ProVQ™

PETROL ENGINE TECHNOLOGY

PHASE THREE

Contents

Intake system

Valve Mechanisms

Increasing efficiency

Power/Torque

SI Fuel systems

Emissions Injection systems

Composition of fuels

Combustion, air fuel ratio

Emission limits

Variable valve timing

Engine management / Electronic control

Ignition systems

Diagnosis

Fuel systems

If we recap, there are two main fuel systems currently in use:

- Spark Ignition (SI) system which uses Petrol as fuel
- Compression Ignition (CI) system which uses Diesel as fuel

The main purpose of any fuel system is to:

- Atomise the fuel (create a fine mist/ vapour of fuel)
- Mix the fuel and air at the correct ratio
- Provide the correct mixture of air and fuel for all operating conditions (this can be infinitely variable). The correct air/fuel ratio is approx. 14.7:1 also known as stoichiometric.

Induction system

Air filtration

It is important that particles of dirt and dust are not sucked into the engine, as they will cause damage to occur in several different parts of the engine. If any dirt gets into the cylinders of the engine it is likely to mix with oil and stick to the cylinder wall. The dirt and oil mix would make a basic form of grinding paste and as the piston travels up and down heavy engine wear is going to occur. The task of the air filter is to filter the dirt out of the air and yet do this without restricting the air flowing into the engine. There are several different types of air filter; the paper type is the most common. These types of filter come in a variety of different shapes and sizes.

Intake manifold

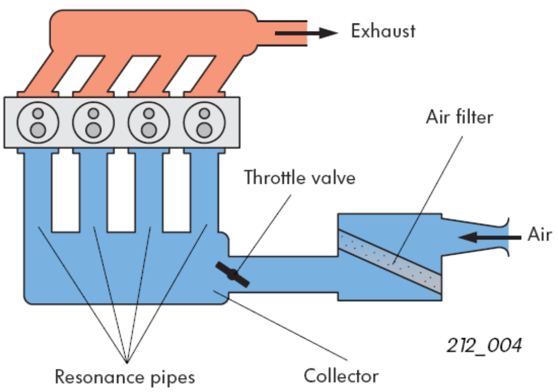
The inlet manifold is the component that distributes the air/fuel mixture to the individual cylinders of an engine. Over the years there have been many different deigns. The manifold should distribute the air/fuel mixture evenly throughout all the cylinders to ensure good power balance throughout the engine. The manifolds should also allow the air and fuel to mix well on their way to the cylinders and assist the fuel at staying in a vaporised state. Additionally, it is possible for the inlet manifold to assist airflow into the cylinders by means of something called dynamic supercharging. The key to understanding this is that moving air has inertia like anything else. As the inlet valve opens and closes, pressure pulsations travel up and down the inlet tract. If it can be timed that the pressure pulsation travelling through the inlet tract arrives at the inlet valve just as it opens an additional quantity of air can get into the cylinder. This will increase the torque of the engine at the specific engine speed where the pressure pulsation arrives at the inlet valve at the correct time. Just as this pressure pulsation can assist the airs entry into the engine, it can also hinder. If the pressure pulsation is just travelling away from the just opened inlet valve it will hinder airflow into the cylinder and actually reduce the torque of the engine at a certain engine speed.

Petrol engine intake

With most petrol engines, an intake manifold uses a throttle valve (sometimes referred to as a throttle butterfly) to control the volume of air being introduced to the engine. The driver has control of the throttle valve and can vary the volume of air at a rate dependent on the power required. The fuel is added either just before the intake valve or directly into the combustion chamber (direct injection).

Variable intake manifolds

The output and torque of an engine have the greatest effect on the engine's character.
These, in turn, are greatly affected by the degree to which the cylinder is filled and the geometric form (shape) of the intake tract. High torque requires an intake manifold with a different geometry to one for high power output. A medium intake manifold length with a medium diameter represents a compromise, but a variable intake manifold provides the solution.



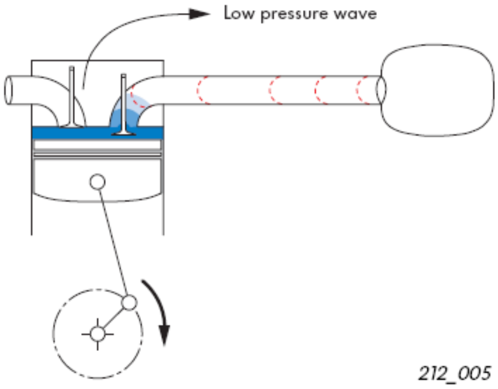
Basic structure of an air channel on an engine

The principle of resonance charging

An intake system works according to the principle of resonance charging, that is, high and low-pressure waves are used to charge the cylinder, to achieve greater volumetric efficiency.

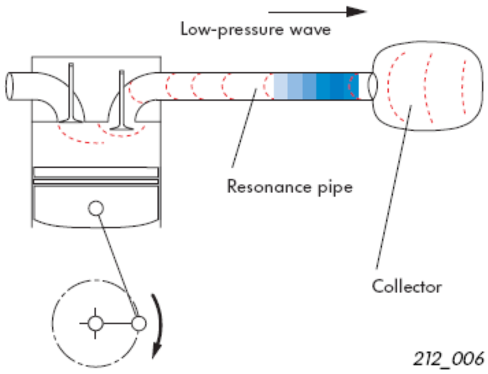
Consider the events in the intake tract.

- The inlet valve opens.
- The piston moves downwards in the cylinder, in the direction of bottom dead centre (BDC).
- It creates a low-pressure wave in the vicinity of the inlet valve.



Start of resonance charging

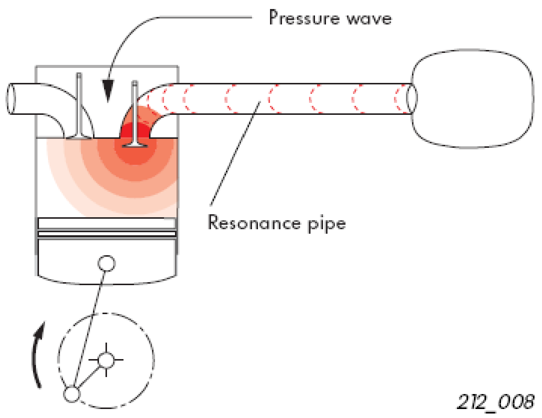
This low-pressure wave propagates itself though the resonance pipe to the other end, which protrudes into a collector. The low-pressure wave at the end of the pipe acts on the volume of air present in the collector. The pressure of the volume of air in the collector is approximately equal to ambient air pressure. This is significantly higher than the air pressure at the open end of the resonance pipe. The low pressure now present at the end of the pipe pulls along the air mass present here. They force themselves simultaneously into the resonance pipe so that where the low-pressure wave was, an equally large high-pressure wave develops, which propagates itself towards the inlet valve. This effect is also characterised in this way:



Propagation of low-pressure wave

- The low-pressure wave is reflected at the open end of the pipe in the collector.

This high-pressure wave travels back through the resonance pipe and pushes the air mass past the still-open inlet valve into the cylinder.



