CHAPTER

Engine systems

6.1 Introduction

The main sections in this chapter that relate to an area of the vehicle start with an explanation of the particular system. The sections then conclude with appropriate diagnostic techniques and symptom charts. Extra tests and methods are explained where necessary.

6.2 Engine operation

6.2.1 Four-stroke cycle

Figure 6.1 shows a modern vehicle engine. Engines like this can seem very complex at f rst but keep in mind when carrying out diagnostic work that, with very few exceptions, all engines operate on the four-stroke principle. The complexity lies in the systems around the engine to make it operate to its

Figure 6.1 Ford Focus engine (Source: Ford Media)

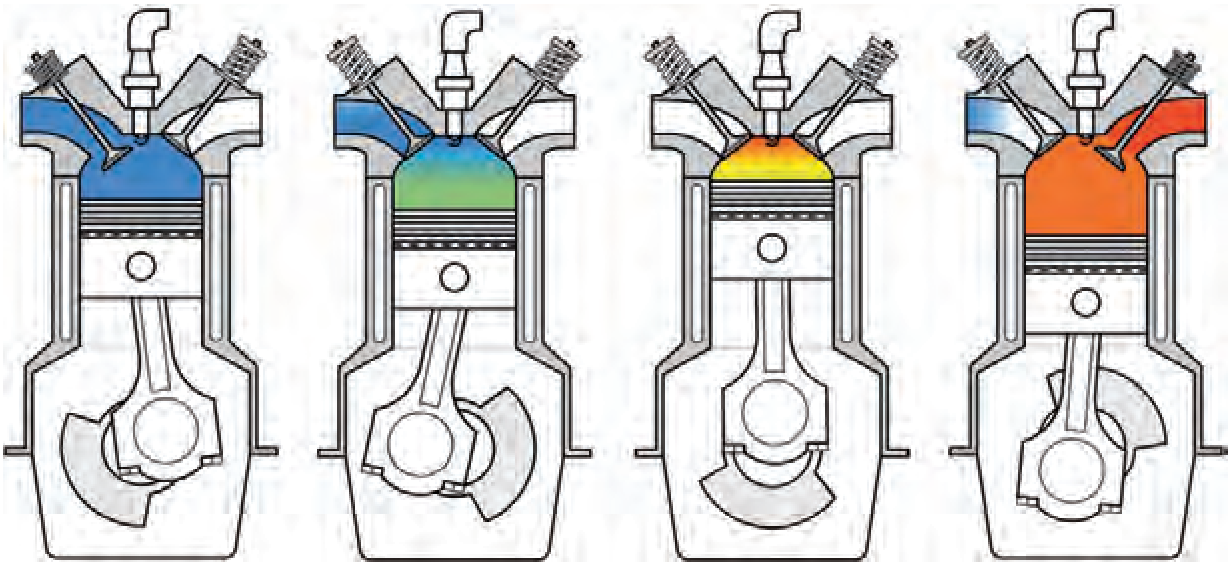


Figure 6.2 Four-stroke cycle: induction, compression, power and exhaust

Key fact

Stroke means the movement of a piston from top dead centre (TDC) to bottom dead centre (BDC) or the other way round.

maximum eff ciency or best performance. With this in mind then, back to basics: The engine components are combined to use the power of expanding gas to drive the engine.

When the term 'stroke' is used, it means the movement of a piston from top dead centre (TDC) to bottom dead centre (BDC) or the other way round. The following table explains the spark ignition (SI) and compression ignition (CI) four-stroke cycles – for revision purposes. Figure 6.2 shows the SI cycle.

Stroke	Spark ignition	Compression ignition
Induction	The fuel air mixture is forced into the cylinder through the open inlet valve because as the piston moves down, it makes a lower pressure. It is acceptable to say the mixture is drawn into the cylinder	Air is forced into the cylinder through the open inlet valve because as the piston moves down, it makes a lower pressure. It is acceptable to say the air is drawn into the cylinder
Compression	As the piston moves back up the cylinder, the fuel air mixture is compressed to about an eighth of its original volume because the inlet and exhaust valves are closed. This is a compression ratio of 8:1, which is typical for many normal engines	As the piston moves back up the cylinder, the fuel air mixture is compressed in some engines to about a sixteenth of its original volume because the inlet and exhaust valves are closed. This is a compression ratio of 16:1, which causes a large build-up of heat
Power	At a suitable time before TDC, a spark at the plug ignites the compressed mixture. The mixture now burns very quickly and the powerful expansion pushes the piston back down the cylinder. Both valves are closed	At a suitable time before TDC, a very high pressure atomised diesel fuel (at approximately 180 bar) is injected into the combustion chamber. The mixture burns very quickly and the powerful expansion pushes the piston back down the cylinder. The valves are closed
Exhaust	The final stroke occurs as the piston moves back up the cylinder and pushes the spent gases out of the now open exhaust valve	The final stroke occurs as the piston moves back up the cylinder and pushes the spent gases out of the now open exhaust valve

6.2.2 Cylinder layouts

Great improvements can be made to the performance and balance of an engine by using more than one cylinder. Once this is agreed, the actual layout of the cylinders must be considered. The layout can be one of three possibilities as follows:

- **In-line or straight –** The cylinders are in a straight line. They can be vertical, inclined or horizontal.
- **Vee –** The cylinders are in two rows at a set angle. The actual angle varies but is often 60° or 90°.
- **Opposed –** The cylinders are in two rows opposing each other and are usually horizontal.

By far the most common arrangement is the straight four, and this is used by all manufacturers in their standard family cars. Larger cars do, however, make use of the 'Vee' conf guration. The opposed layout although still used is less popular. Engine f ring order is important. This means the order in which the power strokes occur. It is important to check in the workshop manual or data book when working on a particular engine.

6.2.3 Camshaft drives

The engine drives the camshaft in one of three ways: gear drive, chain drive or by a drive belt. The last of these is now the most popular, as it tends to be simpler and quieter. Note in all cases that the cam is driven at half the engine speed. This is done by the ratio of teeth between the crank and cam cogs which is 1:2, for example 20 crank teeth and 40 cam teeth.

- **Camshaft drive gears –** Gears are not used very often on petrol engines but are used on larger diesel engines. They ensure a good positive drive from the crankshaft gear to the camshaft.
- **Camshaft chain drive –** Chain drive is still used but was even more popular a few years ago. The problems with it are that a way must be found to tension the chain and also provide lubrication.
- **Camshaft drive belt –** Camshaft drive belts have become very popular. The main reasons for this are that they are quieter, do not need lubrication and are less complicated. They do break now and then, but this is usually due to lack of servicing. Cam belts should be renewed at set intervals. Figure 6.3 shows an example of the data available relating to camshaft drive belt f tting. This is one of the many areas where data is essential for diagnostic checks.

Key fact

A camshaft is driven at half the speed of the crankshaft.

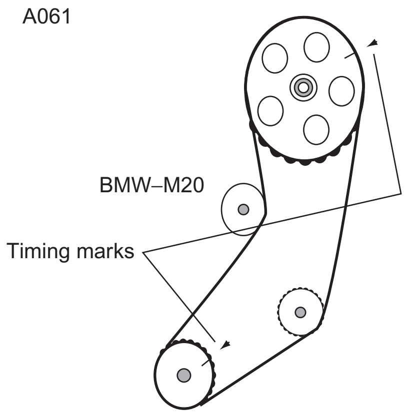
6.2.4 Valve mechanisms

A number of methods are used to operate the valves. Three common types are shown in Figure 6.4 and a basic explanation of each follows:

- Overhead valve with push rods and rockers – The method has been used for many years and although it is not used as much now, many vehicles still on the road are described as overhead valve (OHV). As the cam turns, it moves the follower, which in turn pushes the push rod. The push rod moves the rocker, which pivots on the rocker shaft and pushes the valve open. As the cam moves further, it allows the spring to close the valve.

BMW 5 Series 2.5 525i SE

Timing belt



Replacement intervals:
at 36 000 miles

Engine setting position:
TDC at No. 1 cylinder

Special tools:

Viscous coupling tool	11.5.040
Pulley retaining tool	11.5.030

Torque settings:

Crank pulley	23 Nm
Tensioner	23 Nm
Fan coupling	43 Nm

Special notes:

The fan coupling has left hand thread. Set timing for camshaft and crankshaft and check TDC mark on the flywheel. Check for rotor arm alignment to distributor casing. After fitting belt, rotate engine two full turns and recheck the timing marks.

Figure 6.3 Timing belt data

- Overhead cam with followers – Using an overhead cam (OHC) reduces the number of moving parts. In the system shown here, the lobe of the cam acts directly on the follower which pivots on its adjuster and pushes the valve open.
- Overhead cam, direct acting and automatic adjusters – Most new engines now use an OHC with automatic adjustment. This saves on repair and service time and keeps the cost to the customer lower. Systems vary between manufacturers, some use followers and some have the cam acting directly on to the valve. In each case, though, the adjustment is by oil pressure. A type of plunger, which has a chamber where oil can be pumped under pressure, operates the valve. This expands the plunger and takes up any unwanted clearance.

Valve clearance adjustment is very important. If it is too large, the valves will not open fully and will be noisy. If the clearance is too small, the valves will not close and no compression will be possible. When an engine is running, the valves become very hot and therefore expand. The exhaust valve clearance is usually larger than the inlet, because it gets hotter. Regular servicing is vital for

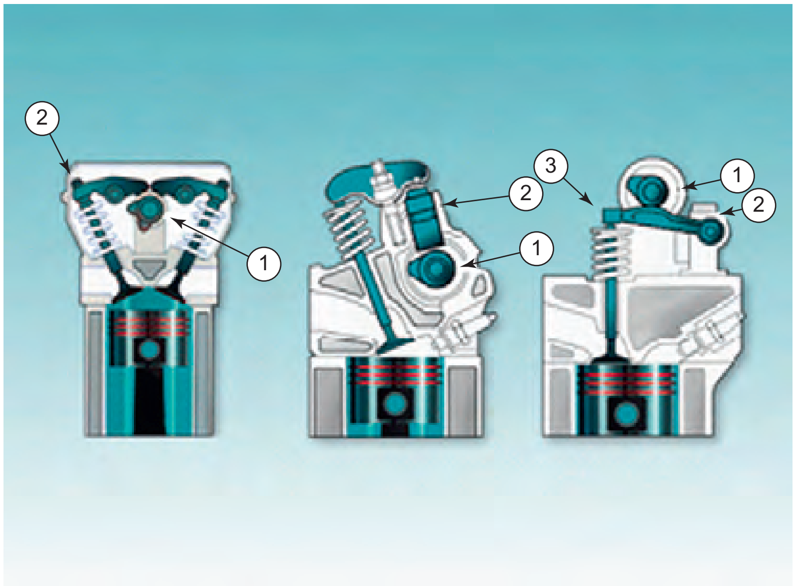


Figure 6.4 Valve operating mechanisms. Left: 1 – Cam; 2 – adjusting screw in direct acting rocker. Centre: 1 – Cam; 2 – hydraulic follower. Right: 1 – Cam; 2 – pivot and adjuster; 3 – finger follower

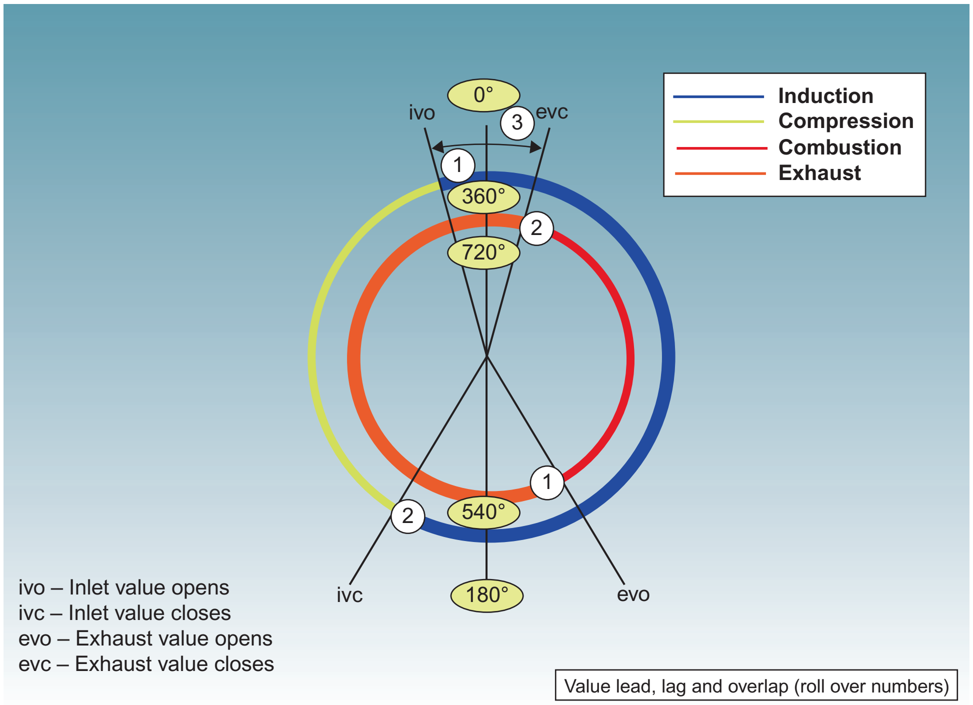


Figure 6.5 Valve timing diagrams (1 – lead; 2 – lag; 3 – overlap)

all components but, in particular, the valve operating mechanism needs a good supply of clean oil at all times.

6.2.5 Valve and ignition timing

Valve timing is important. The diagram in Figure 6.5 shows accurately the degrees of rotation of the crankshaft where the inlet and exhaust valves open and close during the four-stroke cycle. The actual position in the cycle of operation when valves open and close depends on many factors and will vary slightly with different designs of engine. Some cars now control valve timing by electronics. The diagram is marked to show what is meant by valve lead, lag and overlap. Ignition timing is marked on the diagram. Note how this changes as engine speed changes.

The valve timing diagram shows that the valves of a four-stroke engine open just before and close just after the particular stroke. Looking at the timing diagram, if you start at position IVO, the piston is nearly at the top of the exhaust stroke when the inlet valve opens (IVO). The piston reaches the top and then moves down on the intake stroke. Just after starting the compression stroke, the inlet valve closes (IVC). The piston continues upwards and, at a point several degrees before TDC, the spark occurs and starts the mixture burning.

Key fact

Maximum expansion is 'timed' to occur after TDC on the power stroke.

The maximum expansion is 'timed' to occur after TDC; therefore, the piston is pushed down on its power stroke. Before the end of this stroke, the exhaust valve opens (EVO). Most of the exhaust gases now leave because of their very high pressure. The piston pushes the rest of the spent gases out as it moves back up the cylinder. The exhaust valve closes (EVC) just after the end of this stroke and the inlet has already opened, ready to start the cycle once again.

The reason for the valves opening and closing like this is that it makes the engine more eff cient by giving more time for the mixture to enter and the spent gases to leave. The outgoing exhaust gases in fact help to draw in the fuel air mixture from the inlet. Overall, this makes the engine have a better 'volumetric eff ciency'.

6.3 Diagnostics – engines

6.3.1 Systematic testing example

If the reported fault is excessive use of engine oil, proceed as follows:

1. Question the customer to f nd out how much oil is being used.
2. Examine the vehicle for oil leaks and blue smoke from the exhaust.
3. For example, oil may be leaking from a gasket or seal – if no leaks are found, the engine may be burning the oil.
4. A compression test, if the results were acceptable, would indicate a leak to be the most likely fault. Clean down the engine and run for a while, the leak might show up.
5. For example, change the gasket or seals.
6. Run a thorough inspection of vehicle systems, particularly those associated with the engine. Double check that the fault has been rectif ed and that you have not caused any other problems.

Safety f rst

Note: You should always refer to the manufacturer's instructions appropriate to the equipment you are using.

6.3.2 Test equipment

Compression tester

With this device the spark plugs are removed and the tester screwed or held in to each spark plug hole in turn. The engine is cranked over by the starter and the gauge will read the compression or pressure of each cylinder.

Figure 6.6 Diagnostic gauges

Table 6.1 Tests and information required

Test carried out	Information required
Compression test	Expected readings for the particular engine under test. For example, the pressure reach for each cylinder may be expected to read 800 kPa ±15%
Cylinder leakage test	The percentage leak that is allowed for the tester you are using – some allow approximately 15% leakage as the limit

Cylinder leakage tester

A leakage tester uses compressed air to pressurise each cylinder in turn by a f tting to the spark plug hole. The cylinder under test is set to TDC compression. The percentage of air leaking out and where it is leaking from helps you determine the engine condition. For example, if air is leaking through the exhaust pipe, then the exhaust valves are not sealing. If air leaks into the cooling system, then a leak from the cylinder to the water jacket may be the problem (blown head gasket is possible). Figure 6.6 shows a selection of Snap-on diagnostic gauges – vacuum, compression and leakage.

6.3.3 Test results

Some of the information you may have to get from other sources such as data books or a workshop manual is listed in Table 6.1.

6.3.4 Engine fault diagnosis table 1

Symptom	Possible causes or faults	Suggested action
Oil consumption	Worn piston rings and/or cylinders Worn valve stems, guides or stem oil seals	Engine overhaul Replace valves (guides if possible) and oil seals
Oil on engine or floor	Leaking gaskets or seals Build-up of pressure in the crankcase	Replace appropriate gasket or seal Check engine breather system
Mechanical knocking noises	Worn engine bearings (big ends or mains for example) Incorrect valve clearances or defective automatic adjuster Piston slap on side of cylinder	Replace bearings or overhaul engine, good idea to also check the oil pressure Adjust clearances to correct settings or replace defective adjuster Engine overhaul required now or quite soon
Vibration	Engine mountings loose or worn Misfiring	Secure or renew Check engine ancillary systems such as fuel and ignition

6.3.5 Engine fault diagnosis table 2

Please note that this section covers related engine systems as well as the engine itself.

Symptom	Possible cause
Engine does not rotate when trying to start	Battery connection loose or corroded Battery discharged or faulty Broken, loose or disconnected wiring in the starter circuit Defective starter switch or automatic gearbox inhibitor switch Starter pinion or flywheel ring gear loose Earth strap broken, loose or corroded
Engine rotates but does not start	No fuel in the tank! Discharged battery (slow rotation) Battery terminals loose or corroded Air filter dirty or blocked Low cylinder compressions Broken timing belt Damp ignition components Fuel system fault Spark plugs worn to excess Ignition system open circuit
Difficult to start when cold	Discharged battery (slow rotation) Battery terminals loose or corroded Air filter dirty or blocked Low cylinder compressions Fuel system fault Spark plugs worn to excess Enrichment device not working (choke or injection circuit)
Difficult to start when hot	Discharged battery (slow rotation) Battery terminals loose or corroded Air filter dirty or blocked Low cylinder compressions Fuel system fault

(Continued)

Symptom	Possible cause
Starter noisy	Starter pinion or flywheel ring gear loose Starter mounting bolts loose Starter worn (bearings, etc.) Discharged battery (starter may jump in and out)
Starter turns engine slowly	Discharged battery (slow rotation) Battery terminals loose or corroded Earth strap or starter supply loose or disconnected Internal starter fault
Engine starts but then stops immediately	Ignition wiring connection intermittent Fuel system contamination Fuel pump or circuit fault (relay) Intake system air leak Ballast resistor open circuit (older cars)
Erratic idle	Air filter blocked Incorrect plug gaps Inlet system air leak Incorrect CO setting Uneven or low cylinder compressions (maybe valves) Fuel injector fault Incorrect ignition timing Incorrect valve timing
Misfire at idle speed	Ignition coil or distributor cap tracking Poor cylinder compressions Engine breather blocked Inlet system air leak Faulty plugs
Misfire through all speeds	Fuel filter blocked Fuel pump delivery low Fuel tank ventilation system blocked Poor cylinder compressions Incorrect plugs or plug gaps HT leads breaking down
Engine stalls	Idle speed incorrect CO setting incorrect Fuel filter blocked Air filter blocked Intake air leak Idle control system not working
Lack of power	Fuel filter blocked Air filter blocked Ignition timing incorrect Low fuel pump delivery Uneven or low cylinder compressions (maybe valves) Fuel injectors blocked Brakes binding or clutch slipping
Backfires	Incorrect ignition timing Incorrect valve timing (cam belt not fitted correctly) Fuel system fault (airflow sensor on some cars)

(Continued)

Symptom	Possible cause
Oil pressure gauge low or warning light on	Low engine oil level Faulty sensor or switch Worn engine oil pump and/or engine bearings Engine overheating Oil pick-up filter blocked Pressure relief valve not working
Runs on when switched off	Ignition timing incorrect Idle speed too high Anti-run on device not working Carbon build-up in engine Engine overheating
Pinking or knocking under load	Ignition timing incorrect Ignition system fault Carbon build-up in engine Knock sensor not working
Sucking or whistling noises	Leaking exhaust manifold gasket Leaking inlet manifold gasket Cylinder head gasket Inlet air leak Water pump or alternator bearing
Rattling or tapping	Incorrect valve clearances Worn valve gear or camshaft Loose component
Thumping or knocking noises	Worn main bearings (deep knocking/rumbling noise) Worn big-end bearings (heavy knocking noise under load) Piston slap (worse when cold) Loose component
Rumbling noises	Bearings on ancillary component

6.4 Fuel system

Author's Note: Even though carburettor fuel systems are now very rare, they are still used on some specialist vehicles. For this reason, and because it serves as a good introduction to fuel systems, I decided to include this section.

6.4.1 Introduction

Key fact

A fuel system should produce the mixture at just the right ratio to run the engine under all operating conditions.

All vehicle fuel systems consist of the carburettor or fuel injectors, the fuel tank, the fuel pump and the fuel filter, together with connecting pipes. An engine works by the massive expansion of an ignited fuel air mixture acting on a piston. The job of the fuel system is to produce this mixture at just the right ratio to run the engine under all operating conditions. There are three main ways in which this is achieved:

- Petrol is mixed with air in a carburettor.
- Petrol is injected into the manifold, throttle body or cylinder to mix with the air.
- Diesel is injected under very high pressure directly into the air already in the engine combustion chamber.

This section examines only the carburettor systems; diesel and injection come under engine management later.

Figure 6.7 Single-choke and twin-choke carburettors

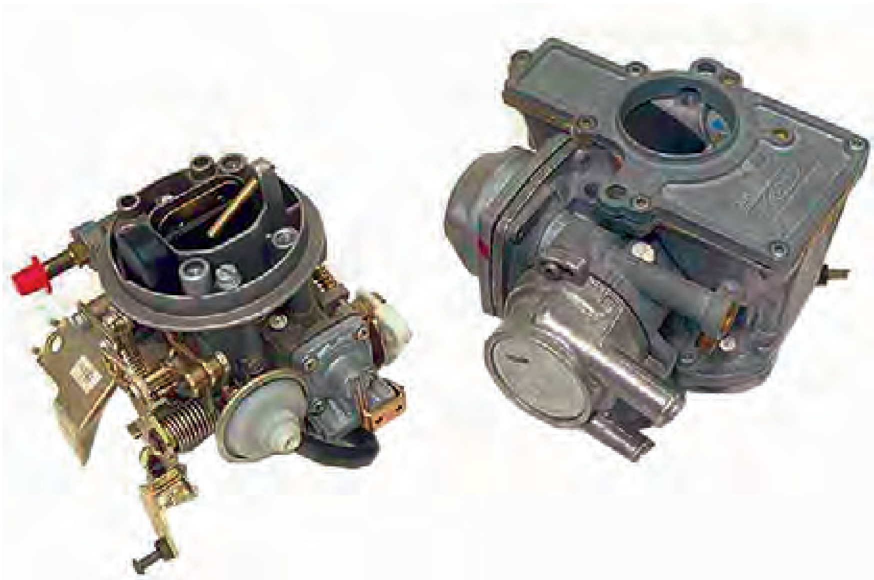


Figure 6.8 Fixed-choke and variable-choke carburettors

6.4.2 Carburation

The carburettor was the traditional method of mixing petrol with air as it enters the engine. However, a simple carburettor is only capable of providing a correct air and fuel mixture ratio within a very small engine speed range. For road vehicles, a wide engine speed range and a wide engine load is required. In order to respond to the speed and load variations, complex carburettors are used (Figure 6.7).

There are two basic carburettor designs: the f xed venturi and the variable venturi types. The term ‘choke’ is often used to describe the venturi and this gives the alternative carburettor def nitions of f xed choke and variable choke types. The usual meaning of the term ‘choke’ is to describe the engine cold start device f tted to the carburettor (Figure 6.8).

The function of the carburettor is to meter a quantity of petrol into the air stream entering the engine cylinders. As the pistons move down in the cylinders on the induction stroke, the pressure in the space above the cylinders falls. On naturally

Key fact

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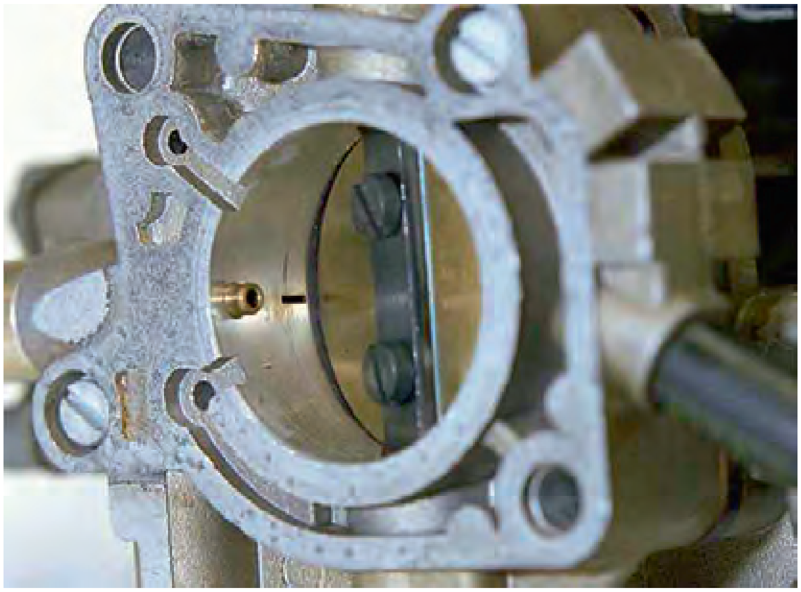


Figure 6.9 Throttle butterfly

aspirated engines, that is, those that are not f tted with pressure chargers, atmospheric pressure provides the force for the airf ow into the cylinders.

The greater the difference in pressure, the greater will be the volume of air that enters the engine and the speed of the airf ow through the carburettor and inlet manifold. A valve to meter the airf ow is f tted at the base of the carburettor just in front of the inlet manifold. This valve is called the throttle and it consists of a round plate on a spindle. The spindle has a lever attached to one end and this is connected directly to the throttle pedal with a cable or rods. The throttle restricts the airf ow in all positions except when wide open and this gives a range of variable pressures in the carburettor and the inlet manifold (Figure 6.9).

The basic carburettor consists of the venturi, through which the air f ows, and the f oat chamber which holds a supply of petrol at a constant level in relation to the supply beak in the venturi. The level of petrol in the f oat chamber is maintained by a needle valve that is lifted onto its seat by the f oat so that it stops the f ow when the chamber is full. As petrol is used the level drops, the needle valve opens and the f ow of petrol into the chamber resumes. In this way, a constant petrol level is maintained. The f oat level should be checked and adjusted if necessary, if problems occur or if the carburettor is stripped for cleaning (Figure 6.10).

The main jet in the fuel feed to the venturi forms a restriction in the petrol f ow and by virtue of its size acts as a metering device. The venturi is a tube with an inward curving restriction. Airf ow through the venturi speeds up as it passes through the restriction. The effect of this is to reduce the air pressure at that point. Inside the f oat chamber, atmospheric pressure is applied to the top of the petrol held there. A vent in the top of the f oat chamber allows a free passage of air and atmospheric pressure (Figure 6.11).

A pressure differential exists at each end of the fuel supply tube between the f oat chamber and the venturi supply beak, when there is suff cient airf ow to create a vacuum in the venturi. It is this pressure differential that is used to lift petrol up to the beak. From here, it passes into the air stream through the venturi and into the engine cylinders.

Although there is an increase in fuel delivery with an increase in airf ow, these do not match suff ciently to maintain the correct air and fuel ratio over the full

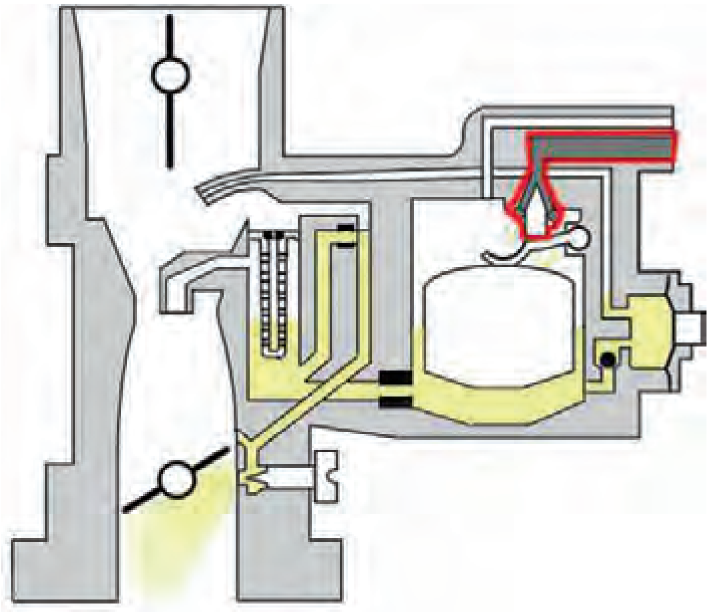


Figure 6.10 Fuel level is controlled by float and needle valve

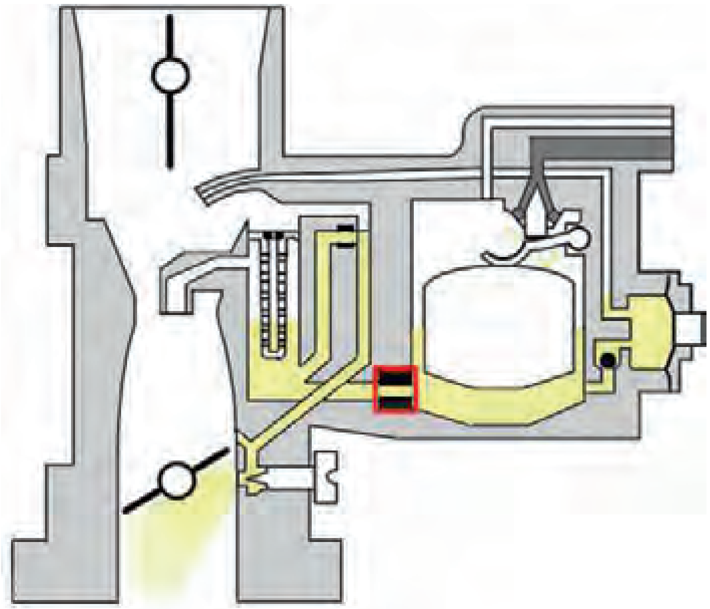


Figure 6.11 Main jet in the fuel feed to the venturi

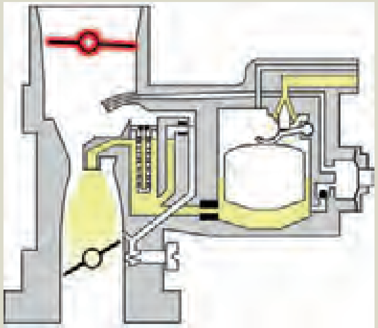
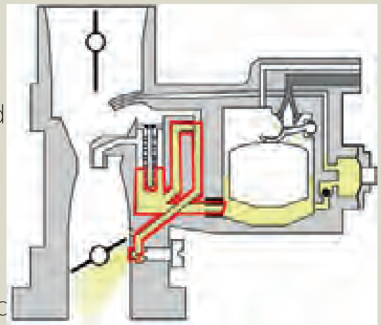
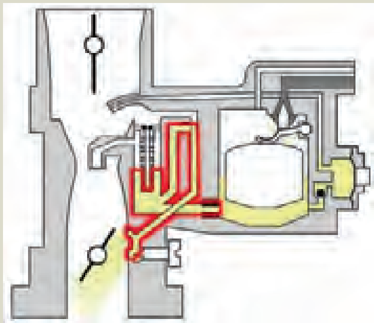
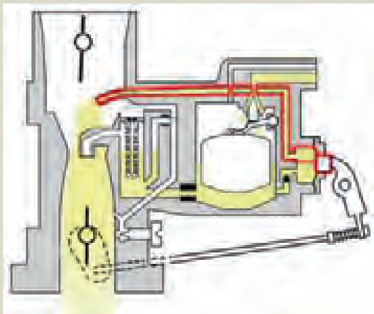
operating range. Other devices are needed to adjust the metering of petrol to the correct ratios. These are explained later in this section. The venturi can be positioned vertically with the airf ow being downward or upward or it can be positioned horizontally. This gives the expressions downdraft, updraft and sidedraft for descriptions of carburettors.

There are six clearly identif able engine and vehicle use conditions, known as the stages of carburation. These are outlined in Table 6.2.

Key fact

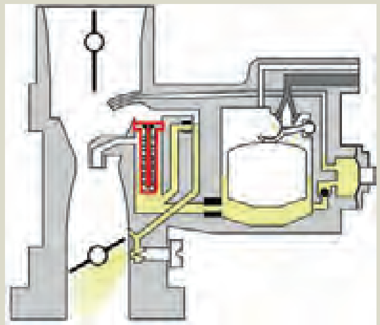
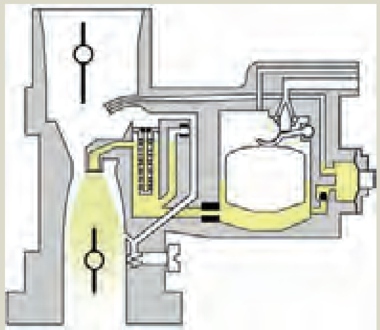
There are six clearly identifiable engine and vehicle use conditions, known as the stages of carburation.

