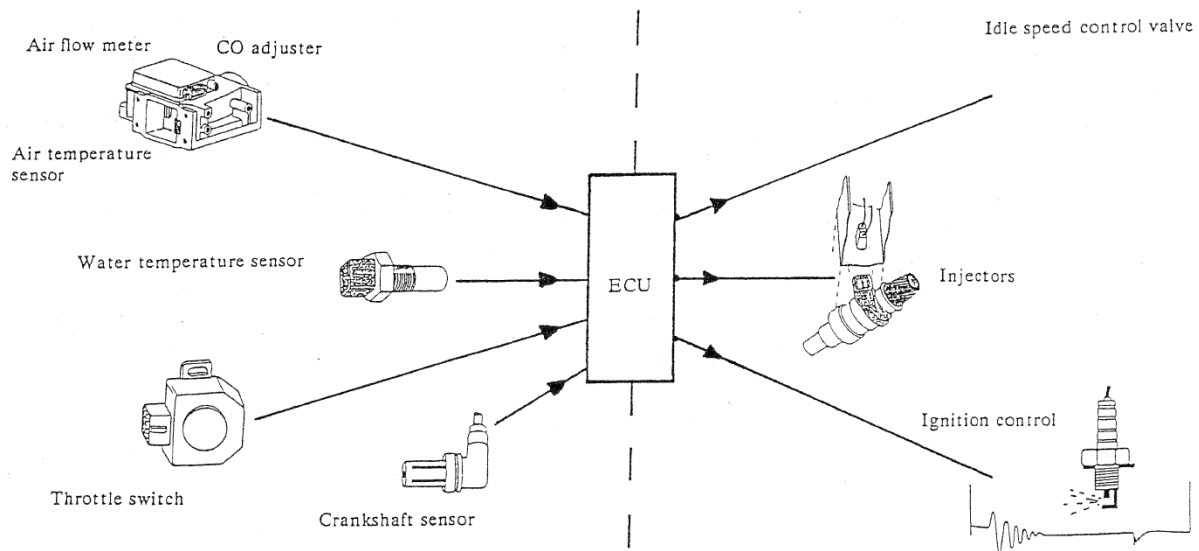


University of Wales Trinity Saint David
Wales Institute of Science and Art

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Electronic Ignition & Fuel Injection Systems

Electrical Control Systems (ACHA4010)



PRIFYSGOL CYMRU

Y Drindod Dewi Sant

UNIVERSITY OF WALES

Trinity Saint David

Liam Chess (2004144)

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1 Introduction

The traditional carburettor has been rendered obsolete by exhaust discharge laws, formed since the rise of electric fuel and ignition systems for but not limited to automotive drivetrains. The European Emission Standards (EU Parliament, 2007) has demanded engineers to continually innovate their systems for minimal nasty gas emissions from their engines, to prevent disallowance in motorsports and or the mass market. Nasty gases consist of particulate matter, unused hydrocarbons, NOx, and carbon mono/dioxide, highlighted by the Euro classification gas omittance laws introduced in 1992 for cars (and '99 for bikes). Since then, overall vehicle emissions have pleasantly dropped with significance, at the almost-demise of 'screamer' engines through developments in forced induction, exhaust gas recirculation, ultra-high pressure fuel systems and other technologies.

This report will investigate two dated BOSCH electronic control systems on two of the same engines: Motronic and LE3-Jetronic, on the GM/Vauxhall/Opel engine circa 1980s. With use of external information, research into the significance of the measured values from the engine lab, to which see if and how the ignition and fuel systems can be upgraded to conform to tighter modern standards. This will become a hot topic when the ban of new vehicles with ICEs comes into effect, expected 2030, and electric cars fill the showrooms. However, the number of EVs on the road are a big minority (albeit growing) compared to cars with a gearbox and engine, many millions, lots with systems like the LE3 or Motronic. A nationwide scrappage grant scheme wouldn't be cool, especially if there is a solution to keep these vehicles on the road.

