THE XK8 ENGINE MANAGEMENT SYSTEM AND ELECTRONIC ENGINE CONTROL MODULE

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Abstract

The increasing demand for feature enhancements on passenger vehicles combined with more stringent emissions and legislative requirements world-wide has lead to a high level of complexity within engine control modules, associated emission control hardware and equally important, software.

This paper briefly explains how the functions of the AJV8 engine control work and how the diagnostics form an integrated part of the system design.

Introduction

The XK8 is powered by an all new Jaguar 4-litre V8 engine known as the AJV8. Its Engine Control Module (ECM) in addition to governing 'standard' engine functions such as fuel injection, ignition timing and closed loop fuelling also controls an electronic throttle body, knock sensing, variable valve timing, engine cooling fans and high speed real time serial communications with other control modules using the CAN protocol to manage traction control and shift quality etc. In addition, it continually adapts to take account of engine to engine variation, component and engine ageing and any default actions that may be required. With this increased complexity comes the need for a diagnostic system to allow faults to be detected quickly, accurately and be rectified easily should they occur.

Several of these functions already exist on previous engines and engine control modules. However, the AJV8 is the first ECM to command such an extensive range, and as such is the most complex and technologically advanced controller Jaguar has ever launched.

For the purpose of this paper the functions of the AJV8 Engine Management System (EMS) can be viewed as comprising:

1. Engine Control Module
2. Throttle Control
3. Ignition Control
4. Fuelling Control
5 Diagnostics

It should be noted that these systems have a great deal of inter dependency.

We shall start with an overview of the EMS.

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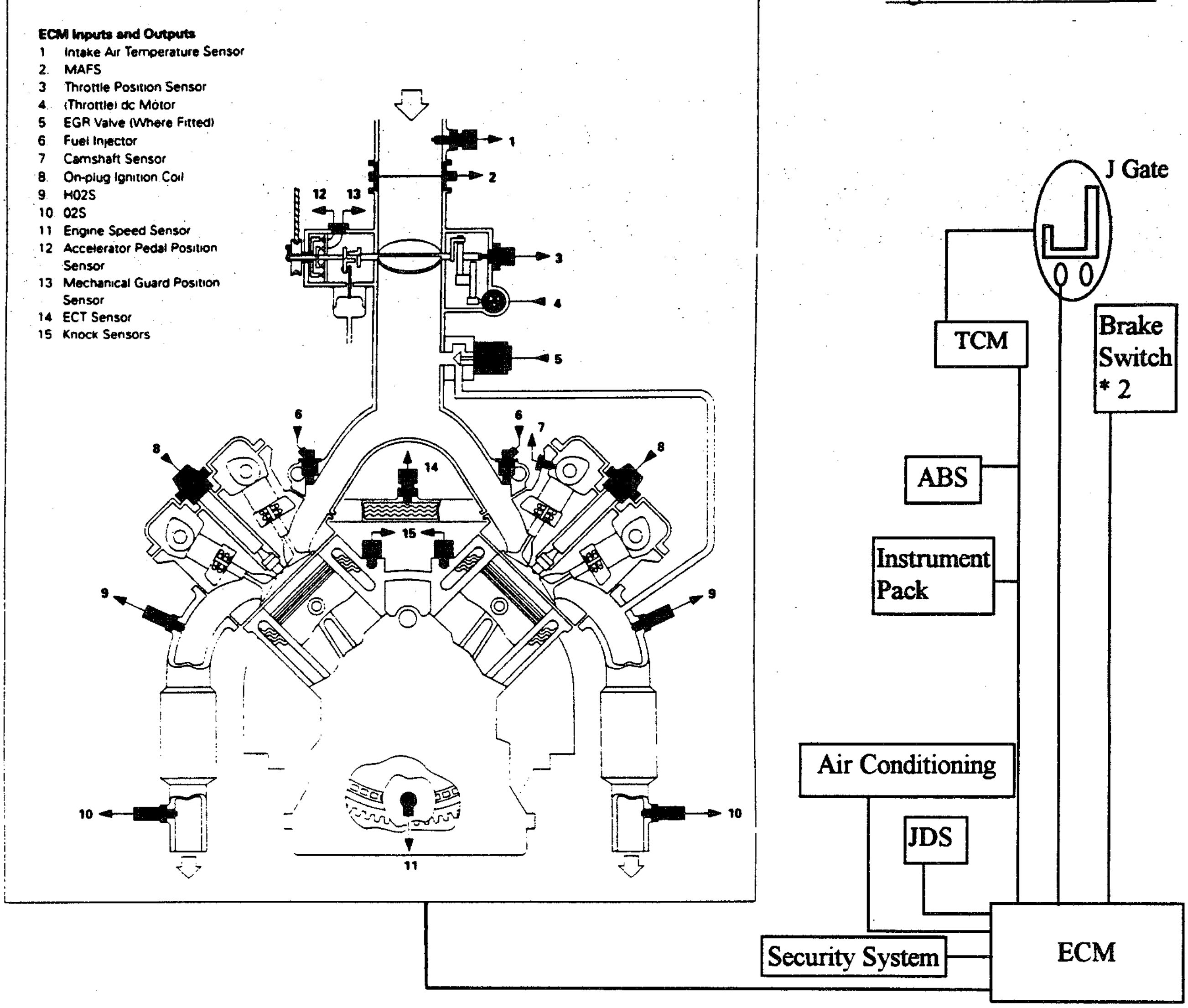
EMS Overview

An engine management system consists of a number of actuators and sensors with a central control unit, the engine control module (ECM). The ECM receives inputs from the sensors and operates closed loop control of the engine by driving the actuators to a required state. High speed real time communications with other control modules (for example the Anti Lock Brakes Controller) allow the integration of functions such as cruise and traction control. Figure 1 below shows some of the control exercised by the engine control module together with some of the sensors and actuators that make up the engine management system.