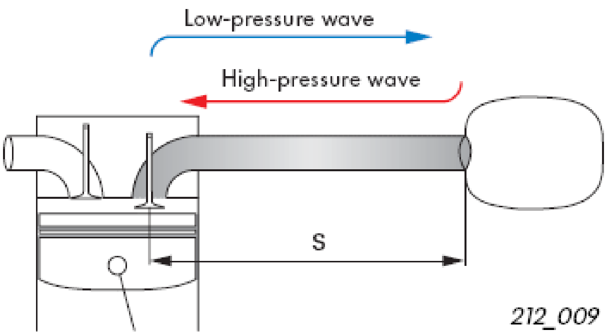
"Ram-effect" charging

This continues until the pressure before the inlet valve and the pressure in the cylinder are equal. The engine experiences "ram-effect" charging.

$$t = \frac{s = \text{constant (length of resonance pipe)}}{v = \text{constant (speed of sound)}} \quad [\text{ms}]$$

As a result, when the inlet valve closes, backflow of the ram-effect charging into the intake pipe is prevented.

The time t (in milliseconds) required by the low and high-pressure waves to cover the distance S from the inlet valve to the collector and back is always the same because they move at the speed of sound, v. But the time period during which the inlet valve is opened is dependent on engine speed. As engine speed increases, the period of time during which the inlet valve is open and air can flow into the cylinder decreases. A high-pressure wave returning through a resonance pipe designed for low engine speeds will run into an inlet valve which has already closed. “Ram-effect” charging cannot take place. It is clear that resonance pipes of different lengths are required for optimal charging at every engine speed.



The technical compromise is resonance pipes of different lengths!

- Long pipes (torque stage) for low to middle engine speeds.
- Short pipes (power stage) for high engine speeds.

Resonance pipes of different lengths can be opened or closed depending on engine speed
= variable intake manifold.

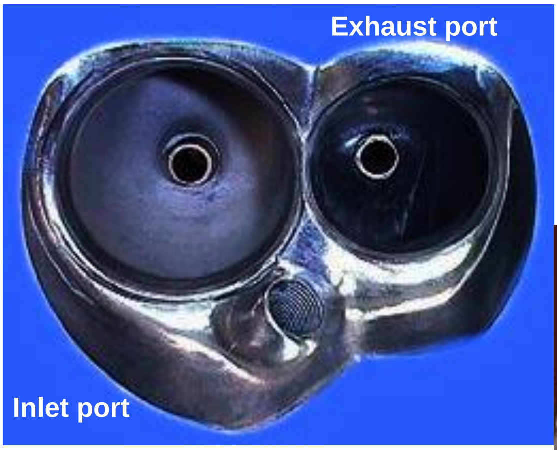
Diesel vehicle intake

As diesel vehicle require air only due to the fuel being delivered into each cylinder. The intake manifold is used simply to direct the filtered air into each cylinder. Modern diesel engines tend to use a throttle valves to aid with reducing intake noise and controlling exhaust gas recirculation (EGR) levels precisely.

Valve mechanisms

Increasing the number of valves means we can increase the volumetric efficiency of the engine (allow more air into the cylinder within a limited time).

Using just two valves leaves most of the cylinder bore area unused, by reducing the size of the valves it is possible to fit three valves per cylinder, if the valves are made smaller it makes it possible to fit four valves per cylinder or five or even six.



Two valve wedge combustion chamber

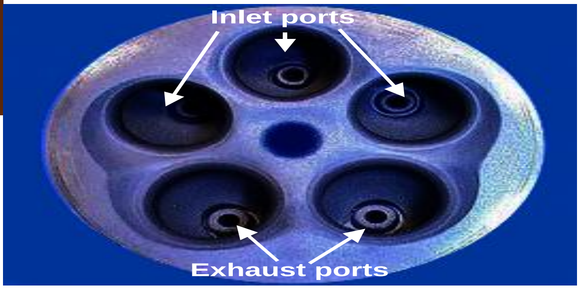
Nissan three valve combustion chamber, one exhaust port and two inlet ports

The more valves fitted the greater is the volumetric efficiency, the greater is the power produced. The main disadvantage of increasing the number of valves is that the strength of the cylinder head would be affected, so five and six valve engines are not as popular as the four valve.

Note: Maserati flirted with the six-valve configuration for a while but reverted to the standard layout.
Honda tried an experiment with an oval piston and eight valves per cylinder but this idea was soon discarded, it was too complex.

Four valve layout

Five valve combustion chamber. Three intake ports at the top and two larger exhaust valves are at the bottom



Volumetric efficiency

Volumetric efficiency in internal combustion engine design refers to the efficiency with which the engine can move the *charge* into and out of the cylinders. More specifically, volumetric efficiency is a ratio (or percentage) of what quantity of fuel and air actually enters the cylinder during induction to the actual capacity of the cylinder under static conditions. Therefore, those engines that can create higher induction manifold pressures - above ambient - will have efficiencies greater than 100%. Volumetric efficiencies can be improved in several ways, but most notably the size of the valve openings compared to the volume of the cylinder and streamlining the ports. Engines with higher volumetric efficiency will generally be able to run at higher speeds (commonly measured in RPM) and produce more overall power due to less parasitic power loss moving air in and out of the engine.

There are several standard ways to improve volumetric efficiency. A common approach for manufacturers is to use larger valves or multiple valves. Larger valves increase flow but weigh more. Multi-valve engines combine two or more smaller valves with areas greater than a single, large valve while having less weight, but with added complexity. Carefully streamlining the ports increases flow capability. This is referred to as porting and is done with the aid of an air flow bench for testing. Another major aspect of design is to use a cross flow cylinder head, which has become the standard configuration in modern engines.

Many high-performance cars use carefully arranged air intakes and tuned exhaust systems to push air into and out of the cylinders, making use of the resonance of the system. Two-stroke engines take this concept even further with expansion chambers that return the escaping air-fuel mixture back to the cylinder. A more modern technique, variable valve timing, attempts to address changes in volumetric efficiency with changes in speed of the engine: at higher speeds the engine needs the valves open for a greater percentage of the cycle time to move the charge in and out of the engine.

Volumetric efficiencies above 100% can be reached by using forced induction such as supercharging or turbocharging. With proper tuning, volumetric efficiencies above 100% can also be reached by naturally aspirated engines. The limit for naturally aspirated engines is about 137% these engines are typically of a DOHC layout with four valves per cylinder.

Power

An engines power is determined by the amount of air that it can consume per minute i.e. its cylinder capacity and the speed at which it runs. The greater the speed of the engine the faster the power strokes occur. Engine speed is limited by the weight (mass) of the internal parts. That is why multi cylinder engines have lighter internal mass and a shorter stroke than that of a single cylinder engine. This advantage of the multi cylinder engine can run at higher speeds, have a good balance and develop greater power.

Power is the rate of doing work and is measured in Newton metres per second or Watts, named after James Watt.