Therefore, this report's intent is to evaluate the retrofitting of new ignition and fuel system components to older ICE powertrains, and its potential effectiveness towards 'saving the planet'. This can at first seem a no-brainer; upgrading the onboard electronic management system should easily improve an engine's efficiency, power, and cleanliness, but each vehicle and drivetrain have their own challenges. Cost is always enemy to the masses, and the wide variety of engine powered cars, bikes, vans, and large 4+ wheelers on the road mean there will be no one-for-all solution.



Figure 1.1: Logo and motto of the company that thought ahead

2 Literature Review

BOSCH is a global technical innovation company with large stake holding in the automotive industry, as manufacturers of sensors, control units, injectors, coil packs, batteries and much more aside.

The Motronic 1.0 system was first used in the early 1980s featuring electronic spark timing paired with then Jetronic fuel injection on the BMW 7 series, and road-testers commended the unusually smooth operation of the straight 6. (BOSCH, 2006) Refinement into the computer-controlled ignition sees its appearance in many engines since, including General Motors' Family II engine. This spark-ignition inline 4 powertrain is used in many Holden, Opel, Vauxhall and other cars, therefore millions of vehicles on the road. BOSCH improved their fuel and ignition on one control unit concept during the engine's production life and beyond, as late as 2016 in Brazil. (Ovidiu, 2008) Interesting to note that BOSCH tested their systems rigorously prior to launch; test vehicles covered over half a

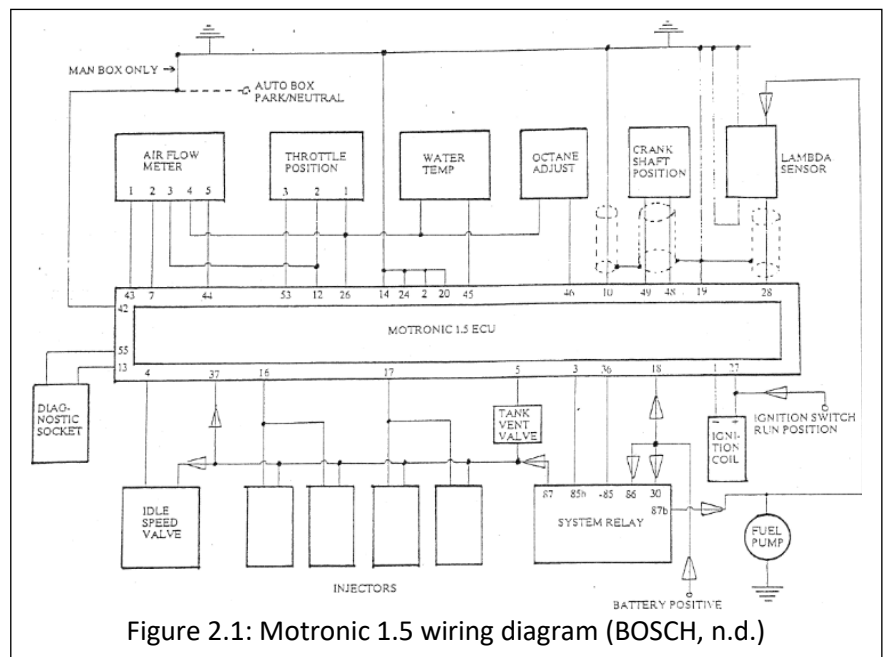


Figure 2.1: Motronic 1.5 wiring diagram (BOSCH, n.d.)

million kilometers/300,000+ miles and devised arctic-like conditions of -40°C , engine temperatures of $>100^{\circ}\text{C}$ over long periods, vibrations and hard bumps caused by poor road conditions (BOSCH, 2006). And yet, (bar plugs) the entire system is maintenance free.