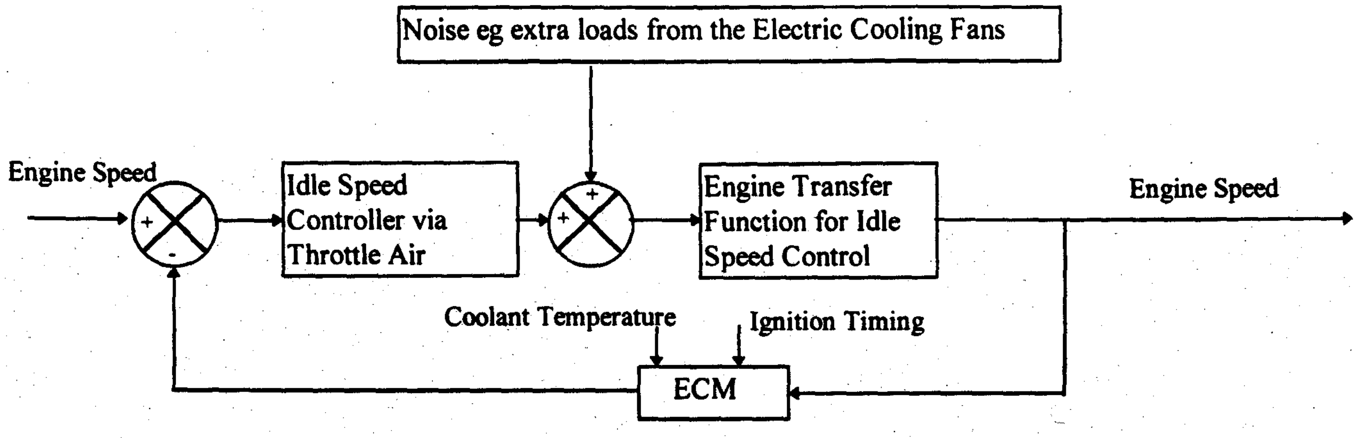
Figure 1: EMS Overview



The closed loop control operated by the ECM/EMS is usually affected when perturbations and noise (usually in the form changing loads on the engine) alter the operating conditions of the engine which are detected via the engine sensors. The control of the actuators is then altered to compensate for the new conditions. The AJV8 engine management controller typically operates two (Proportional and Integral) or three (Proportional, Integral and Derivative) term classical control over sub systems. A 3 term PID controller for idle speed control is used with proportional and integral terms controlling the air flow via the throttle blade, whilst changes to the ignition timing act as a derivative term due to the excessive transport lag of the air control.

Figure 2 shows a simplified closed loop control block diagram. The transfer function is not shown but is described in Ref 1. The model will contain two state variables, inlet manifold absolute pressure and engine speed. There are three inputs, throttle angle, ignition advance and the load torque.

Figure 2: Idle Speed Control Closed Loop Control Block Diagram

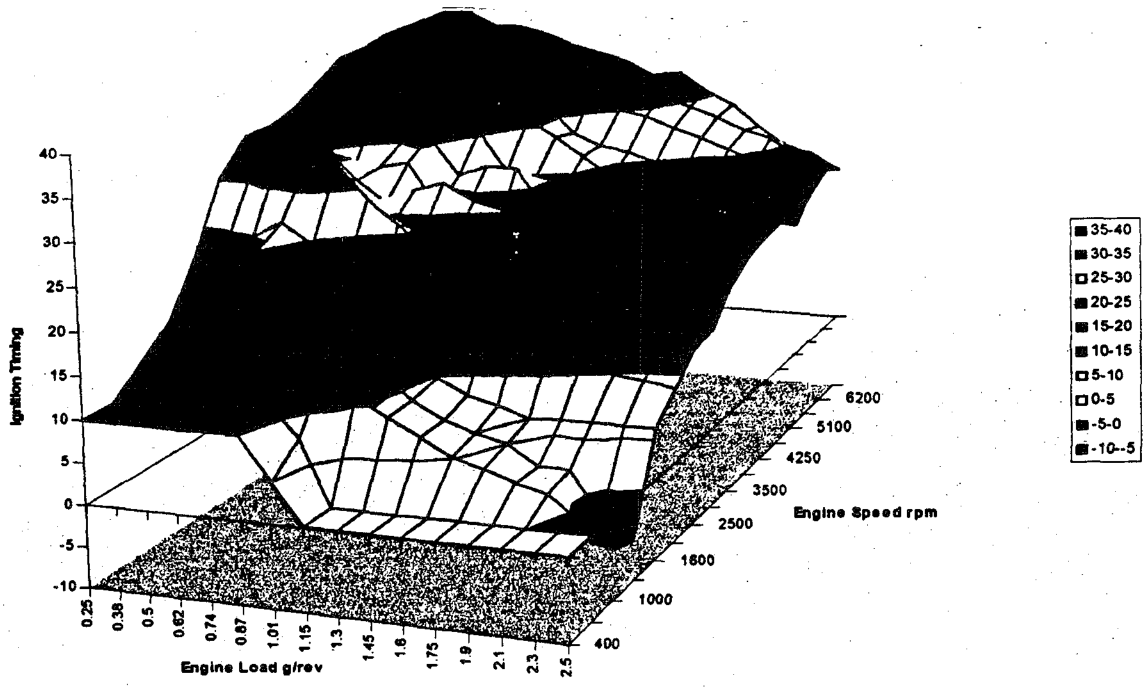


To determine the required actuator operation the ECM uses a series of look up tables which are usually referred to as maps. Figures 3 and 4 show a typical ignition map.

