

Emissions  
Emissions Control & Diagnosis (M5X02202)

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15-03-2019

## 1. Abstract

Engine exhaust emissions have an impact on air quality resulting in detriment to human health and the environment. Governing bodies dictate emissions regulations to improve air quality, however vehicle manufactures must meet the limits that are progressively getting more difficult to reach. Vehicle manufacturers use emission control devices (ECDs) to achieve limits but these have varying levels of success and no single additional device can resolve the system as a whole. Outlined in this report is various ECDs and the impact, functionality and monitoring of the system including limitations. Live data collection and testing is conducted to show development of system over time and how diagnostics and validation for road use is conducted. Lastly future predictions for limits shall be discussed, the development for accurate testing results and investigating the wider picture of emissions in the world.

## 2. Contents

|                               |    |
|-------------------------------|----|
| 1. Abstract.....              | 2  |
| 2. Contents .....             | 3  |
| 3. Introduction.....          | 5  |
| 4. Literature Review.....     | 6  |
| 5. Safety and Equipment ..... | 13 |
| 6. Methodology .....          | 14 |
| 7. Results.....               | 15 |
| 8. Analysis.....              | 16 |
| 9. Conclusion .....           | 18 |
| 10. Evaluation .....          | 18 |
| 11. References.....           | 19 |
| 12. Appendix.....             | 21 |

|                                                                                                    |    |
|----------------------------------------------------------------------------------------------------|----|
| Figure 1: General Exhaust emissions for rich and lean burn air/fuel ratios (R. Bywater, 2014)..... | 6  |
| Figure 2: Euro 6 Emission Limits Table (EU, 2007a) .....                                           | 7  |
| Figure 3: EU, 2007b. Annex 6 section 3.2 measurement conditions for PCV Test (Test III) .....      | 9  |
| Figure 4: EU, 2007b. Annex 7 Figure 7/1 for EVAP Emissions Test.....                               | 10 |
| Figure 5: EU, 2019. SBC for Catalytic converter test.....                                          | 12 |
| Figure 6: Ford EECIV Pin 21, Pulse side of idle control valve. ....                                | 21 |
| Figure 7: Ford EECIV Pin 24, AC input for Camshaft sensor.....                                     | 21 |
| Figure 8: Ford EECIV Pins 35 & 39, injectors 4 & 3 EARTH.....                                      | 22 |
| Figure 9: Vauxhall Ecotec Pin 42, EGR negative side of solenoid. ....                              | 22 |
| Figure 10: Vauxhall Ecotec Pin 52, idle control negative side of solenoid.....                     | 23 |
| Figure 11: Vauxhall Motronic Schematic .....                                                       | 23 |
| Figure 12: Ford EECIV Schematic .....                                                              | 24 |
| Figure 13: Vauxhall Ecotec/ Simtec schematic .....                                                 | 25 |

|                                                                                                                |   |
|----------------------------------------------------------------------------------------------------------------|---|
| Table 1: Abbreviations .....                                                                                   | 4 |
| Table 2: Petrol Emissions throughout Euro Regulation iterations for Passengers vehicle (DieselNet, 2018) ..... | 7 |
| Table 3: Diesel Emissions throughout Euro Regulation iterations for Passengers vehicle (DieselNet, 2018) ..... | 8 |

| <u>Abbreviation</u> | <u>Meaning</u>                                     |
|---------------------|----------------------------------------------------|
| CO                  | Carbon monoxide                                    |
| CO <sub>2</sub>     | Carbon dioxide                                     |
| COSHH               | Control of Substances Hazardous to Health          |
| DPFE                | Delta Pressure Feedback of the EGR                 |
| ECD                 | Emission Control Device                            |
| EGR                 | Exhaust Gas Recirculation                          |
| EMF                 | Electromotive force                                |
| EVAP                | Evaporative emission control system                |
| HC                  | Hydrocarbons                                       |
| HEV                 | Hybrid Electric Vehicle                            |
| ICE                 | Internal Combustion Engine                         |
| NO <sub>x</sub>     | Nitrogen oxides                                    |
| OBD                 | On Board Diagnostics                               |
| PCM                 | Powertrain Control Module                          |
| PCV                 | Positive Crank Ventilation                         |
| PEM                 | Portable Emissions Measurement                     |
| PM                  | Particulate Matter                                 |
| PPE                 | Personal Protective Equipment                      |
| RDE                 | Real Drive Emissions                               |
| SAI (SAIR)          | Secondary Air Induction (Reaction)                 |
| SBC (SDBC)          | Standard Bench Cycle (Standard Diesel Bench Cycle) |
| SO <sub>2</sub>     | Sulfur dioxide                                     |
| SRC                 | Standard Road Cycle                                |
| VOCs                | Volatile Organic Compounds                         |

*Table 1: Abbreviations*

### 3. Introduction

Vehicle manufactures used ECDs to meet emissions regulations such as Euro 6. These systems are monitored for operation but how do these compare to older systems which followed different regulations such as Euro 5, 4, 3, 2 and 1. In this report engine emissions such as CO, CO<sub>2</sub>, NO<sub>x</sub>, HC, VOCs and PM have be discussed from engines using various ECDs from older regulations. These ECDs include the catalytic converter, SAIR, PCV, EGR and EVAP. The operation, effects and monitoring of each of these ECDs has been included. Then a discussion for how to bring an older engine up to modern regulations is included. The impact that air and fuel mixtures have on emissions and the effects of an engine running too rich or too lean is discussed in this report.

Data has been collected in a workshop to conduct a detailed evaluation of these three systems tested. These systems include Vauxhall Motronic 1.5, Ford Zetec EECIV and a Vauxhall Ecotec/Simtec. Workshop safety and personal safety have been explained in detail and well as the reasoning for equipment use and why alternatives weren't used. The results of data collect has been reviewed.

Analysis of overall data and external referenced resources has been conducted with interesting results.

## 4. Literature Review

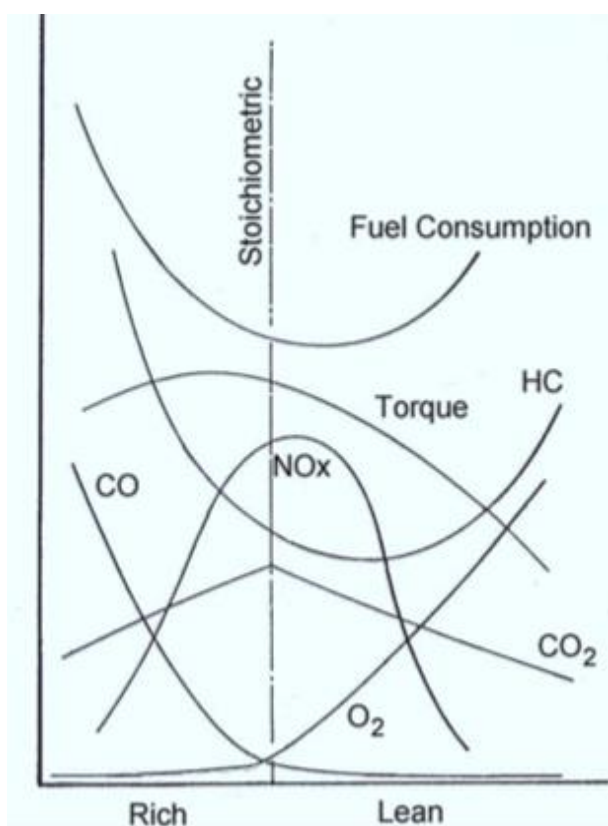


Figure 1: General Exhaust emissions for rich and lean burn air/fuel ratios (R. Bywater, 2014)

### Air/Fuel Ratio and Emissions

The Air/Fuel ratio (A/F ratio) has a large impact on the change in exhaust emissions from a vehicle. Figure 1 (R. Bywater, 2014) shows a general trend dependent on the A/F ratio. The Stoichiometric can be taken as a 14.7/1 A/F ratio ( $\lambda=1$ ).

At Stoichiometric ( $\lambda=1$ ) HC and Oxygen ( $O_2$ ) can be seen at their lowest due to the burn process burning it all (Hence not seen in exhaust). NOx is at its highest as the gas is produced at high temperatures. CO<sub>2</sub> is also at the highest as the burning of HC and O<sub>2</sub> at stoichiometric results in a balanced chemical reaction producing predominantly CO<sub>2</sub>. CO is low as the gas is only produced in the burn process when O<sub>2</sub> is low.