Table 6.2 Stages of carburetion

Stage	Description	Diagram
Cold starting	Cold-start and warm-up conditions require a rich mixture. This is to keep the engine running smoothly and allow a smooth acceleration response. The mixture ratio for starting a very cold engine can be as low as 4:1. This ratio increases as the engine temperature increases, so that by the time the engine is at normal operating temperature, a correct ratio can be used. Cold-start enrichment devices on fixed venturi carburettors use a choke plate at the top of the venturi. This lifts engine vacuum higher into the carburettor. A manual choke plate is a flap fitted to an offset spindle, which is rotated to the 'on' position by a spring when the choke is applied. The choke is held in the partial, and 'off' positions, by a cam connected to the choke cable. There is usually a linkage between the choke plate lever and the throttle, to increase the engine speed. This increase in speed is called fast idle	 **Figure 6.12** Choke operation
Idle	On this carburettor, the devices for engine idle or tick over can be seen. The airflow through the venturi restriction is insufficient at idle speeds to give the pressure differential requirement for petrol flow into the venturi at the supply beak. The idle device is required to supply the low quantity of fuel needed at engine idle speeds. The vacuum in the inlet manifold is high when the throttle plate is closed. This vacuum is used in the idle device to create a flow of petrol and air through jets and drillings in the carburettor body. The petrol and air mixture enters the air intake through the idle port just below the throttle plate. The size of the pilot petrol jet and adjustment of the airflow provides a suitable air to fuel ratio for engine idle operation	 **Figure 6.13** Idle circuit
Progression	Progression is used to describe the increase in engine speed from idle, up to the point where the venturi and main jet come into operation. At idle speeds, the airflow through the venturi is not enough to provide a suitable pressure differential. Normal venturi mixing of petrol in the air stream flowing into the engine is therefore, not possible. Additional drillings in the lower part of the venturi, just above the throttle plate, connect to the float chamber. This allows an extra fuel supply during this phase. There are some variations in the number and routing of these drillings, but they all provide for a smooth response to initial acceleration from idle	 **Figure 6.14** Progression air and fuel paths
Acceleration	If rapid acceleration is demanded, the vacuum in the venturi is lost for an instant when the throttle is opened quickly. The petrol flow through the supply beak from the float chamber cuts off and without a supplementary supply; a 'flat spot' would be experienced. To prevent flat spots on acceleration, an accelerator pump and petrol discharge nozzle are fitted. The pump consists of a piston or diaphragm, a one-way valve, and drillings for a petrol supply from the float chamber. The pump is connected by a rod or cam linkage to the throttle plate lever. This causes a pulse of petrol to be sprayed into the venturi when rapid opening of the throttle is made	 **Figure 6.15** Accelerator pump and jet

(*Continued*)

Table 6.2 (Continued)

Stage	Description	Diagram
Cruising	The cruising speed range is wide and covers most operating conditions from light cruising up to a position just below full throttle. Petrol is drawn from the float chamber into the air stream passing into the engine. The supply beak design and position gives good atomization and distribution of the fuel in the air flow. The air fuel ratio in a simple venturi becomes richer with an increase in engine speed. In order to maintain the correct ratio mixture correction devices are used. It is also desirable for the engine to run on a lean mixture when the vehicle is cruising	 **Figure 6.16** Emulsion tube in use at cruise
Full load	Carburettors were designed to meet full throttle conditions without additional devices being fitted. However, these designs were unable to meet tougher environmental regulations, which required accurate control of exhaust emissions	 **Figure 6.17** Emulsion tube and 'beak' at full load

The development of twin-choke progressive carburettors was a way by which designers tackled the problems of maintaining correct mixture strengths, over the full range of engine operating conditions. The primary venturi works at the low throttle positions and a secondary venturi is added at the higher throttle positions. Electronic control using a temperature sensor and then a stepper motor to operate the choke has also been used. However, carburettors have had their chance, so fuel injection it is from now on!

6.5 Diagnostics – fuel system

6.5.1 Systematic testing example

If the reported fault is excessive fuel consumption, proceed as follows:

1. Check that the consumption is excessive for the particular vehicle. Test it yourself if necessary.
2. Are there any other problems with the vehicle, misfiring, for example, or difficult starting?
3. For example, if the vehicle is misfiring as well, this may indicate that an ignition fault is the cause of the problem.
4. Remove and examine spark plugs, check HT lead resistance and ignition timing. Check CO emissions.
5. Renew plugs and set fuel mixture.
6. Road-test the vehicle for correct engine operation.

Safety first

Note: You should always refer to the manufacturer's instructions appropriate to the equipment you are using.

6.5.2 Test equipment

Exhaust gas analyser

This is a sophisticated piece of test equipment used to measure the component gases of the vehicle's exhaust. The most common requirement is the measuring of carbon monoxide (CO). A sample probe is placed in the exhaust tail pipe or a special position before the catalytic converter (if fitted), and the machine reads out the percentage of certain gases produced. A digital readout is most common. The fuel mixture can then be adjusted until the required readings are obtained.

Fuel pressure gauge

The output pressure of the fuel pump can be tested to ensure adequate delivery. The device is a simple pressure gauge but note the added precautions necessary when dealing with petrol (Figure 6.18).

6.5.3 Test results

Some of the information you may have to get from other sources such as data books or a workshop manual is listed in Table 6.3.

Figure 6.18 Exhaust gas analyser

Table 6.3 Tests and information required

Test carried out	Information required
Exhaust gas analysis	CO setting. Most modern vehicles will have settings of approximately 1% or less. If a 'cat' is fitted then the readings will be even lower when measured at the tail pipe
Fuel pressure	The expected pressure readings will vary depending on the type of fuel system. Fuel injection pressure will be approximately 2.5 bar, whereas fuel pressure for a carburettor will be approximately 0.3 bar
Fuel delivery	How much fuel the pump should move in a set time will again vary with the type of fuel system. One litre in 30 seconds is typical for some injection fuel pumps

6.5.4 Fuel fault diagnosis table 1

Symptom	Possible faults	Suggested action
No fuel at carburettor or injection fuel rail	Empty tank! Blocked filter or line Defective fuel pump No electrical supply to pump	Fill it! Replace filter, renew/repair line Renew/check it is being driven Check fuses/trace fault
Engine will not or is difficult to start	Choke or enrichment device not working	Check linkages or automatic actuator
Engine stalls or will not idle smoothly	Idle speed incorrectly set Mixture setting wrong Ignition problem	Look up correct settings and adjust Look up correct settings and adjust Check ignition system
Poor acceleration	Blockage in carburettor accelerator pump Partially blocked filter Injection electrical fault	Strip down and clean out or try a carburettor cleaner first Renew Refer to specialist information
Excessive fuel consumption	Incorrect mixture settings Driving technique!	Look up correct settings and adjust Explain to the customer – but be diplomatic!
Black smoke from exhaust	Excessively rich mixture Flooding	Look up correct settings and adjust Check and adjust carburettor float settings and operation

6.5.5 Fuel fault diagnosis table 2

Symptom	Possible cause
Excessive consumption	Blocked air filter Incorrect CO adjustment Fuel injectors leaking Ignition timing incorrect Temperature sensor fault Load sensor fault Low tyre pressures Driving style!
Fuel leakage	Damaged pipes or unions Fuel tank damaged Tank breathers blocked
Fuel smell	Fuel leak Breather incorrectly fitted Fuel cap loose Engine flooding
Incorrect emissions	Incorrect adjustments Fuel system fault Air leak into inlet Blocked fuel filter Blocked air filter Ignition system fault

6.6 Introduction to engine management

Key fact

Engine management is a general term that describes the control of engine operation.

Engine management is a general term that describes the control of engine operation. This can range from a simple carburettor to control or manage the fuel, with an ignition distributor with contact breakers to control the ignition to a very sophisticated electronic control system. The fundamental tasks of an engine management system are to manage the ignition and fuelling, as well as other aspects, and to ref ne the basic control of an engine.

Many of the procedures and explanations in this chapter are generic. In other words, the ignition system explained in the following sections may be the same as the system used by a combined ignition and fuel control system.

6.7 Ignition

6.7.1 Basics

The purpose of the ignition system is to supply a spark inside the cylinder, near the end of the compression stroke, to ignite the compressed charge of air fuel vapour. For a spark to jump across an airgap of 0.6 mm under normal atmospheric conditions (1 bar), a voltage of 2–3 kV is required. For a spark to jump across a similar gap in an engine cylinder having a compression ratio of 8:1, a voltage of approximately 8 kV is required. For higher compression ratios and weaker mixtures, a voltage up to 20 kV may be necessary. The ignition system has to transform the normal battery voltage of 12 V to approximately 8–20 kV and, in addition, has to deliver this high voltage to the right cylinder, at the right time. Some ignition systems will supply up to 40 kV to the spark plugs.

Key fact

The fundamental operation of most ignition systems is vey similar; one winding of a coil is switched on and off causing a high voltage to be induced in a second winding.

Conventional ignition is the forerunner of the more advanced systems controlled by electronics. However, the fundamental operation of most ignition systems is very similar; one winding of a coil is switched on and off causing a high voltage to be induced in a second winding. A coil ignition system is composed of various components and subassemblies; the actual design and construction of these depend mainly on the engine with which the system is to be used.

6.7.2 Advance angle (timing)

For optimum eff ciency, the ignition advance angle should be such as to cause the maximum combustion pressure to occur approximately 10° after TDC. The ideal ignition timing is dependent on two main factors: engine speed and engine load. An increase in engine speed requires the ignition timing to be advanced. The cylinder charge, of air fuel mixture, requires a certain time to burn (normally approximately 2 ms). At higher engine speeds, the time taken for the piston to travel the same distance reduces. Advancing the time of the spark ensures that full burning is achieved.

A change in timing due to engine load is also required, as the weaker mixture used in low-load conditions burns at a slower rate. In this situation, further ignition advance is necessary. Greater load on the engine requires a richer mixture, which burns more rapidly. In this case, some retardation of timing is necessary. Overall, under any condition of engine speed and load, an ideal advance angle is required to ensure maximum pressure is achieved in the cylinder just after TDC. The ideal advance angle may also be determined by engine temperature and any risk of detonation.

Spark advance is achieved in a number of ways. The simplest of these is the mechanical system comprising a centrifugal advance mechanism and a vacuum (load sensitive) control unit. Manifold depression is almost inversely proportional to the engine load. I prefer to consider manifold pressure, albeit less than atmospheric pressure; the absolute manifold pressure (MAP) is proportional to engine load. Digital ignition systems may adjust the timing in relation to the temperature as well as speed and load. The values of all ignition timing functions are combined either mechanically or electronically in order to determine the ideal ignition point.

The energy storage takes place in the ignition coil. The energy is stored in the form of a magnetic f eld. To ensure that the coil is charged before the ignition point, a dwell period is required. Ignition timing is at the end of the dwell period.

6.7.3 Electronic ignition

Electronic ignition is now f tted to all spark ignition vehicles. This is because the conventional mechanical system has some major disadvantages:

- Mechanical problems with the contact breakers not least of which is the limited lifetime.
- Current f ow in the primary circuit is limited to approximately 4 A, otherwise damage will occur to the contacts – or at least the lifetime will be seriously reduced.
- Legislation requires stringent emission limits which means the ignition timing must stay in tune for a long period of time.
- Weaker mixtures require more energy from the spark to ensure successful ignition, even at very high engine speed.

These problems can be overcome by using a power transistor to carry out the switching function and a pulse generator to provide the timing signal. Very early forms of electronic ignition used the existing contact breakers as the signal provider. This was a step in the right direction but did not overcome all the mechanical limitations such as contact bounce and timing slip. All systems nowadays are constant-energy systems ensuring high-performance ignition even at high engine speed. Figure 6.19 shows the circuit of a standard electronic ignition system.

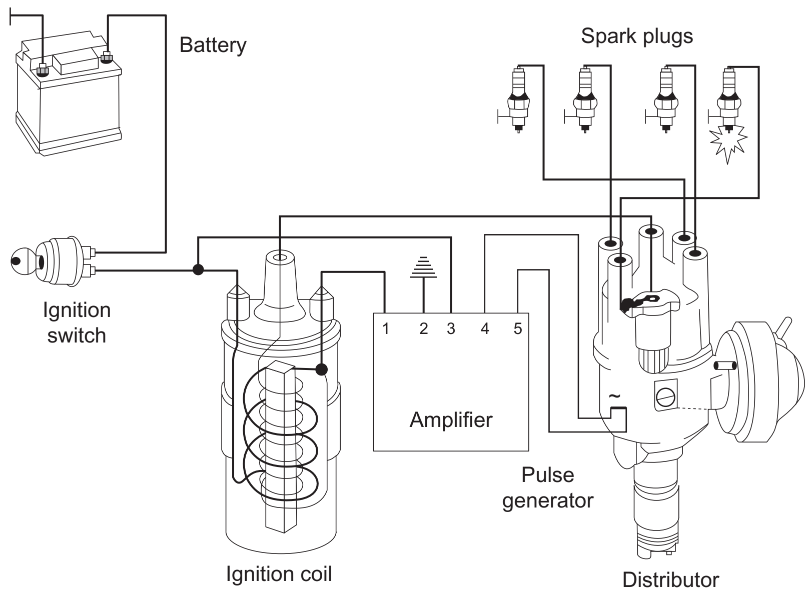


Figure 6.19 Early electronic ignition system

Key fact

The term 'dwell' when applied to ignition is a measure of the time during which the ignition coil is charging – in other words, when primary current is flowing.

Key fact

In order for a constant-energy electronic ignition system to operate, the dwell must increase with engine speed.

The term 'dwell' when applied to ignition is a measure of the time during which the ignition coil is charging – in other words, when primary current is flowing. The dwell in conventional systems was simply the time during which the contact breakers were closed. This is now often expressed as a percentage of one charge–discharge cycle. Constant-dwell electronic ignition systems have now been replaced almost without exception by constant-energy systems discussed in the next section.

Although this was a very good system in its time, constant dwell still meant that at very high engine speeds, the time available to charge the coil could only produce a lower-power spark. Note that as engine speed increases, dwell angle or dwell percentage remains the same but the actual time is reduced.

In order for a constant-energy electronic ignition system to operate, the dwell must increase with engine speed. This will only be of benefit, however, if the ignition coil can be charged up to its full capacity, in a very short time (the time available for maximum dwell at the highest expected engine speed). To this end, constant-energy coils are very low resistance and low inductance. Typical resistance values are less than 1 Ω (often 0.5 Ω). Constant energy means that, within limits, the energy available to the spark plug remains constant under all operating conditions.

Owing to the high-energy nature of constant-energy ignition coils, the coil cannot be allowed to remain switched on for more than a certain time. This is not a problem when the engine is running, as the variable-dwell or current-limiting circuit prevents the coil from overheating. Some form of protection must be provided, however, for when the ignition is switched on but the engine is not running. This is known as stationary engine primary current cut-off.

6.7.4 Hall effect distributor

The Hall effect distributor has become very popular with many manufacturers. Figure 6.20 shows a typical example. As the central shaft of the distributor rotates, the chopper plate attached under the rotor arm alternately covers and uncovers the Hall chip. The number of vanes corresponds with the number of cylinders. In constant-dwell systems, the dwell is determined by the width of the vanes. The vanes cause the Hall chip to be alternately in and out of a magnetic

Figure 6.20 Hall effect distributor

f eld. The result of this is that the device will produce almost a square wave output, which can then easily be used to switch further electronic circuits.

The three terminals on the distributor are marked '−', '0' and '+'; the terminals '−' and '+' are for a voltage supply and terminal '0' is the output signal. Typically, the output from a Hall effect sensor will switch between 0 V and approximately 8 V. The supply voltage is taken from the ignition ECU and on some systems is stabilised at approximately 10 V to prevent changes to the output of the sensor when the engine is being cranked.

Hall effect distributors were very common due to the accurate signal produced and long-term reliability. They are suitable for use on both constant-dwell and constant-energy systems. Operation of a Hall effect pulse generator can easily be tested with a DC voltmeter or a logic probe. Note that tests must not be carried out using an ohmmeter, as the voltage from the meter can damage the Hall chip.

6.7.5 Inductive distributor

Many forms of inductive-type distributors exist and all are based around a coil of wire and a permanent magnet. The example distributor shown in Figure 6.21 has the coil of wire wound on the pick-up, and as the reluctor rotates, the magnetic f ux varies due to the peaks on the reluctor. The number of peaks or teeth on the reluctor corresponds to the number of engine cylinders. The gap between the reluctor and pick-up can be important and manufacturers have recommended settings.

Key fact

Many forms of inductive-type distributors exist and all are based around a coil of wire and a permanent magnet.

6.7.6 Current-limiting and closed-loop dwell

Primary current limiting not only ensures that no damage can be caused to the system by excessive primary current but also forms a part of a constant-energy system. The primary current is allowed to build up to its pre-set maximum as soon as possible and is then held at this value. The value of this current is calculated and then pre-set during construction of the amplif er module. This technique, when combined with dwell angle control, is known as closed-loop control as the actual value of the primary current is fed back to the control stages.

Figure 6.21 Inductive distributor

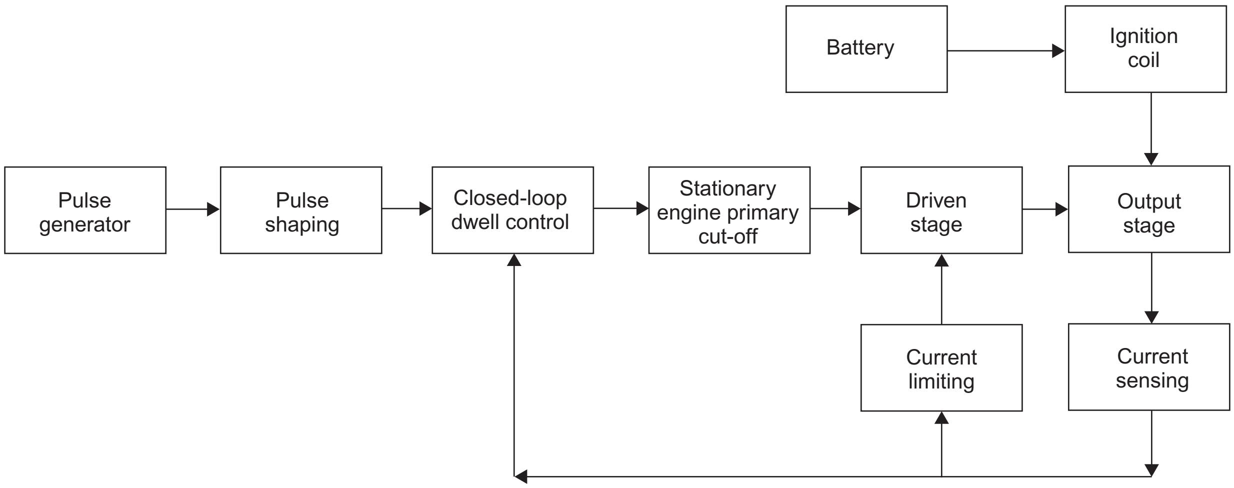


Figure 6.22 Closed-loop dwell control system

A very low resistance, high power precision resistor is used in this circuit. The resistor is connected in series with the power transistor and the ignition coil. A voltage-sensing circuit connected across this resistor is activated at a pre-set voltage (which is proportional to the current) and causes the output stage to hold the current at a constant value.

Stationary current cut-off is for when the ignition is on but the engine is not running. This is achieved in many cases by a simple timer circuit, which will cut the output stage after about one second (Figure 6.22).

6.7.7 Programmed ignition/electronic spark advance

Def nition

ESA: Electronic spark advance.

Programmed ignition is the term used by some manufacturers; others call it electronic spark advance (ESA). Constant-energy electronic ignition was a major step forwards and is still used on countless applications. However, its limitations lay in still having to rely upon mechanical components for speed and load advance characteristics. In many cases, these did not match ideally the requirements of the engine.

ESA systems have a major difference compared with earlier systems in that they operate digitally. Information about the operating requirements of a particular engine is programmed into memory inside the ECU. The data for storage in ROM is obtained from rigorous testing on an engine dynamometer and further development work in the vehicle under various operating conditions. Programmed ignition has several advantages:

- The ignition timing can be accurately matched to the individual application under a range of operating conditions.
- Other control input can be utilised such as coolant temperature and ambient air temperature.
- Starting is improved, fuel consumption and emissions are reduced, and idle control is better.
- Other inputs can be taken into account such as engine knock.
- The number of wearing components in the ignition system is considerably reduced.

Programmed ignition or ESA can be a separate system or included as part of the fuel control system. In order for the ECU to calculate suitable timing and dwell outputs, certain input information is required.

The crankshaft sensor consists of a permanent magnet, a winding and a soft iron core. It is mounted in proximity to a reluctor disc. The disc has 34 teeth spaced at 10° intervals around to periphery. It has two teeth missing 180° apart, at a known position BTDC. Many manufacturers use this technique with minor differences. As a tooth from the reluctor disc passes the core of the sensor, the reluctance of the magnetic circuit is changed. This induces a voltage in the winding, the frequency of the waveform being proportional to the engine speed. The missing tooth causes a 'missed' output wave and hence engine position can be determined.

Engine load is proportional to manifold pressure in that high-load conditions produce high pressure and lower-load conditions, such as cruise, produce lower pressure. Load sensors are therefore pressure transducers. They are either mounted in the ECU or as a separate unit and are connected to the inlet manifold with a pipe. The pipe often incorporates a restriction to damp out f uctuations and a vapour trap to prevent petrol fumes reaching the sensor.

Key fact

Engine load is proportional to manifold pressure in that high-load conditions produce high pressure and lowerload conditions, such as cruise, produce lower pressure.

Coolant temperature measurement is carried out by a simple thermistor. In many cases, the same sensor is used for the operation of the temperature gauge and to provide information to the fuel control system. A separate memory map is used to correct the basic timing settings. Timing may be retarded when the engine is cold to assist in more rapid warm-up.

Key fact

Combustion knock can cause serious damage to an engine if sustained for long periods.

Combustion knock can cause serious damage to an engine if sustained for long periods. This knock or detonation is caused by overadvanced ignition timing. At variance with this is that an engine in general will run at its most eff cient when the timing is advanced as far as possible. To achieve this, the data stored in the basic timing map will be as close to the knock limit of the engine as possible. The knock sensor provides a margin for error. The sensor itself is an accelerometer often of the piezoelectric type. It is f tted in the engine block between cylinders 2 and 3 on in-line four-cylinder engines. Vee engines require two sensors, one on each side. The ECU responds to signals from the knock sensor in the engine's knock window for each cylinder; this is often just a few degrees each side of TDC. This prevents clatter from the valve mechanism being interpreted as knock. The signal from the sensor is also f ltered in the ECU to remove unwanted noise. If detonation is detected, the ignition timing is retarded on the fourth ignition pulse after detection (four-cylinder engine), in steps until knock is no longer detected. The steps vary between manufacturers, but approximately 2° is typical. The timing is then advanced slowly in steps of say 1° over a number of engine revolutions, until the advance required by memory is restored. This f ne control allows the engine to be run very close to the knock limit without risk of engine damage.

Correction to dwell settings is required if the battery voltage falls, as a lower voltage supply to the coil will require a slightly larger dwell f gure. This information is often stored in the form of a dwell correction map.

As the sophistication of systems has increased, the information held in the memory chips of the ECU has also increased. The earlier versions of programmed ignition system produced by Rover achieved accuracy in ignition timing of ±1.8°, whereas a conventional distributor is ±8°. The information, which is derived from dynamometer tests as well as running tests in the vehicle, is stored in ROM. The basic timing map consists of the correct ignition advance for 16 engine speeds and 16 engine load conditions.

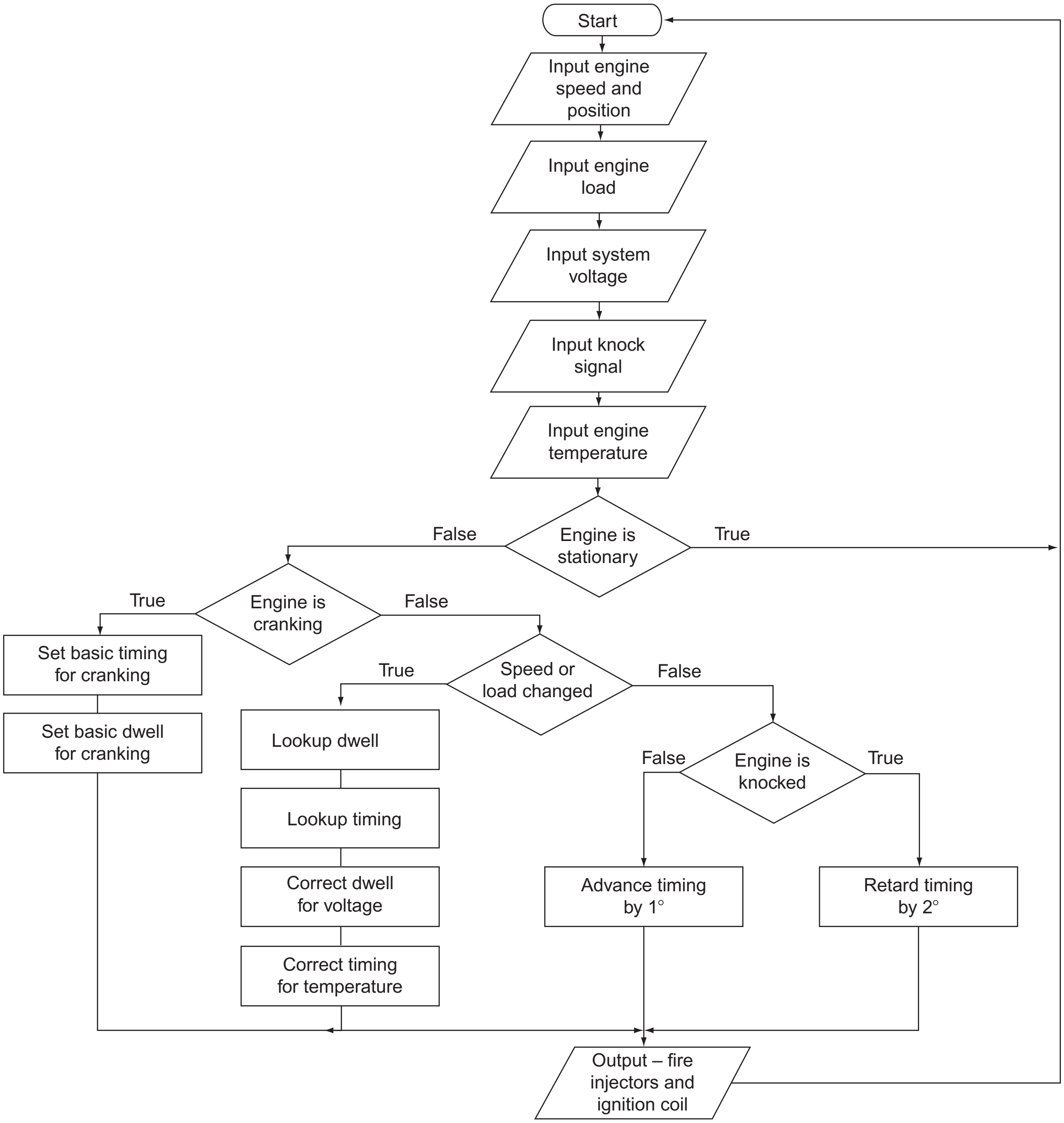


Figure 6.23 Electronic spark advance: representation of the process

A separate three-dimensional map is used which has eight speed and eight temperature sites. This is used to add corrections for engine coolant temperature to the basic timing settings. This improves driveability and can be used to decrease the warm-up time of the engine. The data is also subjected to an additional load correction below 70 °C. Figure 6.23 shows a f ow chart representing the logical selection of the optimum ignition setting. Note that the ECU will also make corrections to the dwell angle, both as a function of engine speed to provide constant energy output and due to changes in battery voltage. A lower battery voltage will require a slightly longer dwell and a higher battery voltage will require a slightly shorter dwell. A Windows® shareware program that simulates the ignition system (as well as many other systems) is available for download from my website.

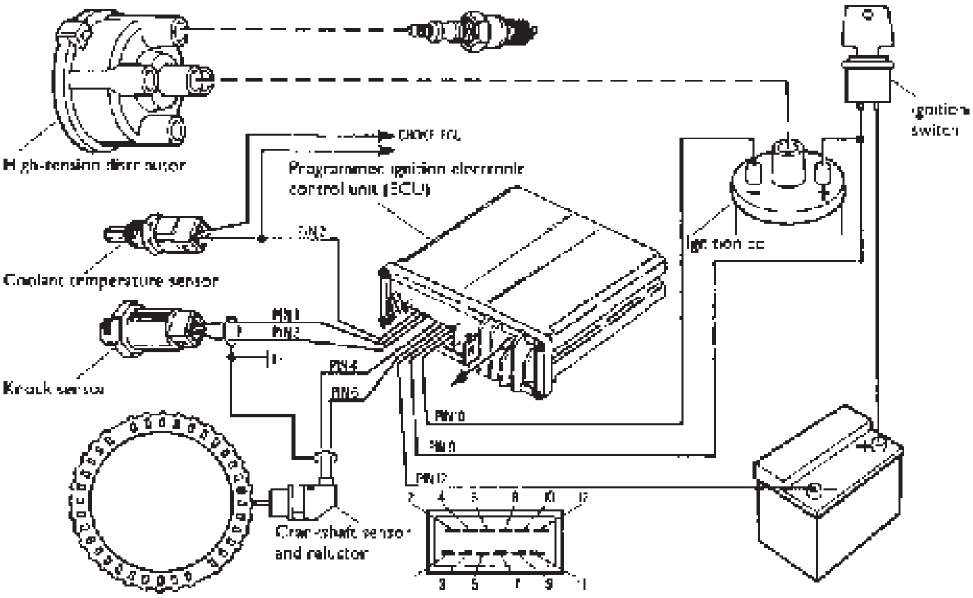


Figure 6.24 Programmed ignition system electronic spark advance (ESA)

The output of a system such as this programmed ignition is very simple. The output stage, in common with most electronic ignition, consists of a heavy-duty transistor which forms part of, or is driven by, a Darlington pair. This is simply to allow the high ignition primary current to be controlled. The switch-off point of the coil will control ignition timing and the switch-on point will control the dwell period.

The high-tension distribution is similar to a more conventional system. The rotor arm, however, is mounted on the end of the camshaft with the distributor cap positioned over the top. Figure 6.24 shows an early programmed ignition system.

6.7.8 Distributorless ignition

Distributorless ignition has all the features of ESA ignition systems but, by using a special type of ignition coil, outputs to the spark plugs without the need for an HT distributor. The system is generally only used on four-cylinder engines, as the control system becomes too complex for higher numbers. The basic principle is that of the 'lost spark'. The distribution of the spark is achieved by using double-ended coils, which are f red alternately by the ECU. The timing is determined from a crankshaft speed and position sensor as well as load and other corrections. When one of the coils is f red, a spark is delivered to two-engine cylinders, either 1 and 4, or 2 and 3. The spark delivered to the cylinder on the compression stroke will ignite the mixture as normal. The spark produced in the other cylinder will have no effect, as this cylinder will be just completing its exhaust stroke.

Because of the low compression and the exhaust gases in the 'lost spark' cylinder, the voltage used for the spark to jump the gap is only approximately 3 kV. This is similar to the more conventional rotor arm to cap voltage. The spark produced in the compression cylinder is therefore not affected.

An interesting point here is that the spark on one of the cylinders will jump from the earth electrode to the spark plug centre. Many years ago, this would not have been acceptable, as the spark quality when jumping this way would not have

Key fact

Because of the low compression and the exhaust gases in the 'lost spark' cylinder, the voltage used for the spark to jump the gap is only approximately 3kV.

Figure 6.25 DIS coil on a four-cylinder engine

been as good as when it jumps from the centre electrode. However, the energy available from modern constant-energy systems will produce a spark of suitable quality in either direction.

The direct ignition system (DIS) consists of three main components: the electronic module, a crankshaft position sensor and the DIS coil. In many systems, a MAP sensor is integrated in the module. The module functions in much the same way as has been described for the ESA system.

The crankshaft position sensor is similar in operation to the one described in the previous section. It is again a reluctance sensor and is positioned against the front of the f ywheel or against a reluctor wheel just behind the front crankshaft pulley. The tooth pattern consists of 35 teeth. These are spaced at 10° intervals with a gap where the 36th tooth would be. The missing tooth is positioned at 90° BTDC for numbers 1 and 4 cylinders. This reference position is placed a f xed number of degrees before TDC, in order to allow the timing or ignition point to be calculated as a f xed angle after the reference mark (Figure 6.25).

The low-tension winding is supplied with battery voltage to a centre terminal. The appropriate half of the winding is then switched to earth in the module. The high-tension windings are separate and are specif c to cylinders 1 and 4, or 2 and 3.

6.7.9 Direct ignition

Direct ignition is in a way the follow-on from distributorless ignition. This system utilises an inductive coil for each cylinder. These coils are mounted directly on the spark plugs. Figure 6.26 shows a cross-section of the direct ignition coil. The use of an individual coil for each plug ensures that the rise time for the low-inductance primary winding is very fast. This ensures that a very high voltage, high-energy spark is produced. This voltage, which can be in excess of 400 kV, provides eff cient initiation of the combustion process under cold starting conditions and with weak mixtures. Some direct ignition systems use capacitor discharge ignition.

Key fact

The use of an individual coil for each plug ensures that the rise time for the low-inductance primary winding is very fast.

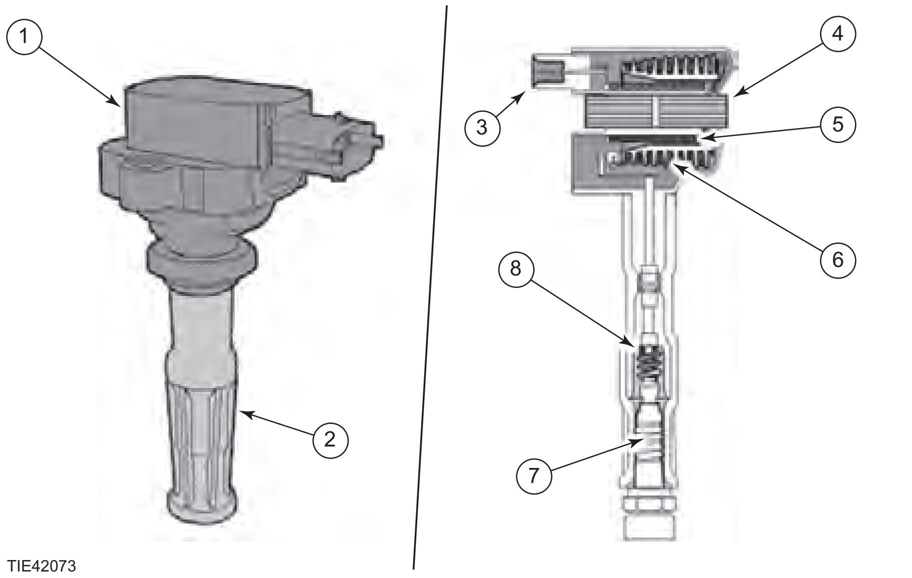


Figure 6.26 Direct ignition coil features: 1 – direct ignition coil; 2 – spark plug connector; 3 – low-voltage connection; outer: 4 – laminated iron core; 5 – primary winding; 6 – secondary winding; 7 – spark plug; 8 – high-voltage connection; inner: via spring contact. (Source: Ford Motor Company)

In order to switch the ignition coils, igniter units may be used. These can control up to three coils and are simply the power stages of the control unit but in a separate container. This allows less interference to be caused in the main ECU due to heavy current switching and shorter runs of wires carrying higher currents.