Figure 3: Part of the base ignition map

Engine Load g/rev \ Engine Speed rpm	400	700	1000	1300	1600	2000	2500	3000	3500	4000	4250	4500	5100	5700	6200	6800
0.25	9.9	9.9	13	16	22.1	30.1	34.1	34.1	35	37.1	39	39	39.5	39.5	39.5	39.5
0.38	9.9	11	16	17	23	30.1	34.1	34.1	31	35.9	39	38	37.6	39.5	39.5	39.5
0.5	9.9	12	19.1	20	24.9	32.9	32	31.3	27	32.9	35	35.9	35.9	37.1	38	38
0.62	9.9	12	20.9	24.9	27	32.9	29.6	27.7	28.2	30.1	34.1	35	35.5	37.1	37.1	38
0.74	9.9	12	20.9	24	24.5	32.9	26.6	25.2	28.9	31	32.9	34.5	35	35.9	35.9	37.1
0.87	9.9	12	17.9	20	20.9	28.9	24	27	23.3	26.1	30.5	32.9	33.6	34.5	34.5	35.9
1.01	5	8	13.9	15.1	17.9	26.1	23	28.2	23.5	27.5	25.4	31	31.5	33.6	33.6	35
1.15	0.1	0.1	11.1	12	13.9	23	22.1	26.1	20.2	27.5	24.7	28.9	28	32	32.4	34.1
1.3	0.1	0.1	9	9	9.9	19.1	20.2	25.2	19.8	22.6	24	26.6	26.6	30.1	31.5	32.4
1.45	0.1	0.1	7.1	7.1	8	17	18.1	23.3	19.8	20	23	24	25.9	29.4	30.8	32.9
1.6	0.1	0.1	5.2	5.9	7.1	15.1	17.2	20.9	17.7	19.1	20.9	23	24.9	28.2	29.6	30.5
1.75	0.1	0.1	4.1	5	5.9	13	16	19.8	16	20.5	21.9	23.3	23.8	27	28.4	28.9
1.9	0.1	0.1	2.9	2.7	6.2	11.1	12.7	18.1	18.1	21.2	22.8	23.5	22.6	25.6	27	26.1
2.1	0.1	0.1	2	2.7	6.2	9.9	11.8	16.7	16.3	19.5	21.2	21.6	20.7	24.2	26.1	23.8
2.3	0.1	0.1	-1.1	-2.5	6.2	9.5	11.8	15.5	14.1	18.1	19.1	20.9	18.4	22.1	23.8	23
2.5	0.1	0.1	-3.9	-5.1	6.2	9	11.8	12.5	16	17.9	19.1	19.3	17.4	20.2	22.1	20.9

Figure 4: Base Ignition Map



A better understanding of the operation of an EMS can be understood when compared to that of a standard carburettor system. This is explained in the simple example below.

Carburettor System

1. Driver estimates the engine temperature based upon ambient temperature and time since the engine was last run.
2. Driver uses the choke to compensate for wall wetting of the fuel on the cold cylinder.
3. Driver starts engine
4. Driver re-estimates the engine temperature and attempts a re-start.
5. Driver sets off on the journey as required and re-estimates the engine temperature based upon time since start, road speed and driving style, and re-adjusts the choke.

Engine Management System

1. ECM receives an input from the coolant temperature sensor giving an accurate measurement of engine temperature.
2. ECM uses a look up table to determine the amount of starting fuel required.
3. Driver cranks engine
4. Engine starts
5. ECM receives a new input from the coolant sensor every 30ms and automatically adjusts the fuelling as the engine warms up.

It should be noted that the driver of the carburettor vehicle will usually be able to achieve a first time start after a learning period, during which time more careful changes to the start fuelling can be made. This learning is another feature of an engine management system as it adapts for engine to engine variation and engine ageing.

1. Engine Control Module

The Engine Control Module (ECM) manages all primary engine functions including fuelling, ignition and an electronic throttle body for air control. It also controls secondary systems such as knock sensing (see later), variable valve timing (see later), engine cooling fans, high speed serial communications with other control modules (CAN) and On Board Diagnostics (OBD). Hardwired links are also provided to other control modules such as the body processor for cranking information, the security system for engine immobilisation as part of the whole vehicle security package and the air conditioning control module for idle speed control and as an aid to air conditioning operation. Figure 5 gives an indication of the overall software split within the ECM, this clearly indicates the level of control required for all features but particularly diagnostics.

The ECM consists of two 16 bit Motorola 68HC16 microprocessors each with a memory capacity of 96kB operating with a clock speed of 16MHz. A back up IC communicates with the main processor and can be used to run the engine in a limp home mode in the event of the main processor failing. A power module IC is used as part of the motor drive circuitry for the electronic throttle. High speed communications are processed using a discrete physical layer CAN I/O. A PCB mounted atmospheric pressure sensor is used for fuelling and diagnostic adaptions. The ECM performs signal processing on a variety of inputs, both digital and analogue and contains numerous drivers for the actuators that it controls. The ECM also contains EEPROM memory for non volatile storage (See Figure 6). The ECM is able to perform high speed calculations, high speed analogue to digital conversion and has the capability to handle multiple interrupts.

The first processor controls fuelling, ignition and some diagnostics whilst the second processor controls the throttle and additional diagnostics. Numerous inputs are split between the processors which continually communicate critical information between them to ensure system robustness.

The design requirements for all EMS components and the ECM ensure that correct operation can be maintained in all markets and that component failures do not occur when environmental extremes are encountered. Consequently the inputs to the ECM have been designed to withstand adverse voltages up to 30V yet still operate at voltages as low as 6.5V. Input currents from μA to A are also coped with and each input is monitored to ensure the correct signal occurs during normal operation. The quiescent drain of < 1mA for the system helps ensure that the vehicle meets its overall stand time performance.

The ECM has been designed to operate at ambient temperatures of -30 °C to 85 °C and survive temperatures of -40°C to 100°C. High vibration levels are also withstood and the system is able to survive all electro magnetic compatibility (EMC) immunity tests with field strengths exceeding $75Vm^{-1}$ and pass the radiated emissions tests to the legislative and Jaguar standards within the frequency band 1MHz - 1GHz.