During a rich burn ( $\lambda<1$ ) exhaust emissions for HC is higher and O<sub>2</sub> is lower (compared to stoichiometric) due to O<sub>2</sub> being all burnt but excess HC cant burn with no O<sub>2</sub>, hence goes to exhaust. Due to the lack of O<sub>2</sub> the burn process produces more CO and Less CO<sub>2</sub> (Chemical

reaction balances to the gas requiring less oxygen). NOx is lower as excess HC cools the combustion chamber therefore lowering the temperature, preventing NOx production.

Lean Burn ( $\lambda>1$ ) results with higher to O<sub>2</sub> and HC compared to stoichiometric for a few reasons. As lean there is a higher presence of O<sub>2</sub> compared to HC, this results in higher values of O<sub>2</sub> but also causes misfires. Misfires causes HC to not burn hence higher levels of both. High HC same as rich Burn results in temperature reduction preventing NOx production. The Misfires also prevent NOx. CO<sub>2</sub> is lower as less burning is taking place. With excess O<sub>2</sub>, CO is unlikely to form hence the low value.

Max torque occurs in a slightly rich burn whereas lowest fuel consumption occurs in a slightly lean burn. "The maximum power is obtained with rich air-fuel mixtures. Putting more fuel in the cylinder at high engine load and speed, cools down the combustion chamber (through fuel evaporation and heat absorption) which allows the engine to produce maximum engine torque thus maximum power. We cannot get the maximum power of the engine and the lowest fuel consumption with the same air-fuel ratio. The lowest fuel consumption (best fuel economy) is obtained with lean air-fuel mixtures" (x-engineer, 2019).

Overall Figure 1 shows that whether the burn is rich, lean or stoichiometric emissions will be produced and this leads on to the regulations of emissions.

## Regulations and emission impacts

Vehicles are equipped with ECDs to reduce various emissions such as CO, CO<sub>2</sub>, NO<sub>x</sub>, HC, VOCs, PM and SO<sub>2</sub> as previously mentioned. These emissions can cause negative impacts to human lives and the environment. For people these negative impacts include heart attacks, premature births, premature deaths, cancer, increased mortality, lung diseases, reduced lung efficiency, asthma, chronic obstructive pulmonary disease (COPD), death (BBC, 2019), ischemic heart diseases (IHD), strokes and many more (ALA, 2016) (HSE, 2004). Environmental impacts include ozone layer depletion, acid rain, smog and excessive greenhouse effect leading to global warming/ climate change causing rising sea levels, flooding and heat waves each of these causing more and more negative impacts.

Due to these negative impacts governments and external bodies have set limits on vehicle emissions that the manufactures must meet. These limits differ by location such as the Europe Union has EU regulations (Euro regulations) which are currently at Euro 6 standard (EU, 2007a).

| Euro 6 emission limits |       |                                |                                 |     |                                     |    |                                            |    |                                                  |     |                                                                                        |     |                                    |     |                            |    |    |
|------------------------|-------|--------------------------------|---------------------------------|-----|-------------------------------------|----|--------------------------------------------|----|--------------------------------------------------|-----|----------------------------------------------------------------------------------------|-----|------------------------------------|-----|----------------------------|----|----|
| Category               | Class | Reference mass<br>(RM)<br>(kg) | Limit values                    |     |                                     |    |                                            |    |                                                  |     |                                                                                        |     |                                    |     |                            |    |    |
|                        |       |                                | Mass of carbon monoxide<br>(CO) |     | Mass of total hydrocarbons<br>(THC) |    | Mass of non-methane hydrocarbons<br>(NMHC) |    | Mass of oxides of nitrogen<br>(NO <sub>x</sub> ) |     | Combined mass of total hydrocarbons and oxides of nitrogen<br>(THC + NO <sub>x</sub> ) |     | Mass of particulate matter<br>(PM) |     | Number of particles<br>(P) |    |    |
|                        |       |                                | L <sub>1</sub><br>(mg/km)       |     | L <sub>2</sub><br>(mg/km)           |    | L <sub>3</sub><br>(mg/km)                  |    | L <sub>4</sub><br>(mg/km)                        |     | L <sub>2</sub> + L <sub>4</sub><br>(mg/km)                                             |     | L <sub>5</sub><br>(mg/km)          |     | L <sub>6</sub><br>(#/km)   |    |    |
|                        |       |                                | PI                              | CI  | PI                                  | CI | PI                                         | CI | PI                                               | CI  | PI                                                                                     | CI  | PI <sup>(2)</sup>                  | CI  |                            | PI | CI |
| M                      | —     | All                            | 1 000                           | 500 | 100                                 | —  | 68                                         | —  | 60                                               | 80  | —                                                                                      | 170 | 5,0                                | 5,0 |                            |    |    |
| N <sub>1</sub>         | I     | RM ≤ 1 305                     | 1 000                           | 500 | 100                                 | —  | 68                                         | —  | 60                                               | 80  | —                                                                                      | 170 | 5,0                                | 5,0 |                            |    |    |
|                        | II    | 1 305 < RM ≤ 1 760             | 1 810                           | 630 | 130                                 | —  | 90                                         | —  | 75                                               | 105 | —                                                                                      | 195 | 5,0                                | 5,0 |                            |    |    |
|                        | III   | 1 760 < RM                     | 2 270                           | 740 | 160                                 | —  | 108                                        | —  | 82                                               | 125 | —                                                                                      | 215 | 5,0                                | 5,0 |                            |    |    |
| N <sub>2</sub>         |       |                                | 2 270                           | 740 | 160                                 | —  | 108                                        | —  | 82                                               | 125 | —                                                                                      | 215 | 5,0                                | 5,0 |                            |    |    |

Key: PI = Positive ignition, CI = Compression ignition  
(1) A number standard is to be defined for this stage.  
(2) Positive ignition particulate mass standards apply only to vehicles with direct injection engines.

Figure 2: Euro 6 Emission Limits Table (EU, 2007a)

Figure 1 shows the Euro 6 emissions limits set out by the EU in 2007 which came in to force in September 2014 (EU, 2007a). In Figure 1 there are different categories vehicles come under based on the vehicles Mass. The trend across the emissions can be seen that as the vehicles mass increases the more lenient the regulations become.

Prior to Euro 6 there had been other standards (Euro 5, 4, 3, 2 and 1) which became increasingly more stringent through there iterations over time. Tables 2 and 3 below show the changes of the emission limits going through these iterations. In Tables 2 and 3 the values for Euro 5 and 6 will be for passenger vehicles which are noted as Category N<sub>1</sub> in the Figure 2, mass less than 1305kg. Passenger vehicles mass for Euro 1-4 regulations in category N<sub>1</sub> are less than 2500kg.

| Positive Ignition (Petrol) | Date    | CO   | HC  | HC+NO <sub>x</sub> | NO <sub>x</sub> | PM    | PN                   |
|----------------------------|---------|------|-----|--------------------|-----------------|-------|----------------------|
|                            |         | g/km |     |                    |                 |       | #/km                 |
| Euro 1                     | 1992.07 | 2.72 | -   | 0.97               | -               | -     | -                    |
| Euro 2                     | 1996.01 | 2.2  | -   | 0.5                | -               | -     | -                    |
| Euro 3                     | 2000.01 | 2.3  | 0.2 | -                  | 0.15            | -     | -                    |
| Euro 4                     | 2005.01 | 1    | 0.1 | -                  | 0.08            | -     | -                    |
| Euro 5                     | 2009.09 | 1    | 0.1 | -                  | 0.06            | 0.005 | -                    |
| Euro 6                     | 2014.09 | 1    | 0.1 | -                  | 0.06            | 0.005 | 6.0×10 <sup>11</sup> |

Table 2: Petrol Emissions throughout Euro Regulation iterations for Passengers vehicle (DieselNet, 2018)

Table 2 proves the previous statement that the regulations become more stringent through there iterations as all the limits decrease throughout. In Euro 1 and 2 the HC and NOx were measured together but since Euro 3 onwards these have been measured separately. PM only started to be limited in Euro 5.

