

It can also be observed from Table 16 that injection on-time decreased while decelerating when compared to idle, this is a result of less load being placed on the engine. When decelerating only enough fuel to keep the engine rotating must be added to the cylinder and as such this is less load than at idle, where enough fuel must be added to maintain a target engine speed.

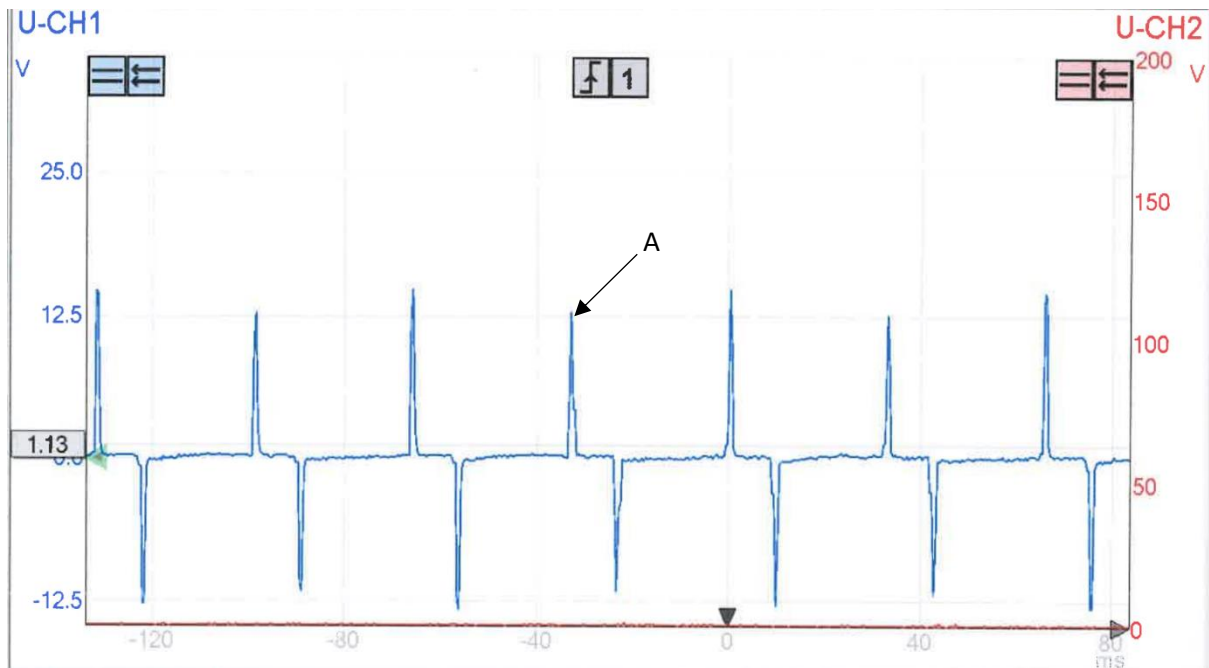


Figure 12 - LE3 Crankshaft Sensor Scope Pattern

Figure 12 shows the signal from the crankshaft position sensor. Data point A represents a full rotation of the crankshaft.