Figure 5: Software Split Within the ECM

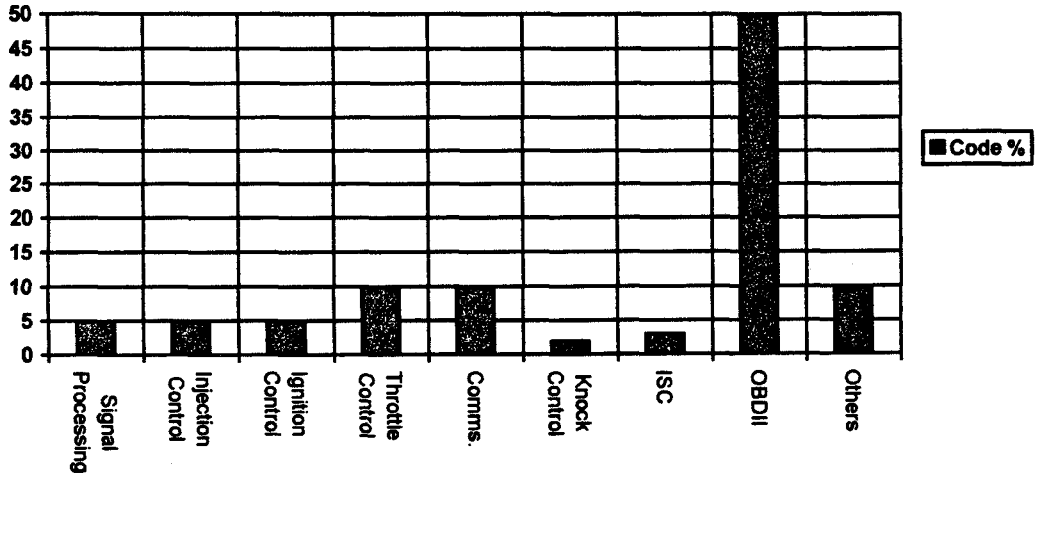
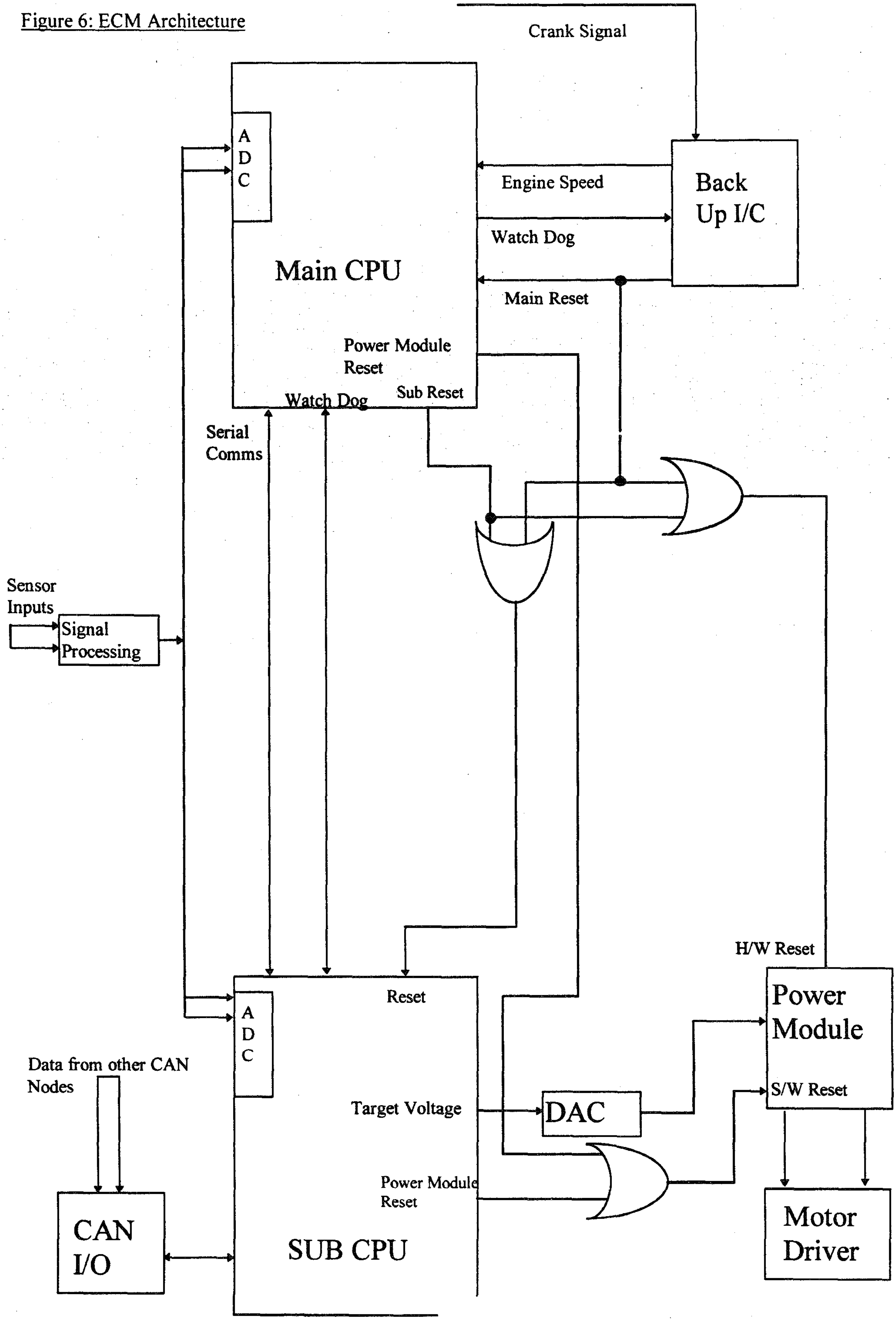


Figure 6: ECM Architecture



2. Throttle Control

The electronic throttle is one of the major innovations of the AJV8 Engine. As on conventional engines it controls the air required for normal engine operating conditions. The AJV8 throttle also automatically governs the air requirement for idle speed control, traction control (reduction of engine power to prevent wheel slip), power limitation (for either gearbox protection or vehicle speed limiting) and cruise control (to maintain the current set vehicle speed).

The overall system design of the electronic throttle includes a mechanical limiter and actuators. This allowed integration of traction control, cruise control, power/torque limitation and idle speed control whilst ensuring that power cannot exceed demand and giving excellent redundancy in the event of any failure.

The throttle has been designed to match or better the performance of current throttle air flow systems typically employing a 4 pole stepper motor. With this in mind the throttle response, resolution, absolute accuracy and air leakage have been designed and developed to meet both the customer and engine requirements.

As well as allowing integration of additional vehicle features the use of electronic throttle control benefits drivability, for example allowing torque converter lock up at lower vehicle speeds and improved tip in/out (dynamic throttle transients) response. Also a more robust starting performance has been achieved since the throttle can be controlled to a known position lower than and independent of the drivers demand.