| Compression Ignition (Diesel)    | Date    | CO   | HC | HC+NOx | NOx  | PM    | PN                   |
|----------------------------------|---------|------|----|--------|------|-------|----------------------|
|                                  |         | g/km |    |        |      |       | #/km                 |
| Euro 1                           | 1992.07 | 2.72 | -  | 0.97   | -    | 0.14  | -                    |
| Euro 2, Indirect injection (IDI) | 1996.01 | 1    | -  | 0.7    | -    | 0.08  | -                    |
| Euro 2, Direct injection (DI)    | 1996.01 | 1    | -  | 0.9    | -    | 0.1   | -                    |
| Euro 3                           | 2000.01 | 0.64 | -  | 0.56   | 0.5  | 0.05  | -                    |
| Euro 4                           | 2005.01 | 0.5  | -  | 0.3    | 0.25 | 0.025 | -                    |
| Euro 5a                          | 2009.09 | 0.5  | -  | 0.23   | 0.18 | 0.005 | -                    |
| Euro 5b                          | 2011.09 | 0.5  | -  | 0.23   | 0.18 | 0.005 | $6.0 \times 10^{11}$ |
| Euro 6                           | 2014.09 | 0.5  | -  | 0.17   | 0.08 | 0.005 | $6.0 \times 10^{11}$ |

Table 3: Diesel Emissions throughout Euro Regulation iterations for Passengers vehicle (DieselNet, 2018)

Table 3 shows a contrast to the emissions limits compared to petrol limits in table 2. The diesel limit for CO is half that of Petrol. Petrol's limitation for NOx is less than diesel and diesel HC is only regulated with NOx. Therefore looking at figure 1; if HC is high NOx would be low and vice versa. Also note the changes in indirect injection and direct injection limits (NOx increases with direct injection due to better quality of burn that creating higher temperatures, thus the including NOx limit in Euro 3).

These limits have been dropping therefore car manufacturers have implemented ECDs to reduce vehicle emission output. These ECDs include PCV, EVAP, EGR, SAIR and the Catalytic converter. Functionality, efficiency and the effects of these systems will be discussed.

#### Positive Crank Ventilation (PCV)

In a PCV system “release of the blow-by gas to the atmosphere is prevented by returning blow-by gas, containing nitrogen oxides, carbon monoxide and hydrocarbons to the intake passage of the engine via a blow-by gas passage” (Subaru, 2018). Blow-by gases are what have leaked from combustion chamber into the crank case. These gases reside in the crank case until the PCV opens under high load or RPM. When open the blow-by gases go to the intake and the HC is burnt in the process (purging the system). CO and NOx travel through the combustion chamber and get processed further down the exhaust. Without PCV the pressure in the crankcase can get too high resulting in seals breaking causing oil and blow-by gases to leak to atmosphere. HC vapour can condense in the crank case this can mix with the oil leading to damage of components over time, PCV prevents this. (P.Jeya Prakash Singh et al, 2009)

Within Euro 6 regulations any system that controls emissions must monitored. This is the same with PCV. During a purge at high RPM or load the air/fuel ratio goes slightly lean (fuel trim characteristic). Hence when the HC from the crank case is burnt the same performance is expected. This is confirmed by the lambda sensor. Also the oxygen sensor in the intake would see the valve opening as the oxygen value would drop due to the presence of the CO and NOx. When a PCV system has a fault this can be diagnosed in a number of ways. When a PCV valve fails (remains closed) higher oil pressure will be seen, this can be validated by testing for pressure coming from the dip stick orifice. Also by using the lambda and oxygen sensor as previously mentioned the OBD system can see if the valve is opening.

A standardized test for PCV operation is outlined in UN/ECE Regulation No 83 as Test 3 (EU, 2007b) (EU, 2019). Simplified below.

*“Method of verification of the crankcase ventilation system. The engine’s apertures shall be left as found. The pressure in the crankcase shall be measured at an appropriate location. It shall be measured at the dip-stick hole with an inclined-tube manometer. The vehicle shall be deemed satisfactory if, Idling shall be regulated in conformity with the manufacturer’s recommendations. See 3.2. (See Figure 2) The pressure measured in the crankcase does not exceed the atmospheric pressure prevailing at the time of measurement. (EU, 2007b).*

3.2. The measurement shall be performed in the following three sets of conditions of engine operation:

| Condition Number | Vehicle speed (km/h)            |
|------------------|---------------------------------|
| 1                | Idling                          |
| 2                | 50 ± 2 (in 3rd gear or ‘drive’) |
| 3                | 50 ± 2 (in 3rd gear or ‘drive’) |

Figure 3: EU, 2007b. Annex 6 section 3.2 measurement conditions for PCV Test (Test III)

### Evaporative emission control system (EVAP)

Evap systems collect and retain fuel vapours preventing HC and VOCs venting to atmosphere. There are five sources that EVAP prevent; diurnal (tank expansion/contraction due to heat leading to vapour loss), running loss (leaks from fuel cap), permeation (plastics degrading due to vapour), hot soak (engine heat creates fuel vapour leaks in engine bay) and refueling (liquid fuel disperses vapour in the tank to atmosphere). (MECA, 2010)

*“The fuel tank is vented into a canister called an “EVAP canister” that contains an adsorbent material Such as activated carbon granules. As the fuel vapor enters an inlet of the canister, the fuel vapor diffuses into the carbon granules and is temporarily adsorbed ... After the engine is started, the control system uses engine intake vacuum to draw air through the adsorbent to desorb the fuel.”* (S.Reddy, 2007)

This canister collects and retains the fuel vapour until PCM dictates its use (Engine and CAT at operating temperature and RPM at midrange or above). Preventing the vapour from leaving the system also requires a fuel filler cap with vacuum lock capability and an expansion tank. On-board refueling vapour recovery systems (ORVR) can be used to process fuel vapour from the fuel tank back in to liquid fuel, this prevents vapour leaks and vehicles are better at monitoring fuel in the system than HC vapour when purged from the canister. Lambda 2 is used to limit the solenoid percentage opening of the canister while in purge as this prevents a rich burn mixture.

A standardized test for EVAP operation is outlined in UN/ECE Regulation No 83 as Test 4 (EU, 2007b) (EU, 2019).

*“The evaporative emissions test (Figure 7/1) is designed to determine hydrocarbon evaporative emissions as a consequence of diurnal temperatures fluctuation, hot soaks during parking, and urban driving... The vehicle shall be in good mechanical condition and have been run in and driven at least 3 000 km before the test. The evaporative emission control system shall be connected and have been functioning correctly over this period and the carbon canister(s) shall have been subject to normal use, neither undergoing abnormal purging nor abnormal loading”* (EU, 2007b)