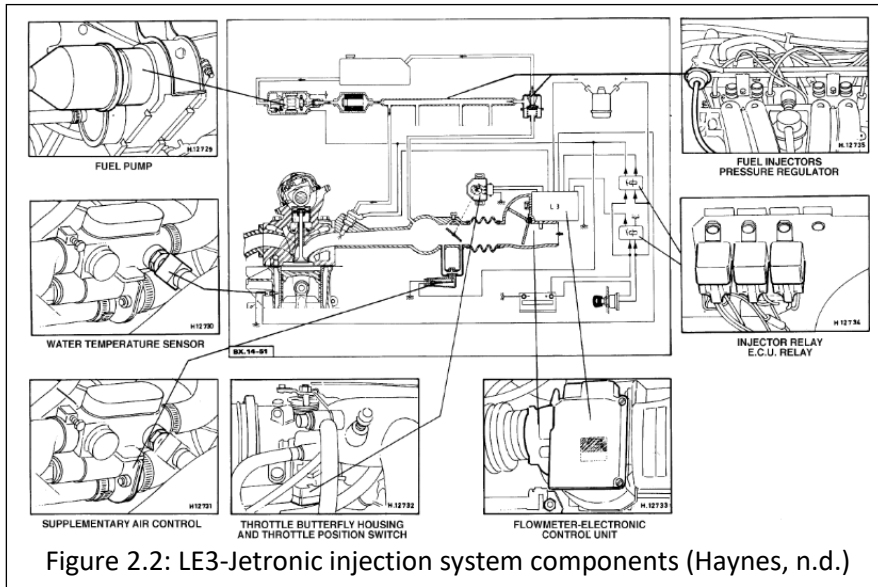
Motronic 1.5 was a step-up for the technology as the then new 55-pin ECU was in control of the ignition distribution and multi-point fuel injection, mathematising values regarding engine speed, crank angle, lambda, coolant temperature and throttle position with a variable potentiometer air flow meter, full throttle giving the biggest signal up to 5volts. (Cicco, n.d.) The components of Motronic remain largely the same in its worldwide usage, with timely ECU upgrades, new features, and optimized algorithms from the sensor-provided operating conditions.

The lab-tested GM engines were circa late 80s, early 90s, and albeit the engine configurations were slightly different, analysis of the ignition patterns should compare with each other. The first engine tested with Motronic 1.5, was a 2.0L DOHC Family II but the other LE3-Jetronic system was on a 1.6L

SOHC Family II unit. Engine output, reliability, NVH and other factors would vary between the two, but this report's intention regards the operation of the electronic ignition and fuel system. As the powertrains are fundamentally the same, they will be comparable for the end goal of evaluating effectiveness of upgrading the dated systems.

The LE3-Jetronic system is somewhat primitive compared to Motronic; initially it's L-Jetronic analog injection coupled with a modern ECU of the time controlling both fuel delivery and ignition timing

(Cicco, n.d.). The LE3's control unit is 'miniaturized', and 'hybrid' compared to previous ECUs, less expensive to produce while capacitating inputs from all the sensors for crank angle and coolant temperature, the speed and load, of the engine. The LE3 and Motronic operate similarly, but this system has no lambda sensor for catalytic



converters, and the control unit has less contact pins for future upgrades and eventual unsuitability.

The lambda exhaust gas recirculation system was and is a key development in reducing vehicle emissions, most notably Nitrogen Oxides, NO_x (Piqueras, et al., 2020) and unused hydrocarbons from the tailpipe. Simply a portion of the exhaust stroke's gas charge is redirected back into the cylinder during the four-stroke cycle, with aim to maintain lambda, λ at =1. In emissions testing, if λ is more than >1 it indicates high oxygen and that the engine's running lean on fuel, vice versa if λ is less than <1 then possible incomplete combustion, as lots of fuel is present. (Cooper, n.d.) The lambda sensor is fitted inside the exhaust to aid the catalytic converter's performance.

The system can be seen as a secondary verification of the powertrain's air-fuel ratio; under different engine operating states the AFR varies. Cold Cranking, Warm-up Phase, Idle Control, Snap Acceleration and Deceleration all affect the engine's instantaneous AFR. The stoichiometric air-fuel ratio (goldilocks zone) is 14.7:1 but cold cranking to start enriches the mix to 9:1, warm-up and acceleration ~12:1 and lift-off deceleration leans the AFR to 17:1 (Gibson, 2021), in approximation. Responsiveness and accuracy for optimum conditions is down to the ECU's processing power and RAM capacity, to which 90s electronics are primitive comparing to today's <10nm microchip density.