Ignition timing and dwell are controlled in a manner similar to the previously described programmed system. The one important addition to this on some systems is a camshaft sensor to provide information as to which cylinder is on the compression stroke. A system which does not require a sensor to determine which cylinder is on compression (engine position is known from a crank sensor) determines the information by initially f ring all the coils. The voltage across the plugs allows measurement of the current for each spark and will indicate which cylinder is on its combustion stroke. This works because a burning mixture has a lower resistance. The cylinder with the highest current at this point will be the cylinder on the combustion stroke.

A further feature of some systems is the case when the engine is cranked over for an excessive time making f ooding likely. The plugs are all f red with multisparks for a period of time after the ignition is left in the 'on' position for f ve seconds. This will burn away any excess fuel.

During diff cult starting conditions, multisparking is also used by some systems during 70° of crank rotation before TDC. This assists with starting and then once the engine is running, the timing will return to its normal calculated position.

6.7.10 Spark plugs

Figure 6.27 shows a standard spark plug. The centre electrode is connected to the top terminal by a stud. The electrode is constructed of a nickel-based alloy.

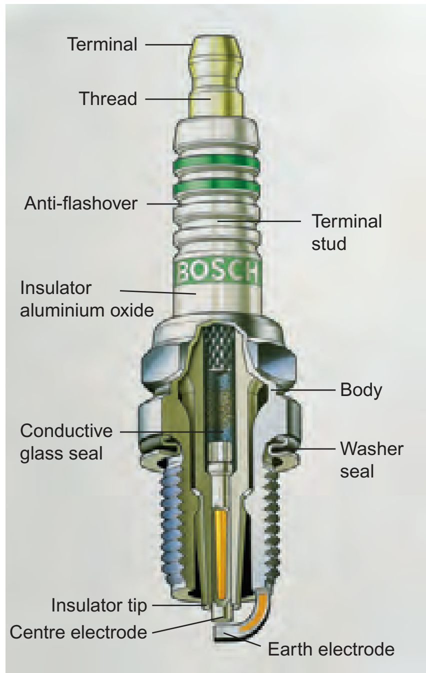


Figure 6.27 Construction of a copper cored spark plug

Silver and platinum are also used for some applications. If a copper core is used in the electrode, this improves the thermal conduction properties.

The insulating material is ceramic based and of a very high grade. The electrically conductive glass seal between the electrode and terminal stud is also used as a resistor. This resistor has two functions: f rst to prevent burn-off of the centre electrode, and second to reduce radio interference. In both cases, the desired effect is achieved because the resistor damps the current at the instant of ignition.

Flashover or tracking down the outside of the plug insulation is prevented by ribs. These effectively increase the surface distance from the terminal to the metal f xing bolt, which is of course earthed to the engine.

Owing to the many and varied constructional features involved in the design of an engine, the range of temperatures a spark plug is exposed to can vary signif cantly. The operating temperature of the centre electrode of a spark plug is critical. If the temperature becomes too high then pre-ignition may occur, as the fuel air mixture may become ignited due to the incandescence of the plug electrode. On the other hand, if the electrode temperature is too low then carbon and oil fouling can occur, as deposits are not burnt off. Fouling of the plug nose can cause shunts (a circuit in parallel with the spark gap). It has been shown through experimentation and experience that the ideal operating temperature of the plug electrode is between 400 and 900 °C.

Key fact

The heat range of a spark plug then is a measure of its ability to transfer heat away from the centre electrode.

The heat range of a spark plug then is a measure of its ability to transfer heat away from the centre electrode. A hot running engine will require plugs with a higher thermal loading ability than a colder running engine. Note that hot and cold running of an engine in this sense refers to the combustion temperature and not to the eff ciency of the cooling system.

The following factors determine the thermal capacity of a spark plug:

- insulator nose length;
- electrode material;
- thread contact length;
- projection of the electrode.

It has been found that a longer projection of the electrode helps to reduce fouling problems due to low-power operation, stop-go driving and high-altitude conditions. To use greater projection of the electrode, better-quality thermal conduction is required to allow suitable heat transfer at higher power outputs. Figure 6.28 shows the heat conducting paths of a spark plug together with changes in design for heat ranges.

For normal applications, alloys of nickel are used for the electrode material. Chromium, manganese, silicon and magnesium are examples of the alloying constituents. These alloys exhibit excellent properties with respect to corrosion and burn-off resistance. To improve on the thermal conductivity, compound electrodes are used. This allows a greater nose projection for the same temperature range as discussed in the last section. A common example of this type of plug is the copper core spark plug.

Silver electrodes are used for specialist applications, as silver has very good thermal and electrical properties. Again with these plugs nose length can be increased within the same temperature range. Platinum tips are used for some

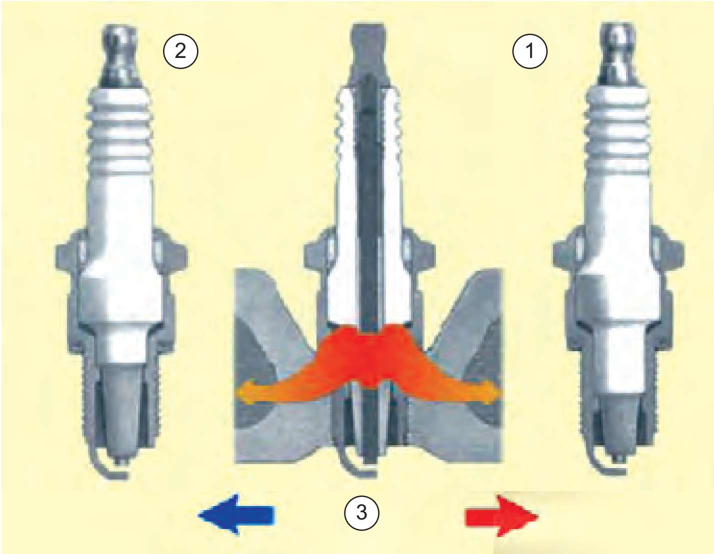


Figure 6.28 Heat-loss paths: 1 – cold plug; 2 – hot plug; 3 – temperature (the cold plug is able to transfer heat more easily so is suitable for a hot engine)

spark plug applications due to the very high burn-off resistance of this material. It is also possible because of this to use much-smaller-diameter electrodes, thus increasing mixture accessibility. Platinum also has a catalytic effect, further accelerating the combustion process.

Spark plug electrode gaps in general have increased as the power of the ignition systems driving the spark has increased. The simple relationship between plug gap and voltage required is that as the gap increases, so must the voltage (leaving aside engine operating conditions). Further, the energy available to form a spark at a f xed engine speed is constant, which means that a larger gap using higher voltage will result in a shorter-duration spark. A smaller gap will allow a longer-duration spark. For cold starting an engine and for igniting weak mixtures, the duration of the spark is critical. Likewise, the plug gap must be as large as possible to allow easy access for the mixture to prevent quenching of the f ame.

The f nal choice is therefore a compromise reached through testing and development of a particular application. Plug gaps in the region of 0.6–1.2 mm seem to be the norm at present.

Key fact

Spark plug electrode gaps in general have increased as the power of the ignition systems driving the spark has increased.

6.8 Diagnostics – ignition system

6.8.1 Testing procedure

The following procedure is generic and with a little adaptation can be applied to any ignition system. Refer to manufacturer's recommendations if in any doubt (Figure 6.29).

Safety f rst

Warning: Caution/Achtung/Attention – High voltages can seriously damage your health.

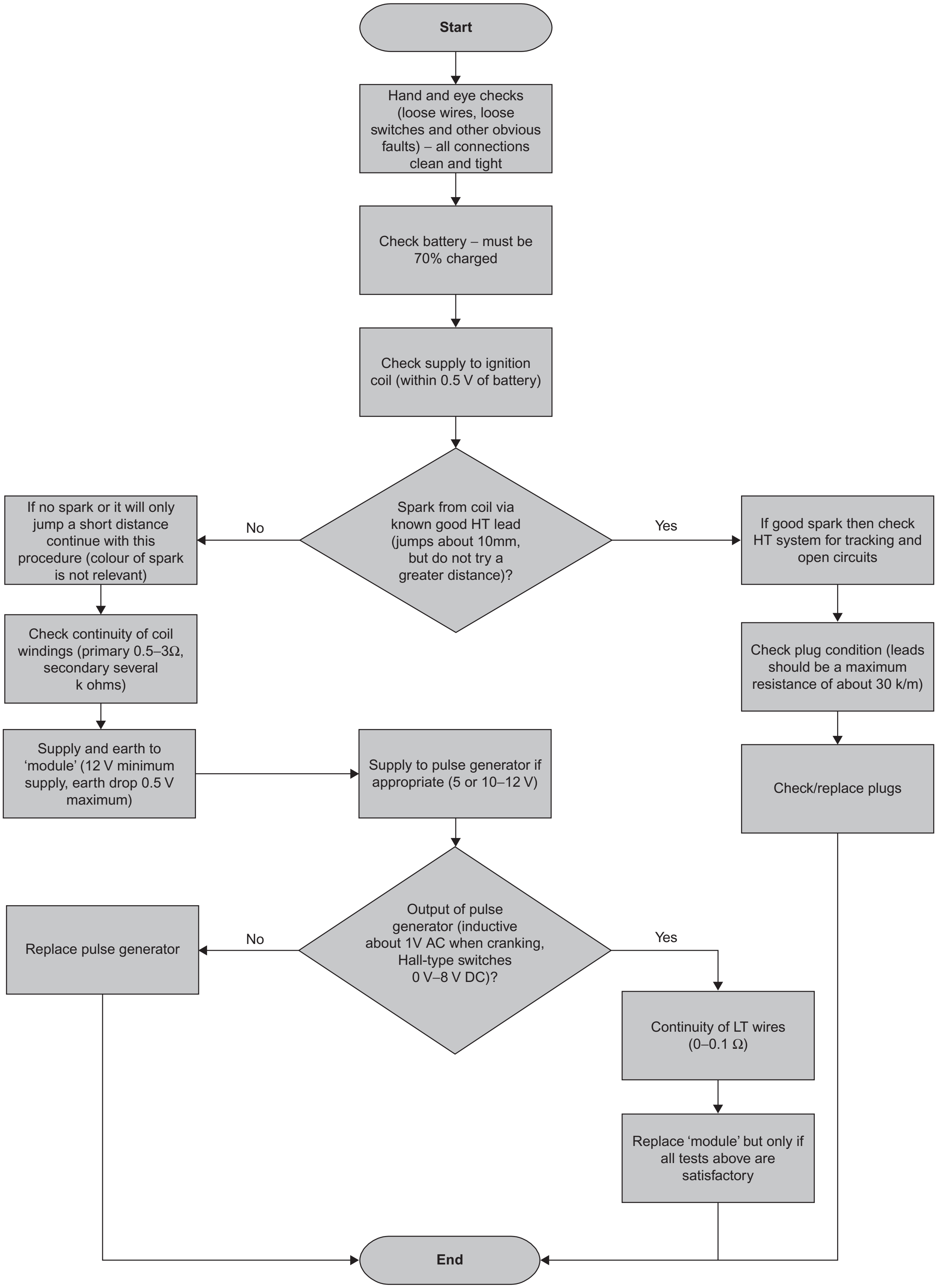


Figure 6.29 Ignition system diagnosis chart

6.8.2 Ignition fault diagnosis table

Symptom	Possible fault
Engine rotates but does not start	Damp ignition components Spark plugs worn to excess Ignition system open circuit
Difficult to start when cold	Spark plugs worn to excess High resistance in ignition circuit
Engine starts but then stops immediately	Ignition wiring connection intermittent Ballast resistor open circuit (older cars)
Erratic idle	Incorrect plug gaps Incorrect ignition timing
Misfire at idle speed	Ignition coil or distributor cap tracking Spark plugs worn to excess Dwell incorrect (old systems)
Misfire through all speeds	Incorrect plugs or plug gaps HT leads breaking down Timing incorrect
Lack of power	Ignition timing incorrect HT components tracking
Backfires	Incorrect ignition timing Tracking
Runs on when switched off	Ignition timing incorrect Carbon build-up in engine Idle speed too high Anti-run on device inoperative
Pinking or knocking under load	Ignition timing incorrect Ignition system electronic fault Knock sensor not working

Figure 6.30 shows a typical ignition timing light, essential to ensure correct settings where these are adjustable, or to check programmed advance systems for correct operation.

6.8.3 Ignition components and testing

Component	Description	Test method
Spark plug	Seals electrodes for the spark to jump across the cylinder. Must withstand very high voltages, pressures and temperatures	Compare nose condition to a manufacturer's chart Inspect ignition secondary waveform, particularly when the engine is under load
Ignition coil	Stores energy in the form of magnetism and delivers it to the distributor via the HT lead. Consists of primary and secondary windings	Resistance checks of the primary and secondary windings: Primary: 1.5Ω (ballasted) to 3Ω Secondary: 5–10kΩ

(Continued)

Component	Description	Test method
Ignition switch	Provides driver control of the ignition system and is usually also used to cause the starter to crank	Voltage drop across the contacts
Ballast resistor	Shorted out during the starting phase to cause a more powerful spark. Also contributes towards improving the spark at higher speeds	Resistance (often approximately 1.5Ω) or check voltage at coil supply (approximately 6 or 7V when the contact breakers are closed)
Contact breakers (breaker points)	Switch the primary ignition circuit on and off to charge and discharge the coil	Voltage drop across them should not exceed approximately 0.2V General condition
Capacitor (condenser)	Suppresses most of the arcing as the contact breakers open. This allows for a more rapid break of primary current and hence a more rapid collapse of the coil magnetism, which produces a higher voltage output	Charge the capacitor up across a 12V battery. Connect a digital meter and watch the voltage discharge from 12V to almost 0V over approximately five seconds
HT distributor	Directs the spark from the coil to each cylinder in a pre-set sequence	Visual inspection for signs of tracking (conducting lines) and contamination
Centrifugal advance (engine speed)	Changes the ignition timing with engine speed. As speed increases, the timing is advanced	Measure the timing at certain speeds using an 'advance' timing light. Refer to data
Vacuum advance (engine load)	Changes timing depending on engine load. On conventional systems, the vacuum advance is most important during cruise conditions	Apply a known vacuum and note timing changes or often just sucking on the pipe and noting movement is adequate

Figure 6.30 Timing light (used on earlier cars)

6.8.4 DIS diagnostics

The DIS system is very reliable due to the lack of any moving parts. Some problems can be experienced when trying to examine HT oscilloscope patterns due to the lack of a king lead. This can often be overcome with a special adapter, but it is still necessary to move the sensing clip to each lead in turn.

The DIS coil can be tested with an ohmmeter. The resistance of each primary winding should be 0.5 Ω and the secondary windings between 11 and 16 kΩ. The coil will produce in excess of 37 kV in an open circuit condition. The plug leads have integral retaining clips to prevent water ingress and vibration problems. The maximum resistance for the HT leads is 30 kΩ per lead.

No service adjustments are possible with this system, with the exception of octane adjustment on some models. This involves connecting two pins together on the module for normal operation, or earthing one pin or the other to change to a different fuel. The actual procedure must be checked with the manufacturer for each particular model.

6.8.5 Spark plugs

Examination of the spark plugs is a good way of assessing engine and associated systems condition. Figure 6.31 shows a new plug and Figures 6.32–6.36 show various conditions with diagnostic notes added.

Key fact

Examination of the spark plugs is a good way of assessing engine and associated systems condition.

Figure 6.31 New spark plug

Use this image to compare with used spark plugs. Note in particular, on this standard design, how the end of the nose is flat, and that the earth/ground electrode has a consistent size and shape

Figure 6.32 Carbon fouled (standard plug)

This plug has black deposits over the centre electrode and insulator in particular. It is likely that this engine was running too rich – or on an older vehicle the choke was used excessively. However, carbon fouling may also be due to

poor-quality spark due to ignition fault

incorrect plug gap

overretarded timing

loss of cylinder compression

prolonged low-speed driving

incorrect (too cold) spark plug fitted

(*Continued*)

Figure 6.33 Deposits

The deposits on this plug are most likely to be caused by oil leaking into the cylinder. Alternatively poor-quality fuel mixture supply or very short, cold engine operation could result in a similar condition

Figure 6.34 Damaged insulation

A plug that is damaged in this way is because of either overheating or impact damage. Impact is most likely in this case. The damage can of course be caused as the plug is being fitted. However, in this case a possible cause would be that the reach was too long for the engine and the piston hit the earth/ground electrode, closing up the gap and breaking the insulation

Figure 6.35 Carbon fouled (platinum plug)

The carbon build-up on this plug would suggest an incorrect mixture. However, before diagnosing a fault based on spark plug condition, make sure the engine has been run up to temperature – ideally by a good road test. The engine from which this plug was removed is in good condition – it had just been started from cold and only run for a few minutes

Figure 6.36 Overheating

When a plug overheats, the insulator tip becomes glossy and/or they are blistered or melted away. The electrodes also wear quickly. Excessive overheating can result in the electrodes melting and serious piston damage is likely to occur. Causes of overheating are

overadvanced ignition
mixture too lean
cooling system fault
incorrect plug (too hot)
incorrect fuel (octane low)

6.9 Emissions

6.9.1 Introduction

Table 6.4 lists the four main exhaust emissions which are hazardous to health together with a short description of each.

Table 6.5 describes two further sources of emissions from a vehicle.

Table 6.4 Exhaust emissions

Substance	Description
Carbon monoxide (CO)	This gas is very dangerous even in low concentrations. It has no smell or taste and is colourless. When inhaled, it combines in the body with the red blood cells preventing them from carrying oxygen. If absorbed by the body, it can be fatal in a very short time
Nitrogen oxides (NO_x)	Oxides of nitrogen are colourless and odourless when they leave the engine, but as soon as they reach the atmosphere and mix with more oxygen, nitrogen oxides are formed. They are reddish brown and have an acrid and pungent smell. These gases damage the body's respiratory system when inhaled. When combined with water vapour nitric acid can be formed, which is very damaging to the windpipe and lungs. Nitrogen oxides are also a contributing factor to acid rain
Hydrocarbons (HC)	A number of different hydrocarbons are emitted from an engine and are part of unburnt fuel. When they mix with the atmosphere, they can help to form smog. It is also believed that hydrocarbons may be carcinogenic
Particulate matter (PM)	This heading in the main covers lead and carbon. Lead was traditionally added to petrol to slow its burning rate to reduce detonation. It is detrimental to health and is thought to cause brain damage, especially in children. Lead will eventually be phased out as all new engines now run on unleaded fuel. Particles of soot or carbon are more of a problem on diesel-fuelled vehicles and these now have limits set by legislation

Table 6.5 Emission sources

Source	Comments
Fuel evaporation from the tank and system	Fuel evaporation causes hydrocarbons to be produced. The effect is greater as temperature increases. A charcoal canister is the preferred method for reducing this problem. The fuel tank is usually run at a pressure just under atmospheric by a connection to the intake manifold drawing the vapour through the charcoal canister. This must be controlled by the management system, however, as even a 1% concentration of fuel vapour would shift the lambda value by 20%. This is done by using a 'purge valve', which under some conditions is closed (full-load and idle for example) and can be progressively opened under other conditions. The system monitors the effect by use of the lambda sensor signal
Crankcase fumes (blow by)	Hydrocarbons become concentrated in the crankcase mostly due to pressure blowing past the piston rings. These gases must be conducted back into the combustion process. This is usually via the air intake system. This is described as positive crankcase ventilation

Figure 6.37 EGR valve(Source: Delphi Media)

Figure 6.38 Catalytic converter metal substrates

6.9.2 Exhaust gas recirculation

Key fact

Exhaust gas recirculation (EGR) is used primarily to reduce peak combustion temperatures and hence the production of nitrogen oxides (NO_x).

Exhaust gas recirculation (EGR) is used primarily to reduce peak combustion temperatures and hence the production of nitrogen oxides (NO_x). EGR can be either internal due to valve overlap, or external via a simple arrangement of pipes and a valve (Figure 6.37 shows an example) connecting the exhaust manifold back to the inlet manifold. A proportion of exhaust gas is simply returned to the inlet side of the engine.

This process is controlled electronically as determined by a ROM in the ECU. This ensures that driveability is not affected and also that the rate of EGR is controlled. If the rate is too high, then the production of hydrocarbons increases.

One drawback of EGR systems is that they can become restricted by exhaust residue over a period of time, thus changing the actual percentage of recirculation. However, valves that reduce this particular problem are now available.

6.9.3 Catalytic converters

Key fact

For a three-way catalyst (TWC) to operate correctly the engine must be run at or yernear to stoichiometry.

Stringent regulations in most parts of the world have made the use of a catalytic converter almost indispensable. The three-way catalyst (TWC) is used to great effect by most manufacturers. It is a very simple device and looks similar to a standard exhaust box. Note that in order to operate correctly, however, the engine must be run at or very near to stoichiometry. This is to ensure that the right 'ingredients' are available for the catalyst to perform its function.

Figure 6.38 shows some new metallic substrates for use inside a catalytic converter. There are many types of hydrocarbons, but the example illustrates the main reaction. Note that the reactions rely on some CO being produced by the engine in order to reduce the NO_x. This is one of the reasons that manufacturers have been forced to run the engine at stoichiometry. The legislation has tended to stif e the development of lean burn techniques. The f ne details of the emission regulations can in fact have a very marked effect on the type of reduction techniques used. The main reactions in the 'cat' are as follows:

- Reduction of nitrogen oxides to nitrogen and oxygen:
  $2NO_x \rightarrow xO_2 + N_2$
- Oxidation of carbon monoxide to carbon dioxide:
  $2CO + O_2 \rightarrow 2CO_2$
- Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water:
  $C_xH_{2x+2} + [(3x + 1)/2]O_2 \rightarrow xCO_2 + (x + 1)H_2O$

Figure 6.39 Catalytic converter ceramic substrates

Noble metals are used for the catalysts; platinum promotes the oxidation of HC and CO, and rhodium helps the reduction of NO_x. The whole three-way catalytic converter contains only about 3–4 g of the precious metals.

The ideal operating temperature range is from approximately 400 to 800 °C. A serious problem to counter is the delay in the catalyst reaching this temperature. This is known as catalyst light-off time. Various methods have been used to reduce this time as signif cant emissions are produced before light-off occurs. Electrical heating is one solution, as is a form of burner which involves lighting fuel inside the converter. Another possibility is positioning the converter as part of the exhaust manifold and down pipe assembly. This greatly reduces light-off time, but gas f ow problems, vibration and excessive temperature variations can be problems that reduce the potential life of the unit.

Catalytic converters can be damaged in two ways. The f rst is by the use of leaded fuel which causes lead compounds to be deposited on the active surfaces, thus reducing effective area. The second is engine misf re which can cause the catalytic converter to overheat due to burning inside the unit. BMW, for example, use a system on some vehicles where a sensor monitors output of the ignition HT system and will not allow fuel to be injected if the spark is not present.

For a catalytic converter to operate at its optimum conversion rate to oxidise CO and HC while reducing NO_x, a narrow band within 0.5% of lambda value 1 is essential. Lambda sensors in use at present tend to operate within approximately 3% of the lambda mean value. When a catalytic converter is in prime condition, this is not a problem due to storage capacity within the converter for CO and O_2. Damaged converters, however, cannot store suff cient quantity of these gases and hence become less eff cient. The damage as suggested earlier in this section can be due to overheating or by 'poisoning' due to lead or even silicon. If the control can be kept within 0.5% of lambda, the converter will continue to be effective even if damaged to some extent. Sensors which can work to this tolerance are becoming available. A second sensor f tted after the converter can be used to ensure ideal operation.

6.10 Diagnostics – emissions

6.10.1 Testing procedure

If the reported fault is incorrect exhaust emissions, the procedure shown in Figure 6.40 should be utilized.

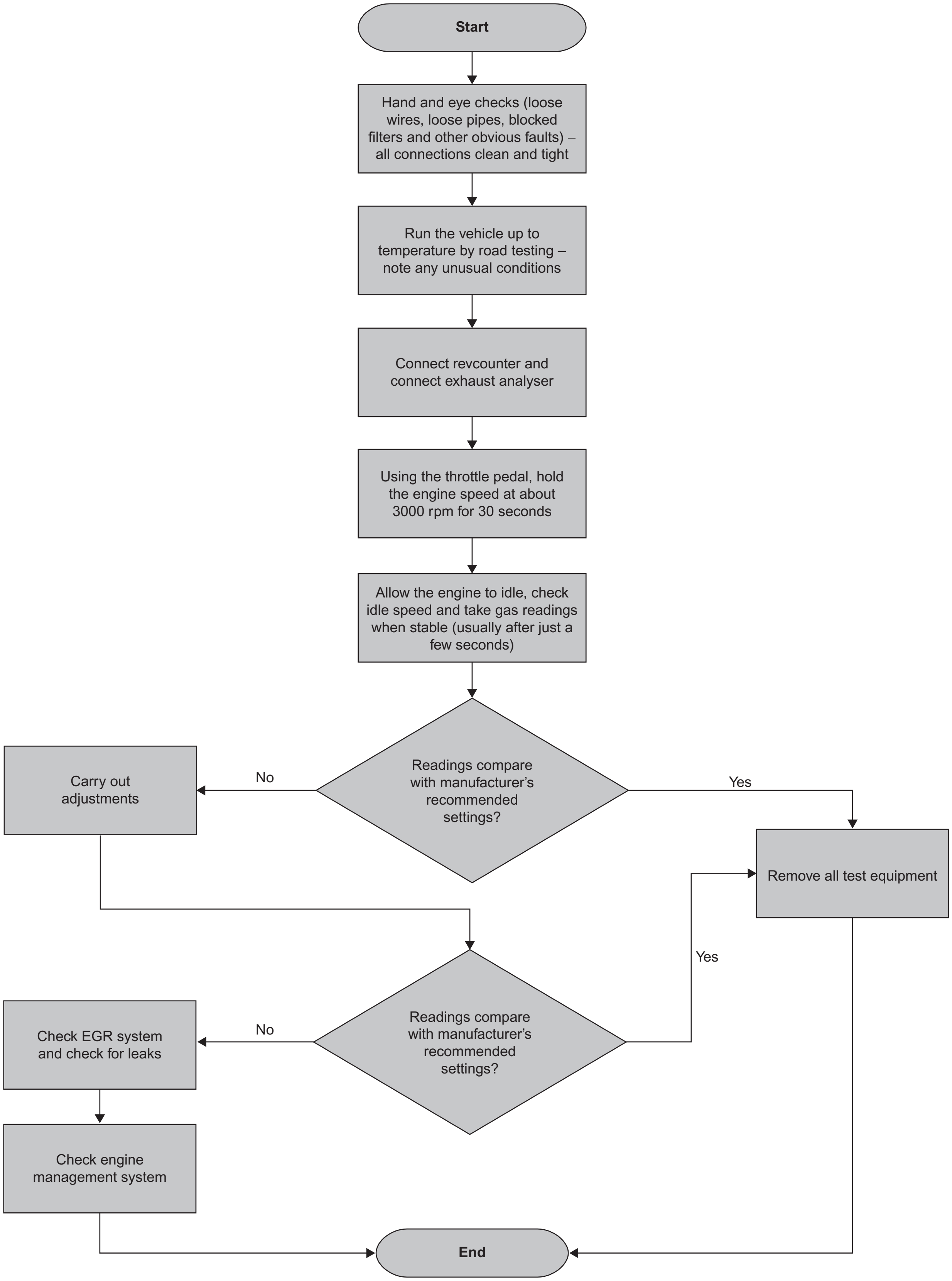


Figure 6.40 Emissions systems diagnosis chart

6.10.2 Emissions fault diagnosis table

Symptom	Possible cause
EGR valve sticking	Build-up of carbon Electrical fault
High CO and high HC	Rich mixture Blocked air lter Damaged catalytic converter Engine management system fault
Low CO and High HC	Misf re Fouled plug(s) Weak mixture
Low CO and low or normal HC	Exhaust leak Fouled injector

6.11 Fuel injection

6.11.1 Introduction

The ideal air fuel ratio is approximately 14.7:1. This is the theoretical amount of air required to completely burn the fuel. It is given a 'lambda (l)' value of 1.

Def nition

λ = actual air quantity÷theoretical air quantity.

Air fuel ratio is altered during the following operating conditions of an engine to improve its performance, driveability, consumption and emissions:

- **cold starting** – richer mixture is needed to compensate for fuel condensation and improve driveability;
- **load or acceleration** – richer to improve performance;
- **cruise or light loads** – weaker for economy;
- **overrun** – very weak (if any) fuel, to improve emissions and economy.

The more accurately the air fuel ratio is controlled to cater for external conditions, the better the overall operation of the engine.

The major advantage, therefore, of a fuel injection system is accurate control of the fuel quantity injected into the engine. The basic principle of fuel injection is that if petrol is supplied to an injector (electrically controlled valve), at a constant differential pressure, then the amount of fuel injected will be directly proportional to the injector open time.

Key fact

The major advantage of a fuel injection system is accurate control of the fuel mixture.

Most systems are now electronically controlled even if containing some mechanical metering components. This allows the operation of the injection system to be very closely matched to the requirements of the engine. This matching process is carried out during development on test beds and dynamometers, as well as development in the car. The ideal operating data for a large number of engine operating conditions is stored in a ROM in the ECU. Close control of fuel quantity injected allows the optimum setting for mixture strength when all operating factors are taken into account (Figure 6.41).

Further advantages of electronic fuel injection control are that overrun cut-off can easily be implemented, fuel can be cut at the engines rev limit and information on fuel used can be supplied to a trip computer (Figure 6.42).

Mazda 626 2.01 GX 16 valve		
Adjustment Data (Fuel)		
DESCRIPTION	SETTING	UNITS
Carburettor/injection make	Mazda	
Carburettor/injection type	MPI	
Fuel pump pressure	5.10 ± 0.70	bar
Injection pressure	1.50	bar
Idle speed	700 ± 50	rev/min
Raised idle speed	Not applicable	rev/min
CO at idle speed	0.50 maximum	%
Carbon dioxide at idle speed	14.50/16.00	%
HC at idle speed	100	ppm
Oxygen at idle speed	0.10/0.50	%

Figure 6.41 Adjustment and emissions data example

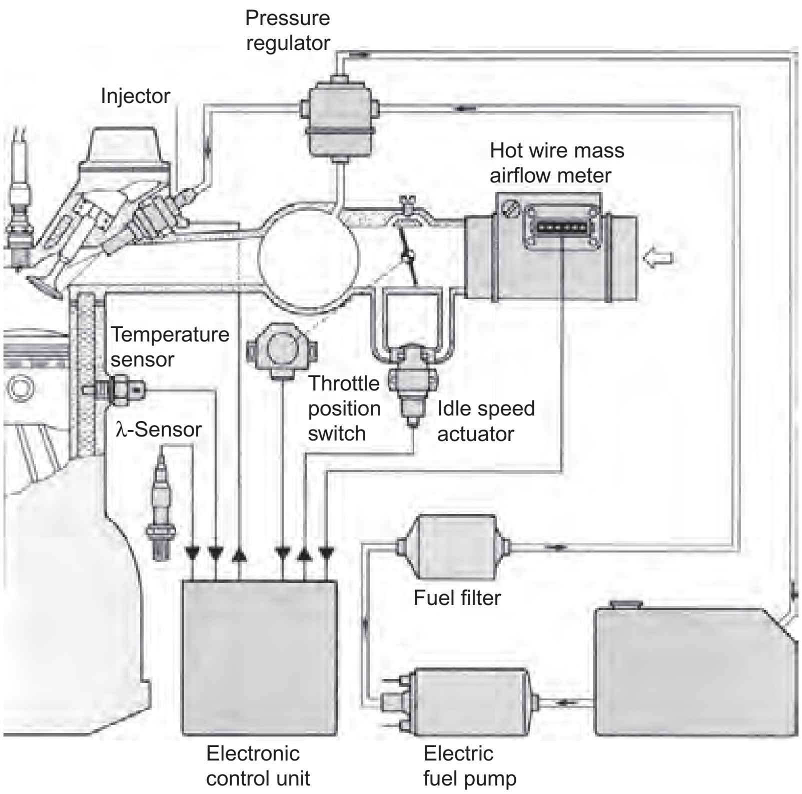


Figure 6.42 Fuel injection system layout

6.11.2 Injection systems

Fuel injection systems can be classif ed into two main categories: single-point injection and multipoint injection. Figure 6.43 shows these techniques. Depending on the sophistication of the system, idle speed and idle mixture adjustment can be either mechanically or electronically controlled.

Figure 6.44 shows a block diagram of inputs and outputs common to most fuel injection systems. Note that the two most important input sensors to the system are speed and load. The basic fuelling requirement is determined from these inputs in a similar way to the determination of ignition timing.

An engine's fuelling requirements are stored as part of a ROM chip in the ECU. When the ECU has determined the 'lookup value' of the fuel required (injector open time), corrections to this f gure can be added for battery voltage, temperature, throttle change or position and fuel cut-off. Figure 6.45 shows an injection system ECU.