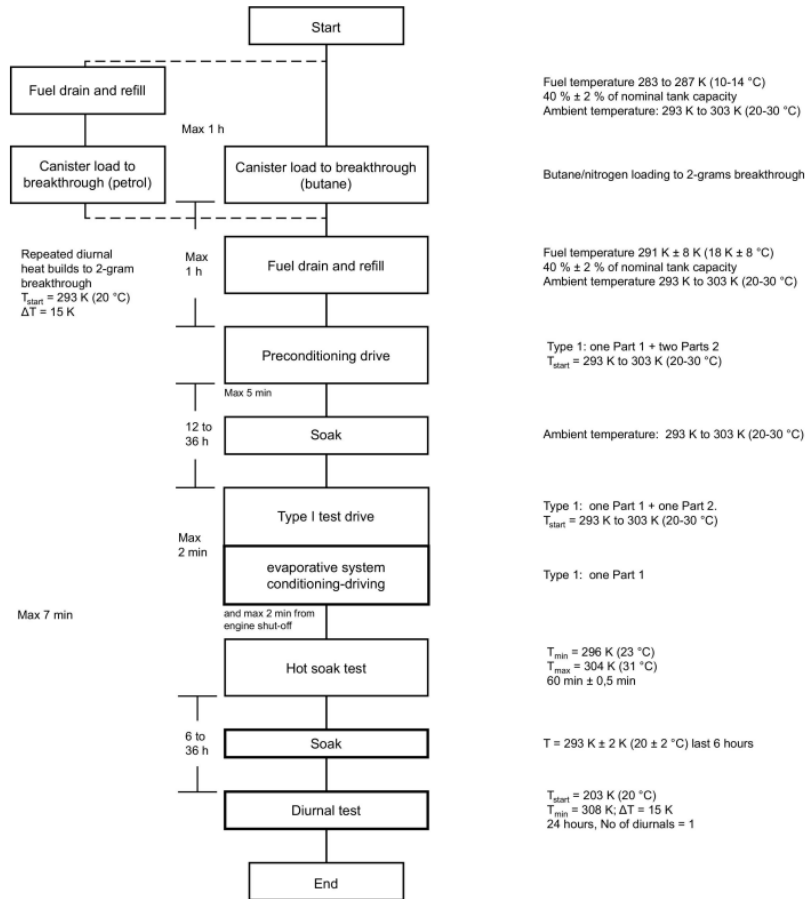


Figure 4: EU, 2007b. Annex 7 Figure 7/1 for EVAP Emissions Test

### Exhaust Gas Recirculation (EGR)

EGR recirculates exhaust gases back to the intake manifold. These inert gases go in to the combustion chamber lowering the oxygen percentage hence reduce the efficiency of the burn therefore the unburnt fuel is used to cool the cylinder. This causes a rich burn characteristic (see Figure 1). “EGR draws the exhaust gases through an appropriate circuit from the exhaust to the intake port, which consists of a recirculated pipe, controllable valves and gas coolers. The recirculated burned gas is usually mixed with fresh air and re-aspirated into combustion chamber...EGR can effectively lower the NO<sub>x</sub> concentration by reducing the combustion temperature thanks to its thermal effects on increasing intake charge heat capacity” (D. Feng et al, 2017)

Lambda is used to validate the burn process by seeing reduce O<sub>2</sub> levels. Less O<sub>2</sub> means more exhaust gases were supplied from the EGR. DPFE Compares the pressure differences between the EGR on the exhaust side, pressure prior to EGR and after EGR therefore Pressure drops confirms EGR valve open. This can determine the amount of exhaust gases that would got through to the intake when opened. EGR is limited due to fuel economy and torque losses however reduces the production of NO<sub>x</sub>. Other limitations of EGR include it can only be used at mid-range RPM. When NO<sub>x</sub> is formed in the chamber below 1370 °C the catalytic converter can control this, EGR controls larger amounts of NO<sub>x</sub> produced above this temperature. EGR is deployed highly in turbo engines for these reasons.

### Secondary Air Induction Reaction (SAIR)

SAIR is an ECD that pumps air into the exhaust system. The process helps oxidize HC in the exhaust from a rich burn, therefore completing the burn after the combustion chamber. This greatly increases the temperature of the catalytic converter and reduces HC as SAIR is used when engine temperature is cold. This reduces warm up the period of the Catalytic converter. Lambda 2 is used to measure the amount of oxygen remaining in the exhaust gases to assess after burn in the exhaust.

*“The pump is electric, and it’s turned on just a few seconds after cold-start. Air is pumped into the exhaust upstream of the oxygen sensor, either to a single point in the manifold or directly to each exhaust port as it was in the 1970s. At the same time, the PCM might lengthen the injector pulse. The extra fuel and air react in the exhaust manifold, causing a rapid rise in exhaust gas temperature that brings the catalyst up to operating temperature quickly. By comparing the front and rear oxygen sensor signals, the PCM can determine when the catalyst begins working. This might take as little as 15 seconds” (J. Marotta, 2010).*

Without SAIR the warm up period would take minutes. Once at operational temperature the SAIR is only used during snap acceleration to burn excess HC. OBD is used to test this ECD for functionality by pulsing the solenoid during ignition. If back EMF is seen then the system is operational. If a lambda fault occurs however then the solenoid could be functional but a leak could allow the air to escape and therefore wouldn’t get picked up on the lambda sensor.

### Catalytic converter

*“The purpose of a catalytic converter is to convert CO, hydrocarbon (HC), and oxides of nitrogen (NOx) emissions from an engine into carbon dioxide (CO<sub>2</sub>) and water (H<sub>2</sub>O), so that tail-pipe emissions are at acceptable levels. Once the catalyst has reached its operating temperature, the optimal conversion efficiency for all three emission components lies within a narrow band of air–fuel ratio near the stoichiometric ( $\lambda=1$ )” (S. SAMUEL et al, 2005)*

The catalytic converter is an after treatment device positioned between the exhaust manifold and the silencer. Metals included in the catalytic converter include rhodium, Palladium, Platinum and cerium, these are all placed onto a monolithic substrate. Cerium to collect oxygen when A/F ratio is lean and release oxygen when A/F ratio is rich. Catalytic converters use pre and post catalytic oxygen sensors to monitor cerium oxygen capture. The closer the cat is to the engine the faster it will warm up (SAIR aids in this warm up). Catalytic converters on maintenance free to a certain degree. Catalytic converter can be damaged from high temperatures, cranking for more than 40 seconds, turning off the ignition in Motion. Primarily a rich A/F ratio damages the catalytic converter. Contaminants such as oil, Sulphur and antifreeze can damage the catalytic converters membrane. The chemical reaction in a catalytic converter is around 50% efficient around 300° C and around 480°C to 870°C for full efficiency.

EU amendments to regulations No 715/2007, 2019 shows annex 7, appendix 1 shows the SBC to test catalytic converter efficiency performed to the EU industry-standard. This test finds the efficiency change in the catalytic converter over time at different temperatures. This is performed using a SBC which consists of running a catalytic converter on an engine in the sequence shown below (Figure 5). The ageing effect can be determined and the R-factor (thermal reactivity co-efficient) can be determined. (EU, 2019)

**Standard Bench Cycle (SBC)**

| Time (seconds) | Engine Air/Fuel Ratio                                                                                                                                | Secondary Air Injection |
|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
| 1-40           | Stoichiometric with load, spark timing and engine speed controlled to achieve a minimum catalyst temperature of 800 °C                               | None                    |
| 41-45          | 'Rich' (A/F ratio selected to achieve a maximum catalyst temperature over the entire cycle of 890 °C or 90 °C higher than lower control temperature) | None                    |
| 46-55          | 'Rich' (A/F ratio selected to achieve a maximum catalyst temperature over the entire cycle of 890 °C or 90 °C higher than lower control temperature) | 3 % (± 1 %)             |
| 56-60          | Stoichiometric with load, spark timing and engine speed controlled to achieve a minimum catalyst temperature of 800 °C                               | 3 % (± 1 %)             |

**Standard Bench Cycle**

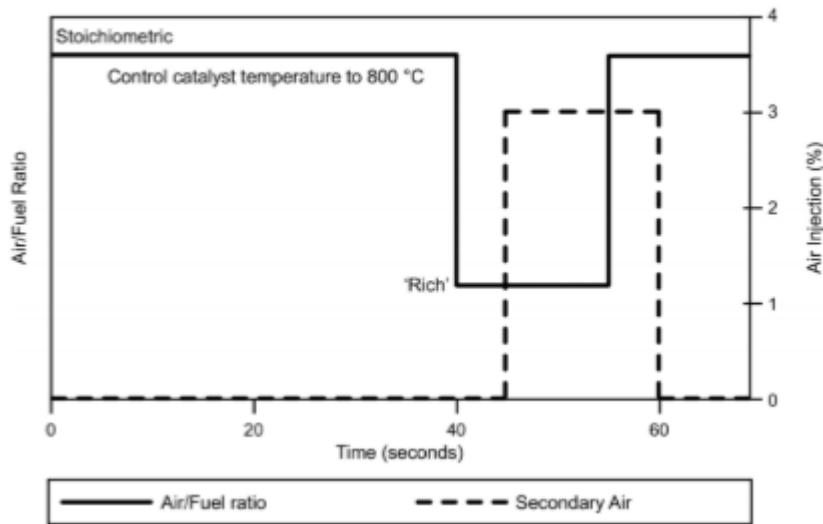


Figure 5: EU, 2019. SBC for Catalytic converter test.

## 5. Safety and Equipment

Safety considerations to consider while conducting the tests consist of workshop and personal safety. Workshop safety (HSE, 2010) relates to the prevention of hazards to people by use of risk assessment and reducing the risk factor. In this case ventilation, moving equipment, COSHH, Emergency procedure and first aid are relevant considerations. Ventilation would be used to extract exhaust gases out of the workshop and provide a circulation of air from outside. Engine rigs will be moved around and safe for these rigs is outlined below. COSHH is considered for the fueling of the rigs used in the test. As mentioned HC is hazardous to health hence the fueling is controlled by a technician and done prior to testing. Emergency procedures are part of workshop induction including fire safety and what to do and where to get help in the emergency situations. First equipment and trained staff are within the workshop environment to aid in the situation in which a person would require medical attention.