3 Methodologies

A sizeable range of equipment was used in the engine analysis in IQ's vehicle workshop: making the spark waveform and duration visible is the scope, a BOSCH BEA850 large oscilloscope. A way to measure signals with it is to clamp on one of the HT leads from the engine's ignition distributor to the coil pack and plug, sends the reading to the screen in real time, with another ground attached for safety. Measuring a more modern coil-on-plug arrangement may require one to improvise, as there would be no (leads from the) distributor.

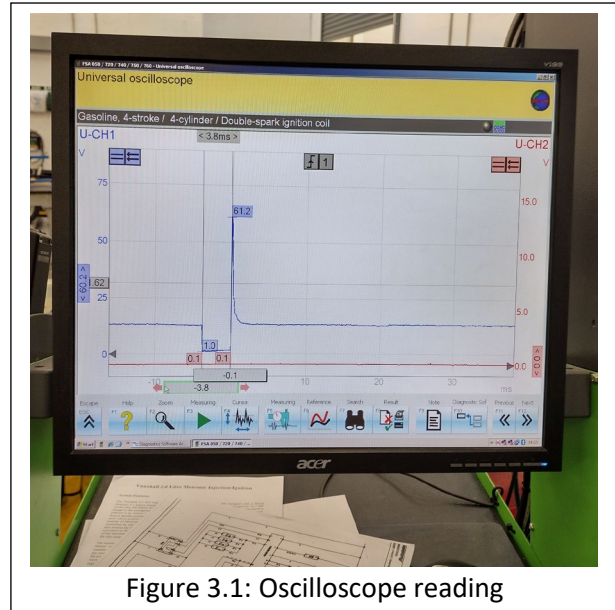


Figure 3.1: Oscilloscope reading

Figure 3.1 shows the injector on-time as observed live in the automotive workshop, engine idle. Applying throttle increases the frequency and more pulse patterns appear on the screen.

The control units' pinout voltages (and resistances) were measured with an analogue voltmeter, partially as it's what had been provided however this is of similar age to the powertrains tested, but

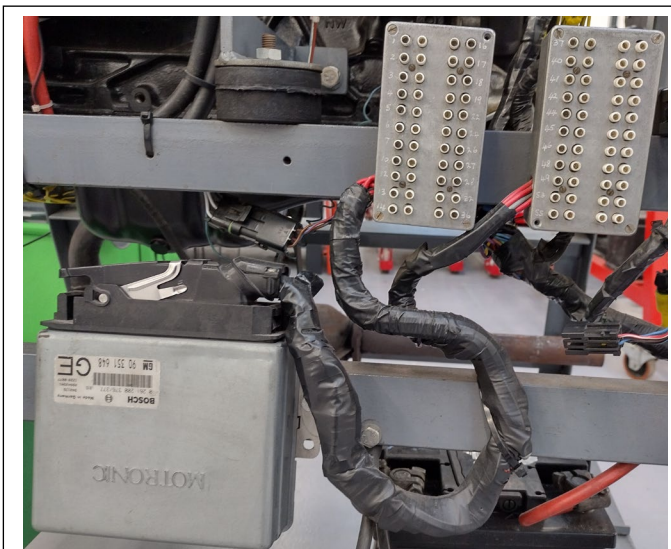


Figure 3.2: Motronic ECU & pinout arrangement

a digital meter will work just as well. During the laboratory session the voltmeter was attached to the throttle potentiometer, air flow sensor, injectors, ignition coil and HT leads for data collection of the engines' ignition and fuel systems. The recorded values then can be compared to provided data from prior lab testing, as well as the manufacturer's specifications. In engine operation the control unit compares the sensor's live data feed with their OEM numbers to run the powertrain as

efficiently as possible. The delegation of tasks in the workshop to record the ECU's values is important, as all those involved ought to have the same documents for analysis by the end.