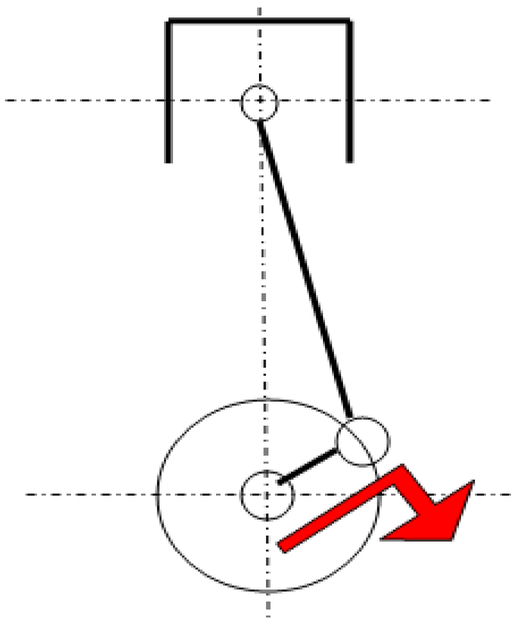
Power is equal to force x distance and is measured in Watts

Torque

Torque is a twisting force; when applied it will turn something or try to turn something. This means that torque doesn't need to be moving anything, just trying to. Importantly you cannot apply a torque if there is no resistance. Torque is measured in Newton metres, named after Sir Isaac Newton. Torque is the result of force acting at a distance from the centre of turn or radius. The more force the greater the torque, the bigger the radius the greater the torque.

The torque of an engine is an indication of the turning force available at the crankshaft. It is only created during the power stroke therefore the greater the expansion of combustion gases, the greater the force acting on the piston.

Torque is calculated as: torque = force x radius



Work

Work is done when a force is applied and movement takes place. If a bolt is being tightened and movement takes place, then work is being done. But if the bolt is tight and no movement takes place then no work is being done. In both situations torque is applied. Here is where confusion can happen. Work is also measured in Newton metres; this time it is the force applied in Newton's and the distance moved in metres.

20 metres

If the man pictured (above) has to apply a force of 400 Newton to make the car move, and moves the car 20 metres he is said to have done 20 x 400 = 8000Nm of work.

To try and separate Nm of torque and Nm of work we use the unit Joule so we can say he has done 8000Joules or 8kJ of work.

Brake horse power (BHP)

When engines were first developed, they were compared with what they were replacing and this normally meant horses. In the early 1700s James Watt conducted an experiment to find out how powerful a horse was and calculated that it could raise 33,000 lb one foot in one minute or more reasonably 330 lb 100feet in one minute. This became the standard in the UK and the US. Europe, however, adopted another version of horsepower Ps Din Pferdetarke Deutsches Institut fur Normung (it just means horse power German standard). Since the 1970s the UK motor industry has dithered - you will see power quoted in magazines in kW, BHP and Ps DIN.

$$BHP = \frac{\text{torque (lbft)} \times 2\pi \times \text{rpm}}{33000}$$

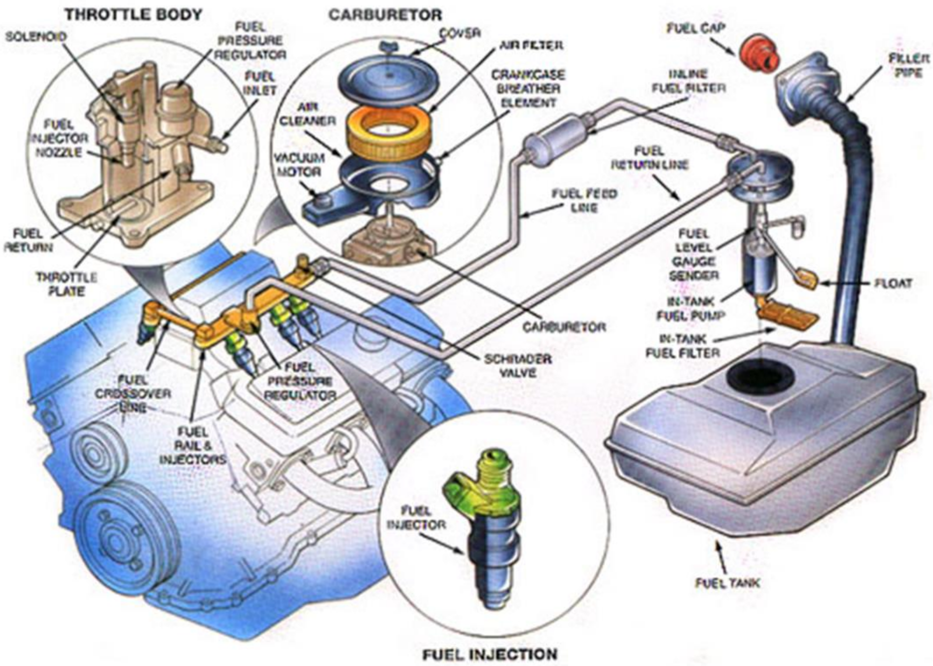
Converting kW to BHP:

1Ps DIN is equal to 0.735 kW

1BHP (US) is equal to 0.745 kW

If you like, 100bhp is 74.5kW or 100Ps DIN is equal to 73.5kW

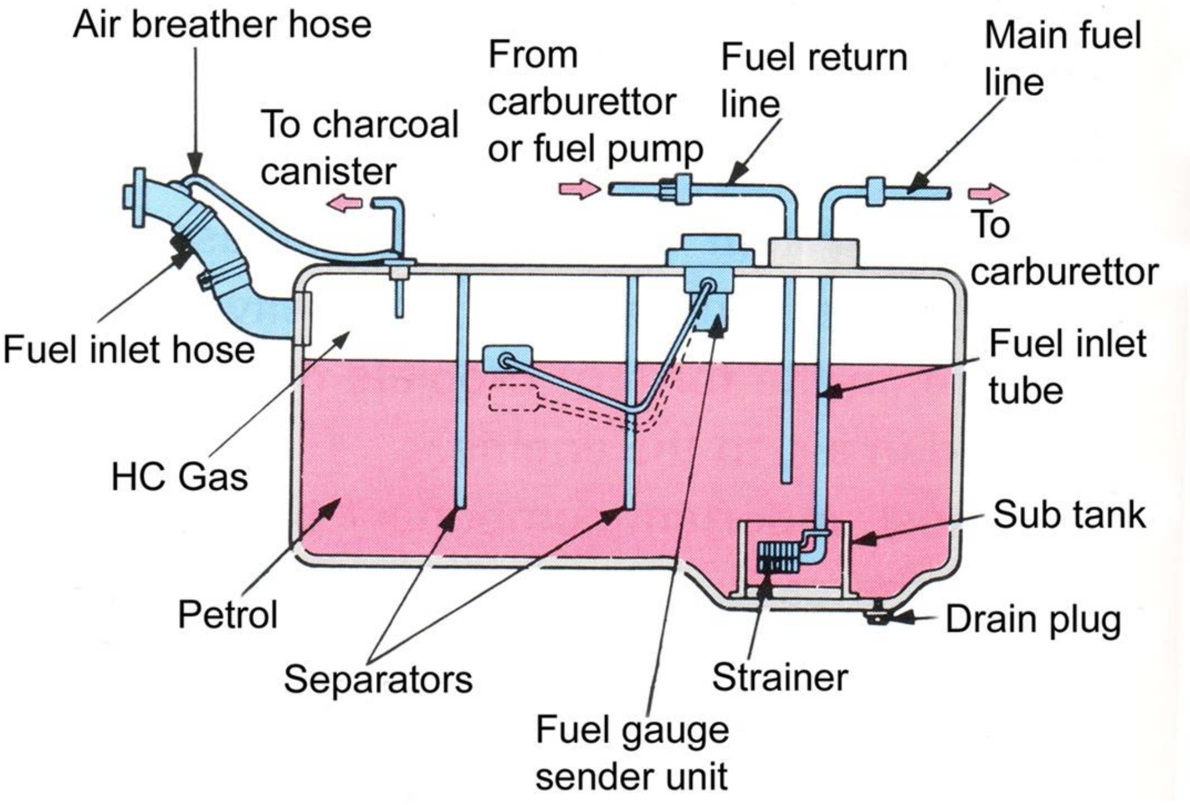
Spark ignition fuel systems



A petrol spark ignition engine relies on the combustion of an air/fuel mixture to provide the energy to make it run. A constant supply of clean air is required to mix with a precise amount of fuel in order to operate efficiently. The air/fuel mixture is ignited inside the combustion chamber and the heat increase causes the gas inside to expand. This expansion of gas increases the pressure inside the combustion chamber and forces the piston down. The downward movement of the piston is transferred into the crankshaft and creates rotary motion.