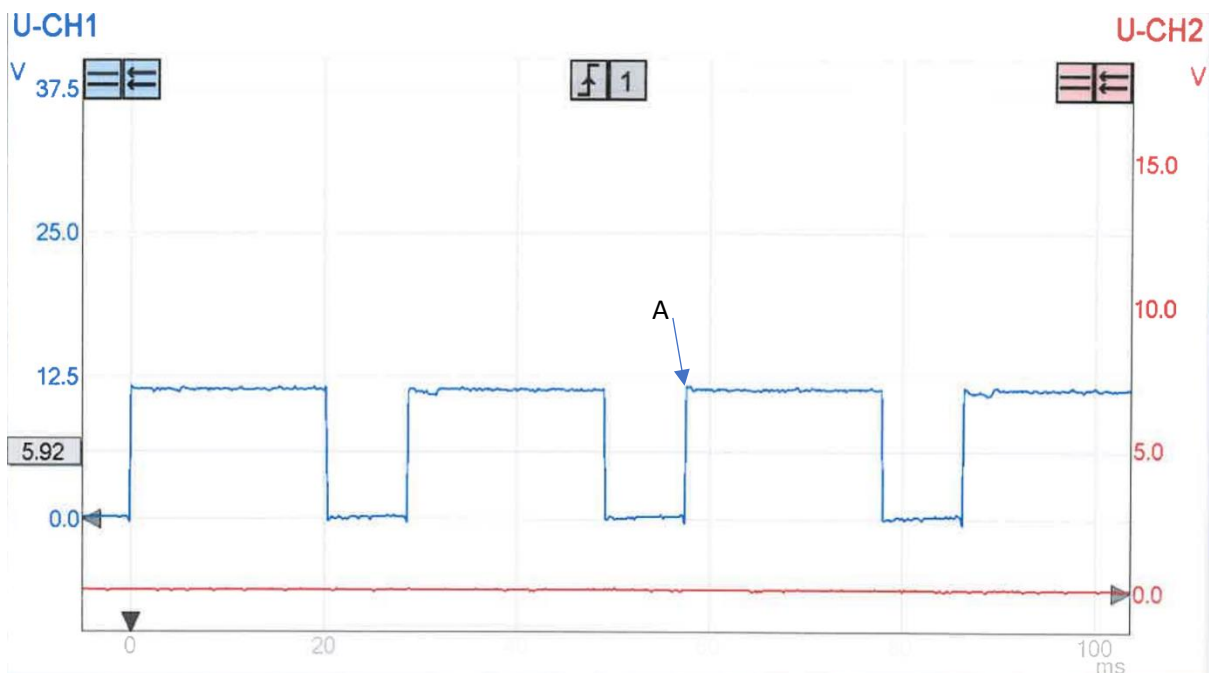


Figure 13 - LE3 Speed Reference for Fuel ECU Scope Pattern

As the LE3 has two ECUs there must be communication between them. Figure 13 shows the signal sent to the fuel ECUI from the ignition ECU for use as a crankshaft speed reference. The signal appears as a square wave as it has been converted from an analog wave to a digital one for information transfer. As such data point A represents the signal showing one full rotation of the crank shaft.

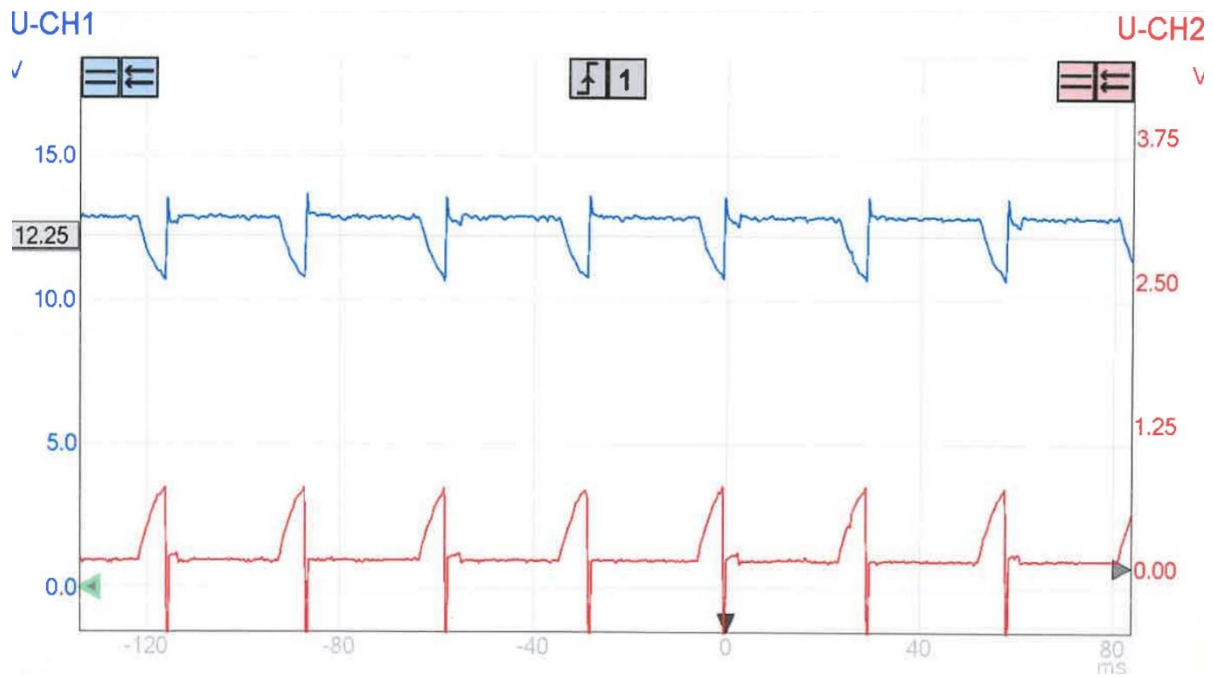


Figure 14 - LE3 Supply and Earth Scope Pattern

Figure 14 shows the scope patterns for the supply and earth.