Before any engine starts, both powertrains were visually inspected before operation and everyone working in the vehicle laboratory requires boots and dust coats. Engine failures are unlikely but the danger of high-temperature fluids escaping at pressure is known and accounted for.

4 Motronic System

Commencing with the ECU's 55 pinout readings and description.

Table 4.1: Motronic pinout values (reserves are 8 11 15 23 25 29 30 31 33 35 38 39 50 52 54)

Prerequisites: Battery starting voltage: 12.4v Ignition on: 12.26v Ambient temp: 17.5° ~ 18.2°C			
Pin no.	Ignition OFF (V)	Ignition ON (V)	Purpose
1	0	12.15	Negative side of ignition coil
2	0	0.04	Earth
3	0	12.04	Control circuit for fuel pump (from relay pin 85B)
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-flow meter
9	-	-	Speedo, mileage frequency sensor
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
34	-	-	A/T ECU
36	12.07	0.31	Control circuit for auxiliaries & ECU (from relay pin 85)
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)
43	-	-	CO potentiometer output (not fitted w/ catalyser)
44	0	3.69	Output from NTC 1
45	0	3.69	Output from NTC 2
46	0	0.25	Octane plug input
47	-	-	Earth (for 4WD vehicles)
48	0	0.07	Output from crankshaft sensor
49	0	0.11	Output from crankshaft sensor
51	-	-	A/T ECU
53	0	0.66	Output from throttle potentiometer
55	0	10.99	Earth for diagnostic socket

Although there are 15 reserved pins and 5+ more in disuse, engine operation can be assessed with but not limited to the highlighted values, to which those are the pins measured in the warm-up

analysis. Table 4.1 was recorded before the engine was at operating temperature, seen at pin 28, $\lambda = 0.45$ – very rich AFR. A low value of <1 for λ would be seen during snap-acceleration, through warm-up, full-throttle or, if unexplainable, may be indicative of a fault. Importantly noted is that the lambda oxygen sensor works via comparing the exhaust airflow's composition with the outside air, assessing the engine's emission cleanliness. In certain scenarios, for example stop-start traffic in a tunnel, the reference atmosphere composition won't be as clean as usual, so the sensor might provide erroneous data for the control unit to compute. In an eventual circumstance the ECU may cease this or any sub-circuit from operation (TSMacNeil, 2011) to try preventing a clog-up within the catalyst and ping an engine fault light/code to the driver.

Table 4.2: Motronic warm-up phase data collection (orange values are potential anomalies)

Engine Temp (°C)	Pin 45 (ohms, Ω)	Pin 45 (volts, V)	Pin 16/17 (time, ms)	Pin 4 (on time, %)	Pin 5 (actuation)	Pin 28 (actuation)	Comments
20	1900	3.3	3.1	44	OFF	OFF	
30	1020	2.5	2.8	42	OFF	OFF	Anomaly risk
40	660	2.2	3.2	41	OFF	30° > 39°C	
50	450	1.6	2.9	42	40° > 52°C	ON	
60	340	1.4	2.9	41	ON	ON	
70	240	0.9	2.6	40	ON	ON	Fan turning on
80	250	1.0	2.8	43	ON	ON	Coolant warm
Temp (°C)	Pin 44 (V)	Comments					
20	3.6	Throttle potentiometer faulty. Actuations happen at a point between $x_1^\circ > x_2^\circ$ C.					
80	3.3						

Injector on-time is of vital significance, as the amount of fuel delivered per Otto cycle is beyond critical. Pins 16 and 17 are for the two injector banks, pin 45 is the NTC2 value and pin 4 is the rotary idle valve. The ECU decides the injection on-time instantaneously with two main influences: speed and load. Other aforementioned factors also affect the fuel quantity delivered to the cylinders, such as cranking, (snap-)acceleration and warm-up. In the pin 16/17 column highlighted orange is the injector on-times for engine temp 30° and 40°C, surprisingly the longest injector pulse was not when the engine is coldest, unlike the NTC2/pin 45 resistance trend. The variance is minor however a longer on-time @40°C than at 20°C may not be ideal, and as the resistance of the NTC2 is less than a third of itself @40°>20°C, this could be a problem either in data acquisition or, engine operation.