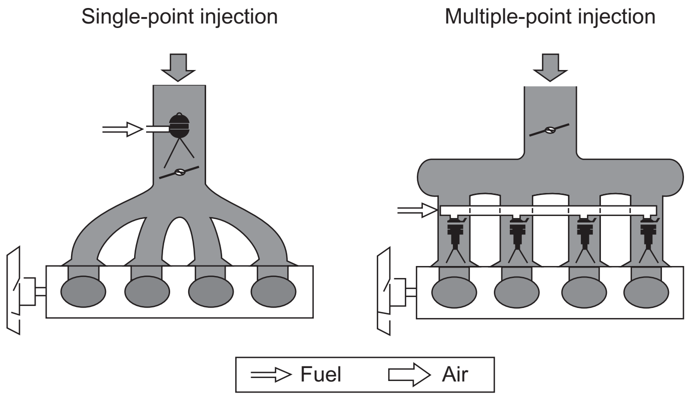


Figure 6.43 Injection methods

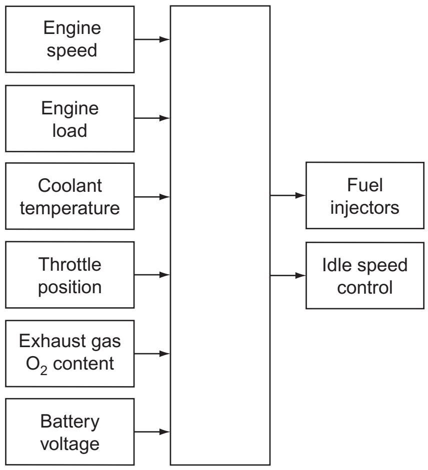


Figure 6.44 Fuel injection simplified block diagram

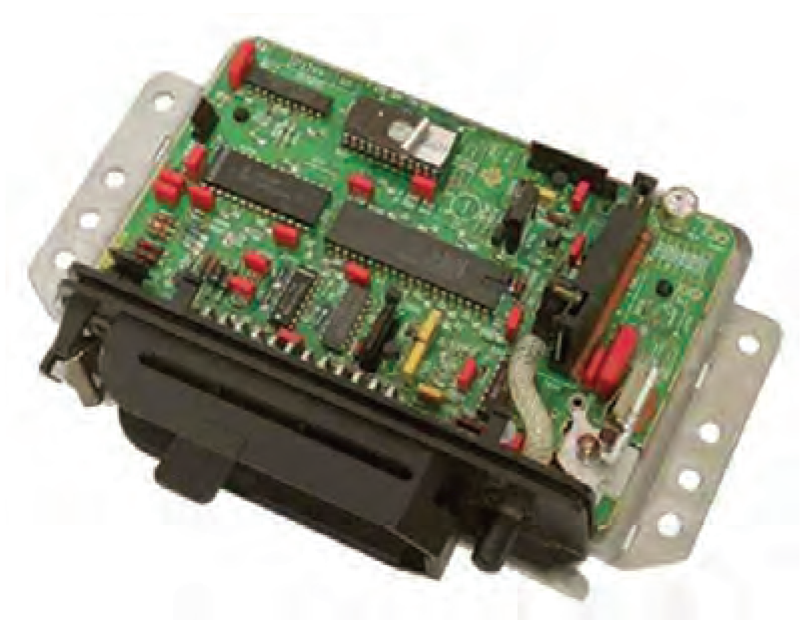


Figure 6.45 Engine management ECU

Idle speed and fast idle are also generally controlled by the ECU and a suitable actuator. It is also possible to have a form of closed-loop control with electronic fuel injection. This involves a lambda sensor to monitor exhaust gas oxygen content. This allows very accurate control of the mixture strength, as the oxygen content of the exhaust is proportional to the air fuel ratio. The signal from the lambda sensor is used to adjust the injector open time.

Key fact

A lambda sensor monitors exhaust gas oxygen content.

6.11.3 Fuel injection components

Many of the sensors and actuators associated with fuel injection are covered in Chapter 4. Figure 6.46 shows those associated with an earlier Motronic injection system. The main fuel components are outlined below:

Airflow meter

The type shown is a hot-wire meter. This allows direct measurement of air mass as temperature compensation is built in. The air quantity helps to determine the fuel required.

Figure 6.46 Earlier Motronic system components

Electronic control unit (ECU)

This is also referred to as the electronic control module (ECM). The circuitry to react to the sensor signals by controlling the actuators is in the ECU. The data is stored in ROM.

Fuel pump

Pressurised fuel is supplied to the injectors. Most pumps work on the centrifugal roller principle. The pump ensures a constant supply of fuel to the fuel rail. The volume in the rail acts as a swamp to prevent pressure f uctuations as the injectors operate. The pump must be able to maintain a pressure of approximately 3 bar.

Fuel f lter

The fuel supplied to the injectors must be free from any contamination or else the injector nozzle will be damaged or blocked.

Lambda sensor

The quantity of oxygen in the exhaust, when accurately measured, ensures that the fuel air mixture is kept within the lambda window (0.97–1.03).

Temperature sensor

A simple thermistor is used to determine the engine coolant temperature.

Fuel injectors

These are simple solenoid-operated valves designed to operate very quickly and produce a f nely atomised spray pattern.

Idle or fast idle control actuator

The rotary actuator is used to provide extra air for cold fast idle conditions and to control idle speed. It is supplied with a variable duty cycle square wave.

Fuel pressure regulator

This device is to ensure a constant differential pressure across the injectors. It is a mechanical device and has a connection to the inlet manifold.

Throttle position switch

This is used to supply information as to whether the throttle is at idle, full load or somewhere in between.

6.11.4 Fuel mixture calculation

The quantity of fuel to be injected is determined primarily by the quantity of air drawn into the engine. This is dependent on two factors:

1. engine speed (rpm);
2. engine load (inlet manifold pressure).

This speed load characteristic is held in the ECU memory in ROM lookup tables.

A sensor connected to the manifold by a pipe senses manifold absolute pressure. The sensor is fed with a stabilised 5 V supply and transmits an output voltage according to the pressure. The sensor is f tted away from the manifold and hence a pipe is required to connect it. The output signal varies between approximately 0.25 V at 0.17 bar to approximately 4.75 V at 1.05 bar. The density of air varies with temperature such that the information from the MAP sensor on air quantity will be incorrect over wide temperature variations. An air temperature sensor is used to inform the ECU of the inlet air temperature such that the quantity of fuel injected may be corrected. As the temperature of air decreases, its density increases and hence the quantity of fuel injected must also be increased. The other method of sensing engine load is direct measurement of air intake quantity using a hot-wire meter or a f ap-type airf ow meter.

To operate the injectors, the ECU needs to know, in addition to air pressure, the engine speed to determine the injection quantity. The same f ywheel sensor used by the ignition system provides this information. All four injectors operate simultaneously once per engine revolution, injecting half of the required fuel. This helps to ensure balanced combustion. The start of injection varies according to ignition timing.

A basic open period for the injectors is determined by using the ROM information relating to manifold pressure and engine speed. Two corrections are then made, one relative to air temperature and another depending on whether the engine is idling, at full or partial load.

The ECU then carries out another group of corrections, if applicable:

- after-start enrichment;
- operational enrichment;
- acceleration enrichment;
- weakening on deceleration;
- cut-off on overrun;
- reinstatement of injection after cut-off;
- correction for battery voltage variation.

Under starting conditions, the injection period is calculated differently. This is determined mostly from a set f gure varied as a function of temperature.

Key fact

The quantity of fuel needed is determined by the mass of air drawn into the engine.

The coolant temperature sensor is a thermistor and is used to provide a signal to the ECU relating to engine coolant temperature. The ECU can then calculate any corrections to fuel injection and ignition timing. The operation of this sensor is the same as the air temperature sensor.

The throttle potentiometer is f xed on the throttle butterf y spindle and informs the ECU of throttle position and rate of change of throttle position. The sensor provides information on acceleration, deceleration and whether the throttle is in the full-load or idle position. It comprises a variable resistance and a f xed resistance. As is common with many sensors, a f xed supply of 5 V is provided and the return signal will vary approximately between 0 and 5 V. The voltage increases as the throttle is opened.

Safety f rst

Warning: Caution/Achtung/ Attention – Burning fuel can seriously damage your health.

6.12 Diagnostics – fuel injection systems

6.12.1 Testing procedure

The following procedure is generic and with a little adaptation can be applied to any fuel injection system. Refer to manufacturer's recommendations if in any doubt. It is assumed that the ignition system is operating correctly. Most tests are carried out while cranking the engine.

6.12.2 Fuel injection fault diagnosis table

Symptom	Possible fault
Engine rotates but does not start	No fuel in the tank! Air flter dirty or blocked Fuel pump not running No fuel being injected
Diff cult to start when cold	Air flter dirty or blocked Fuel system wiring fault Enrichment device not working Coolant temperature sensor short circuit
Diff cult to start when hot	Air flter dirty or blocked Fuel system wiring fault Coolant temperature sensor open circuit
Engine starts but then stops immediately	Fuel system contamination Fuel pump or circuit fault (relay) Intake system air leak
Erratic idle	Air flter blocked Inlet system air leak Incorrect CO setting Idle air control valve not operating Fuel injectors not spraying correctly
Misf re through all speeds	Fuel flter blocked Fuel pump delivery low Fuel tank ventilation system blocked

(Continued)

Symptom	Possible fault
Engine stalls	Idle speed incorrect CO setting incorrect Fuel flter blocked Air flter blocked Intake air leak Idle control system not working
Lack of power	Fuel flter blocked Air flter blocked Low fuel pump delivery Fuel injectors blocked
Backf res	Fuel system fault (airfow sensor on some cars) Ignition timing

6.13 Diesel injection

6.13.1 Introduction

The basic principle of the four-stroke diesel engine is very similar to the petrol system. The main difference is that the mixture formation takes place in the cylinder combustion chamber as the fuel is injected under very high pressure. The timing and quantity of the fuel injected is important from the usual issues of performance, economy and emissions (Figure 6.47).

Fuel is metered into the combustion chamber by way of a high-pressure pump connected to injectors via heavy-duty pipes. When the fuel is injected, it mixes with the air in the cylinder and will self-ignite at approximately 800 °C. The mixture formation in the cylinder is inf uenced by the following factors.

The timing of a diesel fuel injection pump to an engine is usually done using start of delivery as the reference mark. The actual start of injection, in other words when fuel starts to leave the injector, is slightly later than the start of delivery, as this is inf uenced by the compression ratio of the engine, the compressibility of the fuel and the length of the delivery pipes. This timing has a great effect on the production of carbon particles (soot), if too early, and increases the hydrocarbon emissions, if too late.

The duration of the injection is expressed in degrees of crankshaft rotation in milliseconds. This clearly inf uences fuel quantity, but the rate of discharge is also important. This rate is not constant due to the mechanical characteristics of the injection pump.

Pressure of injection will affect the quantity of fuel, but the most important issue here is the effect on atomisation. At higher pressures, the fuel will atomise into smaller droplets with a corresponding improvement in the burn quality. Indirect injection systems use pressures up to approximately 350 bar and direct injection systems can be up to approximately 1000 bar. Emissions of soot are greatly reduced by higher-pressure injection.

The direction of injection must match very closely the swirl and combustion chamber design. Deviations of only 2° from the ideal can greatly increase particulate emissions.

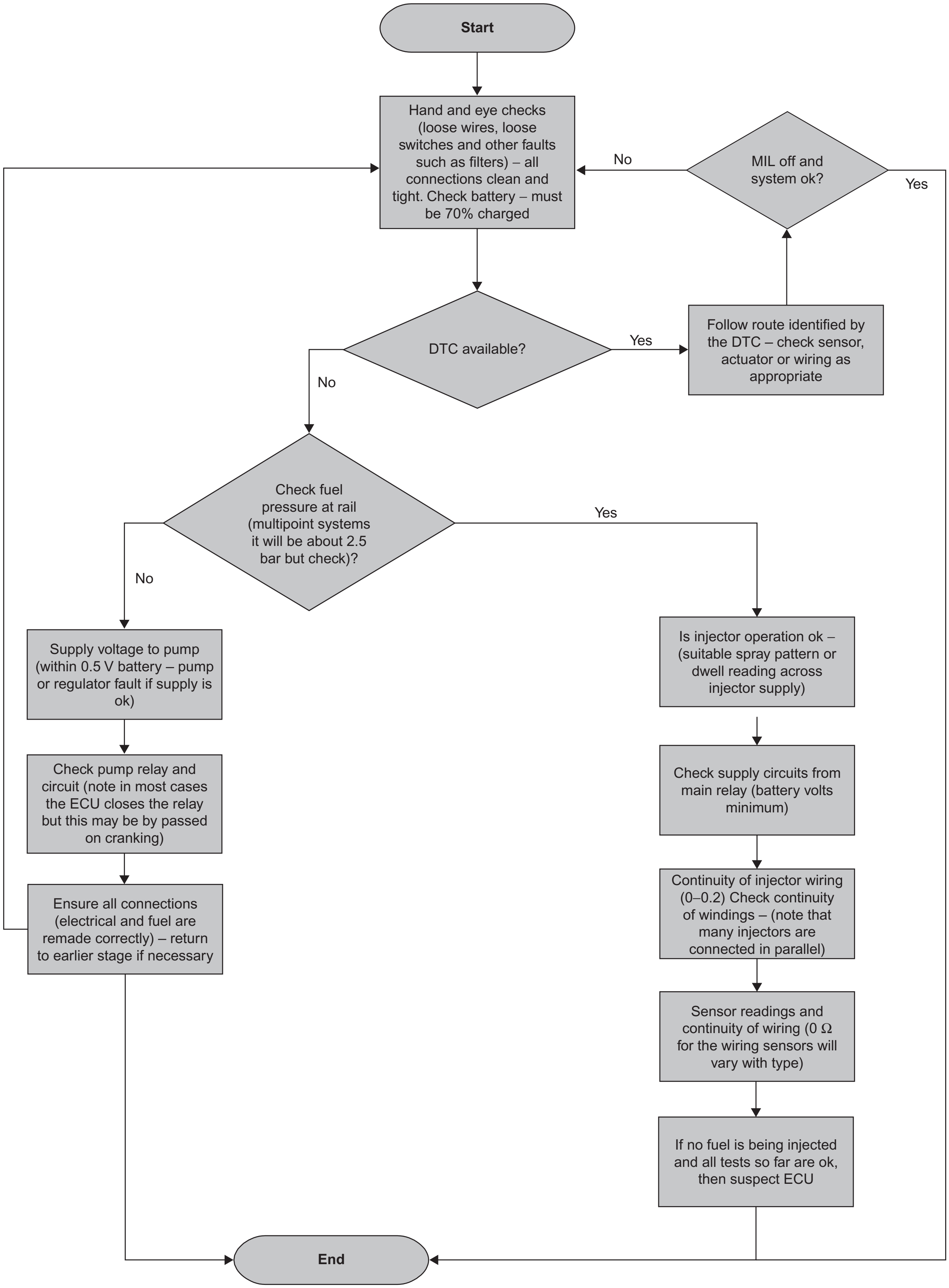


Figure 6.47 Fuel injection system diagnosis chart

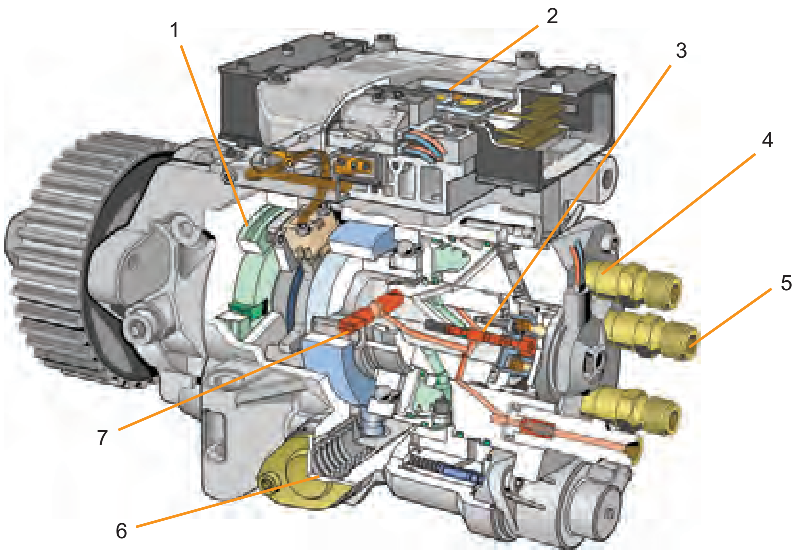


Figure 6.48 Solenoid-valve controlled radial-piston distributor pump: 1– sensor (position/timing); 2 – ECU; 3 – high-pressure solenoid valve needle; 4 – solenoid; 5 – outlets to injectors; 6 – timing device (ignition advance mechanism); 7 – radial-piston high-pressure pump (Source: Bosch Media)

Diesel engines do not in general use a throttle butterf y, as the throttle acts directly on the injection pump to control fuel quantity. At low speeds in particular the very high excess air factor ensures complete burning and very low emissions. Diesel engines operate where possible with an excess air factor even at high speeds.

Figure 6.48 shows a typical diesel fuel injection pump. Detailed operation of the components is beyond the scope of this book. The principles and problems are the issues under consideration, in particular the way electronics can be employed to solve some of the problems.

6.13.2 Electronic control of diesel injection

The advent of electronic control over the diesel injection pump has allowed many advances over the purely mechanical system. The production of high pressure for injection is, however, still mechanical with all current systems. The following advantages are apparent over the non-electronic control system:

- more precise control of fuel quantity injected;
- better control of start of injection;
- idle speed control;
- control of EGR;
- drive by wire system (potentiometer on throttle pedal);
- an anti-surge function;
- output to data acquisition systems, etc.;
- temperature compensation;
- cruise control.

Because fuel must be injected at high pressure, the hydraulic head, pressure pump and drive elements are still used. An electromagnetic moving iron actuator adjusts the position of the control collar, which in turn controls the delivery stroke and therefore the injected quantity of fuel. Fuel pressure is applied to a roller

Key fact

Electronic control of diesel injection has allowed many advances over the purely mechanical system.

ring and this controls the start of injection. A solenoid-operated valve controls the supply to the roller ring. These actuators together allow control of start of injection and injection quantity.

Ideal values for fuel quantity and timing are stored in memory maps in the ECU. The injected fuel quantity is calculated from the accelerator position and the engine speed. Start of injection is determined from the following:

- fuel quantity;
- engine speed;
- engine temperature;
- air pressure.

The ECU is able to compare start of injection with actual delivery from a signal produced by the needle motion sensor in the injector.

Control of EGR is a simple solenoid valve. This is controlled as a function of engine speed, temperature and injected quantity. The ECU is also in control of the stop solenoid and glow plugs via a suitable relay.

Key fact

Common rail diesel injection operates at very high injection pressures and has piloted and phased injection to reduce noise and vibration.

6.13.3 Common rail diesel systems

The development of diesel fuel systems is continuing, with many new electronic changes to the control and injection processes. One of the latest developments is the 'common rail' system, operating at very high injection pressures. It also has piloted and phased injection to reduce noise and vibration (Figure 6.49).

The common rail system has made it possible, on small, high-speed diesel engines, to have direct injection, whereas previously they would have been of indirect injection design. These developments are showing improvements in fuel consumption and performance of up to 20% over the earlier indirect injection engines of a similar capacity. The common rail injection system can be used on the full range of diesel engine capacities.

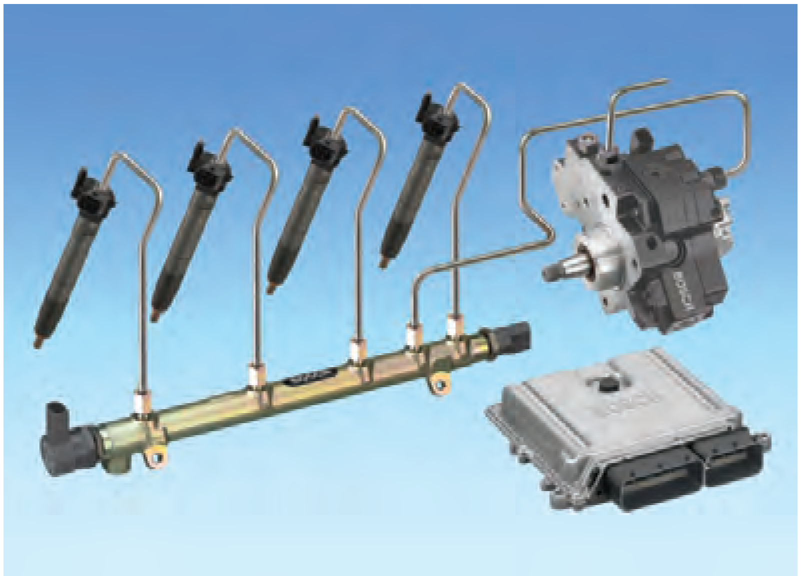


Figure 6.49 Common rail diesel system components (Source: Bosch Media)

The combustion process, with common rail injection, is improved by a pilot injection of a very small quantity of fuel, at between 40° and 90° BTDC. This pilot fuel ignites in the compressing air charge so that the cylinder temperature and pressure are higher than in a conventional diesel injection engine at the start of injection. The higher temperature and pressure reduce ignition lag to a minimum, so that the controlled combustion phase during the main injection period is softer and more eff cient (Figure 6.50).

Fuel injection pressures are varied – throughout the engine speed and load range – to suit the instantaneous conditions of driver demand and engine speed and load conditions. Data input from other vehicle system ECUs is used to further adapt the engine output, to suit changing conditions elsewhere on the vehicle. Examples are traction control, cruise control and automatic transmission gearshifts.

The electronic diesel control (EDC) module carries out calculations to determine the quantity of fuel delivered. It also determines the injection timing based on engine speed and load conditions.

The actuation of the injectors, at a specif c crankshaft angle, and for a specif c duration, is made by signal currents from the EDC module. A further function of the EDC module is to control the accumulator (rail) pressure.

In summary, common rail diesel fuel injection systems consist of four main component areas:

- low-pressure delivery;
- high-pressure delivery with a high-pressure pump and accumulator (the rail);
- electronically controlled injectors (Figure 6.51);
- electronic control unit and associated sensors and switches.

The main sensors for calculation of the fuel quantity and injection advance requirements are the accelerator pedal sensor, crankshaft speed and position sensor, air mass meter and the engine coolant temperature sensor.

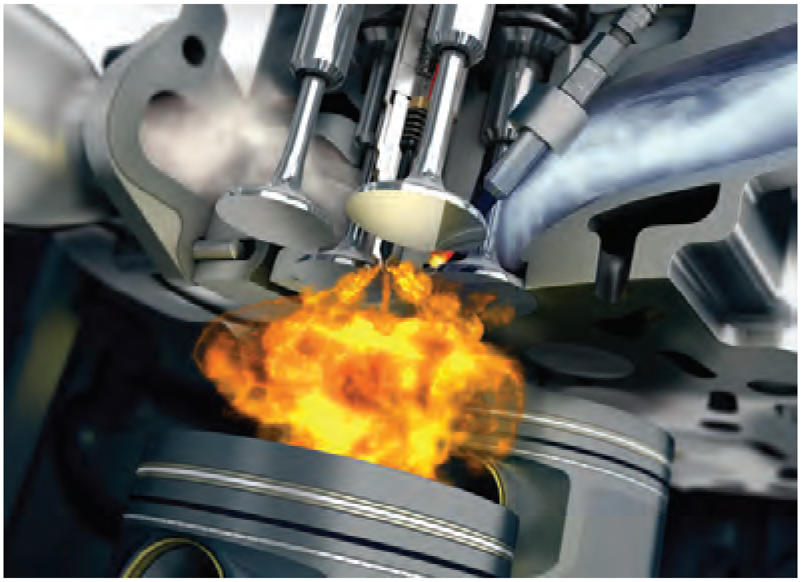


Figure 6.50 Common rail diesel combustion

6.13.4 Diesel exhaust emissions

Exhaust emissions from diesel engines have been reduced considerably by changes in the design of combustion chambers and injection techniques.

More accurate control of start of injection and spill timing has allowed further improvements to be made. Electronic control has also made a signif cant contribution. A number of further techniques can be employed to control emissions.

Key fact

Overall, the gas emissions from diesel combustion are lower than those from petrol combustion; the main problem area is that of particulates.

Overall, the gas emissions from diesel combustion are far lower than those from petrol combustion. The CO, HC and NO_x emissions are lower mainly due to the higher compression ratio and excess air factor. The higher compression ratio improves the thermal eff ciency and thus lowers the fuel consumption. The excess air factor ensures more complete burning of the fuel.

The main problem area is that of particulate emissions. These particle chains of carbon molecules can also contain hydrocarbons, aldehydes mostly. The dirt effect of this emission is a pollution problem, but the possible carcinogenic effect of this soot gives cause for concern. The diameter of these particles is only a few ten thousandths of a millimetre. This means they f oat in the air and can be inhaled.

In much the same way as with petrol engines, EGR is employed primarily to reduce NO_x emissions by reducing the reaction temperature in the combustion chamber. However, if the percentage of EGR is too high, increased hydrocarbons and soot are produced. This is appropriate to turbocharged engines such that if the air is passed through an intercooler and there are improvements in volumetric eff ciency, lower temperature will again reduce the production of NO_x. The intercooler is f tted in the same way as the cooling system radiator.

6.13.5 Catalytic converter diesel

On a diesel engine, a catalyst can be used to reduce the emission of hydrocarbons but will have less effect on nitrogen oxides. This is because diesels are always run with excess air to ensure better and more eff cient burning of the fuel. A normal catalyst therefore will not strip the oxygen off the NO to oxidise the

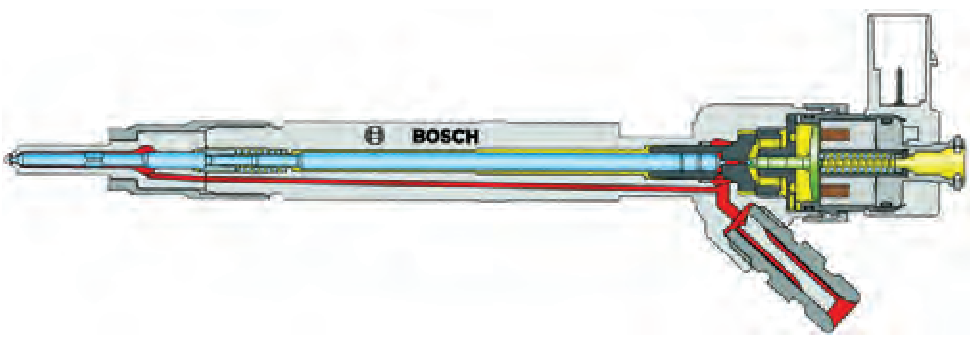


Figure 6.51 Electrically operated diesel fuel injector

hydrocarbons because the excess oxygen will be used. Special NO_x converters are becoming available.

6.13.6 Filters

To reduce the emission of particulate matter (soot), f lters can be used. These can vary from a f ne grid design made from a ceramic material to centrifugal f lters and water trap techniques. The problem to overcome is that the f lters can get blocked, which adversely affects the overall performance. Several techniques are employed including centrifugal f lters.

6.14 Diagnostics – diesel injection systems

Safety f rst

Note: You should always refer to the manufacturer's instructions appropriate to the equipment you are using.

6.14.1 Test equipment

Smoke meter

The smoke meter is an essential device in the United Kingdom and other countries where the level of smoke in the exhaust forms part of the annual test. Most devices use infrared light to 'count' the number of soot particles in the exhaust sample. This particulate matter is highly suspected of being carcinogenic (Figure 6.52).

Injector tester

The pressure required to 'crack' (lift the nozzle) on an injector can be tested (Figure 6.53).

Figure 6.52 Gas analyser and smoke meter

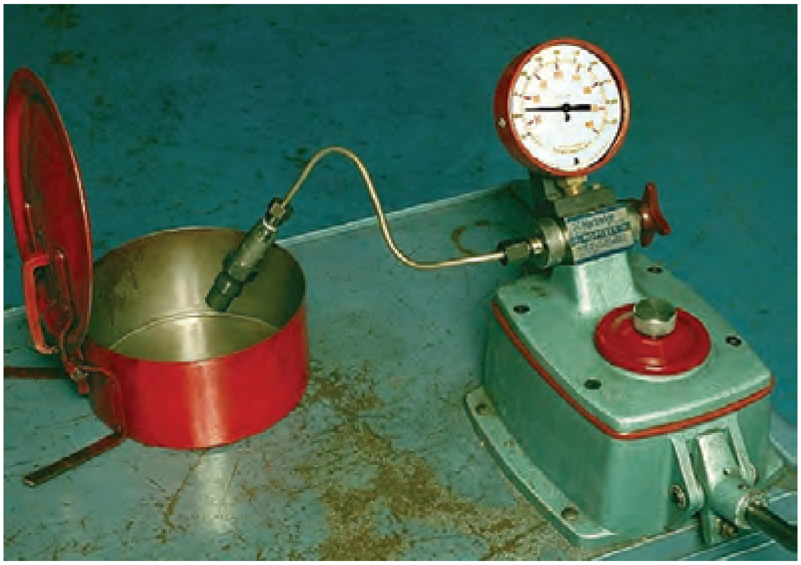


Figure 6.53 Injector pop tester

6.14.2 Diesel injection fault diagnosis table

Symptom	Possible fault
Engine rotates but does not start	No fuel in the tank! Cam belt broken Fuel pump drive broken Open circuit supply to stop solenoid Fuel flter blocked
Excessive smoke	Refer to the next section
Lack of power	Timing incorrect Governor set too low Injector nozzles worn Injector operating pressure incorrect
Diffcult to start	Timing incorrect Glow plugs not working
Fuel smell in the car	Fuel lines leaking Leak off pipes broken
Diesel knock (particularly when cold)	Timing incorrect Glow plug hold on for idle circuit not working
Engine oil contaminated with fuel	Piston broke (like me after a good holiday!) Work piston rings Excessive fuel injected

6.14.3 Diesel engine smoke

Diesel fuel is a hydrocarbon fuel. When it is burned in the cylinder, it will produce carbon dioxide and water. There are, however, many circumstances under which the fuel may not be completely burned and one of the results is smoke. Despite the fact that diesel engines are designed to run under all conditions with an excess of air, problems still occur. Very often, these smoke problems are easily avoided by proper maintenance and servicing of the engine and its fuel system. The emission of smoke is usually due to a shortage of air (oxygen). If insuff cient air is available for complete combustion, then unburnt fuel will be exhausted as tiny particles of fuel (smoke).

The identif cation of the colour of diesel smoke and under what conditions it occurs can be helpful in diagnosing what caused it in the f rst place. Poor-quality fuel reduces engine performance, increases smoke and reduces engine life. There are three colours of smoke: white, blue and black. All smoke diagnosis tests must be carried out with the engine at normal operating temperature.

White or grey smoke

White smoke is vaporised unburnt fuel and is caused by there being suff cient heat in the cylinder to vaporise it but not enough remaining heat to burn it. All diesel engines generate white smoke when starting from cold and it is not detrimental to the engine in any way – it is a diesel characteristic. Possible causes of white smoke are listed below:

- **Faulty cold starting equipment** – Cold engines suffer from a delay in the combustion process. A cold start unit is f tted to advance the injection timing to counteract this delay. This means that white smoke could be a cold start unit problem.
- **Restrictions in the air supply** – A partially blocked air cleaner will restrict the air supply – an easy cause to rectify but often overlooked. Incidentally, a blocked air cleaner element at light load in the workshop becomes a black smoke problem when the engine is under load. In both cases, there will not be suff cient air entering the cylinder for the piston to compress and generate full heat for combustion.
- **Cold running** – Check the cooling system thermostat to see if the correct rated thermostat is f tted.
- **Incorrect fuel injection pump timing** – If fuel is injected late (retarded timing), it may be vaporised but not burned.
- **Poor compressions** – Poor compressions may lead to leakage during the compression stroke and inevitably less heat would be generated.
- **Leaking cylinder head gasket** – If coolant were leaking into the combustion area, the result would be less temperature in the cylinder causing white smoke. Steam may also be generated if the leak is suff cient. All internal combustion engines have water as a by-product from burning fuel – you will have noticed your own car exhaust, especially on a cold morning.

Blue smoke

Blue smoke is almost certainly a lubricating oil burning problem. Possible causes of blue smoke are listed:

- incorrect grade of lubricating oil;
- worn or damaged valve stem oil seals, valve guides or stems where lubricating oil is getting into the combustion chamber;
- worn or sticking piston rings;
- worn cylinder bores.

Black smoke

Black smoke is partly burned fuel. Possible causes are listed below:

- **Restriction in air intake system** – A blocked air cleaner element will not let enough air in to burn all the fuel.

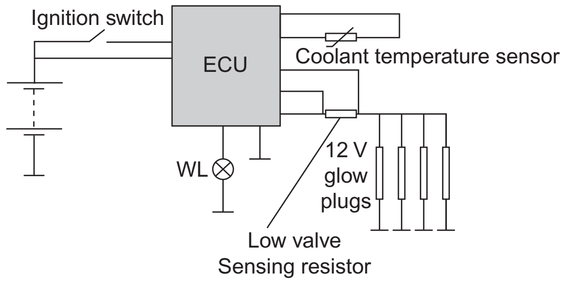


Figure 6.54 Glow plug circuit

- **Incorrect valve clearances –** Excessive valve clearances will cause the valves not to fully open and to close sooner. This is another form of insuff cient air supply.
- **Poor compressions** – Air required for combustion may leak from the cylinder.
- **Defective or incorrect injectors** – Check the injector to see if the spray is fully atomised and solid fuel is not being injected.
- **Incorrect fuel injection pump timing** – This is less likely because the timing would need to be advanced to the point where additional engine noise would be evident.
- **Low boost pressure** – If a turbocharger is f tted and is not supplying enough air for the fuel injected, this is another form of air starvation.

6.14.4 Glow plug circuit

Figure 6.54 shows a typical glow plug circuit controlled by an ECU. Most timer circuits put the glow plugs on for a few seconds before cranking. A warning light may be used to indicate the 'ready' condition to the driver.

Take care to note the type of glow plugs used; most are 12 V and connected in parallel, but some are connected in series (4 − 3 V plugs). To check the operation of most 12 V glow plug circuits, use the following steps:

1. Hand and eye checks.
2. Battery condition – at least 70%.
3. Engine must be cold – it may be possible to simulate this by disconnecting the temperature sensor.
4. Voltage supplied to plugs when ignition is switched on (spring-loaded position in some cases) – 10–12 V.
5. Warning light operation – should go out after a few seconds.
6. Voltage supplied to plugs while cranking – 9–11 V.
7. Voltage supplied to plugs after engine has started – 0 V or if silent idle system is used 5–6 V for several minutes.
8. Same tests with engine at running temperature – glow plugs may not be energised or only for the starting phase.

6.14.5 Diesel systems

It is recommended that when the injection pump or the injectors are diagnosed as being at fault, reconditioned units should be f tted. Other than basic settings of timing, idle speed and governor speed, major overhaul is often required. Figure 6.55 shows a general diagnosis pattern for diesel systems.