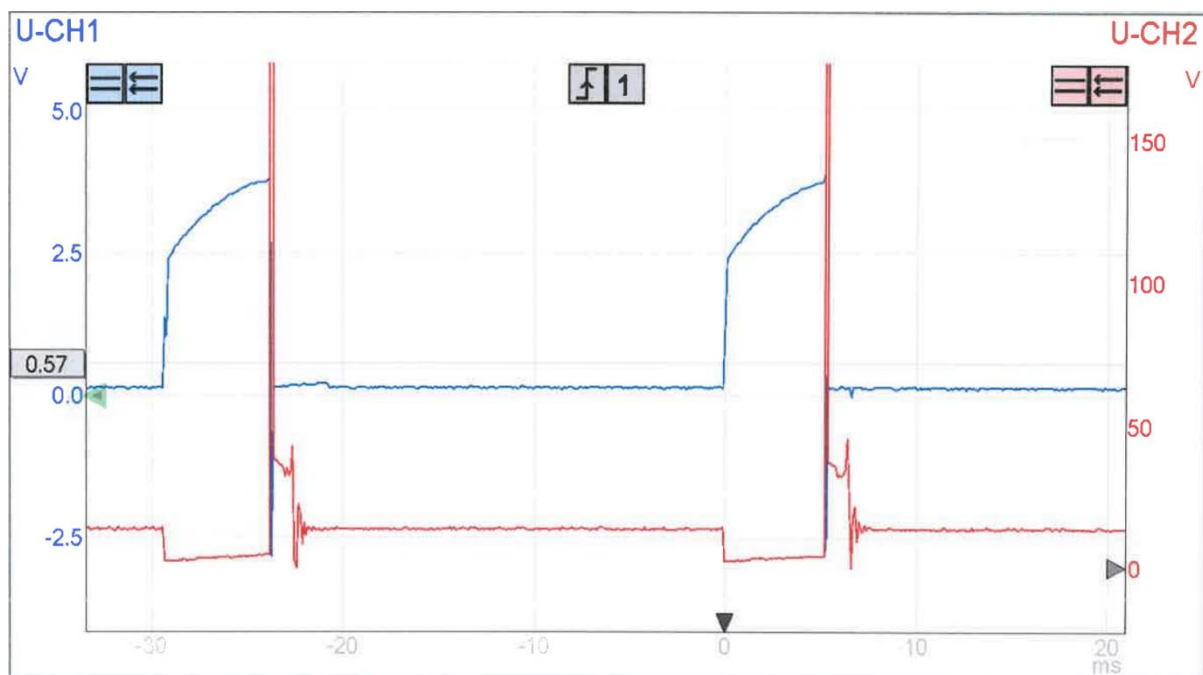


Figure 15 - LE3 Spark Advance Unit and Primary Coil Scope Patterns

Figure 15 shows the scope pattern from the spark advance unit compared against the primary ignition coil.

5 Engine Improvements

This section will detail possible improvements to the engines control systems. The LE3 would benefit from an OBD system and the Motronic would benefit from a wider array of sensors for it's OBD. As such the improved system for both engines would include the following.