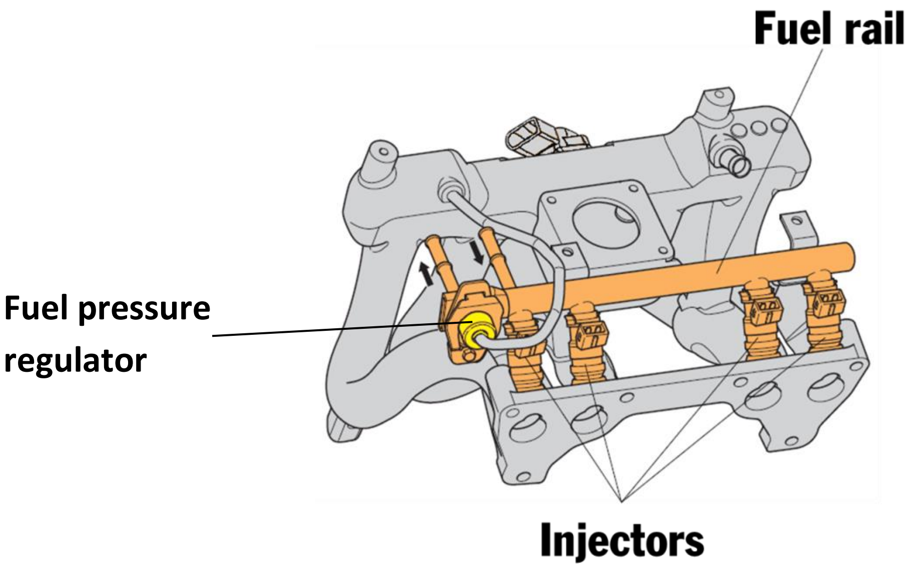
The fuel tank

The fuel tank is a container fitted to the vehicle to hold the fuel until the engine consumes it. The fuel tank must be of a substantial size, as no owner of a vehicle wants to be constantly calling into the petrol station to be filling up. Additionally, it doesn't want to be too big, as it will inversely affect the power to weight ratio of the vehicle. On modern vehicles, it tends to be fitted to the rear of the vehicle. The vehicle is usually designed to try and protect the fuel tank to reduce the fire and explosion risks associated with carrying around large quantities of fuel. Most fuel tanks used to be made from sheet steel although it is now much more common for them to be made out of plastic. Plastic is an ideal material for the production of fuel tanks as it can be easily vacuum formed into a complex shape to optimise space usage underneath the rear of the vehicle. It is less likely to leak in the event of a minor crash as it will just deform and finally there are no corrosion worries, like that of steel tanks.
There are baffles fitted to the inside of the fuel tank to prevent the fluctuation in fuel levels in the event of lateral forces being exerted upon the fuel. I.e. when cornering. Additionally, if the fuel level gets very low it is possible fuel starvation could occur creating a hesitation whilst the vehicle is being driven. The fuel pick up (strainer) is located towards the bottom of the tank although it is not situated right at the bottom, as this would increase the chances of sediment and water being sucked up. The fuel gauge sender unit is situated inside the fuel tank. This provides a signal to the fuel gauge so the driver of the vehicle knows how much fuel is in the tank. It is common for the fuel pump to be internally fitted to the tank these days. A fuel return feeds back into the tank, this is particularly necessary in the case of fuel-injected cars, as a constant pressure needs to be supplied to the injectors. There are various methods employed to achieve this but either way there needs to be a facility to return fuel back to the tank.



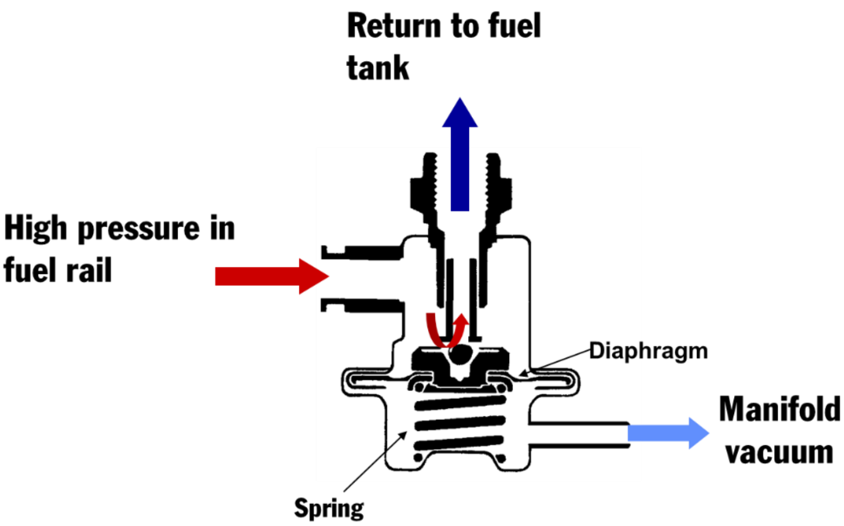
Fuel rail

The fuel rail is a distribution pipe that allows the fuel to flow to all the injectors. Fuel flows from the tank, through the fuel pump and filter to the fuel rail, where the injectors receive their supply of fuel.

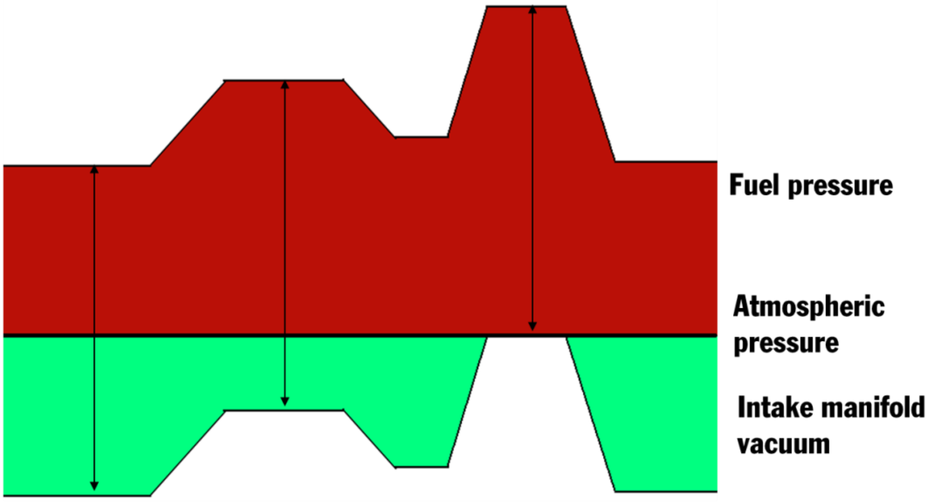


Fuel pressure regulator

The purpose of the fuel pressure regulator is to compensate for any pressure differential variations experienced across the fuel injector due to intake manifold pressure changes.