The rotary idle valve

Resistance measure 8 Ω
 Lead resistance 0.2 Ω
 0.5 @ 2k Ω
 2k Ω bang on
 Wide open 2.68 Ω
 Throttle close 1.48 Ω

Ign. ON: 5.08v @ pin2

Airflow sensor pin:

Pins 4 > 2 potentiometer

Ω 8 – 2500

Pin 2 > 4 exp. 300-550

Recorded 320 Ω

Pin 3 560 Ω +10 more(?)

Pin 4 null/void

Nominal 270-520 Ω

For the CO mixture

Coolant Temperature Sensor

At 0°C 4800-6600 Ω

At 40°C 1000-1400 Ω

At 80°C 270-380 Ω

Recorded @ 17.6°C: 2530 Ω

5 LE3-Jetronic System

Importantly noted is that the data seen in 4.Motronic

Injector on time Pin 3 - Accel/Decel	
At Temp with fan on (60'C+)	
Condition	Duration (ms)
Accel	8.4
Decel	Injector Trace narrows during deceleration (on time reduces), once engine understands its in over run condition during decel (Zero Throttle), the injectors shut off untill Idle or Antistall

Calibri (body) size 11 and 1.5 line spacing from here.

NTC 2	Pin 8	Pin 8
Temperature - C	Voltage - V	Resistance - Ohms
20	1.7	1940
30	1.1	1070
40	0.9	770
50	0.7	538
60	0.5	392

Dfff

Injector on time - Cranking	
Pin	Duration - ms
3	106

Fff

Injector on time - Running		
Temp - C	Pin	Duration - ms
20	3	3.8
30	3	2.9
40	3	2.9
50	3	2.9
60	3	2.7

Fff

Ddd

Static data, Engine Hot

Throttle Switch	Autodata - Ohms	Recorded Data
-----------------	-----------------	---------------

Pin 2 and 18	?	?
Pin 3 and 18	Infintity (OL)	Infintity (OL)

Wish I nkW

Coolant temp sensor - autodata	
Temp	Autodata - Ohms
-10	7000-11600
20	2100-2900
80	270-390
Recorded Value	960

Fdd

Auxillary Air Valve	
Resistance Between Terminals - Ohms	
Autodata	Recorded Value
40	46.5