Personal safety (HSE, 2013) consists of wearing PPE such as dust coats, safety boots, gloves and eye protection. Dust coats provide body protection from *“Temperature extremes, adverse weather, chemical or metal splash, spray from pressure leaks or spray guns, impact or penetration, contaminated dust, excessive wear or entanglement of own clothing”* & *“The choice of materials includes flame-retardant, anti-static, chain mail, chemically impermeable, and high-visibility”* (HSE, 2013). Safety boots consisting of a steel toe insert provide protection from falling objects. Gloves protect hands temperature extremes, cuts, impact, chemicals and punctures. Lastly protective glasses prevents vapour, dust and projectiles damaging the eyes.

During testing a Bosch diagnostic centre BEA 850 (Bosch, 2012a) and a digital multi-meter was used to test three engine rigs. The Bosch BEA 850 Diagnostic Center was used during the test as this equipment was available to the group at the time of testing. This equipment had all the requirements to complete the tests on the three engine rigs. These included a 5 gas analyzer (For monitoring emissions), temperature sensors (to assess when rigs are at operational temperature) and a Multi-channel oscilloscope (Reading sensor values at the ECU). For the test the group could have used the Bosch BEA 950 S1 (Bosch, 2017a) or S3 (Bosch, 2017b). This is newer equipment released by Bosch in 2017 to be more future proof in measuring emissions, however was not available at the time of testing.

Using the data sheets for the Bosch BEA 850 (Bosch, 2012b) and the Bosch BEA 950 Series (Bosch, 2017c) a comparison can be made. Other than the ease of use with Bluetooth equipment and future proofing of emissions and OBD there are no significant difference between 850 and 950. Lack of sensor range data for the 950 Series prevents a full comparison. But with a 5 year gap in release dates the accuracy of the sensors would be more favorable to the 950 Series without the consideration of the sensors becoming inaccurate over time and use on the 850 system. From this comparison using the 950 series could provide higher accuracy results. Between the 950 series 1 and 3 these differences are negligible as both would be equally capable of providing accurate results. BEA 950 Series 2 and 4 could have been considered but these are lower model equivalents of the BEA 950 Series 1 and 3 respectively.

Vauxhall Motronic (A G Block, 2019a), Ford EEC1v (A G Block, 2019b) & Vauxhall Simtec/Ecotec (A G Block, 2019c) are the three engine rigs being tested and follow Euro Regulation 3, 4 and 5 respectively. Each of these rigs provide an ease of access to the ECU of which the group will be taking data from. Unlike a conventional engine these rigs are prepared to be safe such as guards and covers are used on moving parts. The rigs are mounted on wheels which allows moving the equipment safely without the need for lifting. These rigs do get hot during testing and are sharp in areas resulting in the use of appropriate PPE.

## 6. Methodology

Each of the engine rigs were tested for idle control, injection sequencing and ECDs with notes made on other variables. Schematics and notes for the three rigs in in the appendices in figures 11, 12 and 13.

Vauxhall Motronic rig (Figure 11) is to Euro 3 standard. Engine idle control is by a rotary idle valve and plunger system. This system requires a hot wire air mass meter to operate which is more accurate at reaching A/F ratios of 14.7/1. Previously this would have been a volume sensor which is less accurate as the mass of the air changes with temperature. During warm up percentage of idle valve opening went down due to the engine reaching operating temperature. Injection sequencing is simultaneous meaning for each 720° cycle of the crank the injectors pulse twice. Each 360° these injectors pulse half the fuel. Once valve opens all the fuel can be supplied. ECDs on this rig include a catalytic converter, PCV and EVAP (Carbon canister). The warm up period on the engine is long resulting in the catalytic converter taking a long time to get to operational temperature (300°c-800°c) resulting high emissions during warm up. PCV is operated by a valve opening controlled by the vacuum in the intake manifold. Hence the PCV isn't monitored by the ECU (This is the same for all the rigs). The EVAP canister opens at mid-range RPM and higher once the catalytic converter is up to operating temperature. On all the rigs the EVAP canister is solenoid controlled.

Ford EECIV (Figure 12) conforms to Euro 4 regulations. Idle control on this rig is by solenoid and is adaptive. A scope of the idle control can be seen on figure 6 in the appendices. Hot wire air mass meter is in use on this rig. Sequential injection is used on this rig with the use of a camshaft sensor (Figure 7 see appendices). The injectors pulse once every 720° cycle (Figure 8 see appendices). The ECDs on this rig include SAIR, PCV and EVAP. PCV and EVAP are similar to those on the Vauxhall Motronic rig. The SAIR air supply is provided by an engine driven pump and a solenoid is used control air pulses. Lambda is used to limit the amount the solenoid opens.

Vauxhall Simtec/Ecotec (Figure 13) is to Euro 5. Idle control is by solenoid and the scope from this can be seen in the appendices figure 10. This rig uses the Sequential injection as explained in the Ford rig section. ECDs on this rig include SAIR, EVAP, PCV and EGR. Apart from EGR the other ECDs are similar to the ones explained in the Ford rig section. EGR on this system is an early generation of EGR. This EGR is operational at a set RPM range, the gases are controlled via Solenoid and this is tested with the lambda sensor. The fixed RPM range being the only limit on the EGR means even when the engine is cold the engine at the RPM range will still have EGR deployment resulting in engine warm up taking longer. In later generation of EGR a limit on engine temperatures are set.

## 7. Results

The oscilloscope graphs (figures 6, 7, 8, 9 & 10 see appendices) taken from the tests are the results from rigs that will be discussed in this section.

Figure 6 graph shows pulse side of the idle control valve on the Ford rig. The scope shows the voltage drop from 12v to 5v and then rise back to 12v over a 5milliseconds. This repeated pattern shows the solenoid is maintaining a percentage opening remain at base idle. This is the pulse side of the solenoid hence back EMF can't be seen.

Figure 7 graph shows the Camshaft sensor on the Ford engine. With the inclusion of this sensor on the Ford (and Ecotec) it allows the sequential injection. The four pattern sequence shows the ECU a specific cylinder at a specific point in the 720° allowing the ECU to know when to pulse each injector as the firing order is predetermined. An increase in engine RPM would shorten the frequency of the wavelength hence the ECU know when to pulse each injector.

Figure 8 graph shows injector earths for cylinders 4 & 3 on the Ford engine. This backs up the previous scope as it shows sequential injection. In addition the dwell period of the injector shows the amount of fueling going to each cylinder. The spike after the dwell period is back EMF as this graph is showing the earth of each injector.

Figure 9 graph shows EGR solenoid use on the Vauxhall Ecotec system. This scope shows back EMF values in excess of 75v. The period after back EMF at 12v is available voltage as the solenoid is closed. This is then grounded showing 0v meaning the EGR solenoid is open. At the end of the scope the available voltage remains a 12v as the EGR is not in use.

Figure 10 graph shows the idle valve solenoid actuation on the Vauxhall Ecotec system. This scope shows the current draw changes of the solenoid due to temperature changes.

## 8. Analysis

### Emission reduction and upgrading to Euro 6 Standard

Considerations to bring the first rig at Euro 3 up to Euro 6 standard as well emission reduction strategies. Predominantly these changes would include monitoring additional temperatures, pressures, mass (air/exhaust) and gas sensors on the ECDs to verify valves opening and closing, leak detection, amounts of air (going to SAIR) or exhaust (going to EGR) as a mass. Implementation of a gas sensors could prevent false fault codes from lambda cause by leaks or failed mechanical equipment.

Vauxhall Motronic uses simultaneous injection which causes pooling issues and reduced mixture with air preventing a good quality burn. This increases HC emissions but reduces NO<sub>x</sub>. Changing this to sequential injection would prevent HC emissions. Implementing SAIR and EGR would reduce warm up time and prevent NO<sub>x</sub> further improving emissions. The PCV is not monitored on this engine therefore the valve could be stuck open/ closed or the connecting hose between many be damaged. This would result in emissions leaking to atmosphere and/or an uncontrolled supply of HC vapour and contaminants going in to the intake. Using a potentiometer in the valve or a solenoid controlled valve would show movement and a pressure sensor prior to the intake would show pressure in the system showing meaning no leaks. The ECU lacks a lambda 2 sensor to show vapour from the EVAP canister is burnt also means catalytic converter is “blind” to the system as it has no data check correct function.