For example, if the engine is running at light load – engine speed 2000 RPM partial throttle, the pressure in the manifold will be low. When the injector opens, this low pressure will help draw in the fuel, creating an over fuelling situation. The regulator reduces the fuel pressure behind the injector (in the rail) under these conditions so that the difference in pressure across the injector is constant. The manifold pressure either helps or hiders the lifting of the diaphragm and therefore influences the volume of fuel that is able to return to the tank. This directly affects rail pressure. If the manifold hose should become detached, the engine over fuels (atmospheric pressure is acting on the regulator continually, the equivalent of WOT – wide open throttle).



Typical fuel pressure – 3.0 bar without vacuum

Fuel pressure + vacuum = 3.0 bar

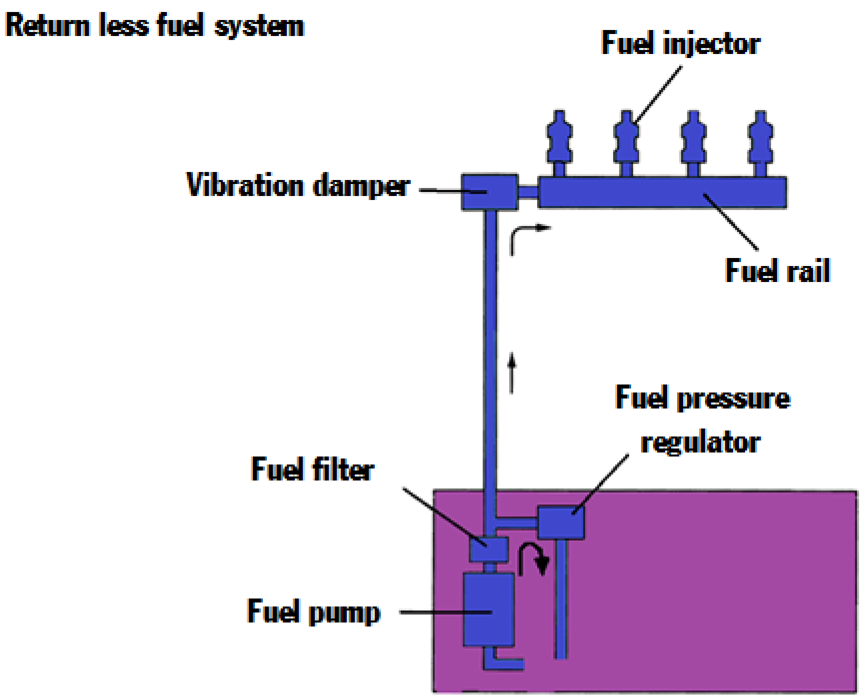
Fuel Pressure	Low	High
Intake Manifold vacuum	High (low pressure)	Low (high pressure)
Injection Volume	Same	Same

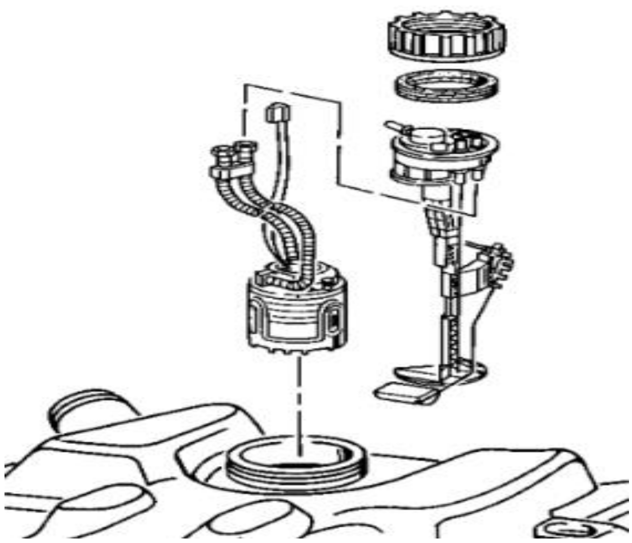
It should be noted that most modern engines have now done away with this type of regulator and use a fuel return less system. Pressure in the rail is kept at a constant through the use of a pressure regulator valve housed inside the fuel tank. A manifold pressure sensor senses any fluctuations in manifold pressure and the engine management computer compensates for these variations in its fuel injection duration calculation. This way, no fuel is returned to the tank from a hot engine and this helps to reduce evaporative emissions (excess fuel vapour) from the tank considerably (a smaller charcoal canister can be fitted).

Fuel return less systems

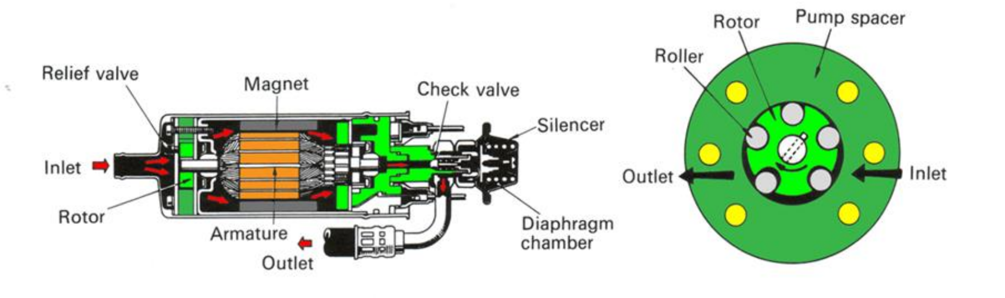
Many vehicles today incorporate a return less fuel system. This system can maintain fuel delivery pressure without the need for a fuel return line. The return less system reduces emissions by cutting out the return line that carries warm fuel. The warm fuel increases fuel vapour in the tank.

The return less system works by incorporating a fuel pressure regulator within the fuel pump assembly within the tank. The regulator supplies the fuel pressure required by the fuel system until the pressure is achieved. The excess fuel is bled directly into the tank.



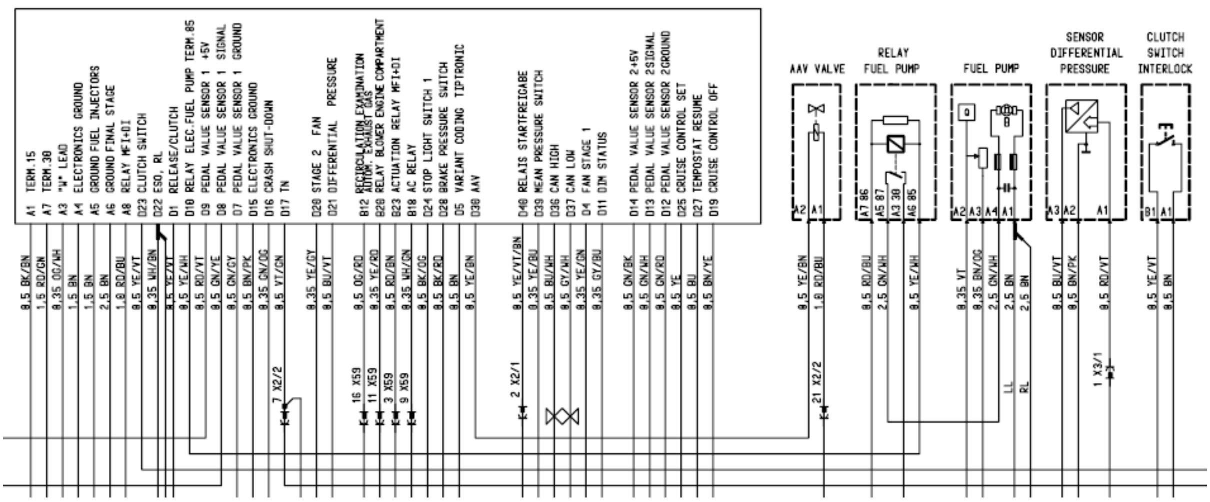


Fuel pump



ROTOR TYPE (IN-LINE TYPE)