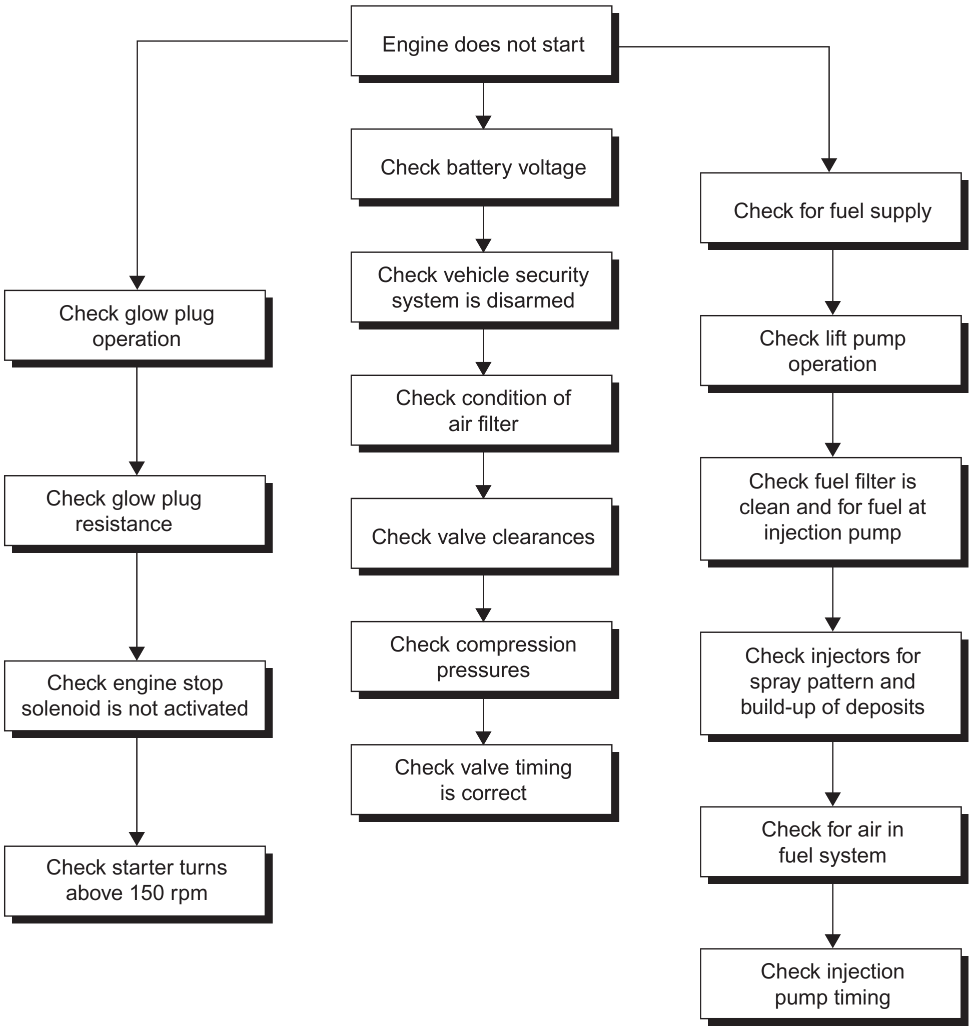


Figure 6.55 Diesel system generic diagnostic process

6.15 Engine management

6.15.1 Introduction

As the requirement for lower and lower emissions continues together with the need for better performance, other areas of engine control are constantly being investigated. This is becoming even more important as the possibility of carbon dioxide emissions being included in the regulations increases. Some of the current and potential areas for further control of engine operation are included in this section. Most of the common aspects have been covered earlier in the 'Ignition' and 'Fuel injection' sections. The main areas of control are as follows:

- ignition timing;
- dwell angle;
- fuel quantity;
- idle speed.

Further areas of engine control may include the following:

- EGR;
- canister purge;

- valve timing;
- inlet manifold length;
- closed-loop lambda control.

It is not possible for an engine to operate at its best volumetric eff ciency with f xed manifolds. This is because the length of the inlet tract determines the velocity of the intake air and in particular the propagation of the pressure waves set up by the pumping action of the cylinders. These standing waves can be used to improve the ram effect of the charge as it enters the cylinder but only if they coincide with the opening of the inlet valves. The length of the inlet tract has an effect on the frequency of these waves.

With the widespread use of twin-cam engines, one cam for the inlet valves and one for the exhaust valves, it is possible to vary the valve overlap while the engine is running. Honda has a system that improves the power and torque range by opening both of the inlet valves only at higher speed.

Many systems use oil pressure controlled by valves to turn the cam with respect to its drive gear. This alters the cam phasing or relative position. The position of the cams is determined from a suitable map held in ROM in the control unit.

6.15.2 Closed-loop lambda control

Current regulations have almost made closed-loop control of air fuel mixture in conjunction with a three-way catalytic converter mandatory. Lambda control is a closed-loop feedback system in that the signal from a lambda sensor in the exhaust can directly affect the fuel quantity injected. The lambda sensor is described in more detail in Chapter 4.

A graph to show the effect of lambda control in conjunction with a catalytic converter is shown in Figure 6.56. The principle of operation is as follows: the lambda sensor produces a voltage which is proportional to the oxygen content of the exhaust which is in turn proportional to the air fuel ratio. At the ideal setting, this voltage is approximately 450 mV. If the voltage received by the ECU is below this value (weak mixture), the quantity of fuel injected is increased slightly. If the signal voltage is above the threshold (rich mixture), the fuel quantity is reduced. This alteration in air fuel ratio must not be too sudden, as it could cause the engine to buck. To prevent this, the ECU contains an integrator, which changes the mixture over a period of time.

A delay also exists between the mixture formation in the manifold and the measurement of the exhaust gas oxygen. This is due to the engine's working cycle and the speed of the inlet mixture, the time for the exhaust to reach the sensor and the sensor's response time. This is sometimes known as dead time and can be as much as one second at idle speed but only a few hundred milliseconds at higher engine speeds.

Owing to the dead time, the mixture cannot be controlled to an exact value of lambda equals 1. If the integrator is adjusted to allow for engine speed, then it is possible to keep the mixture in the lambda window (0.97–1.03), which is the region in which the TWC is at its most eff cient.

Key fact

Lambda control is a closed-loop negative feedback system.

Def nition

TWC: Three-way catalyst.

Key fact

The lambda window (0.97–1.03) is the region in which the TWC is at its most effcient.

6.15.3 Engine management operation

The combination of ignition and injection control has several advantages. The information received from various sensors is used for computing both fuelling

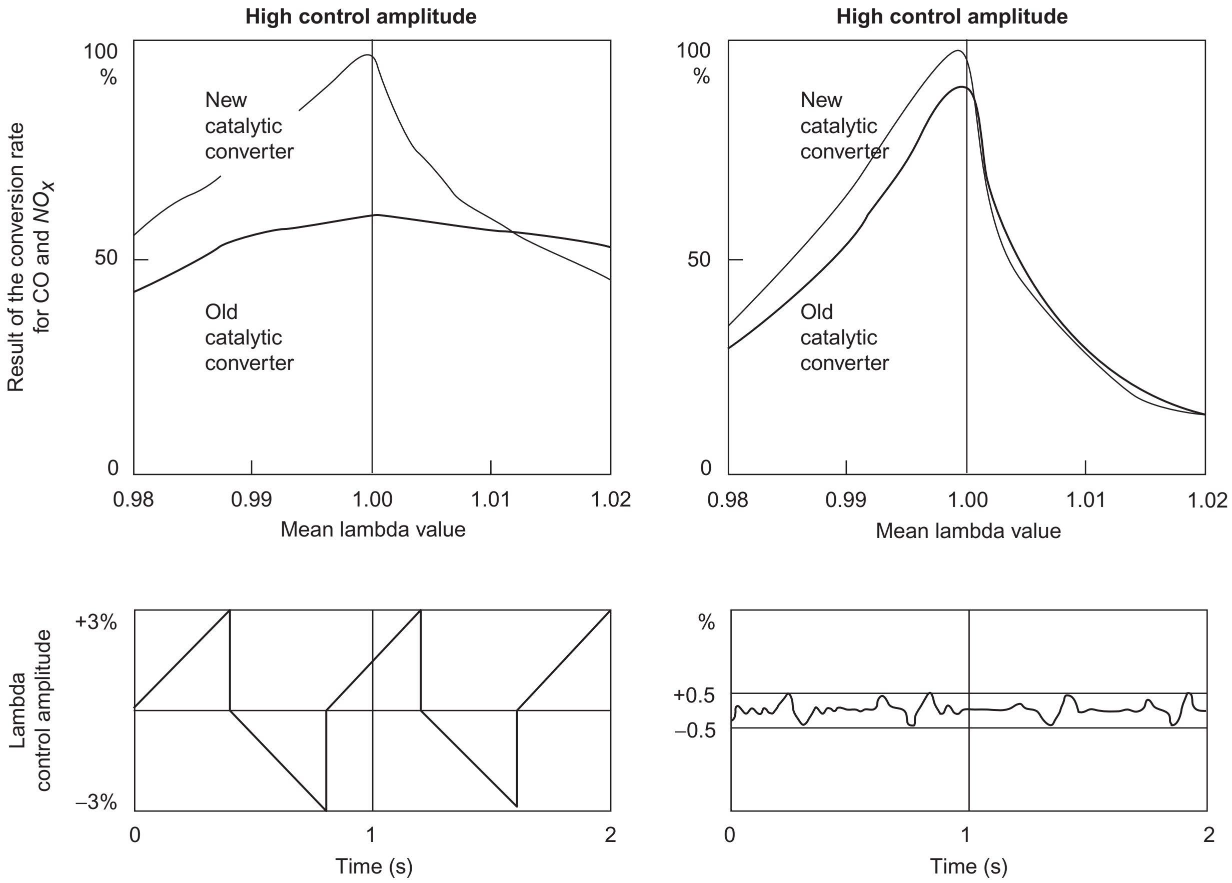


Figure 6.56 Effect of lambda control on catalytic converters

and ignition requirements. Perhaps more importantly ignition and injection are closely linked. The inf uence they have on each other can be easily taken into account to ensure that the engine is working at its optimum, under all operating conditions.

Overall, this type of system is less complicated than separate fuel and ignition systems and in many cases the ECU is able to work in an emergency mode by substituting missing information from sensors with pre-programmed values. This will allow limited but continued operation in the event of certain system failures.

The ignition system is integrated and is operated without a high-tension (HT) distributor. The ignition process is controlled digitally by the ECU. The data for the ideal characteristics are stored in ROM from information gathered during both prototyping and development of the engine. The main parameters for ignition advance are engine speed and load, but greater accuracy can be achieved by taking further parameters into account such as engine temperature. This provides both optimum output and close control of anti-pollution levels. Performance and pollution level control means that the actual ignition point must be in many cases a trade-off between the two.

The injection system shown in Figure 6.57 is multipoint and, as is the case for all fuel systems, the amount of fuel delivered is primarily determined by the amount of air 'drawn' into the engine. The method for measuring this data is indirect in the case of this system as a pressure sensor is used to determine the air quantity.

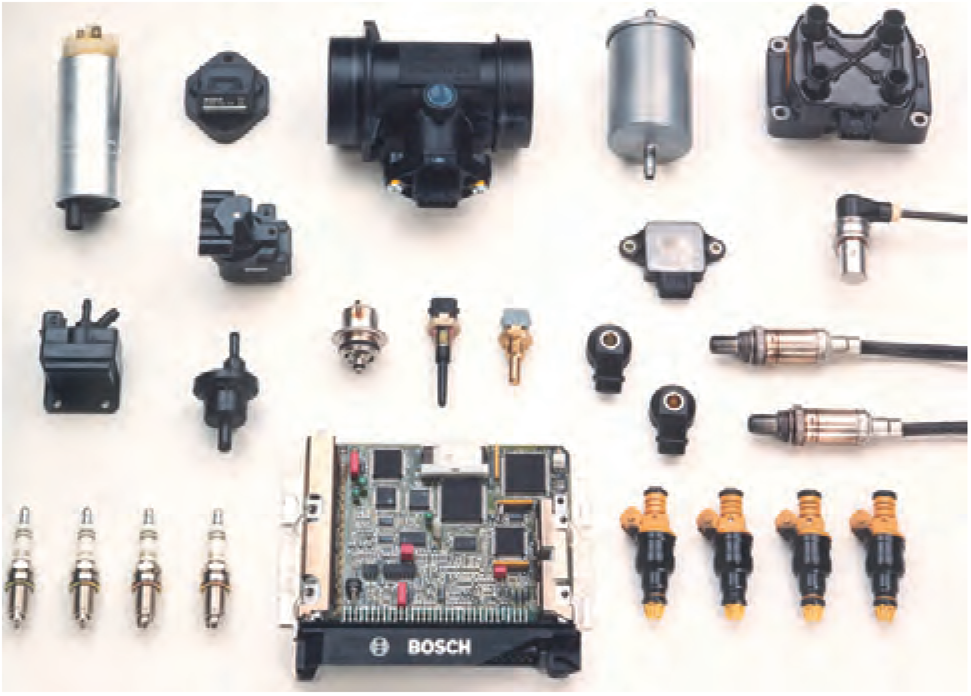


Figure 6.57 Engine management components (Source: Bosch Media)

Key fact

Injector open period is determined by the ECU.

Electromagnetic injectors control fuel supply into the engine. The injector open period is determined by the ECU. This will obtain very accurate control of the air fuel mixture under all operating conditions of the engine. The data for this is stored in ROM in the same way as for the ignition.

The main source of reference for the ignition system is from the crankshaft position sensor. This is a magnetic inductive pick-up sensor positioned next to a f ywheel ring containing 58 teeth. Each tooth takes up a 6° angle of the f ywheel with one 12° gap positioned 114° before top dead centre (BTDC) for number 1 cylinder. The signal produced by the f ywheel sensor is essentially a sine wave with a cycle missing corresponding to the gap in the teeth of the reluctor plate. The information provided to the ECU is engine speed from the frequency of the signal and engine position from the number of pulses before or after the missed pulses.

The basic ignition advance angle is obtained from a memorised cartographic map. This is held in a ROM chip within the ECU. The parameters for this are

- **engine rpm** – given by the f ywheel sensor;
- **inlet air pressure** – given by the MAP sensor.

The above two parameters (speed and load) give the basic setting, but to ensure optimum advance angle the timing is corrected by

- coolant temperature;
- air temperature;
- throttle butterf y position.

The ignition is set to a predetermined advance during the starting phase. Figure 6.58 shows typical advance, fuelling and dwell maps used by an engine management system. This data is held in ROM.

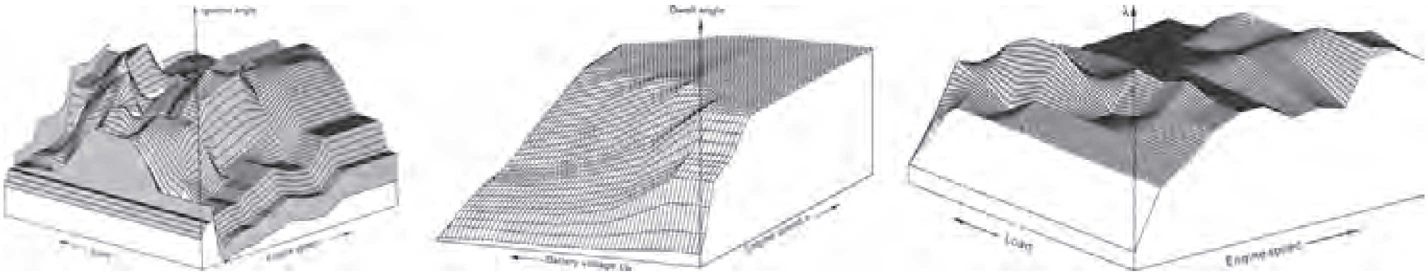


Figure 6.58 Ignition timing, dwell and lambda maps

For full ignition control, the electronic control unit has to f rst determine the basic timing for three different conditions:

- Under idling conditions, ignition timing is often moved very quickly by the ECU in order to control idle speed. When timing is advanced, engine speed will increase within certain limits.
- Full-load conditions require careful control of ignition timing to prevent combustion knock. When a full-load signal is sensed by the ECU (high manifold pressure), the ignition advance angle is reduced.
- Partial throttle is the main area of control and, as already stated, the basic timing is set initially by a programme as a function of engine speed and manifold pressure.

Corrections are added according to

- operational strategy;
- knock protection;
- phase correction.

The ECU will also control ignition timing variation during overrun fuel cut-off and reinstatement and also to ensure anti-jerk control. When starting the ignition timing plan is replaced by a specif c starting strategy. Phase correction is when the ECU adjusts the timing to take into account the time taken for the HT pulse to reach the spark plugs. To ensure good driveability, the ECU can limit the variations between the two ignition systems to a maximum value, which varies according to engine speed and the basic injection period.

An anti-jerk function operates when the basic injection period is less than 2.5 ms and the engine speed is between 720 and 3200 rpm. This function operates to correct the programmed ignition timing in relation to the instantaneous engine speed and a set f ltered speed; this is done to stabilise the engine rotational characteristics as much as possible.

To maintain constant-energy HT, the dwell period must increase in line with engine speed. To ensure that the ignition primary current reaches its maximum at the point of ignition, the ECU controls the dwell by use of another memory map, which takes battery voltage into account.

Fuel is collected from the tank by a pump either immersed in it or outside, but near the tank. The immersed type is quieter in operation, has better cooling and has no internal leaks. The fuel is directed forwards to the fuel rail or manifold, via a paper f lter.

Fuel pressure is maintained at approximately 2.5 bar above manifold pressure by a regulator mounted on the fuel rail. Excess fuel is returned to the tank. The fuel is usually picked up via a swirl pot in the tank to prevent aeration of the fuel. Each of the four inlet manifold tracts has its own injector.

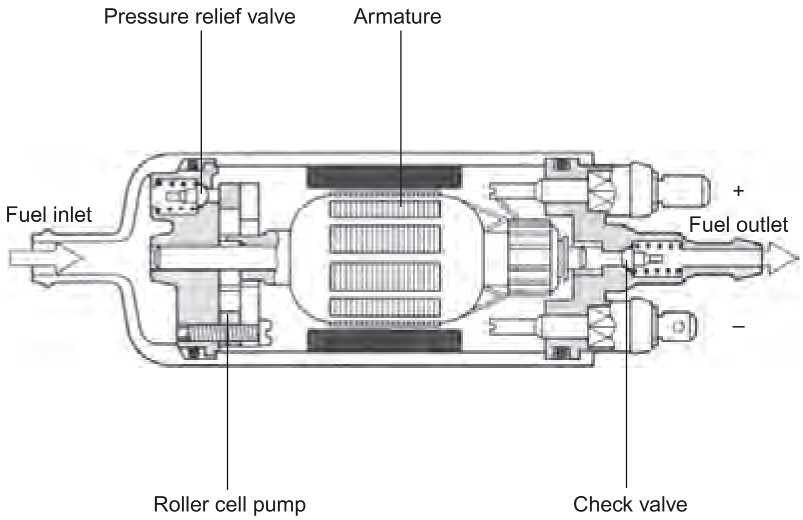


Figure 6.59 Roller cell pump

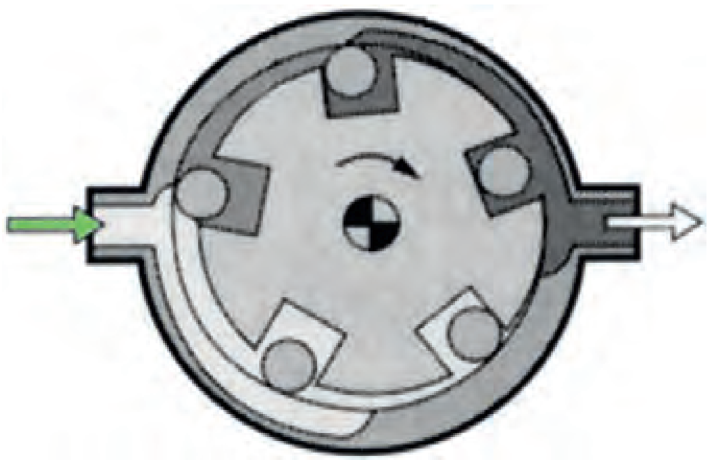


Figure 6.60 Roller cell pump (1)

Most fuel pumps on manifold injection systems are similar to Figure 6.59 and the pump operates as shown in Figures 6.60 and 6.61.

The fuel enters the pump housing where it is pressurised by rotation of the pump and the reduction of the volume in the roller chambers. This pressure opens a residual valve and fuel passes to the f lter. When the pump stops, pressure is maintained by this valve, which prevents the fuel returning. If due to a faulty regulator or a blockage in the line, fuel pressure rises above 7 bar, an overpressure valve will open releasing fuel back to the tank.

The fuel f lter is placed between the fuel pump and the fuel rail. It is f tted one way only to ensure the outlet screen traps any paper particles from the f lter element. The f lter will stop contamination down to between 8 and 10 µm.

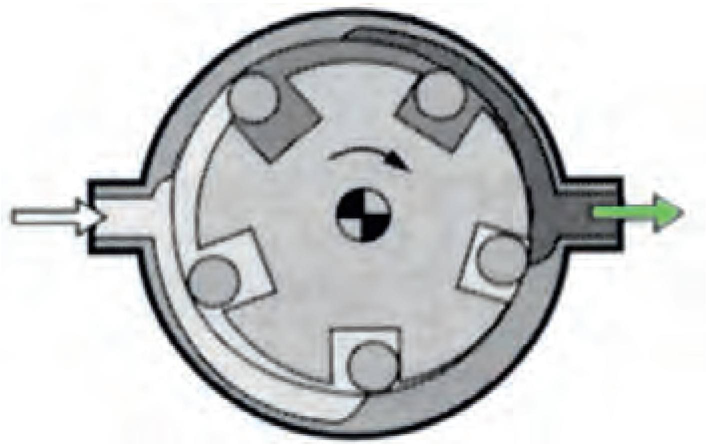


Figure 6.61 Roller cell pump (2)

Replacement varies between manufacturers, but 80 000 km (50 000 miles) is often recommended.

The fuel rail, in addition to providing a uniform supply to the injectors, acts as an accumulator. Depending on the size of the fuel rail, some systems also use an extra accumulator. The volume of the fuel rail is large enough to act as a pressure f uctuation damper, ensuring that all injectors are supplied with fuel at a constant pressure.

Key fact

The fuel rail, in addition to providing a uniform supply to the injectors, acts as an accumulator

Multipoint systems use one injector for each cylinder although very high-performance vehicles may use two. The injectors are connected to the fuel rail by a rubber seal. The injector is an electrically operated valve manufactured to a very high precision. The injector is composed of a body and needle attached to a magnetic core. When the winding in the injector housing is energised, the core or armature is attracted and the valve opens compressing a return spring. The fuel is delivered in a f ne spray to wait behind the closed inlet valve until the induction stroke begins. Provided the pressure across the injector remains constant, the quantity of fuel admitted is related to the open period, which, in turn, is determined by the time the electromagnetic circuit is energised.

The purpose of the fuel pressure regulator is to maintain differential pressure across the injectors at a predetermined constant. This means the regulator must adjust the fuel pressure in response to changes in manifold pressure. It is made of two compressed cases containing a diaphragm, spring and a valve.

The calibration of the regulator valve is determined by the spring tension. Changes in manifold pressure vary the basic setting. When the fuel pressure is suff cient to move the diaphragm, the valve opens and allows the fuel to return to the tank. The decrease in pressure in the manifold, also acting on the diaphragm at say idle speed, will allow the valve to open more easily, hence maintaining a constant differential pressure between the fuel rail and the inlet manifold. This is a constant across the injectors, and hence the quantity of fuel injected is determined only by the open time of the injectors. The differential pressure is maintained at approximately 2.5 bar.

Key fact

Multipoint manifold injection differential pressure is usually maintained at approximately 2.5 bar – but always check data.

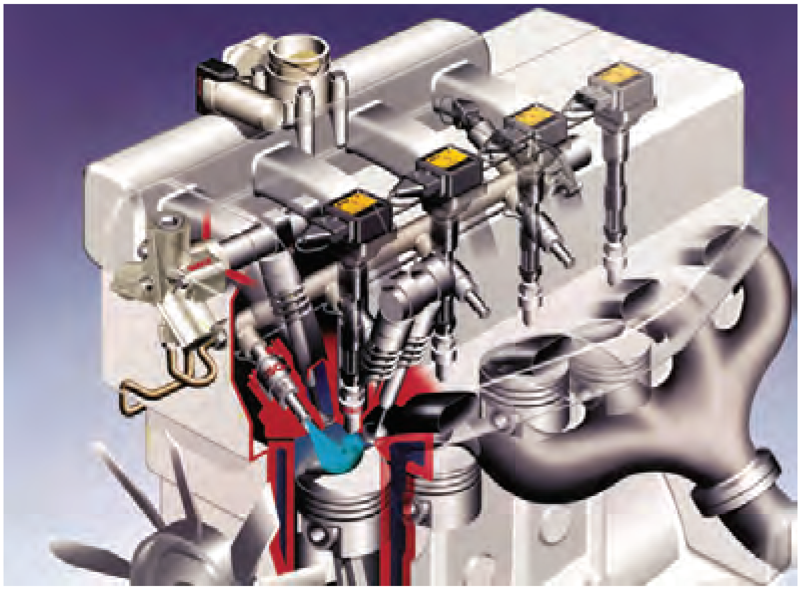


Figure 6.62 Gasoline direct injection (GDI)

Key fact

Gasoline direct injection (GDI) systems use a high-pressure pump to create a regulated pressure of up to 120bar.

Def nition

Homogeneous: A substance that is uniform in composition.

Heterogeneous: A substance that is random and non-uniform in composition.

Def nition

Stratif ed charge: Fuel/air mixture is in layers.

The air supply circuit will vary considerably between manufacturers, but an individual manifold from a collector housing, into which the air is fed via a simple butterf y, supplies essentially each cylinder. The air is supplied from a suitable f lter. A supplementary air circuit is utilised during the warm-up period after a cold start and to control idle speed.

6.15.4 Gasoline direct injection

High-pressure injection systems for petrol/gasoline engines are based on a pressure reservoir and a fuel rail, which a high-pressure pump charges to a regulated pressure of up to 120 bar. The fuel can therefore be injected directly into the combustion chamber via electromagnetic injectors.

The air mass drawn in can be adjusted through the electronically controlled throttle valve and is measured with the help of an air mass meter. For mixture control, a wide-band oxygen sensor is used in the exhaust, before the catalytic converters. This sensor can measure a range between a lambda value of 0.8 and inf nity. The engine electronic control unit regulates the operating modes of the engine with gasoline direct injection (GDI) in three ways:

- stratif ed charge operation – with lambda values greater than 1;
- homogeneous operation – at lambda = 1;
- rich homogeneous operation – with lambda = 0.8.

Compared to the traditional manifold injection system, the Bosch DI-Motronic must inject the entire fuel amount in full-load operation in a quarter of the time. The available time is signif cantly shorter during stratif ed charge operation in part-load. Especially at idle, injection times of less than 0.5 ms are required due to the lower fuel consumption. This is only one-f fth of the available time for manifold injection (Figure 6.62).

The fuel must be atomised very f nely in order to create an optimal mixture in the brief moment between injection and ignition (Figure 6.63). The fuel droplets for

Figure 6.63 Atomization

direct injection are on average smaller than 20 μm. This is only one-f fth of the droplet size reached with the traditional manifold injection and one-third of the diameter of a single human hair. This improves eff ciency considerably.

Direct injection engines operate according to the stratif ed charge concept in the part-load range and function with high excess air. In return, very low fuel consumption is achieved.

The engine operates with an almost completely opened throttle valve, which avoids additional alternating charge losses. With stratif ed charge operation, the lambda value in the combustion chamber is between approximately 1.5 and 3. In the part-load range, GDI achieves the greatest fuel savings with up to 40% at idle compared to conventional petrol injection processes. With increasing engine load, and therefore increasing injection quantities, the stratif ed charge cloud becomes even richer and emission characteristics become worse.

Because soot may form under these conditions, the DI-Motronic engine control converts to a homogeneous cylinder charge at a pre-def ned engine load. The system injects very early during the intake process in order to achieve a good mixture of fuel and air at a ratio of lambda = 1. As is the case for conventional manifold injection systems, the amount of air drawn in for all operating modes is adjusted through the throttle valve according to the desired torque specif ed by the driver.

Diagnosing faults with a GDI system is little different from the manifold injection types. Extra care is needed because of the higher fuel pressures of course. Injector waveforms can be checked as can those associated with the other sensors and actuators.

Key fact

The fuel droplets for direct injection are on average smaller than 20 μm.

6.16 Diagnostics – combined ignition and fuel systems

6.16.1 Testing procedure

The following procedure is very generic but with a little adaptation can be applied to any system. Refer to manufacturer's recommendations if in any doubt (Figure 6.64).

Safety f rst

Warning: Caution/Achtung/Attention – Burning fuel and high voltages can seriously damage your health.

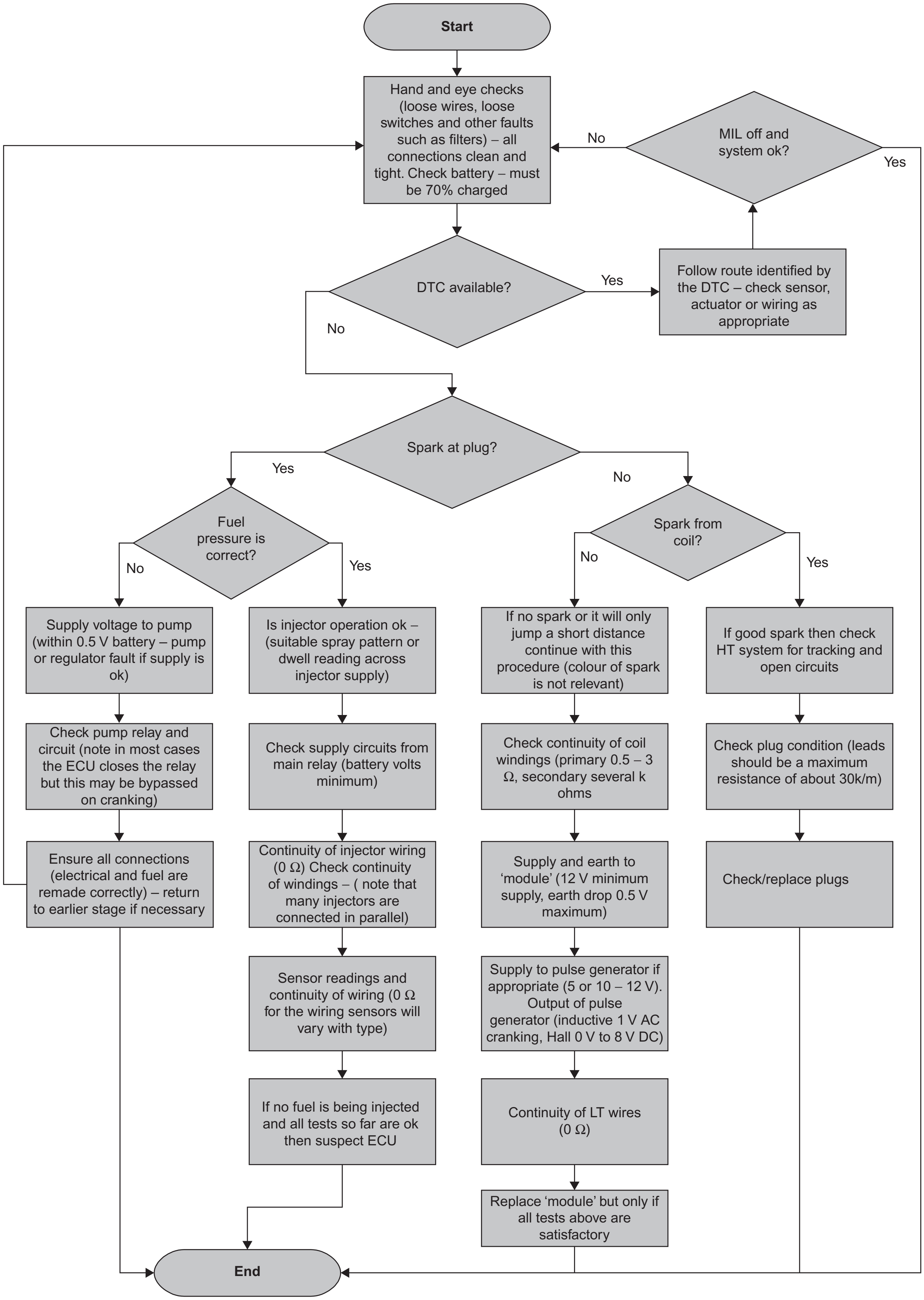


Figure 6.64 Engine management faultfinding chart

6.16.2 Combined ignition and fuel control fault diagnosis table

Symptom	Possible fault
Engine will not start	Engine and battery earth connections Fuel filter and fuel pump Air intake system for leaks Fuses/fuel pump/system relays Fuel injection system wiring and connections Coolant temperature sensor Auxiliary air valve/idle speed control valve Fuel pressure regulator and delivery rate ECU and connector Limp home function – if fitted
Engine difficult to start when cold	Engine and battery earth connections Fuel injection system wiring and connections Fuses/fuel pump/system relays Fuel filter and fuel pump Air intake system for leaks Coolant temperature sensor Auxiliary air valve/idle speed control valve Fuel pressure regulator and delivery rate ECU and connector Limp home function – if fitted
Engine difficult to start when warm	Engine and battery earth connections Fuses/fuel pump/system relays Fuel filter and fuel pump Air intake system for leaks Coolant temperature sensor Fuel injection system wiring and connections Air mass meter Fuel pressure regulator and delivery rate Air sensor filter ECU and connector Knock control – if fitted
Engine starts then stops	Engine and battery earth connections Fuel filter and fuel pump Air intake system for leaks Fuses/fuel pump/system relays Idle speed and CO content Throttle potentiometer Coolant temperature sensor Fuel injection system wiring and connections ECU and connector Limp home function – if fitted
Erratic idling speed	Engine and battery earth connections Air intake system for leaks Auxiliary air valve/idle speed control valve Idle speed and CO content Fuel injection system wiring and connections Coolant temperature sensor Knock control – if fitted Air mass meter Fuel pressure regulator and delivery rate

(Continued)

Symptom	Possible fault
	ECU and connector Limp home function – if fitted
Incorrect idle speed	Air intake system for leaks Vacuum hoses for leaks Auxiliary air valve/idle speed control valve Idle speed and CO content Coolant temperature sensor
Misfire at idle speed	Engine and battery earth connections Air intake system for leaks Fuel injection system wiring and connections Coolant temperature sensor Fuel pressure regulator and delivery rate Air mass meter Fuses/fuel pump/system relays
Misfire at constant speed	Air flow sensor
Hesitation when accelerating	Engine and battery earth connections Air intake system for leaks Fuel injection system wiring and connections Vacuum hoses for leaks Coolant temperature sensor Fuel pressure regulator and delivery rate Air mass meter ECU and connector Limp home function – if fitted
Hesitation at constant speed	Engine and battery earth connections Throttle linkage Vacuum hoses for leaks Auxiliary air valve/idle speed control valve Fuel lines for blockage Fuel filter and fuel pump Injector valves ECU and connector Limp home function – if fitted
Hesitation on overrun	Air intake system for leaks Fuel injection system wiring and connections Coolant temperature sensor Throttle potentiometer Fuses/fuel pump/system relays Air sensor filter Injector valves Air mass meter
Knock during acceleration	Knock control – if fitted Fuel injection system wiring and connections Air mass meter ECU and connector
Poor engine response	Engine and battery earth connections Air intake system for leaks Fuel injection system wiring and connections Throttle linkage Coolant temperature sensor Fuel pressure regulator and delivery rate

(Continued)

Symptom	Possible fault
	Air mass meter ECU and connector Limp home function – fitted
Excessive fuel consumption	Engine and battery earth connections Idle speed and CO content Throttle potentiometer Throttle valve/housing/sticking/initial position Fuel pressure regulator and delivery rate Coolant temperature sensor Air mass meter Limp home function – fitted
CO level too high	Limp home function – fitted ECU and connector Emission control and EGR valve – fitted Fuel injection system wiring and connections Air intake system for leaks Coolant temperature sensor Fuel pressure regulator and delivery rate
CO level too low	Engine and battery earth connections Air intake system for leaks Idle speed and CO content Coolant temperature sensor Fuel injection system wiring and connections Injector valves ECU and connector Limp home function – fitted Air mass meter Fuel pressure regulator and delivery rate
Poor performance	Engine and battery earth connections Air intake system for leaks Throttle valve/housing/sticking/initial position Fuel injection system wiring and connections Coolant temperature sensor Fuel pressure regulator/fuel pressure and delivery rate Air mass meter ECU and connector Limp home function – fitted

6.16.3 Fuel pump testing

Typical high-pressure fuel pump characteristics are as follows (Figure 6.65):

- **delivery** – 120 L/h (1 L in 30 s) at 3 bar;
- **resistance** – 0.8 Ω (static);
- **voltage** – 12 V;
- **current** – 10.5 A.