The mechanical guard effectively leads the throttle blade and also ensures that in the instance of a system fault causing motor shut down the vehicle is still driveable in a mechanical mode as in a normal throttle system.

In normal use the electronically controlled throttle is transparent to the driver and comprises the following components (See Figure 7);

- An input shaft that receives driver inputs from the accelerator pedal via a conventional throttle cable.
- A mechanical guard to prevent the throttle valve position exceeding driver demand and to operate the throttle valve mechanically if the electronic system fails.
- A vacuum actuator to operate the mechanical guard in the cruise control mode of operation.
- A throttle blade to regulate air flow for all engine functions including idle speed control.
- A thermostatic air valve to control a bypass air flow around the throttle valve at very cold temperatures.
- A dc motor to operate the throttle blade via a reduction gear in response to inputs from the ECM.
- Three position sensors comprising
  - Driver Demand: Supplies the ECM with the position of the input shaft. It is a resistive sensor with sufficient outputs to allow system voting.
  - Mechanical Guard: Supplies the ECM with the position of the mechanical guard. It is combined with the driver demand sensors for system voting.
  - Throttle Position: A Hall effect sensor to prevent wear due to throttle dither. It contains integral temperature control circuitry to compensate for drift associated with this sensor type. It is used to determine the throttle valve position.
- Springs connected to the input shaft, the mechanical guard, the throttle valve and the drive gear of the dc motor.

As stated previously electronic throttle control is transparent to the driver. In the normal way the driver will press the accelerator pedal to a required position. The resultant movement via a standard bowden cable moves the input shaft and raises the mechanical guard. The snail cam rotation also rotates a resistive potentiometer which is connected electrically to the ECM. The ECM then drives the DC motor to the required position to achieve the throttle opening that is demanded by that pedal opening. A check is made of the correct throttle position using feedback from the hall effect throttle sensor. (Figure 8)

When cruise control is engaged the ECM calculates the required throttle valve opening and operates the vacuum system connected to the vacuum actuator. The vacuum actuator then turns the mechanical guard to a position that allows the required throttle opening. The inputs from their respective position sensors allow the ECM to monitor and adjust the mechanical guard and throttle blade to maintain the set speed. As the driver releases the accelerator pedal the input shaft disengages from the mechanical guard.

To prevent wheel slip as part of the traction and stability control mechanisms the ECM is able to reduce engine torque by retarding the ignition, inhibiting fuel injection or by closing the throttle. Fast response is provided by ignition retard followed by inhibiting fuel injection and closing the throttle which is capable of achieving a much greater reduction in engine torque if required.

The engine control module uses a voting system on the driver demand inputs to determine the actual driver demand required, therefore even under certain failure conditions normal vehicle operation can be maintained with only a driver warning given. Diagnostics take place to ensure system robustness, driver safety and to ensure that the driver and certification authorities are informed of a failure that will increase the vehicle emissions level.

Figure 7: Electronic Throttle Assembly

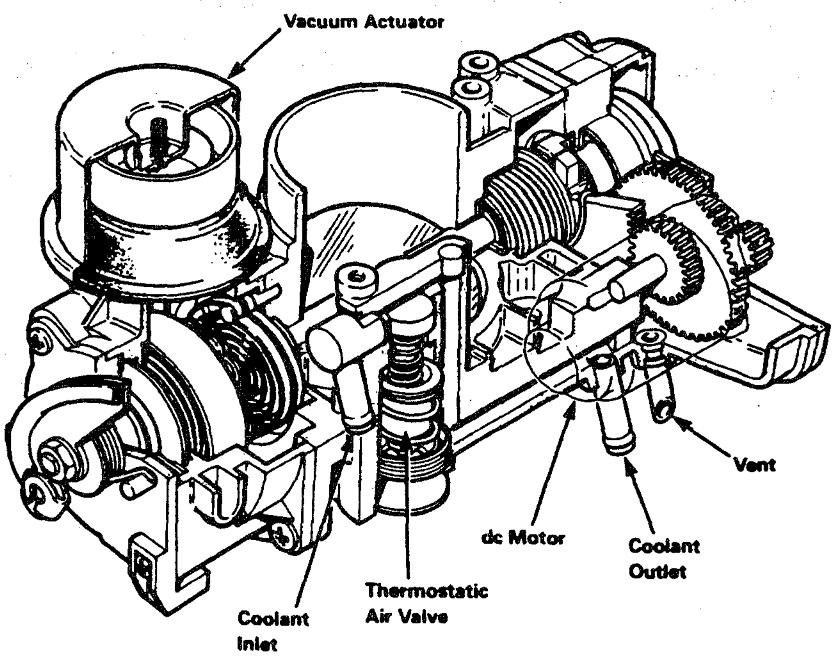
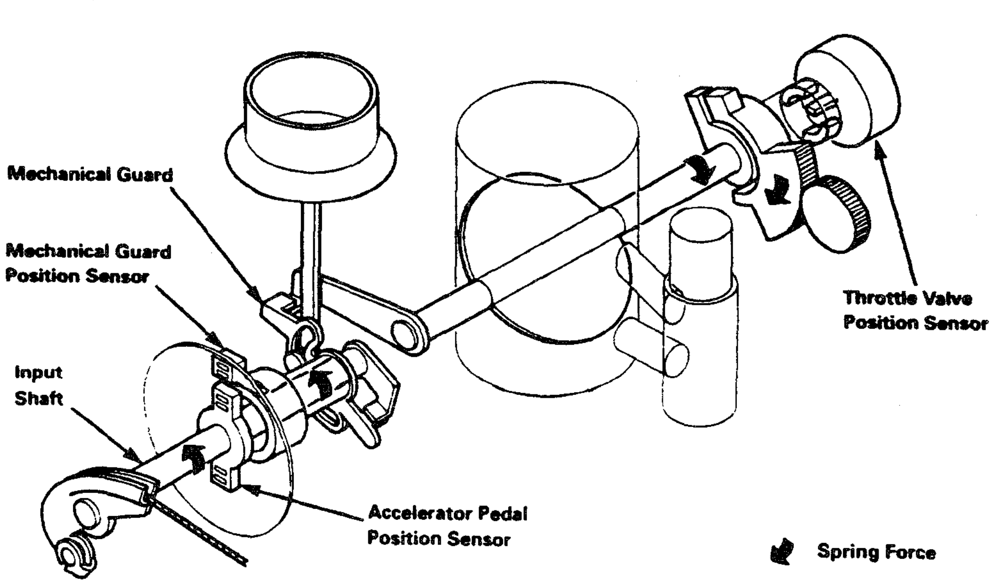


Figure 8: Simplified View of Electronic Throttle



3. Ignition Control

Correct timing is one of the primary requirements for accurate ignition and fuelling control. The ECM timing information comes from 2 sensors as follows:

Primary engine speed sensing is determined from a variable reluctance sensor mounted on the flywheel. The timing disc, sensor, mounting and air gap have all been designed such that accurate engine speed information is available at all engine speeds from 30rpm to over 7000 rpm.