As the electrical fuel pump is not driven directly from the engine it can be operated when the engine is not running. This is particularly handy in the case of fuel injection as the pump can be run to pressurise the fuel rail before the engine is cranked. This type of pump is fitted in line in one of the fuel hose. It is basically an electric motor that functions while it is full of fuel. The rotor is the part that actually creates any pressure. This occurs as the rotor revolves around at the speed of the motor. As it turns it traps a quantity of fuel in the inlet side and moves it over to the outlet side and expels it. There is a silencer fitted to the end of the pump as it can sound quite load when in operation.



Evaporative emissions

All automobile manufacturers have been required to decrease both tail pipe emissions and the evaporative emissions of volatile organic compounds (VOC). Some of these VOCs are hydrocarbons (gasoline and oil), which vaporise and escape from an automobile's engine and fuel system. Automobile manufacturers have addressed this issue with the implementation of Evaporative (EVAP) Emissions Systems.

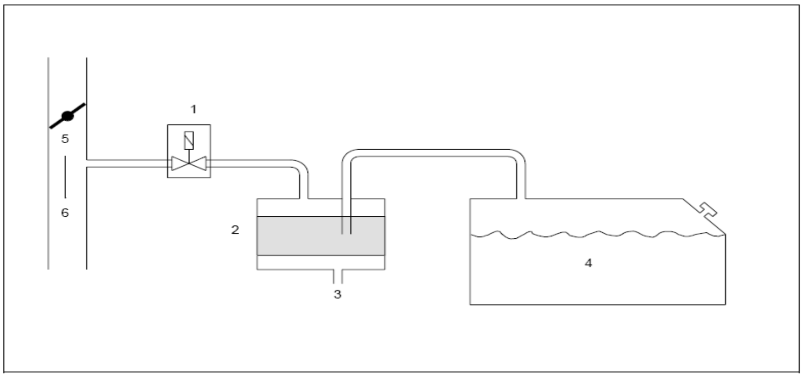
The purpose of all Evaporative (EVAP) Emissions Systems is to prevent the release of VOC. The main concern is Hydrocarbons (HC's) or unburned gasoline vapours. Hydrocarbons are released from gasoline in the form of a vapour, and if the fuel system is not air tight, these vapours can then escape into the atmosphere. The problem with unburned hydrocarbons is that they aid in the production of photochemical smog.

The primary function of the evaporative emissions system is to prevent hydrocarbons from being released into the atmosphere and store them until they can be reintroduced into the intake air stream at a later time. The vapours are stored in a charcoal canister. The charcoal in the canister provides a surface area onto which the fuel vapours can be adsorbed and stored. These stored vapours can then be released back into the incoming air charge when certain criteria are met during vehicle operation. The fact that charcoal is a carbon makes it ideal for use in the fuel system. Carbons are attracted to other carbons. Because of this fact, hydrocarbons will form loose chemical bonds to the charcoal in the carbon canister.

The release of fuel vapours is accomplished by a canister purge solenoid, which is placed in series between the canister and the engine's intake manifold. This solenoid controls the quantity and rate of vapours being released by cycling on and off in what is called a duty cycle. A duty cycle is the solenoid's "on time" (open) compared to its "off time" (closed) as a percent of the cycle. The vehicle's Engine Control Module (ECM) determines the duty cycle of the purge solenoid.

The ECM receives feedback from the exhaust oxygen sensor (O2S) located in the exhaust stream. With O2S feedback the canister purge solenoid can be activated when the vehicle is capable of running lean, most commonly at warm engine cruise. As the canister purge solenoid opens, it permits the vacuum in the engine's intake manifold to draw in fuel vapours. These vapours will enrich the lean air/fuel mixture and the purge will be shut off once the O2S senses this change.

System Overview



1 - EVAP canister purge valve
2 - EVAP canister
3 - Purge air
4 - Tank
5 - Intake manifold

Crankcase emissions

While the engine is running, some gases from combustion leak between the piston rings and the cylinder walls, down into the crankcase.

This leakage is called blow-by. Unburned fuel, and water from condensation, also find their way into the crankcase, and sump. When the engine reaches its full operating temperature, the water and fuel evaporate. To prevent pressure build-up, the crankcase must be ventilated.

In older vehicles, crankcase vapours were vented directly to the atmosphere through a breather tube, or road-draught tube. It was shaped to help draw the vapours from the crankcase, as the vehicle was being driven.

Modern vehicles are required to direct crankcase breather gases and vapours back into the inlet system to be burned.

A common method of doing this is called positive crankcase ventilation, or PCV.

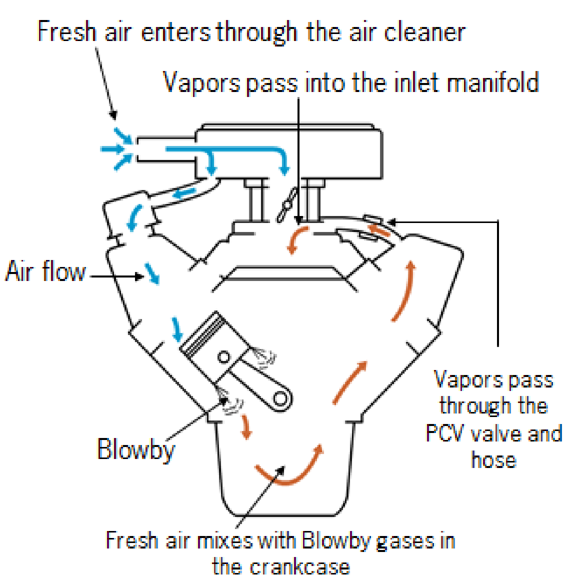
A valve called a PCV valve, regulates gas flow between the crankcase and the inlet manifold. It is controlled by the pressure in the manifold. With the engine off, the valve is closed, and air cannot enter the inlet manifold. This allows the engine to start.

At idle, low pressure in the manifold draws the valve to the other end of the body. This lets a small, measured amount of vapour pass the valve.

At wider throttle openings, the valve plunger position allows maximum flow through the body, which gives maximum crankcase ventilation.

The system is designed to remove more air than just blow-by, so there’s a fresh air intake, usually at the air cleaner, to direct filtered air to the crankcase. This intake is usually as far as possible from the PCV valve.

Wide throttle openings produce maximum blow-by. Gases that can’t be handled through the vacuum system, are directed back through the inlet connection to the air cleaner, where they join the carburettor intake air, and are drawn into the cylinders for burning.