### An analysis of the operation in the tests conducted and the real world

*“The International Council on Clean Transportation (ICCT) had already shown that on-road emission levels of modern cars are on average about seven times higher than the limit set by the Euro 6 emission standard” (EPUK, 2017)*

The statement above shows that vehicles on the road produce more emissions compared to the industry standard tests and MOTs. Therefore Euro 6 regulations have a test for RDE. This uses a PEM system that records emission data on the road. The following statement from Transport for London highlights a fundamental issue this this test. *“It’s not possible for a vehicle to meet the Euro 6 type approval emissions limits under all driving conditions that may be encountered, since the duty cycle that the vehicle is operated over may be more demanding than the test cycles. Therefore a ‘conformity factor’ must be agreed by all parties and applied to the on-highway measurements... At the time of writing, there is no agreement between motor manufacturers and the European Commission on the appropriate level for this conformity factor for Euro 6/VI, nor the date of implementation.” (TFL, 2016)*

This conformity factory mentioned above has only been provisionally announced around 18 February 2019. Put simply this currently; *“RDE conformity factor for NO<sub>x</sub>=2.1, for PN=1.0 (+0.5 measuring tolerance variation) for new passenger car approvals up until 31 December 2020. From 1 January 2020 in compliance with Euro 6d regulations, RDE conformity factor for NO<sub>x</sub>=1.0 (+0.43 measuring tolerance variation)”* (Daimler, 2019). These values are subject to change as they are not yet confirmed.

### What to expect at Euro 7.

The following statements are from the same reference outlining the predicted emission reductions by 2030 compared to 2005.

*“NOx emissions could be further reduced below the baseline level by 15- 20%” (IIASA, 2013)*

*“Decrease VOC emissions in Europe by another 35%” (IIASA, 2013)*

*“Primary emissions of PM2.5 could be further reduced by up to 40%” (IIASA, 2013)*

As these percentages are from a baseline in 2005 here the euro regulations from Euro 4 for Petrol to get an estimation of where the euro 7 regulation could be. In Euro 4 limits for HC (VOCs) =0.1 g/Km, NOx=0.08 g/Km and PM=0.005 g/Km.

Predicted Euro 7 limits, HC (VOCs) = 0.065 g/km, NOx= 0.064 g/Km and PM= 0.003 g/Km.

Comparing this to table 2 brings interesting results. NOx is below the predicted Euro 7 limit at Euro 6. However this predicted limit would operate with the RDE test as mentioned before and would have a conformity factor of 2.1 (Daimler, 2019), this would bring the limit of NOx up to 0.1344 g/Km ( $0.064 \times 2.1 = 0.1344$ ). But another thing to point out that has been previously mentioned “on road emissions of modern cars are on average about seven times higher” (EPUK, 2017). Having said this an average modern car limit would be estimated therefore around 0.42 g/Km ( $0.06 \times 7 = 4.2$ ). Therefore modern cars are currently 3.125 ( $0.42 / 0.1344 = 3.125$ ) times higher than the predicted euro 7 regulations. Following the same calculation for HC= 10.78 times higher ( $0.1 \times 7 = 0.7 / 0.065 = 10.78$ ) and PM= 11.67 times higher ( $0.005 \times 7 = 0.035 / 0.003 = 11.67$ )

Highlighting the fact this is a prediction and accuracy is estimated these values show that the amount of development vehicle manufactures will have to contribute to reach this new and more difficult targets

## 9. Conclusion

To conclude vehicle manufacturers have made large advancements in ECDs to reduce overall emissions. However as the world population is ever increasing so is the demand for cars. This is even more important in developing countries. More cars are going on the road in the future hence the emissions have to be kept as low as limits can take it to reduce the impact these vehicles will have on humans and the planet. Eventually HEVs and EVs will outlive the internal combustion engine due to the emissions.

In terms of ECDs, OBD and monitoring it's clear that in the future cars will need more sensors and therefore require larger pin ECUs resulting in higher voltage systems. Testing the future systems could be very different to the way it's done today and this is noticeable by the number of amendment that are added to regulation referenced in this report.

In the modern day engine there is no simple resolve for all emissions as one emission value falls another rises (see-saw effect). Modern ECDs don't target the source but are more after treatment systems for the engine. This is another reason why EVs and HEVs are gaining traction in the automotive industry.

## 10. Evaluation

Outlined in this report has been a wide discussion on various emissions. The production of the emissions and how this has an effect on the concentration of different amounts of emission gases. The fact that the emissions have on people and the environment has been briefly mentioned. Different emission control devices have been mentioned including their functionality operation monitoring and limitations. Euro regulations have been discussed and future of euro regulations has been touched upon even going as far to it mentioned information that came out a couple weeks ago about conformity Factor. Testing Safety has been discussed thoroughly as well as the equipment used and the validation of this equipment. Methodology and results section have been almost negligible for this report as the main information has predominantly surrounded newer systems, tests and more. However the systems that have been tested using the testing equipment have provided a better background understanding about the systems and how they have become what they are today. In the analysis section there is multiple branches off topic which hopefully show a wider understanding of the topic as well as use of references. The references used have been predominantly government papers, research papers and books of which there are many and are varying in selection. The references have page numbers helping find information to readers. Presentation of this report has been well managed and reading over the work has allowed me to make changes to let the information easier to read. Abbreviations have been used a lot as word count is high and this method reduces this, also makes it easier to read. Time scale for this report has been very well managed and the bulk of the time is around finding and reading papers and books. In the event of doing a report like this again the same time scale would follow suite. Overall the report has been interesting to read around and been completed in a well understood manner however not written very concisely.

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## 12. Appendix

Word count = 6774

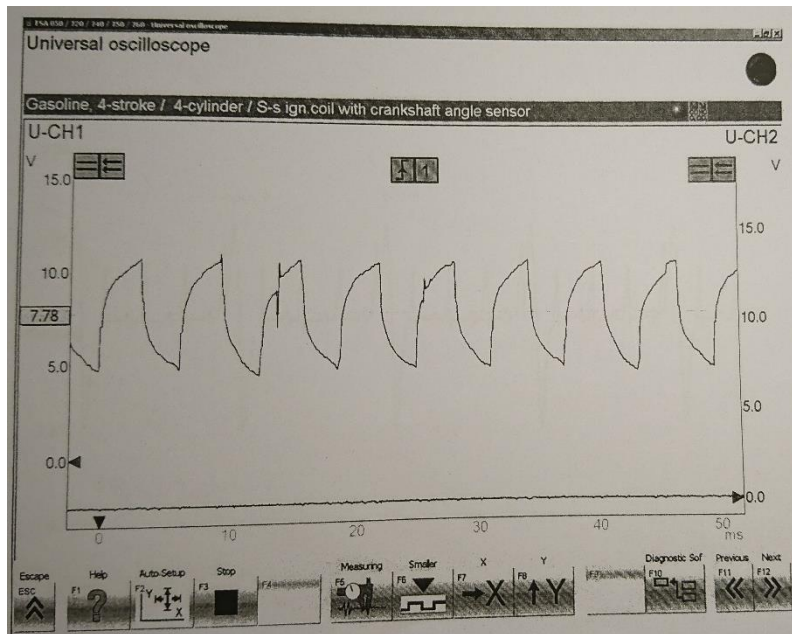


Figure 6: Ford EECIV Pin 21, Pulse side of idle control valve.