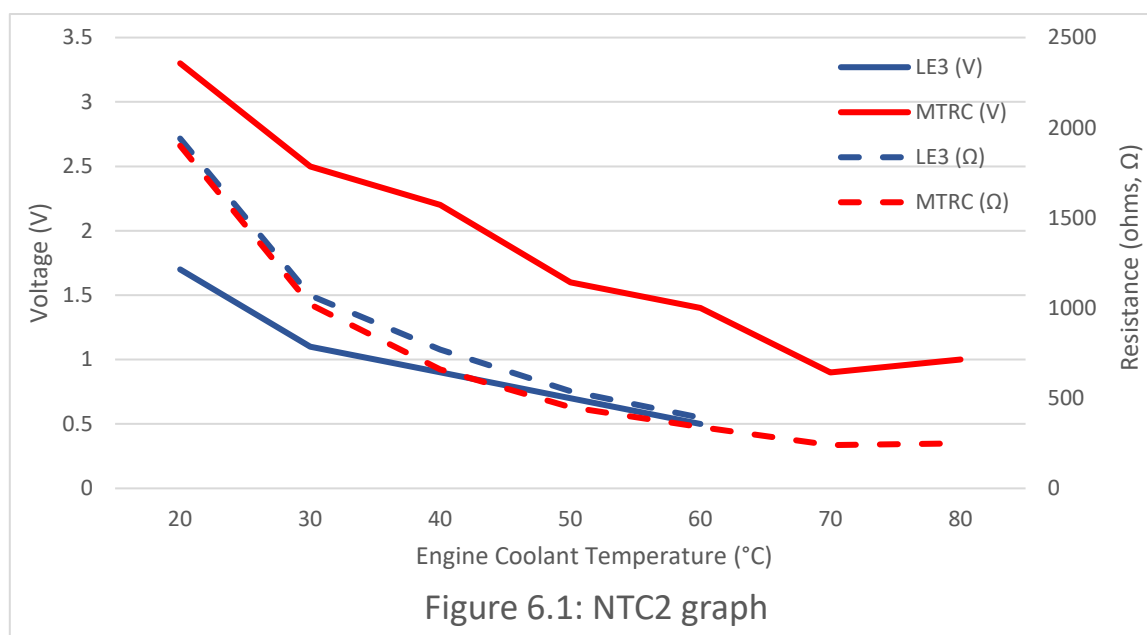
Dd

Injector Resistance - Ohms	
Autodata	Recorded value
15 - 17	16

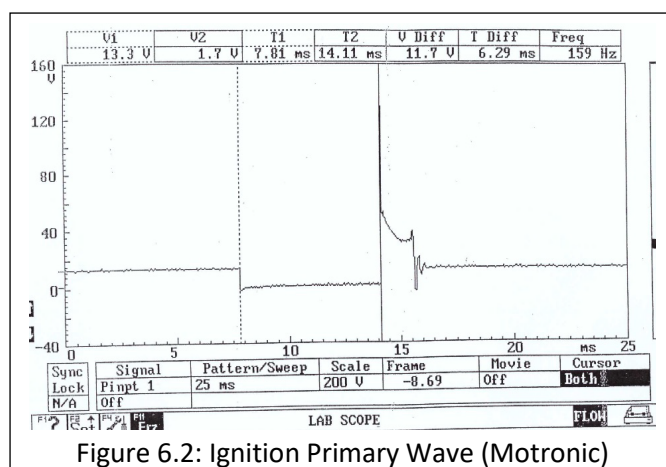
ddd

6 Discussion

NTC1 is the fluid/coolant temperature and NTC2 is the air flow temperature. (KAsensors, n.d.)



Interestingly the Motronic air flow signal is of significantly higher voltage across the entire warm-up period, although the engine's potentiometer/throttle was aftermarket as well as faulty, compared to the LE3-Jetronic system. Despite only having data until 60°C, the LE3's voltage trend is far more linear than the jagged Motronic's NTC2 trendline, however the provided data from a previous test on the Motronic system shows a similar pattern. Altering the voltmeter to resistance has measured much closer ohm values between the two control systems; this is good to see as both powertrains tested have a similar (if not the same) air mass flow meter which works via the potentiometer needle moving round the wire/circuit, changing the resistive path resulting in a voltage change. (Fenske, 2012) The larger the movement/throttle opening, the bigger the voltage signal sent to the ECU. As idle control would open it more when the engine is cold than when warm, this explains the voltage drop over the course of the warm-up period (all readings were taken at idle engine speed,



wildly fluctuating between 710-780rpm, faulty potentiometer likely to blame).

This pattern is the spark formation and duration, measured from pin 1 a length of 1.47ms and a back EMF voltage of 129.2V.

The dwell time is around 6ms before the spark with modest coil oscillation at the

end of the cycle. Comparing this to the LE3-Jetronic system; the dwell time is a tad shorter at just under 6ms with a similar $\sim 1.5\text{ms}$ spark duration. This has a larger coil oscillation however, as this is the recovery period this time could be used, in theory more effectively.