An ideal test for a fuel pump is its delivery. Using a suitable measuring receptacle, bypass the pump relay and check the quantity of fuel delivered in a set time (refer to manufacturer's specifications). A reduced amount would indicate either a fuel blockage, a reduced electrical supply to the pump or an inefficient pump.

Figure 6.65 Airflow meter under test

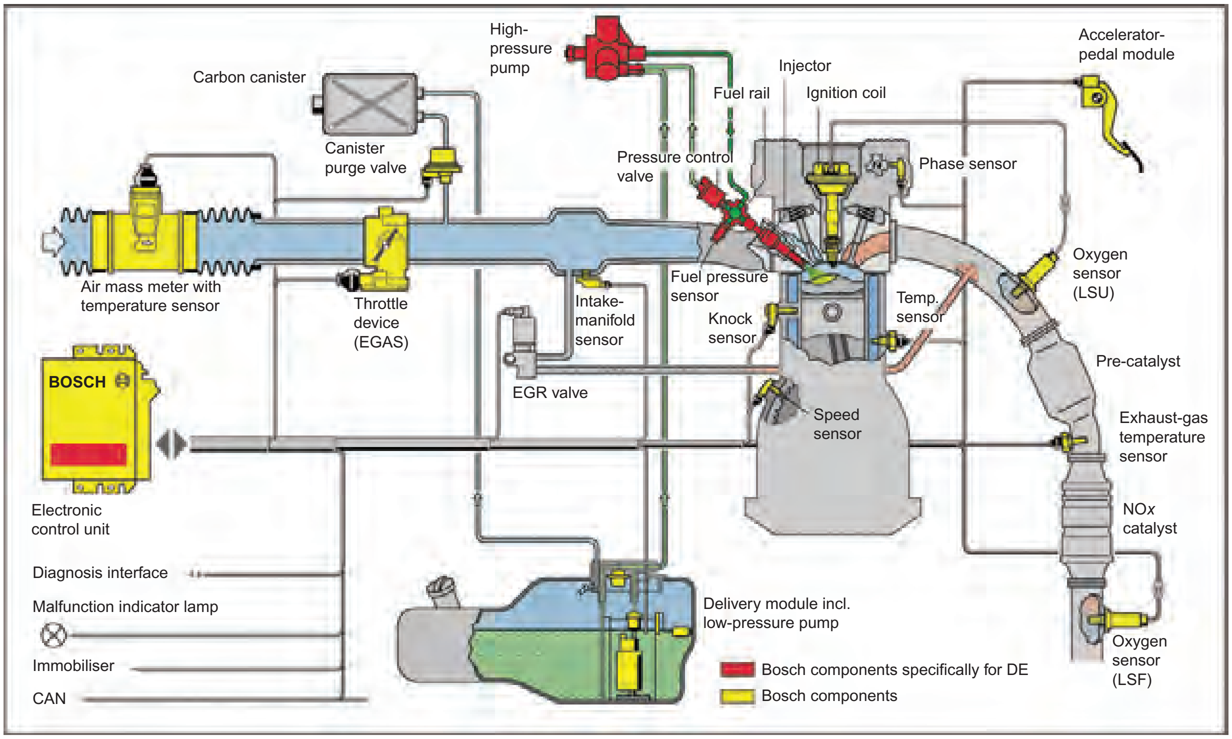


Figure 6.66 Motronic M5 with OBD2 (Source: Bosch Media)

6.16.4 Injector testing

Injectors typically have the characteristics as listed:

- supply voltage – 12 V;
- resistance – 16 Ω;
- static output – 150 cc/min at 3 bar.

As always, check with actual data before carrying out any tests (Figure 6.66).

Resistance checks (with the supply disconnected) are an ideal start to testing injectors. Further tests with the fuel pressurised by the pump and each injector in turn held in a suitable receptacle, include the following:

- **spray pattern** – usually a nice cone shape with good atomisation;
- **delivery** – set quantity over a set time;
- **leakage** – any linkage of more than two drops a minute for standard non-direct injectors is considered excessive (zero is desirable).

6.17 Engine management and faultf nding information

6.17.1 Diagnosis charts

'Autodata' supply diagnosis charts specif c to particular management systems are shown below. Note that some boxes refer you to a further publication (Figure 6.67).

6.17.2 Circuit diagrams

Circuit diagrams can be printed out from some CD-based data sources (Figure 6.68).

6.17.3 Component testing data

Figure 6.69 is an example printout of the type of component testing data that is available.

6.18 Air supply and exhaust systems

6.18.1 Exhaust system

A vehicle exhaust system directs combustion products away from the passenger compartment, reduces combustion noise and, on most modern vehicles, reduces harmful pollutants in the exhaust stream. The main parts of the system are the exhaust manifold, the silencer or muff er, the pipes connecting them and a catalytic converter.

Most exhaust systems are made from mild steel, but some are made from stainless steel which lasts much longer. The system is suspended under the vehicle on rubber mountings. These allow movement because the engine is also rubber mounted, and they also reduce vibration noise.

An exhaust manifold links the engine exhaust ports to the down pipe and main system. It also reduces combustion noise and transfers heat downstream to allow the continued burning of hydrocarbons and carbon monoxide. The manifold is connected to the down pipe, which in turn can be connected to the catalytic converter. Most exhaust manifolds are made from cast iron, as this has the necessary strength and heat transfer properties.

The silencer's main function is to reduce engine noise to an acceptable level. Engine noise is a mixed-up collection of its f ring frequencies (the number of

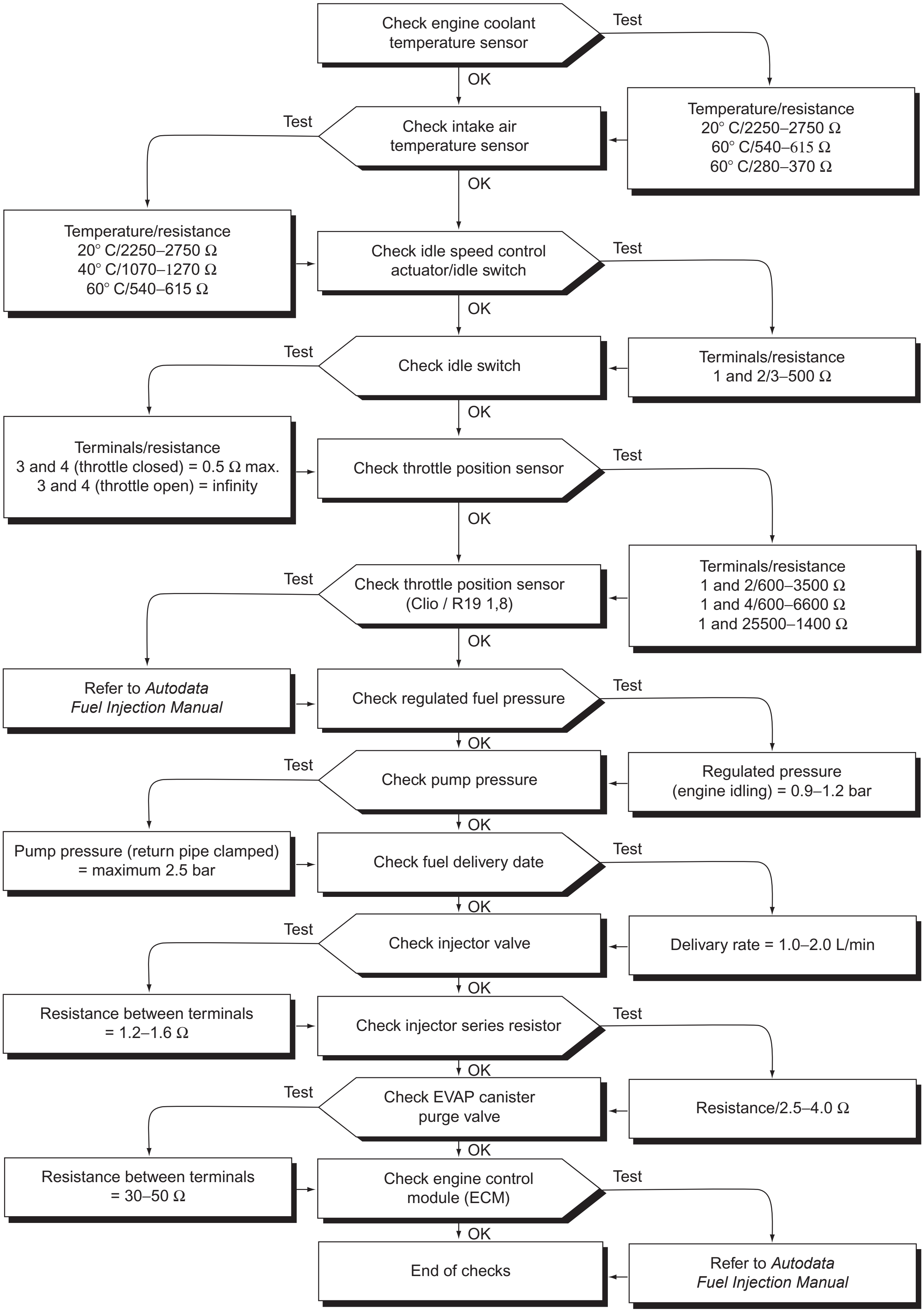


Figure 6.67 Faultfinding chart

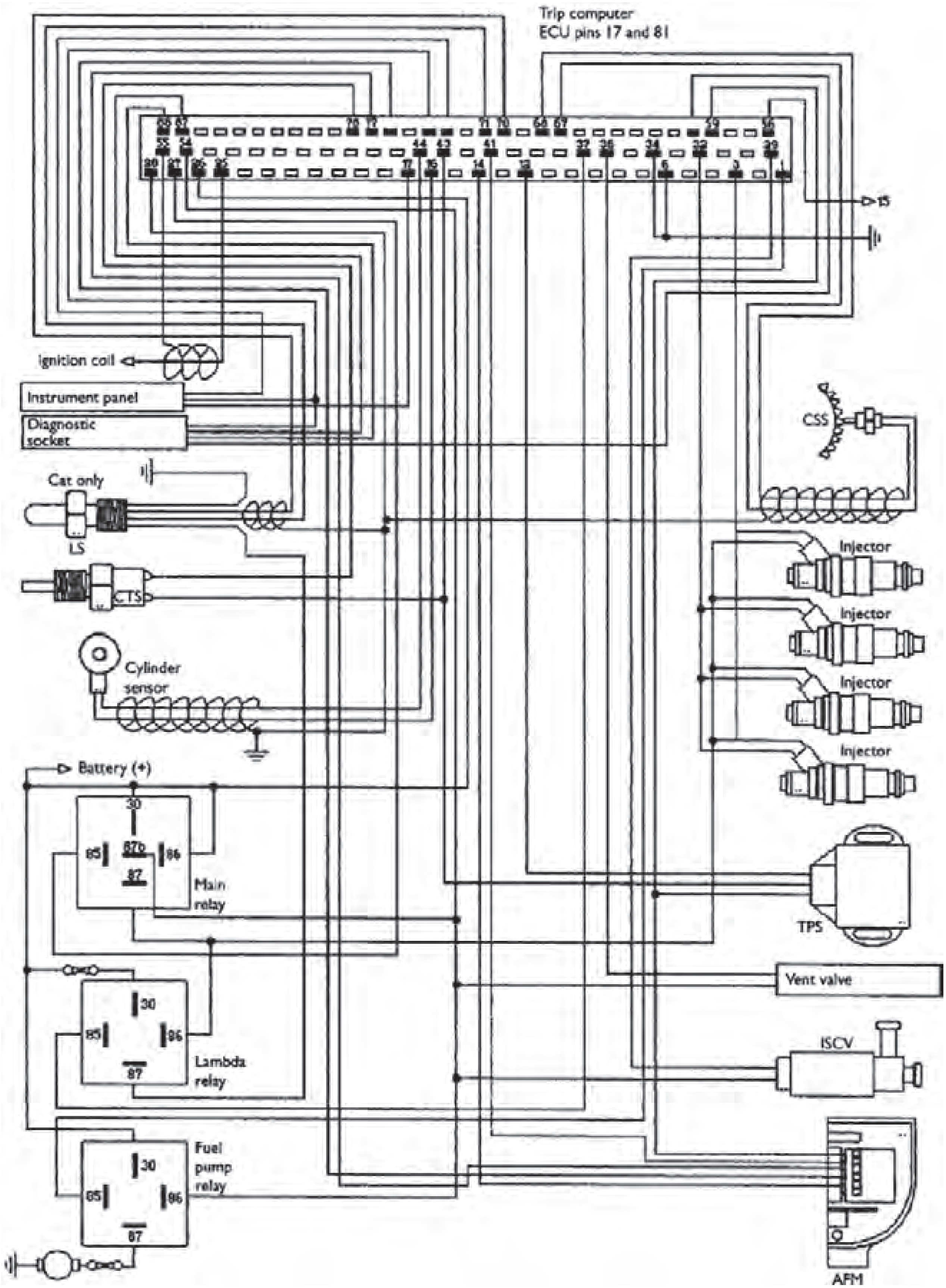


Figure 6.68 Engine management circuit diagram

Mazda 626 2.0i GX 16 valve					
Fuel and ignition Diagnostics					
Air Mass Meter					
position in the intake tubing					
condition					
ignition on / meter plug disconnected					
connection 5 / green / red v+					
	from	4.8	to	5.2	volts
connection 3 / black / orange v–					
condition					
ignition on /meter plug connected					
connection 2 / brown / blue v+					
	from	4	to	6	volts
connection 3 / black / orange v–					
condition					
ignition on /meter plug connected / engine off					
connection 1 / white / blue v+					
	from	0	to	0.3	volts
connection 3 / black / orange v–					
condition					
meter plug connected / engine running at idle					
connection 1 / white / blue v+					
	from	0.4	to	1	volts
connection 3 / black / orange v–					

Figure 6.69 Testing data

times per second each cylinder f res). These range from approximately 100 to 400 Hz (cycles/s). A silencer reduces noise in two main ways:

- interior chambers using baff es, which are tuned to set up cancelling vibrations;
- absorptive surfaces function like sound-deadening wall and ceiling panels to absorb noise.

When the exhaust gases f nally leave the exhaust system, their temperature, pressure and noise have been reduced considerably. The overall length of an exhaust system including the silencers can affect the smooth f ow of gases. For this reason, do not alter the length or change the layout of an exhaust system (Figure 6.70).

6.18.2 Catalytic converters

Key fact

Stringent regulations in most parts of the world have made the use of a catalytic converter essential.

Stringent regulations in most parts of the world have made the use of a catalytic converter essential. The TWC is used to great effect by most manufacturers. It is in effect a very simple device; it looks similar to a standard exhaust silencer box. Note that in order for the 'cat' to operate correctly, the engine must be always well tuned. This is to ensure that the right 'ingredients' are available for the catalyst to perform its function. A catalytic converter works by converting the dangerous exhaust gases into gases which are non-toxic (Figure 6.71).

The core has traditionally been made from ceramic of magnesium aluminium silicate. Owing to the several thousand very small channels, this provides a large surface area. It is coated with a wash coat of aluminium oxide, which again

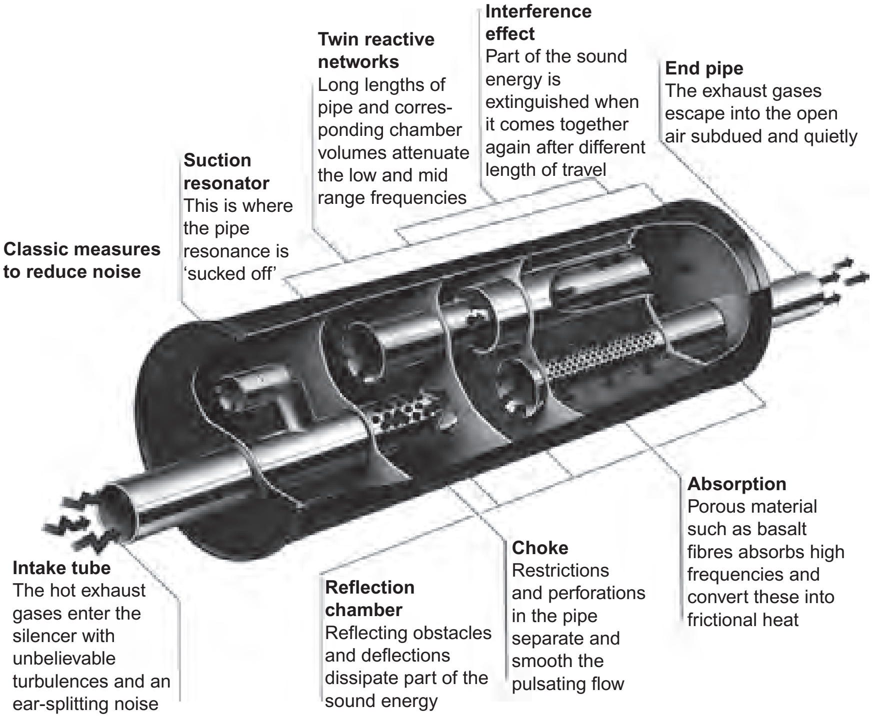


Figure 6.70 Exhaust noise reduction methods

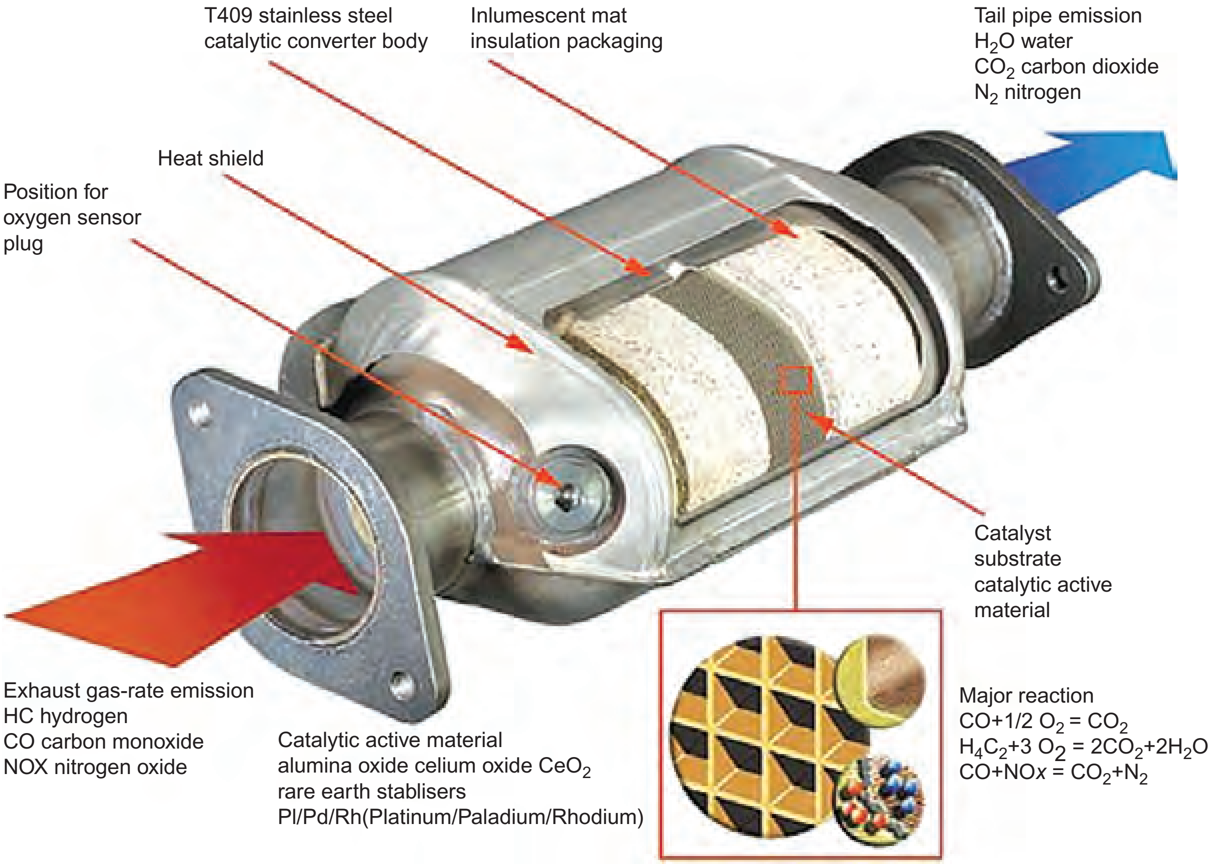


Figure 6.71 Catalytic converter components and operation

increases its effective surface area by about several thousand times. 'Noble' metals are used for the catalysts. Platinum helps to burn off the hydrocarbons (HC) and carbon monoxide (CO), and rhodium helps in the reduction of nitrogen oxides (NO_x). The whole three-way catalytic converter contains only about 3–4 g of these precious metals. Some converters now use metal cores (substrates).

The engine can damage a catalytic converter in one of two ways:

- f rst by the use of leaded fuel which can cause lead compounds to be deposited on the active surfaces;
- second by engine misf re which can cause the catalytic converter to overheat due to burning fuel inside the unit.

Some manufacturers use a system on some vehicles where a sensor checks the output of the ignition HT system and, if the spark is not present, will not allow fuel to be injected. Misf re detection is also part of current on-board diagnostic (OBD) legislation in some countries and future legislation in others.

6.18.3 Air supply system

There are three purposes of the complete air supply system:

1. clean the air;
2. control air temperature;
3. reduce noise.

A f lter does the air cleaning and drawing air from around the exhaust manifold helps to control air temperature. When large quantities of air are drawn into the engine, it causes the air to vibrate and this makes it noisy. In the same way as with the exhaust system, baff es are used to stop resonance. Resonance means that when vibrations reach a natural level they tend to increase and keep going. A good example of how much noise is reduced by the air intake system is to compare the noise when an engine is run with the air f lter removed.

Two types of air f lter are in use, the f rst of these being by far the most popular:

- paper element;
- oil bath and mesh.

Key fact

A paper air lter element is made of resin-impregnated paper.

The paper element is made of resin-impregnated paper. Air f lters using this type of replaceable element are used for both car and commercial vehicles. They provide a very high f ltering eff ciency and reasonable service life. They can be mounted in any position available under the bonnet. Service intervals vary, so check recommendations.

The oil bath and mesh type of air cleaner was widely used on non-turbo charged commercial vehicles. However, it is not very practical for modern low styled bonnets. Because it can be cleaned and fresh oil added, an oil bath air cleaner might still be used for vehicles operating in dusty conditions.

Air temperature control is used to help the vehicle conform to emission control regulations and for good driveability when the engine is cold. Good vaporisation of the fuel is the key. An automatic control is often f tted to make sure that the air intake temperature is always correct. The air cleaner has two intake pipes, one for cold air and the other for hot air from the exhaust manifold or hot box. The proportion of hot and cold air is controlled by a f ap, which is moved by a diaphragm acted on by low pressure from the inlet manifold. The f ap rests in the hot air pick-up position.

A thermo-valve in the air stream senses the temperature of the air going into the engine. When a temperature of approximately 25 °C is reached, the valve opens. This removes the connection to the manifold, which in turn increases the pressure acting on the diaphragm. The f ap is now caused to move and the pick-up is now from the cool air position. The f ap is constantly moving, ensuring that the temperature of air entering the engine remains constant. Picking up hot air when the engine is very cold can also help to prevent icing.

6.19 Diagnostics – exhaust and air supply

6.19.1 Systematic testing

If the reported fault is a noisy exhaust, proceed as follows:

1. Check if the noise is due to the exhaust knocking or blowing.
2. Examine the vehicle on the lift.
3. Check whether further tests are required or the fault is obvious?
4. Cover the end of the exhaust pipe with a rag for a second or two to highlight where the exhaust may be blowing.
5. Renew the exhaust section or complete system as appropriate.
6. Run and test for leaks and knocking.

6.19.2 Test results

Some of the information you may have to get from other sources such as data books or a workshop manual is listed in Table 6.6.

6.19.3 Exhaust and air supply fault diagnosis table 1

Symptom	Possible faults	Suggested action
Exhaust noise	Hole in pipe, box or at joints	Renew as appropriate
Knocking noise	Exhaust incorrectly positioned	Reposition
	Broken mountings	Renew
Rich mixture/smoke	Blocked air lter	Replace
Noisy air intake	Intake trunking or lter box leaking or loose	Repair or secure as required
Poor cold driveability	Hot air pick-up not operating	Check pipe connections to inlet manifold for leaks. Renew temperature valve or actuator

Table 6.6 Tests and information required

Test carried out	Information required
Air flter condition	Clearly a physical examination but note the required service intervals
Exhaust noise	An idea of the normal noise level – note that ‘big-bore’ exhausts will make more noise than the ‘correct’ type

6.19.4 Exhaust fault diagnosis table 2

Symptom	Possible cause
Excessive noise	Leaking exhaust system or manifold joints Hole in exhaust system
Excessive fumes in car	Leaking exhaust system or manifold joints
Rattling noise	Incorrect ftting of exhaust system Broken exhaust mountings Engine mountings worn

6.20 Cooling

6.20.1 Air-cooled system

Air-cooled engines with multicylinders, especially under a bonnet, must have some form of fan cooling and ducting. This is to make sure that all cylinders are cooled evenly. The cylinders and cylinder heads are f nned. Hotter areas, such as near the exhaust ports on the cylinders, have bigger f ns.

Fan-blown air is directed by a metal cowling, so it stays close to the f nned areas. A thermostatically controlled f ap will control airf ow. When the engine is warming up, the f ap will be closed to restrict the movement of air. When the engine reaches its operating temperature, the f ap opens and allows the air to f ow over the engine. The cooling fan is a large device and is driven from the engine by a belt. This belt must not be allowed to slip or break, because serious damage will occur.

Car heating is not easy to arrange with an air-cooled engine. Some vehicles use a heat exchanger around the exhaust pipe. Air is passed through this device where it is warmed. It can then be used for demisting and heating with the aid of an electric motor and fan.

6.20.2 Water-cooled system

The main parts of a water-cooled system are as follows:

- water jacket;
- water pump;
- thermostat;
- radiator;
- cooling fan.

Water-cooled engines work on the principle of surrounding the hot areas inside the engine with a water jacket. The water takes on heat from the engine and, as it circulates through the radiator, gives it off to atmosphere. The heat concentration around the top of the engine means a water pump is needed to ensure proper circulation.

The water pump circulates water through the radiator and around the engine when the thermostat is open. Water circulates only round the engine when the thermostat is closed and not through the radiator. Forcing water around the engine prevents vapour pockets forming in very hot areas. This circulation is assisted by the thermo-siphon action. The thermo-siphon action causes the water to circulate because as the water is heated it rises and moves to the top of the radiator. This pushes down on the colder water underneath which moves into the engine. This water is heated, rises and so on.

Coolant from the engine water jacket passes through a hose to the radiator at the top. It then passes through thin pipes called the radiator matrix to the lower tank and then back to the lower part of the engine.

Many water passages between the top and bottom tanks of the radiator are used to increase the surface area. Fins further increase the surface area to make the radiator even more eff cient. A cooling fan assists airf ow. The heat from the coolant passes to the pipes and f ns and then to the air as it is blown by a fan over the f ns.

Many modern radiators are made from aluminium pipes and f ns with plastic tanks top and bottom (down-f ow), or at each end (cross-f ow). The cross-f ow radiators with tanks at each end are becoming the most popular. The more traditional method was to use copper and brass.

Key fact

Most modern radiators are made from aluminium pipes andf ns with plastic tanks.

A thermostat is a temperature-controlled valve. Its purpose is to allow coolant to heat up more quickly and then be kept at a constant temperature. The total coolant volume in an engine takes time to heat up. Modern engines run more eff ciently when at the correct operating temperature. The action of the thermostat is such as to prevent water circulation from the engine to the radiator, until a set temperature is reached. When the valve opens, there is a full circuit for the coolant and a good cooling action occurs because of full f ow through the radiator. The constant action of the thermostat ensures that the engine temperature remains at a constant level. The thermostat used by almost all modern engines is a wax capsule type. If the thermostat is faulty, ensure that the correct type for the engine is f tted, as some work at different temperatures.

The water pump is driven by a V-belt or multi-V-belt from the crankshaft pulley or by the cam belt. The pump is a simple impeller type and is usually f tted at the front of the engine (where the pulleys are). It assists with the thermo-siphon action of the cooling system, forcing water around the engine block and radiator.

The engine fan, which maintains the f ow of air through the radiator, is mounted on the water-pump pulley on older systems. Most cooling fans now are electric. These are more eff cient because they only work when needed. The forward motion of the car also helps the air movement through the radiator.

6.20.3 Sealed and semi-sealed systems

Cooling systems on most vehicles today are sealed or semi-sealed. This allows them to operate at pressures as much as $100\,\text{N/m}^2$ (100 Pa) over atmospheric pressure, raising the boiling point of the coolant to as much as 126.6 °C (remember water boils at 100° C at atmospheric pressure). The system can therefore operate at a higher temperature and with greater eff ciency.

The pressure build-up is made possible by the radiator pressure cap. The cap contains a pressure valve which opens at a set pressure, and a vacuum valve which opens at a set vacuum. On a semi-sealed system, air is pushed out to atmosphere through the pressure valve as the coolant expands. Air is then drawn back into the radiator through the vacuum valve as the coolant cools and contracts. A sealed system has an expansion tank into which coolant is forced as it expands, and when the engine cools, coolant can f ow from the tank back into the cooling system. Figure 6.72 shows a semi-sealed type cooling system.

Safety f rst

Warning: If a pressure cap is removed from a hot system, hot water under pressure will boil the instant pressure is released. This can be very dangerous.

Correct levels in the expansion tank or in an unsealed radiator are very important. If too much coolant is used, it will be expelled on to the f oor when the engine

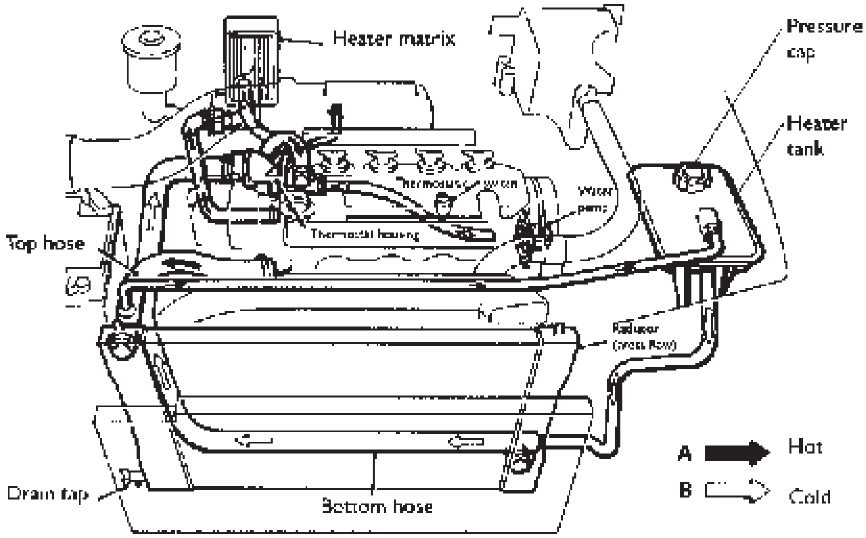


Figure 6.72 Semi-sealed cooling system

gets hot. If not enough is used, then the level could become low and overheating could take place.

Heat from the engine can be used to increase the temperature of the car interior. This is achieved by use of a heat exchanger, often called the heater matrix. Owing to the action of the thermostat in the engine cooling system, the water temperature remains nearly constant. The air being passed over the heater matrix is therefore heated to a set level.

A source of hot air is now available for heating the vehicle interior. Some form of control is required over how much heat is required. The method used on most modern vehicles is blending. This is a control f ap that determines how much of the air being passed into the vehicle is directed over the heater matrix. Some systems use a valve to control the hot coolant f owing to the heater matrix.

By a suitable arrangement of f aps, it is possible to direct air of the chosen temperature to selected areas of the vehicle interior. In general, basic systems allow the warm air to be adjusted between the inside of the windscreen and the driver and passenger footwells. Fresh cool air outlets with directional nozzles are also f tted.

One f nal facility, which is available on many vehicles, is the choice between fresh or recirculated air. The primary reason for this is to decrease the time taken to demist or defrost the vehicle windows and simply to heat the car interior more quickly, and to a higher temperature. The other reason is that for example, in heavy congested traff c, the outside air may not be very clean.

6.21 Diagnostics – cooling

6.21.1 Systematic testing

If the reported fault is loss of coolant, proceed as follows:

1 Check coolant level and discuss with customer how much is being lost.
2 Run the engine to see if it is overheating.

3 If the engine is not overheating, a leak would seem to be most likely.
4 Pressure-test the cooling system and check for leaks from hoses, gaskets and the radiator.
5 Renew a gasket or the radiator, clips or hoses as required. Top up the coolant and check antifreeze content.
6 Road-test the vehicle to conf rm the fault is cured and that no other problems have occurred.

Figure 6.73 Cooling system testing kit (Source: Sykes Pickavant)

6.21.2 Test equipment

Note: You should always refer to the manufacturer's instructions appropriate to the equipment you are using.