- The ignition systems of these engines could benefit from the addition of either a wasted spark ignition system or a coil on plug ignition system as the coil in the current ignition systems is the limiting factor for combustion efficiency at high RPM. A wasted spark system would be a benefit as it uses one coil for each two spark plugs reducing the rate at which the coil must work at high RPMS. However, due to being mounted on the side of the engine, the length of each cable running to the spark plugs is different therefore a slightly different voltage drop is experienced across each one leading to slight variation in combustion efficiency across the cylinders. Another drawback of a wasted spark system is that the system sparks every time the piston reaches TDC, therefore twice a cycle emitting a 'wasted spark', this reduces the expected lifespan of the spark plug. A coil on plug set up solves both problems as the spark plug and coil are combined into one component which sit on top of the combustion chamber. Each spark plug has an individual coil therefore reducing the rate at which each coil must work. The length between each coil and the spark plug it operates is the same, this in addition to the ECU being able to control each spark individually leads to a higher combustion efficiency overall.
- The 'vane-type' MAF sensor on both systems could be replaced by either a hotwire or hot film Air Mass Meter (AMM). These sensors would be more accurate as the work using a heated wired or film in the intake system that loses heat as air passes over it, this heat loss is used to calculate the mass of the air flowing over the sensor. Measuring the mass of the air is more accurate than the volume measured by the 'vane-type' sensor as not adjustment needs to be made for temperature.
- The LE3 could benefit from throttle switch for idle control similar to the Motronic.
- Both engines could benefit the addition of a down-stream lambda sensor. This refers to a lambda sensor that is placed after the catalytic converter. As described by Brosha *et al.* (2002) a downstream lambda sensor can be used to measure the efficiency of the catalytic

converter and as such the ECU can adjust Air/Fuel mix accordingly to reduce emissions generated from the engine.

- The engines could benefit from the use of a wideband lambda. The current Lambda sensor can give false data if the vehicle is traveling behind another vehicle and therefore intaking air containing content from the exhaust of the leading vehicle. A wide band Lambda sensor can account for this as it uses an atmospheric air reference.
- Both systems could benefit from modern OBD software which is capable of informing the driver of specific faults with the vehicle therefore reducing labour costs involved with repairs as the technicians will not have to spend time diagnosing problems.
- Both systems could benefit from the addition of an ECU controlled exhaust gas recirculation valve. As described by Kaiadi, Tunestål and Johansson (2008) EGR can reduce efficiency losses during part load operation as for any given power the throttle plate must be opened further due to inert exhaust gases entering the intake in addition to reducing the peak temperature within the cylinder during combustion therefore reducing NOx emissions.
- The addition of a Manifold Absolute Pressure (MAP) sensor could benefit both engines as it can be used as a cross reference with the AMM to increase the accuracy of the data the ECU uses to calculate Air/Fuel Ratio as such the engine can run more efficiently.
- The addition of an electrical oil pressure sensor could provide benefits over the diaphragm-based system used on these engines. An electrical sensor would be able to provide data about the oil pressure to the ECU and in addition to an electronically controlled valve this can provide the ECU with the data and method required to better regulate oil pressure as well as being able to record data to aid in diagnosis of problems.
- An oil temperature sensor would provide the vehicle with an additional layer of protection against failure as the ECU could detect larger changes in oil temperature and shut off the engine to prevent damage. In addition to this as described by Kim, Shon and Lee (2013) monitoring oil temperature can help the engine stay within its optimal temperature range and as such can increase the fuel efficiency of an engine and reduce emissions.

- An exhaust gas temperature sensor would help reduce the service costs of the vehicle as it can be used to monitor the operating temperature of the catalytic converter and prevent thermal overload which could damage the catalytic converter. Additionally Tamura *et al.* (2011) describes how an exhaust gas temperature sensor can be used to as a diagnosis tool to detect misfires further time spent on diagnosing problems. This temperature sensor can also be used as another reference point for the ECU to ensure that the engine is operating in the temperature range of its peak efficiency.
- The addition of a CAM shaft position sensor can be used as a cross reference for the engine speed against crank position increasing the accuracy of data collected.
- With additional ECU functionality the crankshaft speed sensor may be used to monitor and control functions of safety systems such as ABS and traction control.

6 Test Evaluation

The tests performed were made inaccurate by the following.

- Only one test was completed.
- The ambient temperature over the course of the test rose due to heat from the engines.
- The ambient pressure was not recorded.

The tests could be made more accurate if the following were implemented.

- Multiple tests with an average result taken.
- Check ambient temperature over the course of the test.
- Take ambient pressure readings during the test.
- Run tests in a controlled test cell to ensure ambient temperature and pressure remain the same between tests.

7 Conclusion

The engines can be considered to be in working condition as they meet manufacture requirements despite a few potential issues. The previously mentioned improvements could be made to the engine in order to improve efficiency and reduce emissions.

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