The engine position is determined by a variable reluctance sensor mounted on the camshaft of B bank with a signal generated once every 2 engine revolutions.

The ECM varies the ignition timing to optimise power, emissions and driveability at all engine operating conditions. The ECM controls ignition timing and spark energy via 2 ignition amplifiers and 8 on-plug coils. The ECM triggers the ignition amplifiers which in turn control the flow of current in the coil primary circuit of the on plug coil. The high tension voltage from the coil is created when the primary current is switched off.

The ignition amplifiers have been designed with their own integral hardware diagnostics to enable the ECM to determine if a correct fire of the relevant coil has occurred. Should a failure be detected the ECM disables fuel injection to the affected cylinder preventing unburnt fuel passing through the engine and damaging the expensive exhaust catalyst system.

On plug ignition coils are used to deliver the spark energy to each spark plug. The use of on plug coils has numerous advantages for the electrical and mechanical design of the engine and vehicle.

- *Reduces electromagnetic interference since no open sparks occur*
- *No rotating components*
- *No high tension leads required*
- *Noise reduction*
- *Improves the packaging space available*

Compensations to the ignition timing are made when inputs from the temperature sensors, traction control, transmission controller, knock sensors, Exhaust Gas Recirculation (EGR) flow, fuel cut off (high engine speed with a closed throttle usually referred to as overrun), full load advance and the camshaft position (VVT) determine that this is required.

3.1 Variable Valve Timing

The variable valve timing system improves low and high speed engine performance, engine idle quality and exhaust emissions by altering the basic thermodynamic cycle of the engine. It is a two position system that operates on the intake camshafts only. There is 30° of crankshaft movement between the retarded and advanced positions. Engine oil pressure is used to operate the system to the advanced position under the control of the ECM via two valve timing solenoids (1 per bank), whilst return springs move the camshafts to the retarded position.

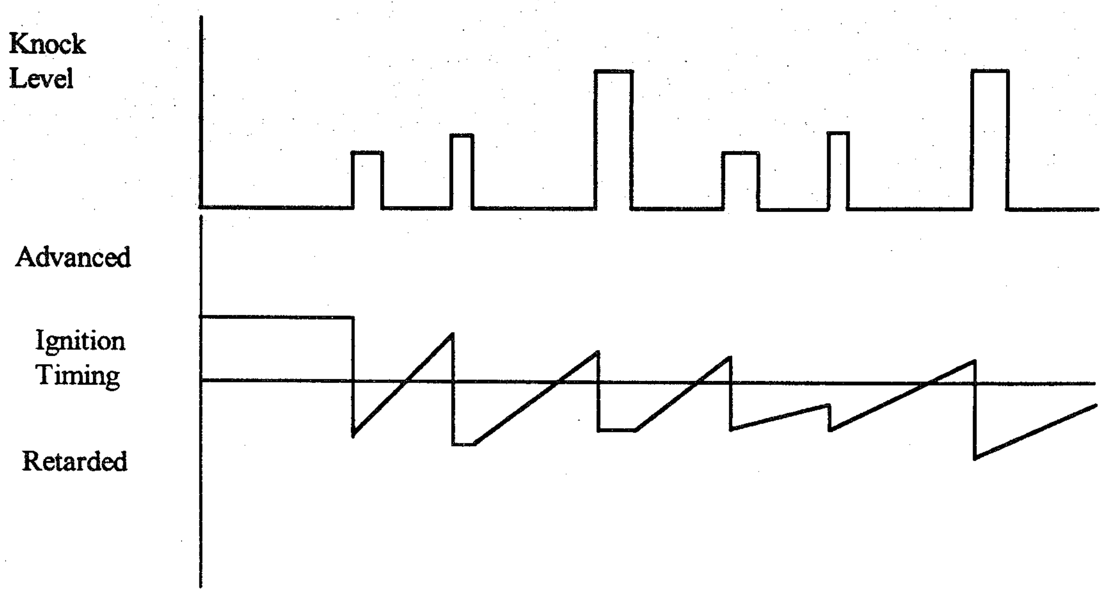
3.2 Transmission Interface

In order to reduce any shock associated with a gearshift the engine torque is momentarily reduced by retarding the ignition simultaneously with a gearshift. The request for torque reduction is communicated by the transmission control module via CAN.

3.3 Knock (Detonation) Control

Engine ignition is normally performed close to the detonation limit in order to improve fuel economy and increase power output. Knock sensing allows calibration of the ignition timing for normal operating conditions with the risk of detonation eliminated by the use of knock control. Two accelerometers (knock sensors) (1 per bank) mounted on the engine block are used to determine the onset of detonation by sensing engine vibrations. The sensors output signals to the ECM, which ascertains which cylinder has detonation present and retards the ignition timing on the affected cylinder to prevent this. The reference level (background noise) for the knock detection is calculated from the average value of sensor signal when detonation is not taking place.

Figure 9: The effect of knock detection on ignition timing



4. Fuelling Control

The ECM operates eight twin jet bottom feed fuel injectors to provide the engine with fuel. The amount of fuel required is determined from a base air fuel ratio map, based on inputs from the engine speed sensor and the hot wire mass air flow meter (The map is a look up table with the axis as described, individual points are referred to as sites). The base air fuel ratio is then adjusted for specific operating conditions. Additionally the ECM also controls the fuel pump via a relay.