Cooling system pressure tester

This is a pump with a pressure gauge built in, together with suitable adapters for f tting to the header tank or radiator f ller. The system can then be pressurized to check for leaks. The pressure can be looked up or it is often stamped on the f ller cap. A good way of doing this test is to pressurise the system when cold and then start the engine and allow it to warm up. You can be looking for leaks, but beware of rotating components.

Antifreeze tester

This piece of equipment is a hydrometer used to measure the relative density of the coolant. The relative density of coolant varies with the amount of antifreeze. A table can be used to determine how much more antifreeze should be added to give the required protection.

Temperature meter/thermometer

Sometimes the dashboard temperature gauge reading too high can create the symptoms of an overheating problem. A suitable meter or thermometer can be used to check the temperature. Note, though, that normal operating temperature is often well above 90 °C (hot enough to burn badly) (Figure 6.73).

6.21.3 Test results

Some of the information you may have to get from other sources such as data books or a workshop manual is listed in Table 6.7.

Table 6.7 Tests and information required

Test carried out	Information required
Leakage test	System pressure. Printed on the cap or from data books. Approximately 1bar is normal
Antifreeze content	Cooling system capacity and required percentage of antifreeze. If the system holds 6 L then for a 50% antifreeze content you will need to add 3 L of antifreeze. Do not forget you will need to drain out 3 L of water to make room for the antifreeze
Operating temperature	This is about the same as the thermostat opening temperature. 88–92°C is a typical range

6.21.4 Cooling fault diagnosis table 1

Symptom	Possible faults	Suggested action
Overheating	Lack of coolant Thermostat stuck closed Electric cooling fan not operating Blocked radiator Water pump/fan belt slipping	Top up but then check for leaks Renew Check operation of thermal switch Renew Check, adjust/renew
Loss of coolant	Leaks	Pressure test when cold and hot, look for leaks and repair as required
Engine does not reach normal temperature or it takes a long time	Thermostat stuck in the open position	Renew

6.21.5 Cooling fault diagnosis table 2

Symptom	Possible cause
Overheating	Low coolant level (maybe due to a leak) Thermostat stuck closed Radiator core blocked Cooling fan not operating Temperature gauge inaccurate Airlock in system (some systems have a complex bleeding procedure) Pressure cap faulty
Overcooling	Thermostat stuck open Temperature gauge inaccurate Cooling fan operating when not needed
External coolant leak	Loose or damaged hose Radiator leak Pressure cap seal faulty Water pump leak from seal or bearing Boiling due to overheating or faulty pressure cap Core plug leaking
Internal coolant leak	Cylinder head gasket leaking Cylinder head cracked
Corrosion	Incorrect coolant (antifreeze, etc.) Infrequent fushing
Freezing	Lack of antifreeze Incorrect antifreeze

6.22 Lubrication

6.22.1 Lubrication system

From the sump reservoir under the crankshaft, oil is drawn through a strainer into the pump. Oil pumps have an output of tens of litres per minute and operating pressures of more than 5 bar at high speeds. A pressure relief valve limits the pressure of the lubrication system to between 2.5 and 4 bar. This control is needed because the pump would produce excessive pressure at high speeds. After leaving the pump, oil passes into a f lter and then into a main oil gallery in the engine block or crankcase.

Drillings connect the gallery to the crankshaft bearing housings and, when the engine is running, oil is forced under pressure between the rotating crank journals and the main bearings. The crankshaft is drilled so that the oil supply from the main bearings is also to the big-end bearing bases of the connecting rods.

The con rods are often drilled near the base so that a jet of oil sprays the cylinder walls and the underside of the pistons. In some cases, the con rod may be drilled along its entire length so that oil from the big-end bearing is taken directly to the gudgeon pin (small end). The surplus then splashes out to cool the underside of the piston and cylinder.

The camshaft operates at half crankshaft speed, but it still needs good lubrication because of the high-pressure loads on the cams. It is usual to supply pressurised oil to the camshaft bearings and splash or spray oil on the cam lobes. On overhead camshaft engines, two systems are used. In the simplest system, the rotating cam lobes dip into a trough of oil. Another method is to spray the cam lobes with oil. This is usually done by an oil pipe with small holes in it alongside the camshaft. The small holes in the side of the pipe aim a jet of oil at each rotating cam lobe. The surplus splashes over the valve assembly and then falls back into the sump.

On cars where a chain drives the cam, a small tapping from the main oil gallery sprays oil on the chain as it moves past or the chain may simply dip in the sump oil.

6.22.2 Oil f lters

Even new engines can contain very small particles of metal left over from the manufacturing process or grains of sand which have not been removed from the crankcase after casting. Old engines continually deposit tiny bits of metal worn from highly loaded components such as the piston rings. To prevent any of these lodging in bearings or blocking oil ways, the oil is f ltered.

The primary f lter is a wire mesh strainer that stops particles of dirt or swarf from entering the oil pump. This is normally on the end of the oil pick-up pipe. An extra f lter is also used that stops very f ne particles. The most common type has a folded, resin-impregnated paper element. Pumping oil through it removes all but smallest solids from the oil.

Most engines use a full-f ow system to f lter all the oil after it leaves the pump. The most popular method is to pump the oil into a canister containing a cylindrical f lter. From the inner walls of the canister, the oil f ows through the f lter and out from the centre to the main oil gallery. Full-f ow f ltration works well, provided the f lter is renewed at regular intervals. If it is left in service too long, it may become blocked. When this happens, the build-up of pressure inside the f lter forces open a spring-loaded relief valve in the housing and the oil bypasses the f lter. This valve prevents engine failure, but the engine will be lubricated with dirty oil until the f lter is renewed. This is better than no oil.

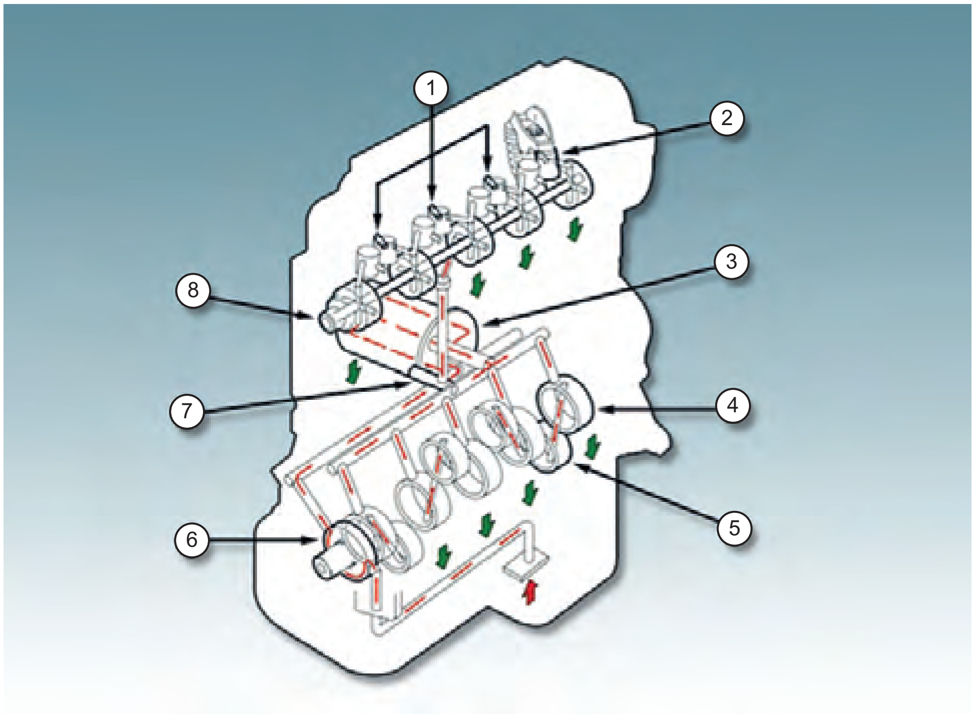


Figure 6.74 Oil f ow: 1 – oil to rocker arms; 2 – hydraulic tappets; 3 – f lter; 4 – crank main bearings; 5 – big-end bearings; 6 – crank driven oil pump; 7 – oil under pressure; 8 – camshaft

A bypass f ltration system was used on older vehicles. This system f lters only a proportion of the oil pump output. The remainder is fed directly to the oil gallery. At f rst view, this seems a strange idea, but all the oil does eventually get f ltered. The smaller amount through the f lter allows a higher degree of f ltration (Figure 6.74).

6.22.3 Oil pumps

In its simplest form, an oil pump consists of two gear wheels meshed together in a tight space so that oil cannot escape past the sides. The engine drives one wheel. As the gears rotate in opposite directions, the gap between each tooth in each wheel traps a small quantity of oil from an inlet port. The trapped oil is carried round by each wheel towards an outlet port on the opposite side where it is forced out by the meshing teeth.

The principle of squeezing oil from an ever-decreasing space is also used in the rotor-type pump. An inner and outer rotor are mounted on different axes in the same cylinder. The inner rotor, which commonly has four lobes, is driven by the engine. It meshes with an outer rotor, which has f ve lobes. As they rotate, the spaces between them change size. The inlet port is at a point where the space between the rotor lobes is increasing. This draws the oil into the pump. The oil is then carried round the pump. As rotation continues, the space between the lobes gets smaller. This compresses the oil out of the outlet port.

Oil pumps can produce more pressure than is required. A valve is used to limit this pressure to a set value. The pressure relief valve is a simple device, which in most cases works on the ball and spring principle. This means that when the pressure on the ball is greater than the spring, the ball moves. The pressure relief

Key fact

Oil pumps can produce more pressure than is required, so a pressure relief valve is used.

valve is placed in the main gallery so that excess pressure is prevented. When the ball moves, oil is simply returned to the sump.

6.22.4 Crankcase ventilation engine breather systems

Breathing is very important; without being able to breathe, we would die. It is almost as important for an engine breathing system to work correctly. There are two main reasons for engine breathers:

1. Prevent pressure build-up inside the engine crankcase due to combustion gases blowing past the pistons. The build-up of pressure will blow gaskets and seals but also there is a high risk of explosion.
2. Prevent toxic emissions from the engine. Emission limits are now very strict, for good reason – our health.

Crankcase breathing or ventilation of the engine was f rst achieved by what is known as an open system, but this has now been completely replaced by the closed system. The gases escaping from an engine with open crankcase ventilation as described above are very toxic. Legislation now demands a positive closed system of ventilation. This makes the pollution from cylinder blow-by gases negligible. Positive crankcase ventilation is the solution to this problem.

In early types of closed-system crankcase ventilation, the lower pressure at the carburettor air cleaner was used to cause an airf ow through the inside of the engine. The breather outlet was simply connected by a pipe to the air cleaner. This caused the crankcase gases to be circulated and then burned in the engine cylinders. A f ame trap was included in the system to prevent a crankcase explosion if the engine backf red.

In modern closed systems, the much lower pressure within the inlet manifold is used to extract crankcase gases. This has to be controlled in most cases by a variable regulator valve or pressure conscious valve (PCV). The valve is f tted between the breather outlet and the inlet manifold. It consists of a spring-loaded plunger, which opens as the inlet manifold pressure reduces. When the engine is stationary, the valve is closed. Under normal running conditions, the valve opens to allow crankcase gases to enter the inlet manifold with minimum restriction. At low manifold pressures during idling and overrun (pressure is less than atmospheric), further travel of the valve plunger against its spring closes it in the opposite direction. This reduces gas f ow to the inlet manifold. This feature makes sure that the fuel control process is not interfered with under these conditions. The valve also acts as a safety device in case of a backf re. Any high pressure created in the inlet manifold will close the valve completely. This will isolate the crankcase and prevent the risk of explosion.

Key fact

Crankcase emission systems are monitored by OBD.

6.23 Diagnostics – lubrication

6.23.1 Systematic testing

If the reported fault is that the oil pressure light comes on at low speed, proceed as follows:

1. Run the engine and see when the light goes off or comes on.
2. Is the problem worse when the engine is hot? Check the oil level. When was it last serviced?

Table 6.8 Tests and information required

Test carried out	Information required
Oil pressure	Oil pressure is measured in bars. A typical reading would be approximately 3 bar
Crankcase pressure	By tradition pressures less than atmosphere are given in strange ways, such as, inches of mercury or inches of water! This is why I like to stick to absolute pressure and then 0 bar is 0 pressure, 1 bar is atmospheric pressure and so on. 2–3 bar is more than atmospheric pressure like in a tyre. The trouble is standards vary so make sure you compare like with like! Back to crankcase pressure – it should be less than atmospheric, check data
Oil condition	Recommended type of lubricant

Figure 6.75 Oil pressure testing kit

Safety first

Note: You should always refer to the manufacturer's instructions appropriate to the equipment you are using.

3 If oil level is correct, then you must investigate further.
4 Carry out an oil pressure test to measure the actual pressure.
5 If pressure is correct, then renew the oil pressure switch. If not, engine strip down is likely.
6 Run and test for leaks.

6.23.2 Test equipment

Oil pressure test gauge

This is a simple pressure gauge that can be fitted with suitable adapters into the oil pressure switch hole. The engine is then run and the pressure readings compared to data.

Vacuum gauge

A simple 'U' tube full of water is often used. This is connected to the oil dipstick tube and the engine is run. The gauge should show a pressure less than atmospheric (a partial vacuum). This checks the operation of the crankcase ventilation system (Figure 6.75).

6.23.3 Test results

Some of the information you may have to get from other sources such as data books or a workshop manual is listed in Table 6.8.

6.23.4 Lubrication fault diagnosis table 1

Symptom	Possible faults	Suggested action
Low oil pressure	Lack of oil Blocked filter Defective oil pump Defective oil pressure relief valve	Top up Renew oil and filter Renew after further tests Adjust if possible or renew
High crankcase pressure	Blocked crankcase breather Blocked hose Pressure blowing by pistons	Clean or replace Clean or renew hose Engine overhaul may be required
Loss of oil	Worn piston rings Leaks	Engine overhaul may be required Renew seals or gaskets

6.23.5 Lubrication fault diagnosis table 2

Symptom	Possible cause
Oil leaks	Worn oil seal (check breather system) Gasket blown Cam or rocker cover loose Oil fıter seal
Blue smoke	Piston rings Valve stem seals Head gasket

6.24 Batteries

6.24.1 Safety

The following points must be observed when working with batteries:

- good ventilation;
- protective clothing;
- supply of water available (running water preferable);
- f rst-aid equipment available, including eyewash;
- no smoking or naked lights permitted.

6.24.2 Lead-acid batteries

Incremental changes over the years have made the sealed and maintenance-free battery, now in common use, very reliable and long-lasting. This may not always appear to be the case to some end users, but note that quality is often related to the price the customer pays. Many bottom-of-the-range cheap batteries with a 12-month guarantee will last for 13 months (Figure 6.76).

Figure 6.76 High-quality vehicle batteries(Source: Bosch Media)

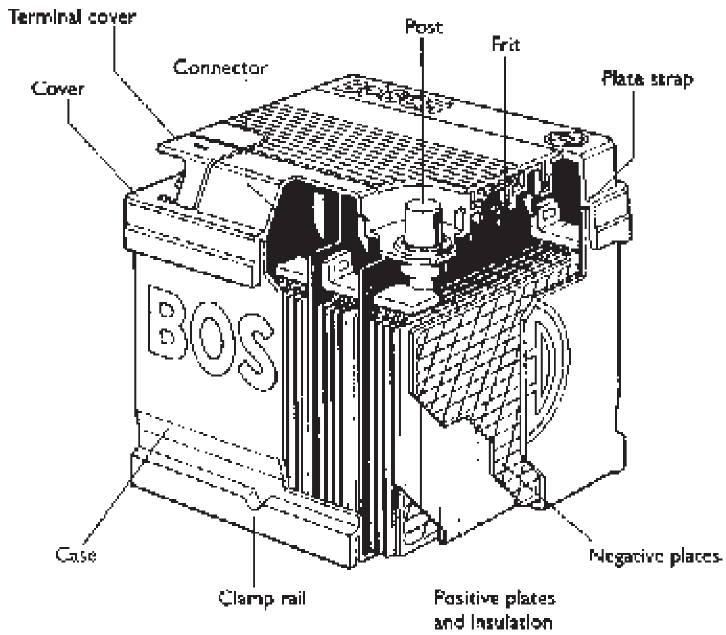


Figure 6.77 Vehicle battery components

The basic construction of a nominal 12 V lead-acid battery consists of six cells connected in series. Each cell producing approximately 2 V is housed in an individual compartment within a polypropylene or similar case. The active material is held in grids or baskets to form the positive and negative plates. Separators made from a microporous plastic insulate these plates from each other (Figure 6.77).

The grids, connecting strips and the battery posts are made from a lead alloy. For many years, this was lead antimony (PbSb), but this has now been largely replaced by lead calcium (PbCa). The newer materials cause less gassing of the electrolyte when the battery is fully charged. This has been one of the main reasons why sealed batteries became feasible as water loss is considerably reduced.

Modern batteries described as sealed do still have a small vent to stop the pressure build-up due to the very small amount of gassing. A further requirement of sealed batteries is accurate control of charging voltage.

6.24.3 Battery rating

In simple terms, the characteristics or rating of a particular battery are determined by how much current it can produce and how long it can sustain this current. The rate at which a battery can produce current is determined by the speed of the chemical reaction. This in turn is determined by a number of factors:

- surface area of the plates;
- temperature;
- electrolyte strength;
- current demanded.

The actual current supplied therefore determines the overall capacity of a battery. The rating of a battery has to specify the current output and the time (Table 6.9).

Table 6.9 Battery capacity ratings

Ampere-hour capacity	This describes how much current the battery is able to supply for either 10 or 20 hours. The 20-hour figure is the most common. For example, a battery quoted as being 44 Ah (Ampere-hour) will be able, if fully charged, to supply 2.2 A for 20 hours before being completely discharged (cell voltage above 1.75 V)
Reserve capacity	A system used now on all new batteries is reserve capacity. This is quoted as a time in minutes for which the battery will supply 25 A at 25 °C to a final voltage of 1.75 V per cell. This is used to give an indication of how long the battery could run the car if the charging system was not working. Typically, a 44 Ah battery will have a reserve capacity of approximately 60 minutes
Cold cranking Amps	Batteries are given a rating to indicate performance at high current output and at low temperature. A typical value of 170 A means that the battery will supply this current for one minute at a temperature of −18 °C at which point the cell voltage will fall to 1.4 V (BS)

Cold cranking amps (CCA) capacity rating methods do vary to some extent: British standards, DIN standards and SAE standards are the three main examples:

- BS 60 seconds
- DIN 30 seconds
- SAE 30 seconds

In summary, the capacity of a battery is the amount of electrical energy that can be obtained from it over a set time. It is usually given in ampere-hours, reserve capacity (RC) and cold cranking amps.

- A 40 Ah battery means it should give 2 A for 20 hours.
- Reserve capacity indicates the time in minutes for which the battery will supply 25 A at 25 °C.
- Cold cranking current indicates the maximum battery current at −18 °C (0 °F) for a set time (standards vary).

A battery for normal light vehicle use may be rated as follows: 44 Ah, 60 RC and 170 A CCA (BS). A 'heavy-duty' battery will have the same Ah rating as its 'standard duty' counterpart, but it will have a higher CCA and RC.

Key fact

The capacity of a battery is the amount of electrical energy that can be obtained from it over a set time.

6.25 Diagnostics – batteries

6.25.1 Servicing batteries

In use a battery requires very little attention other than the following when necessary:

- Corrosion should be cleaned from terminals using hot water.
- Terminals should be smeared with petroleum jelly or Vaseline *not* ordinary grease.
- Battery tops should be clean and dry.
- If not sealed, cells should be topped up with distilled water 3 mm above the plates (not very common now).
- Battery should be securely clamped in position.

6.25.2 Maintenance-free

By far the majority of batteries now available are classed as ‘maintenance-free’. This implies that little attention is required during the life of the battery. Earlier batteries and some heavier types do, however, still require the electrolyte level to be checked and topped up periodically. Battery posts are still a little prone to corrosion and hence the usual service of cleaning with hot water if appropriate and the application of petroleum jelly or proprietary terminal grease is still recommended. Ensuring that the battery case and in particular the top remains clean will help to reduce the rate of self-discharge.

The state of charge of a battery is still very important, and in general it is not advisable to allow the state of charge to fall below 70% for long periods as the sulphate on the plates can harden, making recharging diff cult. If a battery is to be stored for a long period (more than a few weeks), then it must be recharged every so often to prevent it from becoming sulphated. Recommendations vary, but a recharge every six weeks is a reasonable suggestion.

6.25.3 Charging

The recharging recommendations of battery manufacturers vary slightly. The following methods, however, are reasonably compatible and should not cause any problems. The eff ciency of a battery is not 100%. Therefore, the recharging process must ‘put back’ the same Ah capacity as was used on discharge plus a bit more to allow for eff ciency losses. It is therefore clear that the main question about charging is not how much, but at what rate.

Key fact

The ideal charge rate is determined as.

1/10 of the Ah capacity

1/16 of the RC.

1/40 of the CCA.

The traditional recommendation was that the battery should be charged at a tenth of its Ah capacity for approximately 10 hours or less. This is based on the assumption that the Ah capacity is quoted at the 20-hour rate, as a tenth of this f gure will make allowance for the charge factor. This f gure is still valid but as Ah capacity is not always used nowadays, a different method of deciding the rate is necessary. One way is to set a rate at a sixteenth of the reserve capacity, again for up to 10 hours. The f nal suggestion is to set a charge rate at one-fortieth of the cold start performance f gure, also for up to 10 hours. Clearly if a battery is already half charged, half the time is required to recharge to full capacity.

The above-suggested charge rates are to be recommended as the best way to prolong battery life. They do all, however, imply a constant current charging source. A constant voltage charging system is often the best way to charge a battery. This implies that the charger, an alternator on a car for example, is held at a constant level and the state of charge in the battery will determine how much current will f ow. This is often the fastest way to recharge a f at battery. If a constant voltage of less than 14.4 V is used, then it is not possible to cause excessive gassing and this method is particularly appropriate for sealed batteries.

Boost charging is a popular technique often applied in many workshops. It is not recommended as the best method but, if correctly administered and not repeated too often, it is suitable for most batteries. The key to fast or boost charging is that the battery temperature should not exceed 43 °C. With sealed batteries, it is particularly important not to let the battery gas excessively in order to prevent the build-up of pressure. A rate of about f ve times the ‘normal’ charge setting will bring the battery to 70–80% of its full capacity within approximately one hour. Table 6.10 summarises the charging techniques for a lead-acid battery.

Table 6.10 Charging methods

Charging method	Notes
Constant voltage	Constant voltage will recharge any battery in seven hours or less without any risk of overcharging (14.4 V maximum)
Constant current	Ideal charge rate can be estimated as 1/10 of Ah capacity, 1/16 of reserve capacity or 1/40 of cold start current (charge time of 10–12 hours or pro rata original state)
Boost charging	At no more than five times the ideal rate, a battery can be brought up to approximately 70% of charge in about one hour
Smart charging	Let the charger do all the calculations and all the work

Figure 6.78 Smart battery charger (Source: www.ctek.com)

Smart chargers

Nowadays, there are a number of ‘Smart’ or ‘Intelligent’ battery chargers that are able to determine the ideal rate from the battery voltage and the current it will accept. Some also have features such as a ‘recond’ mode, which allows you to correct the acid stratification that often occurs in deeply discharged batteries – particularly leisure batteries. Some key features of a charger produced by a company called Ctek are as follows (Figure 6.78):

- Safe: No sparks and cannot harm vehicle electrics, so no need to disconnect the battery.
- Suitable for all types of 12 V lead-acid batteries up to 150 Ah.
- Connect and forget – can be left connected for months – ideal for vehicles used occasionally.
- Analysis mode to check if battery can hold charge.
- 10 day float maintenance for maximum charge level.
- ‘Recond’ mode – special programme to revive deeply discharged batteries.
- Supply mode – can be used as a 12 V power source to protect electrical settings.

6.25.4 Battery faults

Any electrical device can suffer from two main faults: these are either open circuit or short circuit. A battery is no exception but can also suffer from other problems

Table 6.11 Battery faults

Symptom or fault	Likely causes					
Low state of charge	Charging system fault	Unwanted drain on battery	Electrolyte diluted	Incorrect battery for application		
Low capacity	Low state of charge	Corroded terminals	Impurities in the electrolyte	Sulphated	Old age – active material fallen from the plates	
Excessive gassing and temperature	Overcharging	Positioned too near exhaust component				
Short circuit cell	Damaged plates and insulators	Build-up of active material in sediment trap				
Open circuit cell	Broken connecting strap	Excessive sulphation	Very low electrolyte			
Service life shorter than expected	Excessive temperature	Battery has too low a capacity	Vibration excessive	Contaminated electrolyte	Long periods of not being used	Overcharging

Figure 6.79 Battery charger and engine starter (Source: Bosch Media)

Key fact

Repairing modern batteries is not possible.

such as low charge or low capacity. Often a problem, apparently with a vehicle battery, can be traced to another part of the vehicle such as the charging system. Table 6.11 lists all the common problems encountered with lead-acid batteries, together with typical causes (Figure 6.79).

Most of the problems listed previously will require the battery to be replaced. In the case of sulphation, it is sometimes possible to bring the battery back to life with a very long low current charge. A fortieth of the Ah capacity or about a two-hundredth of the cold start performance for approximately 50 hours is an appropriate rate. Some smart chargers are very good for this.

6.25.5 Testing batteries

For testing the state of charge of a non-sealed type of battery, it was traditional to use a hydrometer. The hydrometer is a syringe which draws electrolyte from a cell and a f oat which will f oat at a particular depth in the electrolyte according to its density. The relative density or specif c gravity is then read from the graduated scale on the f oat. A fully charged cell should show 1.280, when half charged 1.200 and if discharged 1.120.

Most vehicles are now f tted with maintenance-free batteries and a hydrometer cannot be used to f nd the state of charge. This can, however, be determined from the voltage of the battery, as given in Table 6.12. An accurate voltmeter is required for this test – note the misleading surface charge shown in Figure 6.80 (also see Figure 6.81).

To test a battery more thoroughly, it is now preferred to use a volt, amp tester (VAT). There are many variations on the market; however, this section will outline

Table 6.12 Battery voltages

Battery volts at 20 °C	State of charge
12.0V	Discharged (20% or less)
12.3V	Half charged (50%)
12.7V	Charged (100%)

Figure 6.80 Checking battery voltage. In this case, the engine had just been switched off so the reading shows a 'surface charge'

Figure 6.81 MicroVAT (Source: Snap-on)

Key fact

Accuracy: A good tip to reduce surface charge, is after switching off the engine, turn on the headlights for a few minutes, then turn them off, wait another few minutes – then take the reading.

just one type. Snap-on produce a compact and very useful tester called the MicroVAT. This equipment will carry out a range of diagnostic tests.

The device, as with many similar types, will do not only battery condition tests but also tests on the charging and starting system.

This VAT takes advantage of new impedance/current test technology to detect the full range of battery failure modes including bad cells, sulphation, internal short circuits, and other chemical and physical failures. Testing takes less than f ve seconds and will even work on batteries discharged down to as low as 1 V.

Some of the key features of this tester are as follows:

- automated system test of battery, alternator and starter in under a minute;
- detailed test data: alternator ripple, internal resistance, starter draw, state of charge, charging amps, and volts;
- tests discharged batteries down to 1 V;
- impedance/current (IC) test technology;
- wireless printer option;
- integrated high and low amp probe options.

The MicroVAT uses a fan-cooled 50 A load and integrated amp probe to test the quantity and quality of alternator output with an alternator ripple test. Many late-model computer-controlled charging systems virtually shut down under no-load conditions. Diagnostic tests that can be carried out with this tester, when an amps probe is also used, are as follows:

Starting test data

- Average cranking current
- Maximum cranking current
- Pre-set voltage
- Pre-set load voltage
- Average cranking voltage
- Minimum cranking voltage

Battery test data

- Diagnosis
- Actual CCA
- Percentage capacity
- Open circuit voltage
- Impedance (often described as internal resistance)

Alternator test data

- Diagnosis
- Failure mode
- Charging at idle
- Charging volts under load
- Average current at idle
- Peak current
- Peak-to-peak ripple at idle
- Peak-to-peak ripple under load.

6.26 Starting

6.26.1 Starter circuit

In comparison with most other circuits on the modern vehicle, the starter circuit is relatively simple. The problem to overcome, however, is that of volt drop in the main supply wires. A spring-loaded key switch usually operates the starter; the same switch also controls the ignition and accessories. The supply from the key switch, via a relay in many cases, causes the starter solenoid to operate and this in turn, by a set of contacts, controls the heavy current. In some cases, an extra terminal on the starter solenoid provides an output when cranking, usually used to bypass a dropping resistor on the ignition or fuel pump circuits. The problem of volt drop in the main supply circuit is due to the high current required by the starter, particularly under adverse starting conditions such as very low temperatures.

A typical cranking current for a light vehicle engine is in the order of 150 A, but this may peak in excess of 500 A to provide the initial stalled torque. It is generally accepted that a maximum volt drop of only 0.5 V should be allowed between the battery and starter when operating. An Ohm's law calculation indicates that the maximum allowed circuit resistance is 2.5 mΩ, when using a 12 V supply. This is a worst-case situation and lower resistance values are used in most applications. The choice of suitable conductors is therefore very important (Figure 6.82).

Key fact

A typical cranking current for a light vehicle engine is approximately 150 A, but this may peak in excess of 500A to provide the initial stalled torque.

6.26.2 Inertia starters

In all standard motor vehicle applications, it is necessary to connect the starter to the engine ring gear only during the starting phase. If the connection remained permanent, the excessive speed at which the starter would be driven by the engine would destroy the motor almost immediately. The inertia type of starter motor was the technique used for many years, but it is now redundant.

The starter engages with the f ywheel ring gear by means of a small pinion. The toothed pinion and a sleeve splined on to the armature shaft are threaded such that when the starter is operated via a remote relay, the armature will cause the sleeve to rotate inside the pinion. The pinion remains still due to its inertia and,

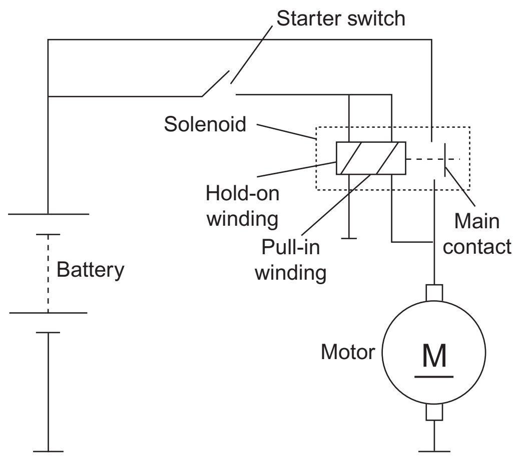


Figure 6.82 Starter circuit

because of the screwed sleeve rotating inside it, the pinion is moved into mesh with the ring gear.

When the engine fires and runs under its own power, the pinion is driven faster than the armature shaft. This causes the pinion to be screwed back along the sleeve and out of engagement with the flywheel. The main spring acts as a buffer when the pinion first takes up the driving torque and also acts as a buffer when the engine throws the pinion back out of mesh.

6.26.3 Pre-engaged starters

Key fact

Pre-engaged starters provide a positive engagement with the ring gear, as full power is not applied until the pinion is fully in mesh.

Pre-engaged starters are fitted to the majority of vehicles in use today. They provide a positive engagement with the ring gear, as full power is not applied until the pinion is fully in mesh. They prevent premature ejection as the pinion is held into mesh by the action of a solenoid. A one-way clutch is incorporated into the pinion to prevent the starter motor being driven by the engine.

Figure 6.83 shows the circuit associated with operating this type of pre-engaged starter. The basic operation of the pre-engaged starter is as follows. When the key switch is operated, a supply is made to terminal 50 on the solenoid. This causes two windings to be energised: the hold-on winding and the pull-in winding. Note that the pull-in winding is of very low resistance and hence a high current flows. This winding is connected in series with the motor circuit and the current flowing will allow the motor to rotate slowly to facilitate engagement. At the same time, the magnetism created in the solenoid attracts the plunger and via an operating lever pushes the pinion into mesh with the flywheel ring gear. When the pinion is fully in mesh, the plunger at the end of its travel causes a heavy-duty set of copper contacts to close. These contacts now supply full battery power to the main circuit of the starter motor. When the main contacts are closed, the pull-in winding is effectively switched off due to equal voltage supply on both ends. The hold-on winding holds the plunger in position as long as the solenoid is supplied from the key switch.

Figure 6.83 Inertia engagement starter and solenoid switch

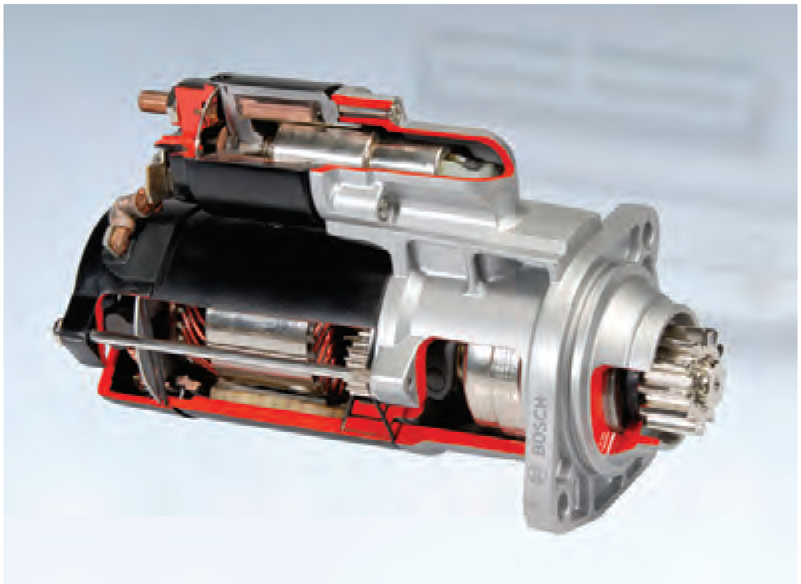


Figure 6.84 Intermediate transmission starter (Source: Bosch Media)

When the engine starts and the key is released, the main supply is removed and the plunger and pinion return to their rest positions under spring tension. A lost motion spring located on the plunger ensures that the main contacts open before the pinion is retracted from mesh (Figure 6.84).

During engagement if the teeth of the pinion hit the teeth of the f ywheel (tooth-to-tooth abutment), the main contacts are allowed to close due to the engagement spring being compressed. This allows the motor to rotate under power and the pinion will slip into mesh.

The torque developed by the starter is passed through a one-way clutch to the ring gear. The purpose of this free-wheeling device is to prevent the starter being driven at excessively high speed if the pinion is held in mesh after the engine has started. The clutch consists of a driving and driven member with several rollers in between the two. The rollers are spring loaded and either wedge-lock the two members together by being compressed against the springs, or free wheel in the opposite direction.