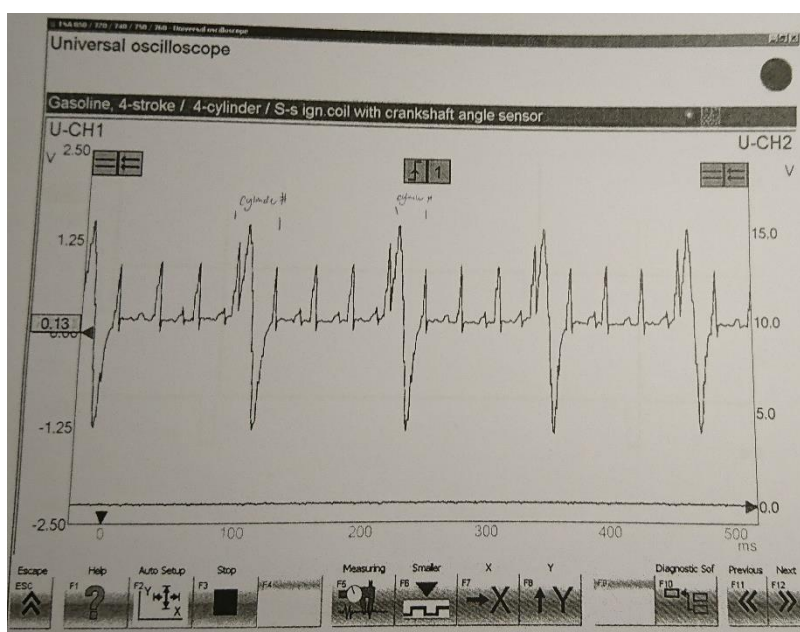


Figure 7: Ford EECIV Pin 24, AC input for Camshaft sensor.

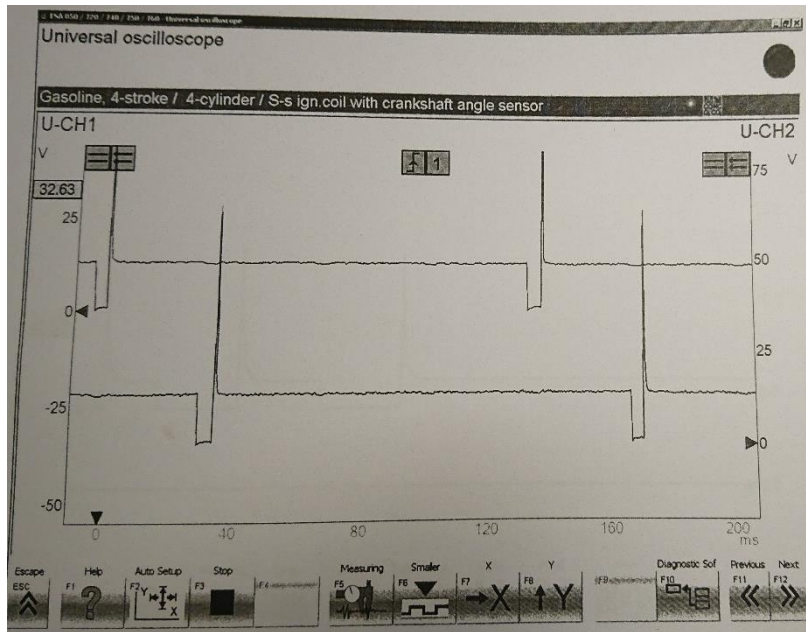


Figure 8: Ford EECIV Pins 35 & 39, injectors 4 & 3 EARTH.

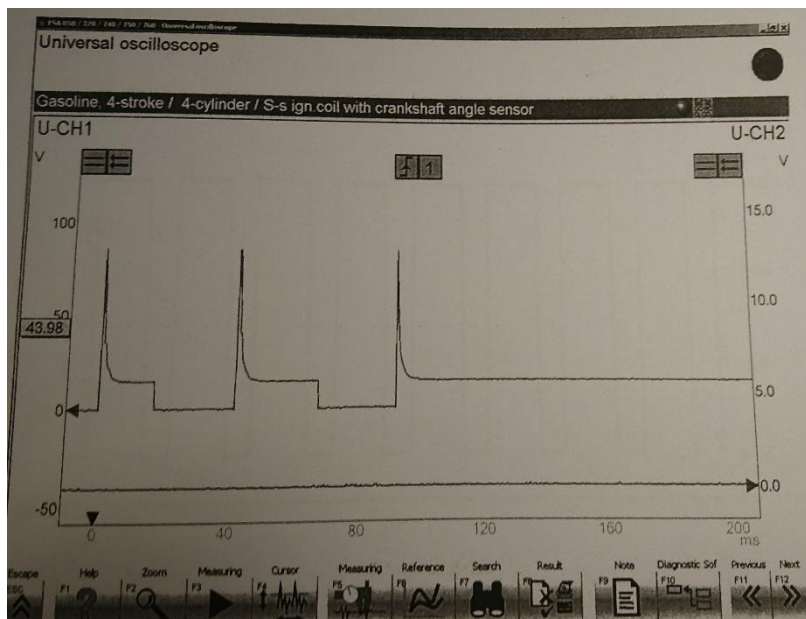


Figure 9: Vauxhall Ecotec Pin 42, EGR negative side of solenoid.

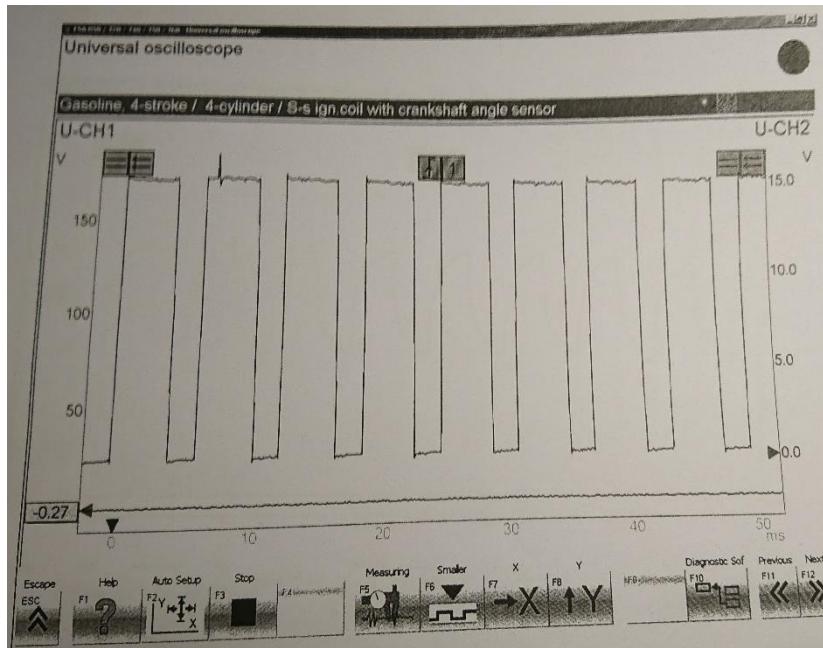


Figure 10: Vauxhall Ecotec Pin 52, idle control negative side of solenoid.