The ECM varies the number and duration of the injector pulses per engine cycle to regulate the fuel flow. Feedback signals from oxygen sensors in the vehicles exhaust system enable the ECM to exercise closed loop control of the fuelling, except during full load enrichment when the injector pulse width is increased to maintain a stable exhaust system temperature.

Adaptive fuelling accommodates engine efficiency variations, system tolerances and engine ageing. Adaptions occur at several sites throughout the speed and load range.

Fuel flow through the injectors changes with voltage, so the ECM monitors their supply voltage and compensates for any variation from the normal.

5. Diagnostics

The increased complexity within the EMS required a more sophisticated diagnostic system with strategies to complement the overall design.

The diagnostic system within the ECM detects abnormalities in the sensors, actuators and vehicle harnesses. When a failure is detected the ECM automatically stores relevant system information to assist the technician in performing a repair on the vehicle. The ECM will also adopt alternative values and assume a 'limp home' condition. The decision on limp home values and strategies is particularly important since electrical failures usually result in a catastrophic failure where as mechanical failures lead to a degradation failure.

The design and development of the diagnostic strategies formed an integrated part of the overall EMS design and has reduced service and repair times to the benefit of both the customer and vehicle dealer.

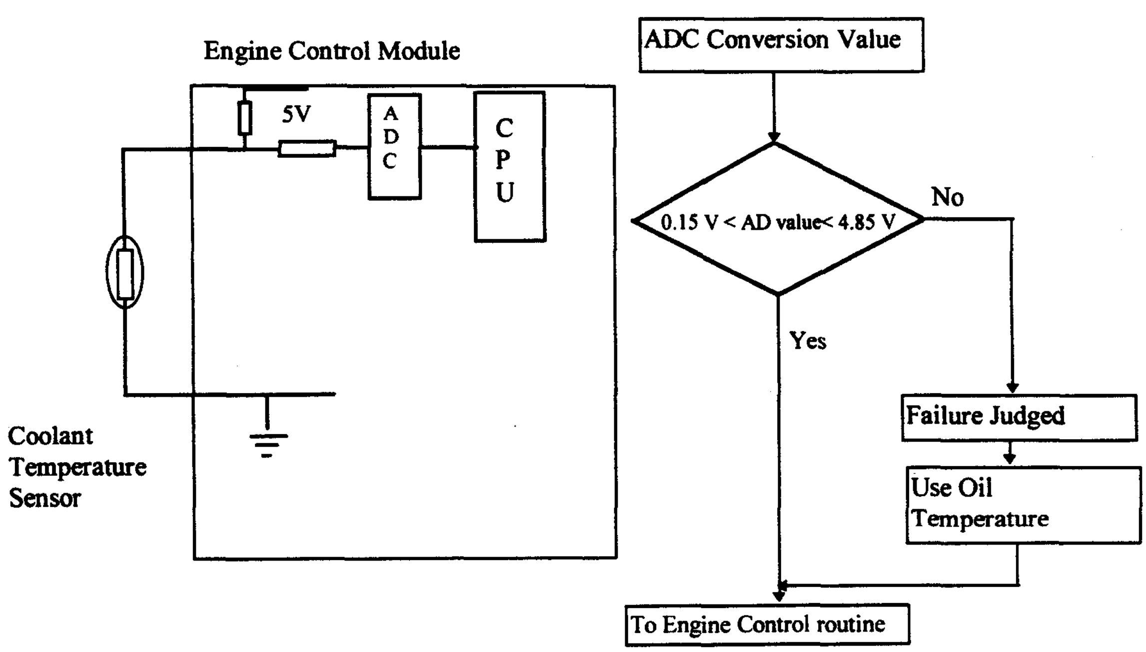
5.1 Diagnosis Method

The increased complexity in the EMS required the diagnostics to be designed to form an integrated part of the overall system design. Without on-board diagnostics it would be impossible for any technician to quickly and accurately diagnose and repair any but the most simple failures. Diagnostics and failure detection is possible by the ECM in around 150ms and on detecting a failure, accurate information is stored on the failure type together with freeze frame data (e.g. engine speed, engine load, coolant temperature, vehicle speed) at the time of the failure.

A number of diagnostic strategies can be applied to the EMS sensors and actuators. The decision on the type of failure diagnosis was made by evaluating the customer, vehicle and legislative requirements.

Sensor open and short circuit failure diagnosis is performed by analysing the inputs from the sensors and judging them against known correct values. The known correct value is determined through theoretical analysis and practical testing. Consideration is given to a number of factors, and these include ambient temperature, atmospheric pressure (and hence altitude), time after start and air flows. A failure is judged when the signal from the sensor is outside the range that is conceivable compared against expected engine and vehicle operating conditions. See Figure 10

Figure 10: Sensor circuit failure detection



Additional sensor faults also diagnosed include 'stuck at' faults where for example the air temperature sensor resistance could stick giving a constant temperature reading of 100°C. These type of faults would not be diagnosed using the above method since the output voltage would fall inside the normal voltage range.

In determining the method of detecting this type of failure the following techniques were considered. The use of additional sensors would allow accurate determination of a failure. However, three sensors would be required for a rationality check and this would mean additional costs for sensors, ECM hardware inputs and harnessing. The vehicle package would also be compromised. A better solution was engineered whereby the sensor to be checked was referenced against a model with inputs from other EMS sensors. For example to detect a stuck inlet air temperature sensor;

1. Is the air temperature = 100 °C (Still within range)
2. Is the coolant temperature < 40°C
3. Is the engine speed > 2000 rpm
4. Is the vehicle speed > 50 kph

Since it is not possible for all four to be true then the appropriate failure judgement will be recorded.

In determining failures of this type experiments were conducted which examined the influence factors for the diagnostic. These factors were then adjusted either in software or by building special hardware to determine what the worse case result could be. These results were then used in software and hardware that ran in durability vehicles at the environmental extremes. Special monitoring equipment was added to these vehicles that recorded the diagnostic result when both pass and failure judgements were recorded. In this way it was possible to determine how much headroom was available between the pass and failure judgement and hence the risk to the programme for false detection. The results were analysed and changes made to either the diagnostic strategy or the vehicle hardware to increase the diagnostic headroom.