Fuel

Crude oil contains hundreds of different types of hydrocarbons all mixed together and, depending on the source of the crude oil, different impurities. In order to produce petrol, diesel or any other oil-based products, the hydrocarbons have to be separated, by refining of one type or another:

Different hydrocarbon chain lengths all have progressively higher boiling points, so they can all be separated by a process known as distillation. In a refinery, in one part of the process, crude oil is heated and the different hydrocarbon chains are pulled out as a vapour according to their vaporisation temperatures and then recondensed. For example:

Petrol - motor fuel:

- Liquid
- mix of alkanes and cycloalkanes (5 to 12 carbon atoms)
- boiling range = 40°C to 205°C

Gas oil or Diesel - motor fuel:

- Liquid
- alkanes containing 12 or more carbon atoms
- boiling range = 250°C to 350°C

Kerosene - fuel for jet engines:

1. Liquid
2. mix of alkanes (10 to 18 carbons) and aromatics
3. boiling range = 175°C to 325°C

Of course, after distillation, there are various techniques that are used to convert some fractions to others:

- cracking, which breaking large hydrocarbon chains into smaller ones
- unification – which combines smaller hydrocarbon chains to make larger ones
- alteration – which re-arranges various pieces to make desired hydrocarbons

For example, this allows a refinery to turn diesel fuel into petrol fuel, depending on the demand for petrol. Refineries will also combine various fractions (processed, unprocessed) into mixtures to make desired products. For example, different mixtures of hydrocarbon chains can create petrol with different octane ratings.

Octane rating

The octane rating of gasoline tells you how much the fuel can be compressed before it spontaneously ignites. When gas ignites by compression rather than because of the spark from the spark plug, it causes knocking in the engine. Knocking can damage an engine, so it is not something you want to have happening. Lower-octane gas (like "regular" 87-octane gasoline) can handle the least amount of compression before igniting.

The compression ratio of your engine determines the octane rating of the petrol you must use in the car. One way to increase the horsepower of an engine of a given displacement is to increase its compression ratio. So, a "high-performance engine" has a higher compression ratio and requires higher-octane fuel. The advantage of a high compression ratio is that it gives your engine a higher horsepower rating for a given engine weight -- that is what makes the engine "high performance." The disadvantage is that the petrol for your engine costs more.

Flash point

The flash point is the temperature at which vapour emitted to the atmosphere from a liquid fuel can be ignited by a spark. This has implications for transport and storage of diesel fuels and they must not have a flash point below 55ºC. It used to be commonplace for operators to add petrol to diesel fuel in cold conditions in order to improve the cold starting of some engines. Adding just 3% petrol is sufficient to reduce the flash point to around room temperature, making storage and handling of the fuel extremely hazardous. Fortunately, modern fuels conforming to legal standards contain chemicals which make adding petrol to diesel fuel unnecessary.

Volatility

Fuels function by releasing combustible gases (vapours)

Boiling Point is an indicator of volatility: the higher the boiling point, the less volatile the fuel.

Vapour pressure is an indicator of volatility: the higher the vapour pressure, the more volatile the fuel. Vapour pressure increases with temperature, so the volatility of a fuel can be increased by raising the temperature.

A highly volatile fuel is more likely to form a flammable or explosive mixture with air than a non-volatile fuel. By definition, gases are volatile.

Liquid fuels are either sufficiently volatile at room temperature to produce combustible vapour (ethanol, petrol) or produce sufficient combustible vapours when heated (kerosene).

Solid fuels decompose above the vaporisation temperature to produce combustible vapours. Solid fuels will have a higher ignition temperature than liquid or gaseous fuels.

Calorific Value

The amount of heat liberated by complete combustion of unit mass of a fuel is called the calorific value. For an average sample of petrol, the calorific value is about 44MJ/Kg (this is measured in mega joules per kilogram).

Emissions

Euro Emission Limits

EU emissions standards for passenger cars (in g/km)

Euro Standard	Implementation date*	CO (g/km)	THC (g/km)	NMHC (g/km)	NOx (g/km)	HC=NOx (g/km)	PM (g/km)
Diesel							
Euro I	July 1993	2.72	-	-	-	0.97	0.14
Euro II	January 1997	1.00	-	-	-	0.70	0.08
Euro III	January 2001	0.64	-	-	0.50	0.56	0.05
Euro IV	January 2006	0.50	-	-	0.25	0.30	0.025
Euro V	September 2010	0.500	-	-	0.180	0.230	0.005
Euro VI	September 2015	0.500	-	-	0.080	0.170	0.005
Petrol							
Euro I	July 1993	2.72	-	-	-	0.97	-
Euro II	January 1997	2.20	-	-	-	0.50	-
Euro III	January 2001	2.30	0.20	-	0.15	-	-
Euro IV	January 2006	1.00	0.10	-	0.08	-	-
Euro V	September 2010	1.000	0.100	0.068	0.060	-	0.005**
Euro VI	September 2015	0.100	0.100	0.068	0.060	-	0.005**

* Market placement (or first registration) dates, after which all new engines placed on the market must meet the standard. EU emission standards also specify Type Approval dates (usually one year before the respective market placement dates) after which all newly type approved models must meet the standard.
** Applies only to vehicles with direct injection engines.

European directives have been instrumental in reducing what are known as the regulated emissions. These include carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HCs) and particulate matter less than 10 microns in size (PM10). First introduced in 1992, these form a set of rolling regulations designed to become more stringent year on year. Currently limits for new cars and light-duty vans must conform to 'Euro IV' standards.

The effect of tighter Euro standards on vehicle emissions has been to accelerate the introduction of greener vehicle technologies. For petrol cars, this has been achieved in part through the use of the three-way catalytic converter and the move to fuel injection systems. For diesels, NOx and particulate emissions have been reduced through the development of direct injection engines and diesel particulate filters (DPFs).

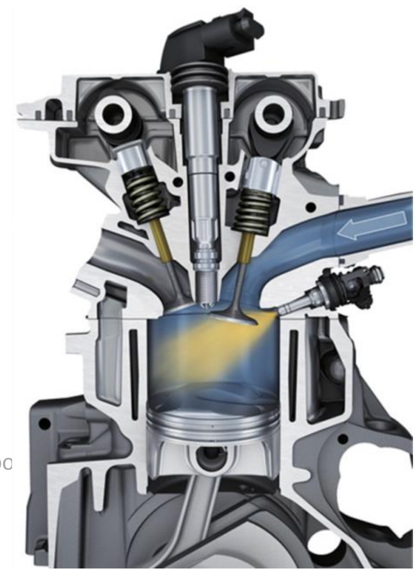
These technological advances, together with the cleaner fuels that made these developments possible, have led to a dramatic reduction in regulated pollutants; so much so, that a car manufactured today produces twenty times fewer emissions than a car made in 1970. Car manufacturers are well aware that future cars will have to conform to yet tighter regulations.

In contrast to the legislation for regulated pollutants, there was until recently no current EU law which limits the amount of carbon dioxide produced by cars. However, in 2009, the European Parliament passed new car CO2 legislation that sets an emissions cap of 130 g/km averaged over all new vehicles produced by each manufacturer by 2015. The 130 g/km average will be the equivalent of 58 mpg for diesel engines and 52 mpg for petrol engines.