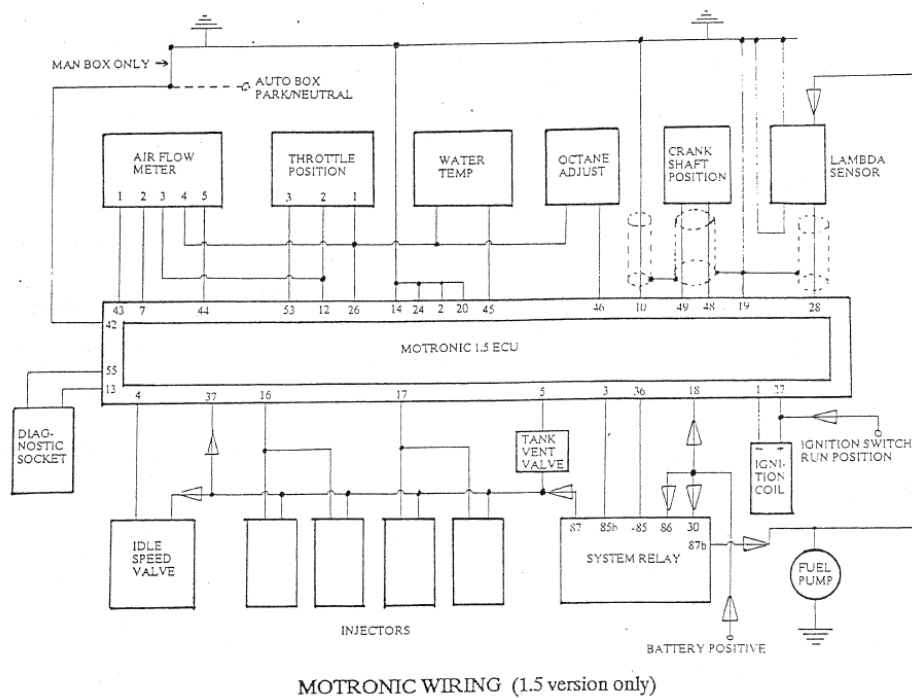


Figure 11: Vauxhall Motronic Schematic

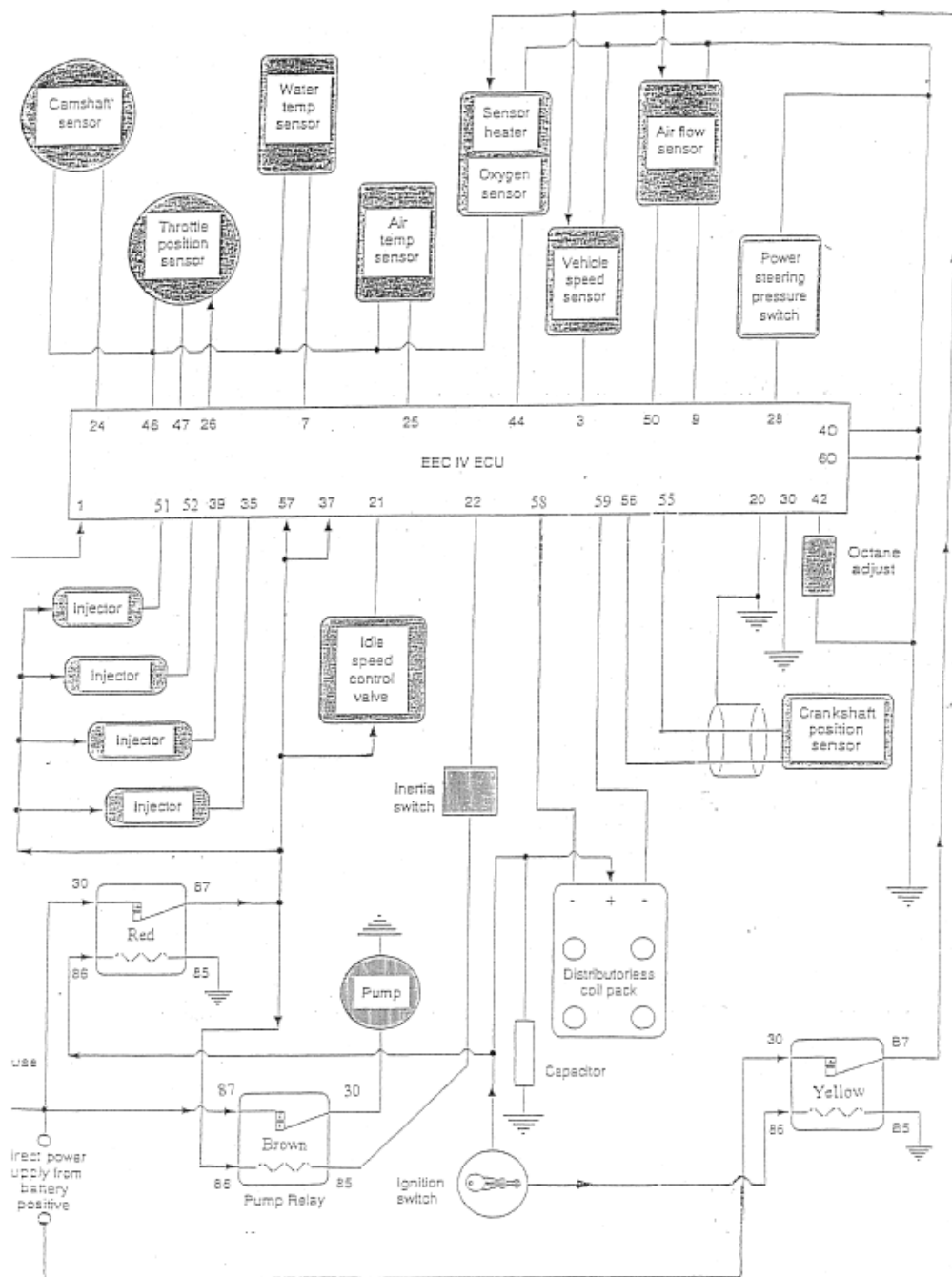


Figure 12: Ford EECIV Schematic

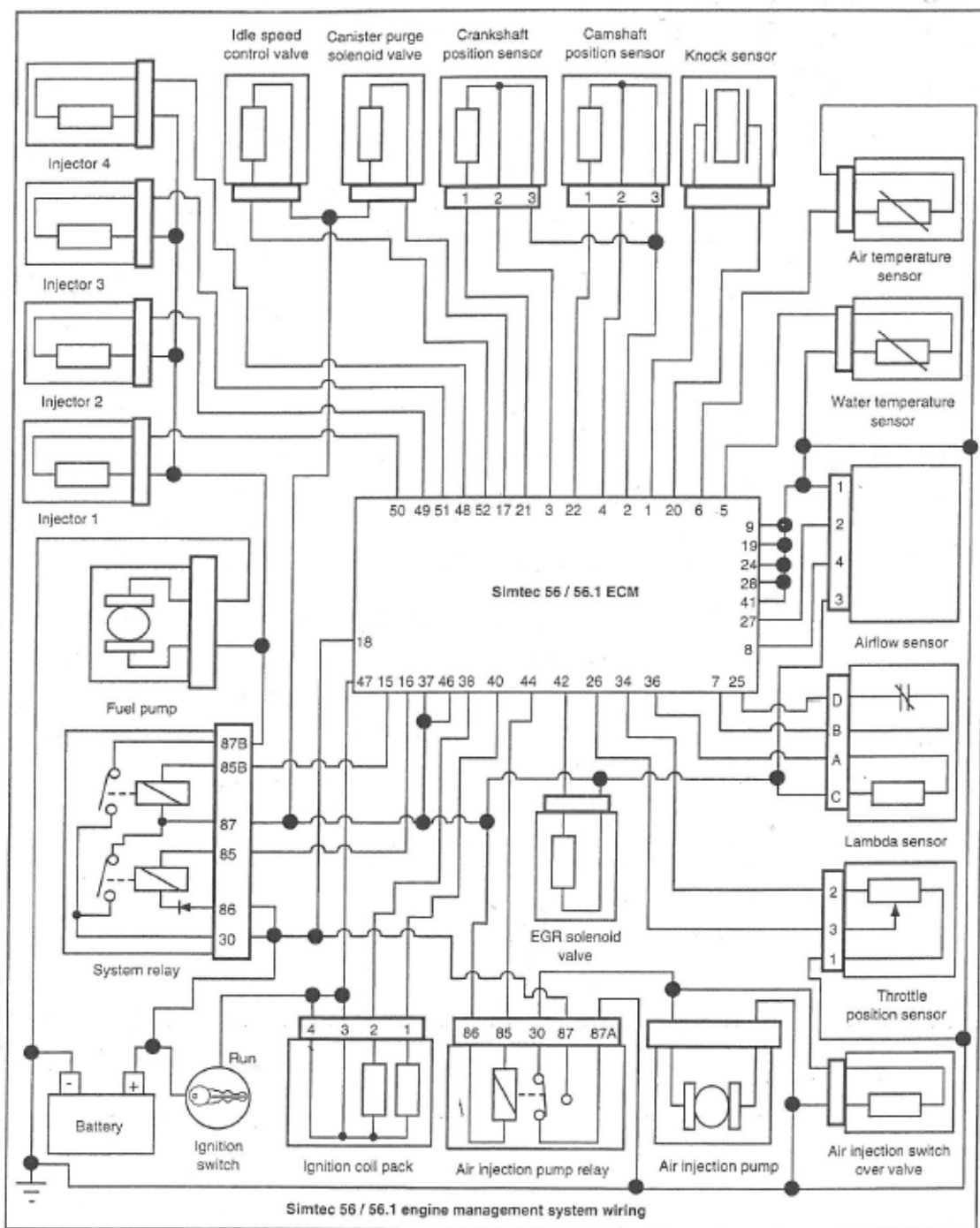


Figure 13: Vauxhall Ecotec/ Simtec schematic