An actuator failure is diagnosed by adding a monitor circuit to the ECMs actuator circuit. See Figure 11. The control signal is checked against the comparator voltage, when a difference is encountered a failure judgement can be made, usually after a counter has exceeded a set time to prevent false detection (See Figure 12).

Figure 11: The addition of a monitor circuit for actuator failure diagnosis

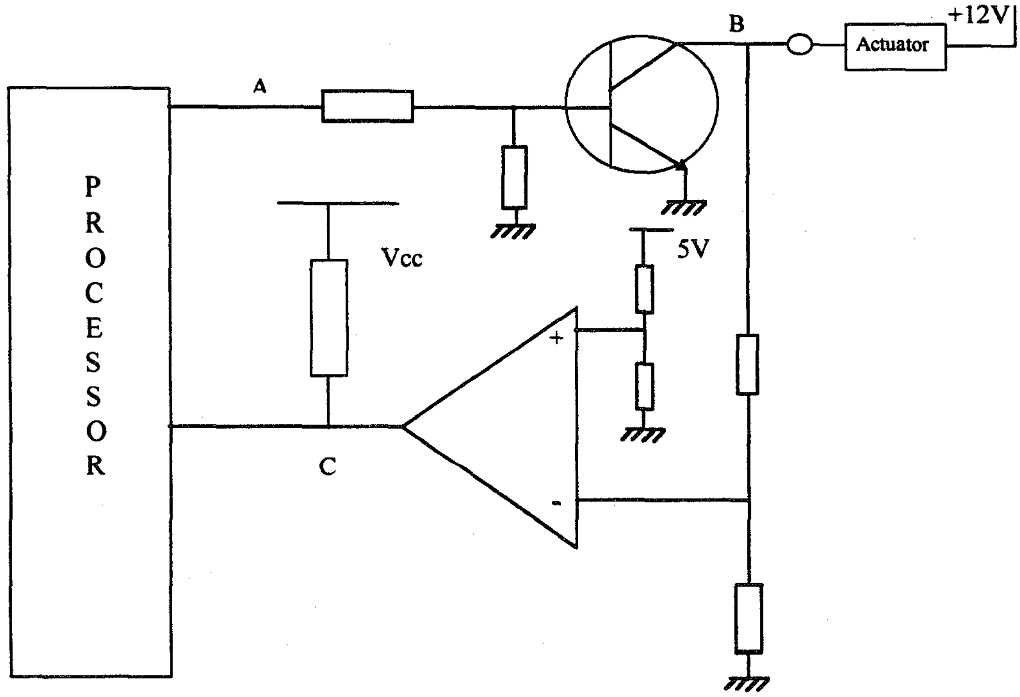
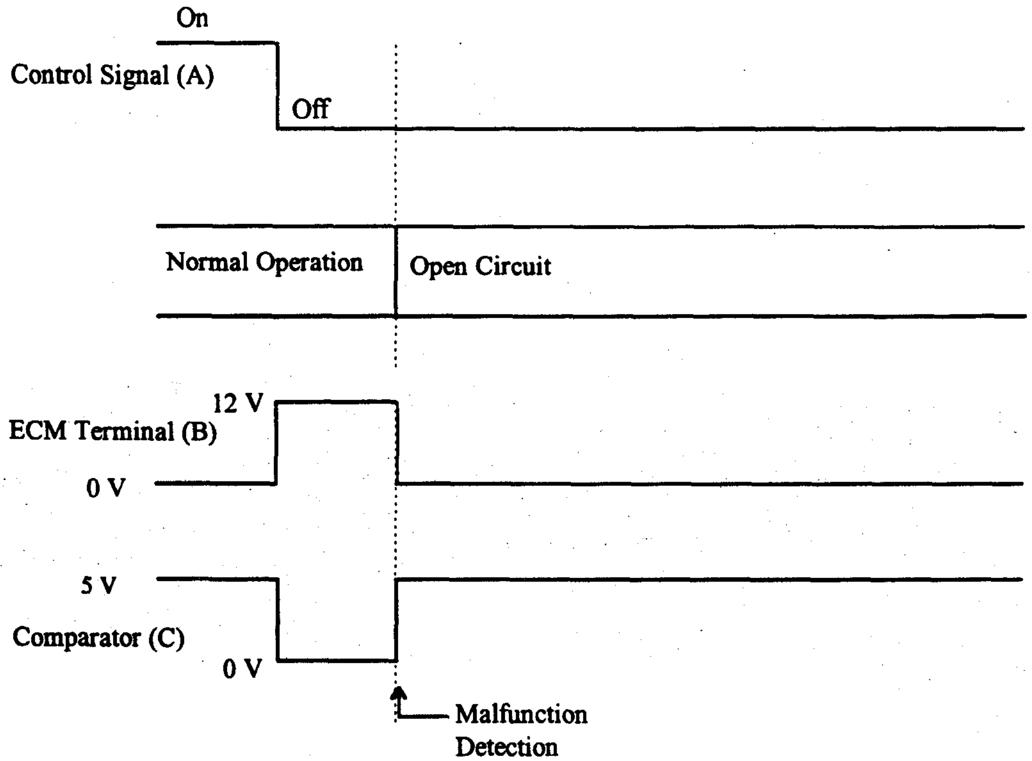


Figure 12: Timing chart for actuator failure diagnosis



Summary

High reliability is essential in modern vehicles and is now (and has been for some time) considered normal by customers. All vehicle components must be capable of correct performance in the harshest of environments but this is particularly true of the EMS given the catastrophic failures that could occur. With this in mind the overall design of the Engine Management System provides highly competitive performance, refinement and fuel economy whilst complying with the most stringent world-wide emission legislation requirements. This assures customer satisfaction and legislative compliance in all markets. The comprehensive diagnostic strategies guarantee ease of service, enhance production quality and prevent excess emissions. The design and use of electronic throttle control improves drivability and allows full system integration, yet gives full mechanical back up in the event of any failure. Communications with other nodes via CAN enable robust transmission of data between all control modules.

Acknowledgements

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