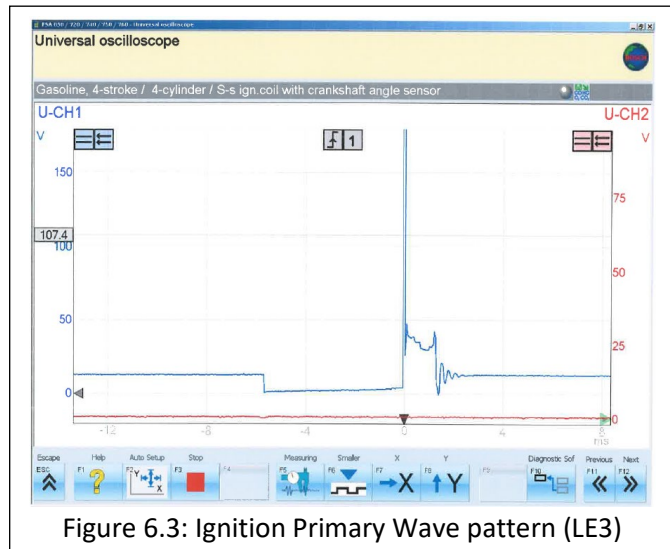


Figure 6.3: Ignition Primary Wave pattern (LE3)

7 Evaluation

Analysis into these dated control systems has shown their brilliance as well as their shortcomings, to which the carburettor's use in the mainstream automotive market is long gone. Thirty years since the systems tested were new, technical innovation has continued to render the Motronic 1.5 and LE3-Jetronic controllers somewhat dated but has also introduced potential upgrades.

A weakness with both systems is their variable potentiometer air mass flow meters; ignoring the faulted test unit on the Motronic, in correct operation the sensor functions adequately but fragility is a concern. The Opel/Vauxhall tuning guide by (Cicco, n.d.) states the OEM airbox has a small square tube to straighten the airflow to the sensor, fine unless it's not in the optimum position to which airflow readings would be skewed. Vibration and harsh bumps throughout a vehicle's lifetime may slowly rattle this little air-shaper out of place, while being potentially difficult to spot by a freelance mechanic. The solution would be a hot wire mass flow sensor, principle being heat transfer from a heated surface/wire being dependant on the flow conditions passing over it. (Kamshah, et al., 2012)

The hot wire AFM uses current to heat the element and a change in airflow/throttle alters the convective heat transfer coefficient to a new equilibrium. As the thermal capacity of air is known, and heat loss is measured in real-time, Ohm's law is used calculating a voltage signal instantaneously and within similar voltage range (0.2v – 4v but this would vary by manufacturer) so would be compatible with both ECUs with minor software tuning. The contraption also has no moving parts for future-proof reliability, however, it's expensive using ductile platinum or tungsten elements.

Another area of improvement is within the lambda recirculation section; an additional sensor within the exhaust will help data accuracy for gas discharge content and composition, to which the ECU would be less likely to get 'confused' in operation from uncertain sensor values. This in turn should improve the control unit's ability to maintain lambda (λ) close to =1, aiding cleanliness.

These are the two main areas identified that the dated electronic control units may not be able to maximize the powertrains' efficiency and minimize emissions conclusively and reliably; other general improvements can rectify the oil pressure sensor(s). Both Family II engines have a rather primitive oil monitor that simply detect if the fluid is at pressure, but little regarding its extent and nothing regarding temperature. A modern oil sensor can measure both pressure and temperature as one unit, while should being able to fit in the socket/mounting of the dated sensor it would replace, to which the ECU would have a stronger understanding of how the engine's lifeblood is performing.

8 Conclusions

These electronic control systems when first pioneered on vehicles in the 80s was utterly groundbreaking technology: cost-effective ignition and fuel management with drastic smoothness, performance, cleanliness and reliability benefits, wrapped up in a near-maintenance free package of minimal installation difficulty. Incredible! However...

The complexity of maintaining these systems when disoperation occurs requires a standard of equipment significantly less common than that of an analogue mechanical injection system, or a good ol' carbureted setup where maintenance could be performed at the roadside. It still can be but reading the control unit's data would require an OBD diagnostic device. Since BOSCH introduced these electrical control units (especially Motronic), that company had and has an enormous and growing stake holding in the automotive (and many more) market(s) worldwide. Development into this technology has and will continue to see potential upgrades for these dated systems.

Some component replacements have been identified, notably lambda, hot-wire AFMs and modernized sensors for data accuracy. The cost is noticeable, especially with the air mass meter, but its effectiveness of solving what is an issue should make it viable to be considered an upgrade, as well as the other mentioned components.

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End of report, thank you for reading.
But it's unfinished >:|