Many variations of pre-engaged starter are in common use, but all work on similar lines to the above description. The wound f eld type of motor is replaced by the permanent magnet version for many applications.

6.26.4 Permanent magnet starters

Permanent magnet starters began to appear on production vehicles in the late 1980s. The two advantages of these motors, compared to conventional types, are less weight and smaller size. This makes the permanent magnet starter a popular choice by vehicle manufacturers, as due to the lower lines of today's cars, less space is now available for engine electrical systems. The reduction in weight provides a contribution towards reducing fuel consumption.

The principle of operation is similar in most respects to the conventional pre-engaged starter motor, the main difference being the replacement of f eld windings and pole shoes with high-quality permanent magnets. The reduction in weight is in the region of 15% and the diameter of the yoke can be reduced by a similar factor.

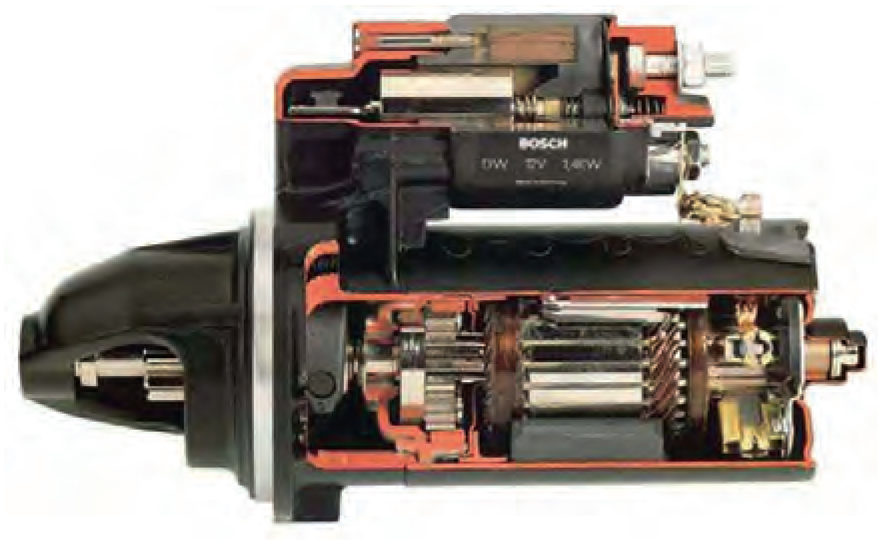


Figure 6.85 Permanent magnet fields are used in this starter motor

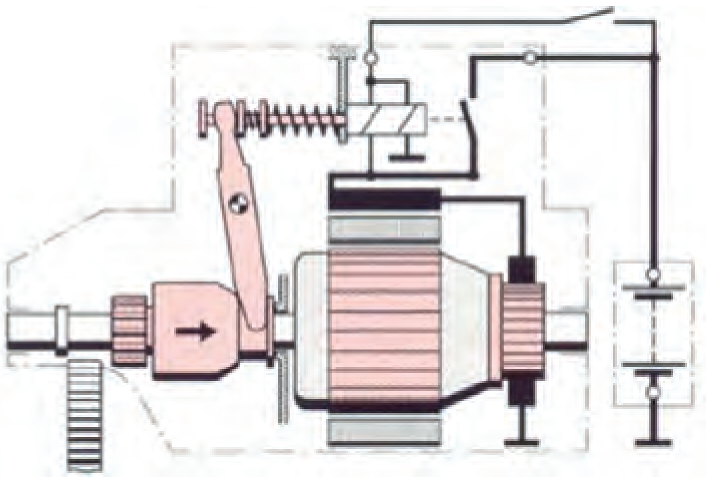


Figure 6.86 Starter circuit and engagement mechanism

Permanent magnets provide constant excitation and it would be reasonable to expect the speed and torque characteristic to be constant. However, owing to the fall in battery voltage under load and the low resistance of the armature windings, the characteristic is comparable to series wound motors.

Development by some manufacturers has also taken place in the construction of the brushes. A copper and graphite mix is used, but the brushes are made in two parts, allowing a higher copper content in the power zone and a higher graphite content in the commutation zone. This results in increased service life and a reduction in volt drop giving improved starter power (Figure 6.85).

For applications with a higher power requirement, permanent magnet motors with intermediate transmission have been developed. This allows the armature to rotate at a higher and more efficient speed while still providing the torque, due to the gear reduction. Permanent magnet starters with intermediate transmission are available with power outputs of approximately 1.7 kW, suitable for spark ignition engines up to approximately 5 L or compression ignition engines up to approximately 1.6 L. This form of permanent magnet motors can give a weight saving of up to 40%. The principle of operation is again similar to the conventional pre-engaged starter (Figure 6.86).

Key fact

For applications with a higher power requirement, permanent magnet starter motors have an intermediate transmission.

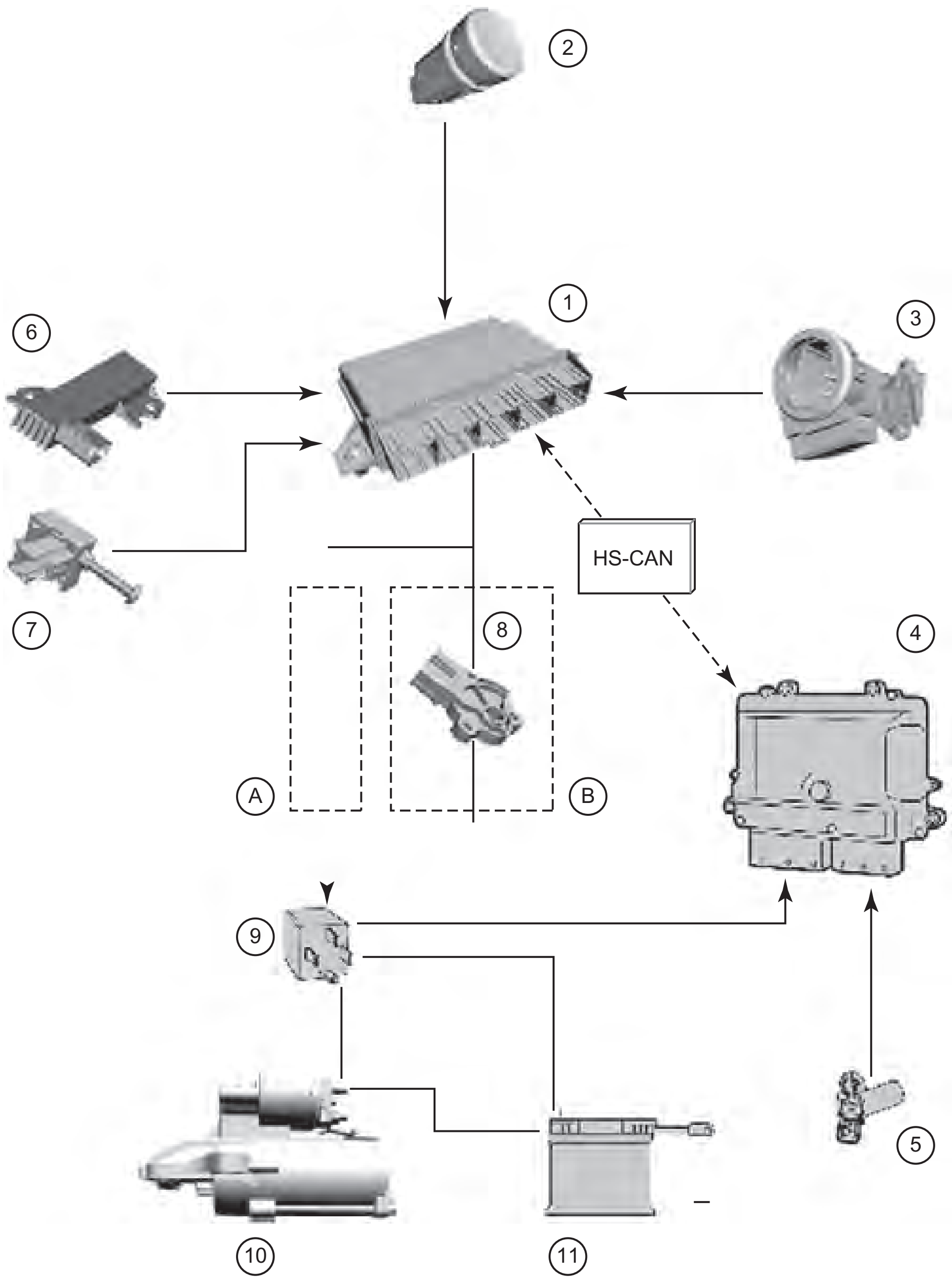


Figure 6.87 Keyless starting system: 1 – keyless vehicle module; 2 – start/stop button; 3 – electronic steering lock; 4 – powertrain control module; 5 – crank sensor; 6 – keyless vehicle antenna; 7 – vehicles with manual transmission: clutch pedal position switch/vehicles with automatic transmission: stoplamp switch; 8 – the TR sensor; 9 – starter relay; 10 – starter motor; 11 – battery (Source: Ford Motor Company)

The sun gear is on the armature shaft and the planet carrier drives the pinion. The ring gear or annulus remains stationary and also acts as an intermediate bearing. This arrangement of gears gives a reduction ratio of approximately 5:1.

6.26.5 Keyless starting system

In the Ford diagram shown in Figure 6.87, the powertrain control module (PCM) allows the engine to start, only when the passive anti-theft system (PATS) reads

Key fact

On a key-free system, the key-free module switches on the control voltage for the starter relay

Key fact

Faults on key-free systems can be diagnosed using standard equipment, but a suitable scanner is almost essential.

a key which transmits a valid code. On a key-free vehicle, the passive key is recognized by the key-free module and if the key is valid the permission to start is issued directly. On vehicles with a manual transmission, it is necessary to depress the clutch pedal; on those with automatic transmission, the brake pedal must be pressed. On a key-free system, the key-free module switches on the control voltage for the starter relay.

The PCM switches the ground in the control circuit of the starter relay which then connects power through to the starter solenoid. As soon as the speed of the engine has reached 750 rpm or the maximum permitted start time of 30 seconds has been exceeded, the PCM switches off the starter relay and therefore the starter motor. This protects the starter. If the engine does not turn or turns only slowly, the starting process is aborted by the PCM.

6.27 Diagnostics – starting

6.27.1 Circuit testing procedure

The process of checking a 12 V starting system operation is shown in Figure 6.88.

The idea of these tests is to see if the circuit is supplying all the available voltage at the battery to the starter. If it is, then the starter is at fault, if not, then the circuit is at fault. The numbered voltmeters relate to the number of the test in the above list (Figure 6.89).

Note that connections to the starter should be made to the link between the solenoid contacts and the motor, not to the main supply terminal (Figure 6.90).

6.27.2 Starting fault diagnosis table

Symptom	Possible fault
Engine does not rotate when trying to start	Battery connection loose or corroded Battery discharged or faulty Broken loose or disconnected wiring in the starter circuit Defective starter switch or automatic gearbox inhibitor switch Starter pinion or flywheel ring gear loose Earth strap broken. Loose or corroded
Starter noisy	Starter pinion or flywheel ring gear loose Starter mounting bolts loose Starter worn (bearings, etc.) Discharged battery (starter may jump in and out)
Starter turns engine slowly	Discharged battery (slow rotation) Battery terminals loose or corroded Earth strap or starter supply loose or disconnected High resistance in supply or earth circuit Internal starter fault

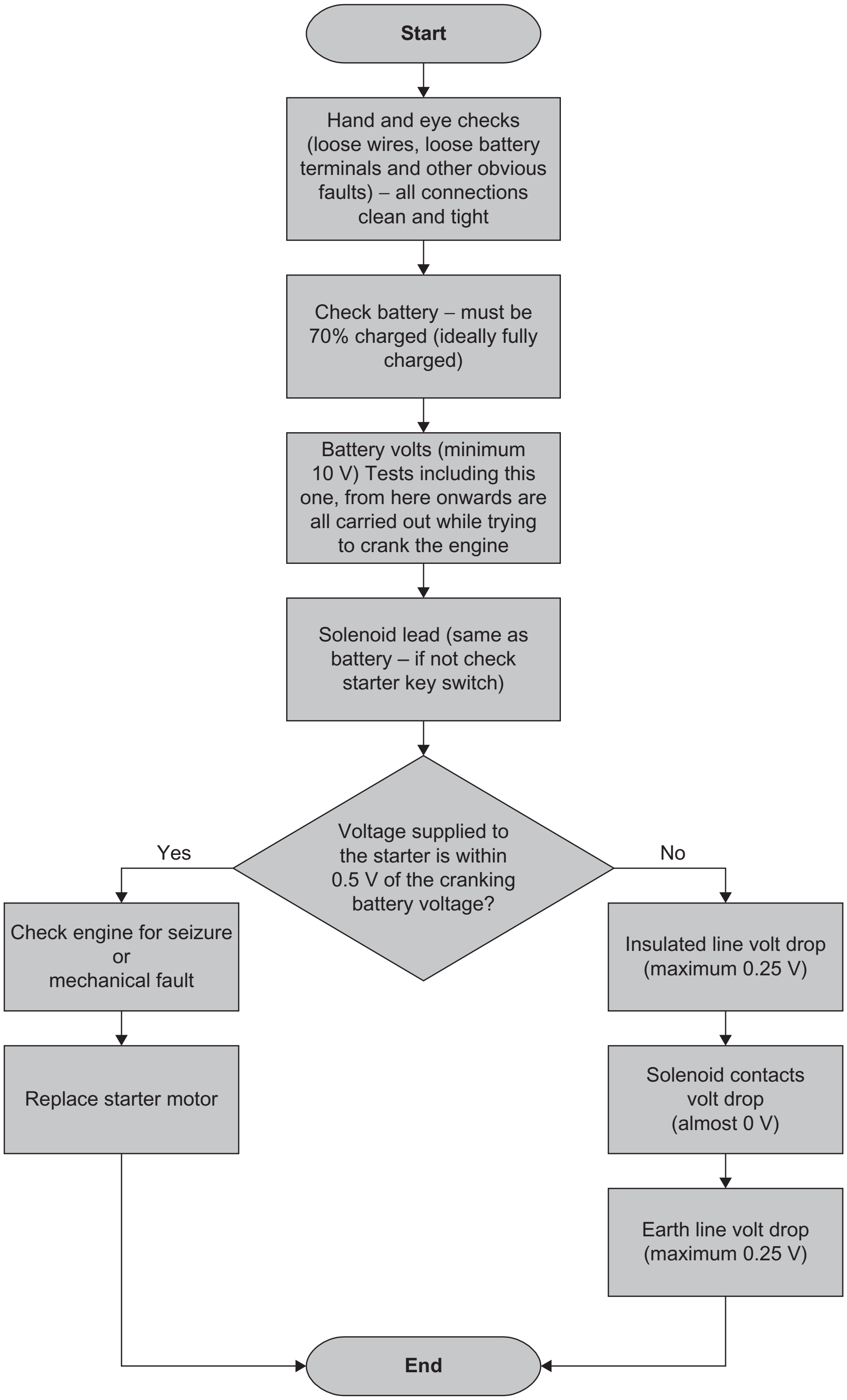


Figure 6.88 Starting system diagnosis chart

6.28 Charging

6.28.1 Introduction

The 'current' demands made by modern vehicles are considerable. The charging system must be able to meet these demands under all operating conditions and still fast charge the battery (Figure 6.91).

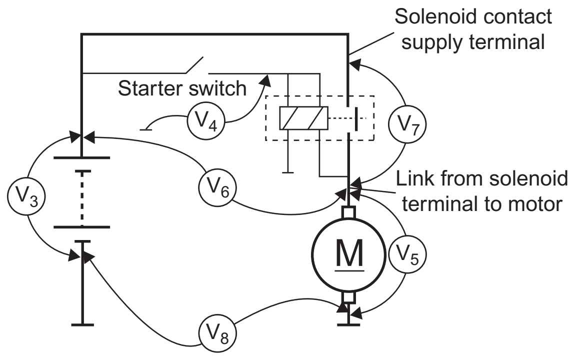


Figure 6.89 Starter circuit testing

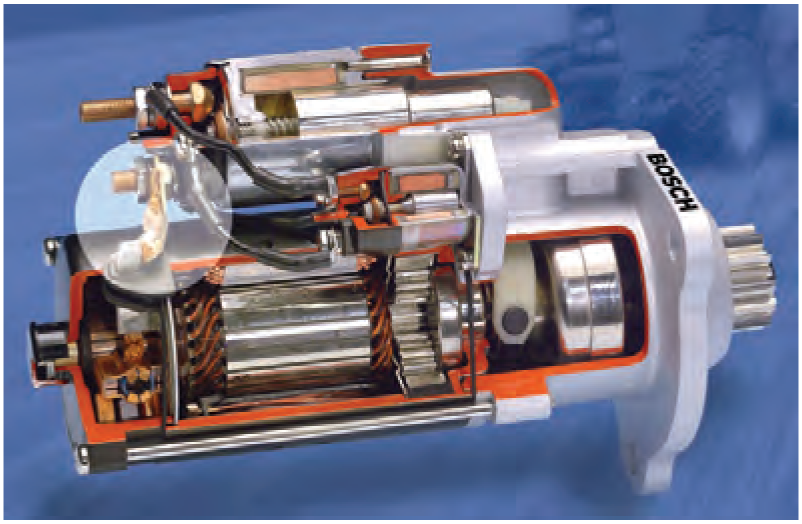


Figure 6.90 The link from the solenoid contacts and the motor is highlighted in this image

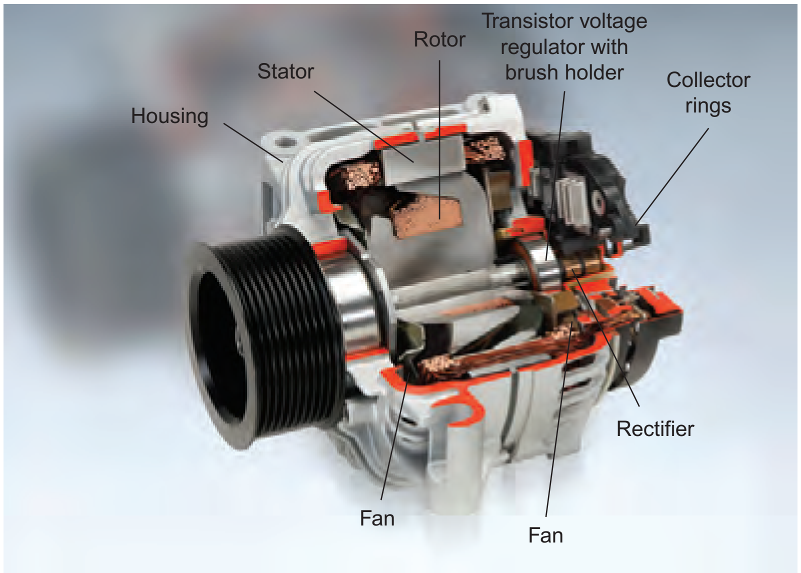


Figure 6.91 Alternator components

The main component of the charging system is the alternator and on most modern vehicles, with the exception of its associated wiring, it is the only component in the charging system. The alternator generates AC but must produce DC at its output terminal, as only DC can be used to charge the battery and run electronic circuits. The output of the alternator must be a constant voltage regardless of engine speed and current load.

The charging system must meet the following criteria (when the engine is running):

- supply the current demands made by some or all loads;
- supply whatever charge current the battery demands;
- operate at idle speed;
- constant voltage under all conditions;
- eff cient power to weight ratio;
- reliable, quiet, resistance to contamination;
- low maintenance;
- provide indication of correct operation.

Key fact

An alternator generates AC but must produce DC at its output terminal, as only DC can be used to charge the battery and run electronic circuits.

6.28.2 Basic principles

When the alternator voltage is less than the battery (engine slow or not running for example), the direction of current f ow is from the battery to the vehicle loads. The alternator diodes prevent current f owing into the alternator. When the alternator output is greater than the battery voltage, current will f ow from the alternator to the vehicle loads and the battery.

It is clear, therefore, that the alternator output voltage must be above battery voltage at all times when the engine is running. The actual voltage used is critical and depends on a number of factors.

The main consideration for charging voltage is the battery terminal voltage when fully charged. If the charging system voltage is set to this value, then there can be no risk of overcharging the battery. This is known as the constant voltage charging technique. The f gure of 14.2 ± 0.2 V is the accepted charging voltage for a 12 V system. Commercial vehicles generally employ two batteries in series at a nominal voltage of 24 V; therefore, the accepted charge voltage would be doubled. These voltages are used as the standard input for all vehicle loads. For the purpose of clarity, the text will just consider a 12 V system.

The other areas for consideration when determining charging voltage are any expected volt drops in the charging circuit wiring and the operating temperature of the system and battery. The voltage drops must be kept to a minimum, but it is important to note that the terminal voltage of the alternator may be slightly above that supplied to the battery.

6.28.3 Rectif cation of AC to DC

In order to full-wave rectify the output of a three-phase machine, six diodes are needed. These are connected in the form of a bridge, which consists of three positive diodes and three negative diodes. The output produced by this conf guration is shown compared to the three phase signals (Figure 6.92).

Three positive f eld diodes are usually included in a rectif er pack. These are often smaller than the main diodes and are only used to supply a small current back to the f eld windings in the rotor. The extra diodes are known as the auxiliary, f eld or excitation diodes.

Key fact

In order to full-wave rectify the output of a three-phase machine, six diodes are needed.

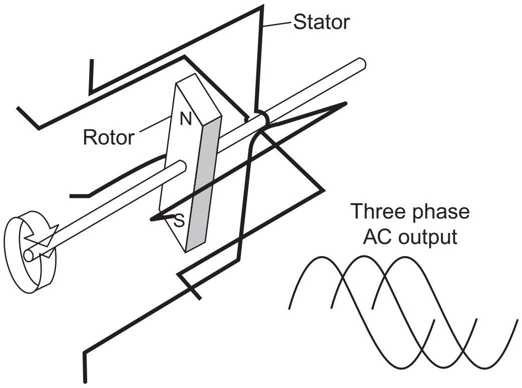


Figure 6.92 Alternator principle

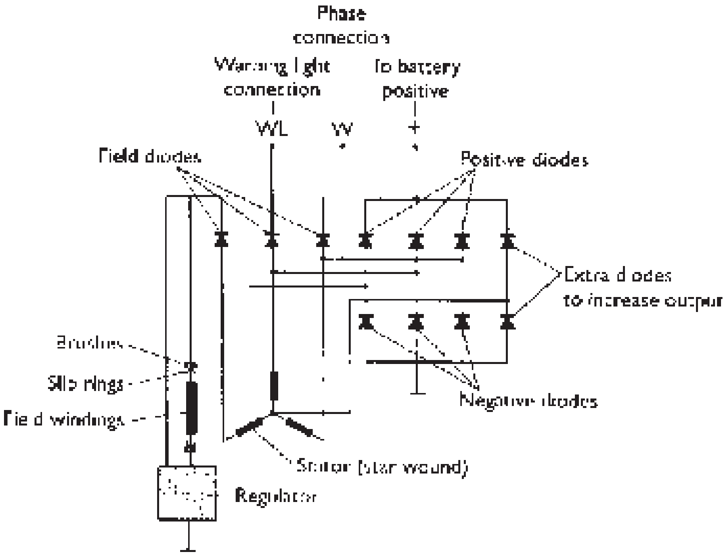


Figure 6.93 Alternator internal circuit

When a star wound stator is used, the addition of the voltages at the neutral point of the star is in theory 0V. In practice, however, due to slight inaccuracies in the construction of the stator and rotor, a potential develops at this point. By employing two extra diodes, one positive and one negative connected to the star point, the energy can be collected. This can increase the power output of an alternator by up to 15%.

Figure 6.93 shows the full circuit of an alternator using an eight-diode main rectif er and three f eld diodes. The voltage regulator, which forms the starting point for the next section, is also shown in this diagram. The warning light in an alternator circuit, in addition to its function in warning of charging faults, also acts to supply the initial excitation to the f eld windings. An alternator will not always self-excite as the residual magnetism in the f elds is not usually enough to produce a voltage which will overcome the 0.6 or 0.7V needed to forward bias the rectif er diodes. A typical wattage for the warning light bulb is 2W. Many manufacturers also connect a resistor in parallel with the bulb to assist in excitation and allow operation if the bulb blows. The charge warning light bulb is extinguished when the alternator produces an output from the f eld diodes, as this causes both sides of the bulb to take on the same voltage (a potential difference across the bulb of 0V).

6.28.4 Regulation of output voltage

To prevent the vehicle battery from being overcharged, the regulated system voltage should be kept below the gassing voltage of the lead-acid battery. A f gure of 14.2 ± 0.2 V is used for all 12 V charging systems. Accurate voltage control is vital with the ever-increasing use of electronic systems. It has also enabled the wider use of sealed batteries, as the possibility of overcharging is minimal.

Key fact

A fgure of 14.2± 0.2V is used for all 12V charging systems – except a few that have a smart charging system – check data.

Voltage regulation is a diff cult task on a vehicle alternator because of the constantly changing engine speed and loads on the alternator. The output of an alternator without regulation would rise linearly in proportion with engine speed. Alternator output is also proportional to magnetic f eld strength and this in turn is proportional to the f eld current. It is the task of the regulator to control this f eld current in response to alternator output voltage. The abrupt switching of the f eld current does not cause abrupt changes in output voltage due to the very high inductance of the f eld (rotor) windings. The whole switching process also only takes a few milliseconds.

Regulators can be mechanical or electronic, the latter now almost universal on modern cars. The mechanical type uses a winding connected across the output of the alternator. The magnetism produced in this winding is proportional to output voltage. A set of normally closed contacts is attached to an armature, which is held in position by a spring. The supply to the f eld windings is via these contacts. When the output voltage rises beyond a pre-set level, say 14 V, the magnetism in the regulator winding will overcome spring tension and open the contacts. This switches off the f eld correct and causes alternator output to fall. As output falls below a pre-set level, the spring will close the regulator contacts again and so the process continues.

The problem with mechanical regulators is the wear on the contacts and other moving parts. This has been overcome with the use of electronic regulators which, due to more accurate tolerances and much faster switching, are far superior, producing a more stable output. Owing to the compactness and vibration resistance of electronic regulators, they are now f tted almost universally on the alternator reducing the number of connecting cables required.

Key fact

Electronic regulators sense either the battery voltage or the machine voltage (alternator) or a combination of the two.

The key to electronic voltage regulation is the Zener diode. This diode can be constructed to break down and conduct in the reverse direction at a precise level. This is used as the sensing element in an electronic regulator (Figure 6.94).

Electronic regulators can be made to sense either the battery voltage or the machine voltage (alternator) or a combination of the two. Most systems in use at present tend to be machine sensed, as this offers some protection against overvoltage in the event of the alternator being driven with the battery disconnected.

Overvoltage protection is required in some applications to prevent damage to electronic components. When an alternator is connected to a vehicle battery system voltage, even in the event of regulator failure, will not often exceed approximately 20 V due to the low resistance and swamping effect of the battery. If an alternator is run with the battery disconnected (which is not recommended), a heavy-duty Zener diode connected across the output will offer some protection as, if the system voltage exceeds its breakdown f gure, it will conduct and cause the system voltage to be kept within reasonable limits. This device is often referred to as a surge protection diode.

6.28.5 Charging circuits

On many applications, the charging circuit is one of the simplest on the vehicle. The main output is connected to the battery via suitable size cable (or in some

Figure 6.94 Voltage regulator and brush box

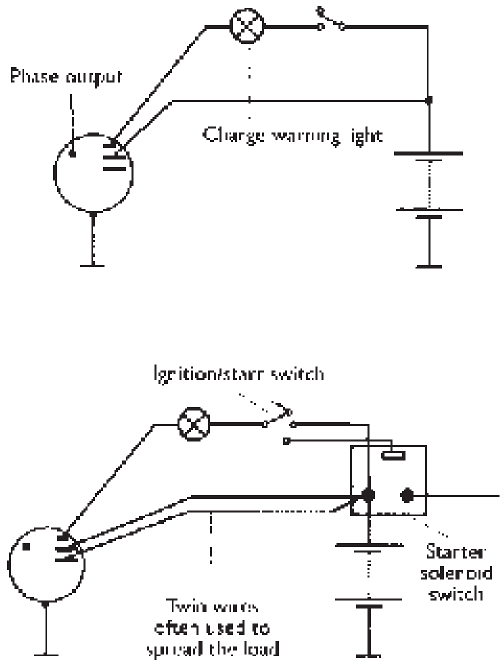


Figure 6.95 Example charging circuits

cases two cables to increase reliability and f exibility). The warning light is connected to an ignition supply on one side and to the alternator terminal at the other. A wire may also be connected to the phase terminal if it is utilised. Note that the output of the alternator is often connected to the starter main supply simply for convenience of wiring. If the wires are kept as short as possible, this will reduce voltage drop in the circuit. The volt drop across the main supply wire when the alternator is producing full output current should be less than 0.5 V (Figure 6.95).

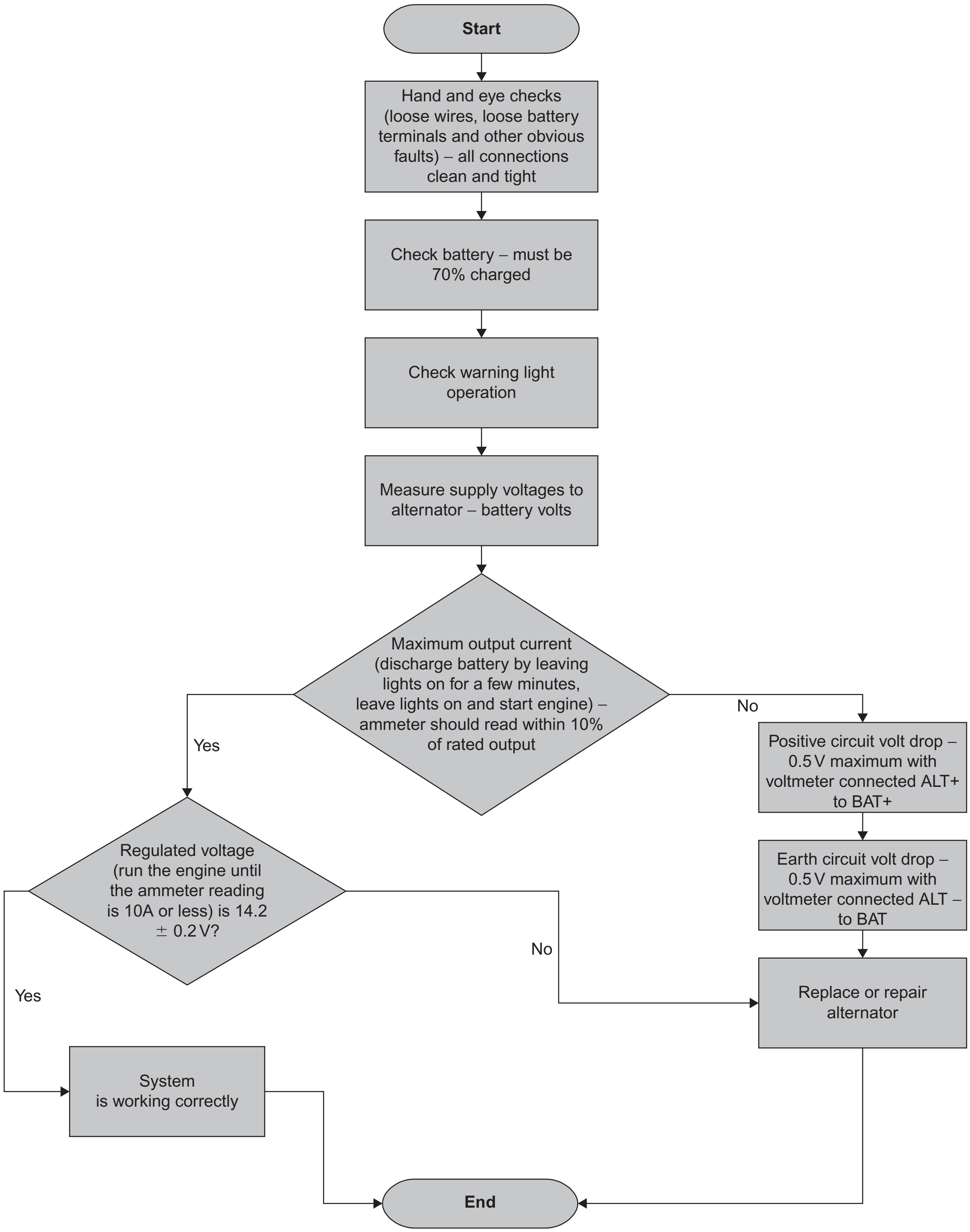


Figure 6.96 Charging system diagnosis chart

Some systems have an extra wire from the alternator to 'sense' battery voltage directly. An ignition feed may also be found and this is often used to ensure instant excitement of the f eld windings. A number of vehicles link a wire from the engine management ECU to the alternator. This is used to send a signal to increase engine idle speed if the battery is low on charge.

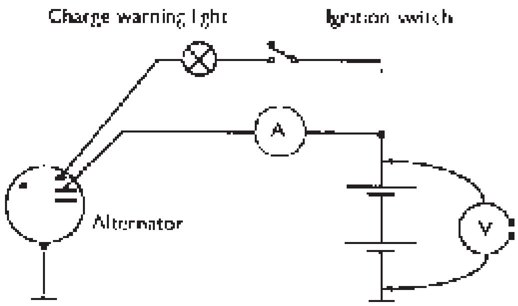


Figure 6.97 Alternator circuit testing

6.29 Diagnostics – charging

6.29.1 Testing procedure

After connecting a voltmeter across the battery and an ammeter in series with the alternator output wire(s), the process of checking the charging system operation is as shown in Figure 6.96.

If the alternator is found to be defective, then a quality replacement unit is the normal recommendation. Repairs are possible but only if the general state of the alternator is good (Figure 6.97).

6.29.2 Charging fault diagnosis table

Symptom	Possible fault
Battery loses charge	Defective battery Slipping alternator drive belt Battery terminals loose or corroded Alternator internal fault (diode open circuit, brushes worn or regulator fault, etc.) Open circuit in alternator wiring, either main supply, ignition or sensing wires fitted Short circuit component causing battery drain even when all switches are off High resistance in the main charging circuit
Charge warning light stays on when engine is running	Slipping or broken alternator drive belt Alternator internal fault (diode open circuit, brushes worn or regulator fault, etc.) Loose or broken wiring/connections
Charge warning light does not come on at any time	Alternator internal fault (brushes worn open circuit or regulator fault, etc.) Blown warning light bulb Open circuit in warning light circuit