Reaching this goal was phased in over three years; by 2012, 65% of each manufacturers' newly registered cars must comply, 75% by 2013 and 80% by 2014 and 100% by 2015. An extended target is set to be an average of 95 g/km by 2020. Manufacturers that exceed targets from 2012 onwards will have to pay a penalty for each car registered, which amounts to €5 for the first g/km of over the limit, €15 for the second g/km, €25 for the third, and €95 for each subsequent gram. From 2019, stricter penalties will be introduced with every exceeding gram costing the manufacturer €95

Air / fuel ratio

Introducing the fuel in an efficient manner is of paramount importance on a modern vehicle. With drivers demanding better fuel economy and performance coupled with governments demanding fewer harmful emissions, only electronic control of the fuelling of an engine can meet all requirements.

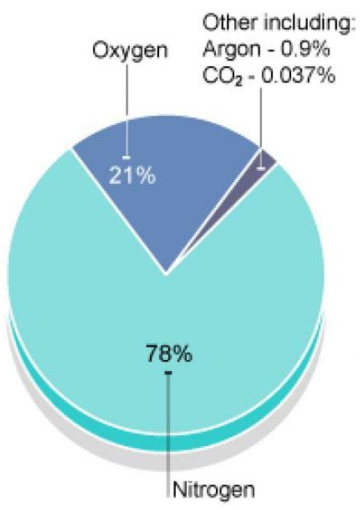


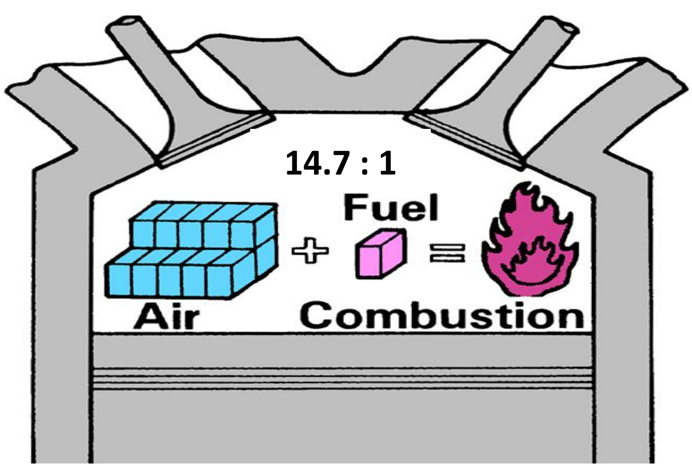
A four-stroke petrol engine running on unleaded fuel will run at its most efficient with an air / fuel ratio of 14.7:1 (that is 14.7 lots of air for every 1 lot of fuel). This is because with such a mixture strength, all the fuel will be burnt and all of the oxygen in the air will be burnt. If you burn all the fuel then you are wasting none, and if you burn all of the oxygen you will create maximum combustion pressure that will translate into maximum torque (if all other conditions are also ideal such as ignition timing).

This magical mixture strength is often referred to as 'stoichiometric'. This is a term borrowed from chemists – they will refer to a reaction as stoichiometric if during the course of that reaction all of the constituents are fully consumed.

It should be noted however that a stoichiometric mixture is rarely achieved in an engine. This is because of their natural inefficiency. Your average 4-stroke petrol engine is around 25% efficient. This means that for every four gallons of fuel that you put in; only one gallon turns the flywheel! This inefficiency is mainly due to heat loss – it is worth noting that a petrol engine is a heat engine – it converts heat energy through the burning of the fuel and air into kinetic energy (the rotation of the flywheel). Inevitably a good deal of the heat energy created escapes through the exhaust pipe, into the cooling system etc.

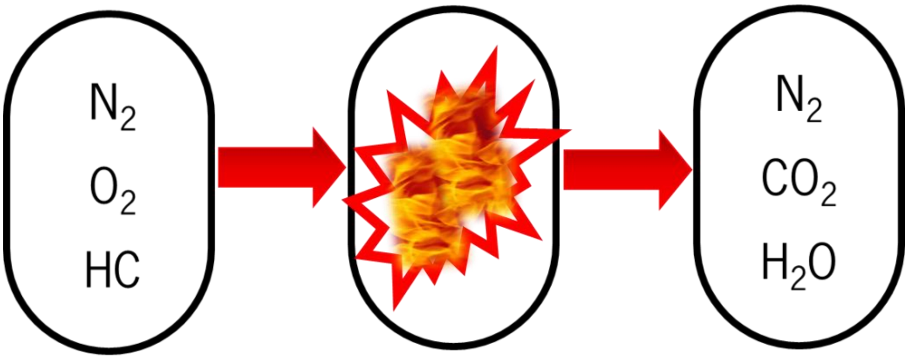
Another area of inefficiency is in the mixing of the fuel and air. Oxygen is the only constituent gas within air that is of any use to us in this instance as it supports combustion. Air is only 21% oxygen (78% nitrogen and 1% others). So only roughly one fifth of all the air drawn into the engine during the induction stroke is of any use to us.





The difficulty that we have is ensuring that the particles of fuel are mixed efficiently with the air to ensure that we make best possible use of that 21% oxygen. If we cannot do that, not all of the oxygen will burn and we have an inefficient engine.

Combustion



Perfect combustion - stoichiometric

Under perfect conditions, when petrol is burnt in air with mixture strength of 14.7:1, nitrogen (N2), carbon dioxide (CO2) and water (H2O) are produced. As we have seen, perfection is a holy grail.

Lambda λ

Lambda is a Greek letter that means 1. Lambda is frequently used to describe air – fuel ratio. The stoichiometric air fuel ratio 14.7:1 is also known as Lambda 1.

Lambda is calculated by:

$$\frac{\text{Actual air/fuel ratio}}{\text{Desired air fuel ratio}} = \lambda \text{ value}$$

For correct air/ fuel ratio:

$$\frac{14.7:1}{14.7:1} = \lambda \ 1.0$$

Weak mixture

$$\frac{17.1:1}{14.7:1} = \lambda\ 1.15$$

Rich mixture

$$\frac{12.5:1}{14.7:1} = \lambda\ 0.85$$

Exercise 1

Complete the following table:

Air / fuel ratio	Lambda value	Rich or lean
17.7:1		
8.7:1		
13.2:1		

Exhaust gas recirculation (EGR)

The basic problem with regard to the internal combustion engine and NOx is that high combustion temperatures cause an increase NOx production. Any aspect of the engine design or operation that is liable to increase combustion temperature is then going to result in high NOx emissions. As an example, many modern engines run fairly high compression ratios with ignition timing hovering just around the point of detonation. This creates high combustion temperatures which only serve to increase the NOx emissions.

Internal EGR

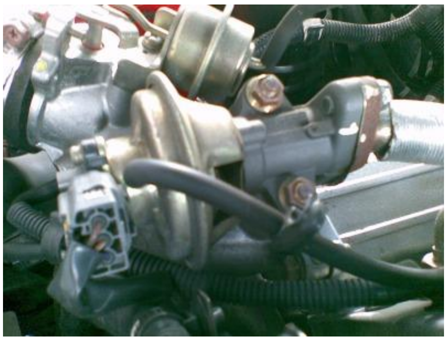
This method was realised once variable valve timing became a common application. At light loads, introducing an increased valve overlap to retain/re introduce exhaust gasses into the combustion chamber becomes an effective EGR system. As mentioned before, slight pumping losses are reduced through a diluted mixture.

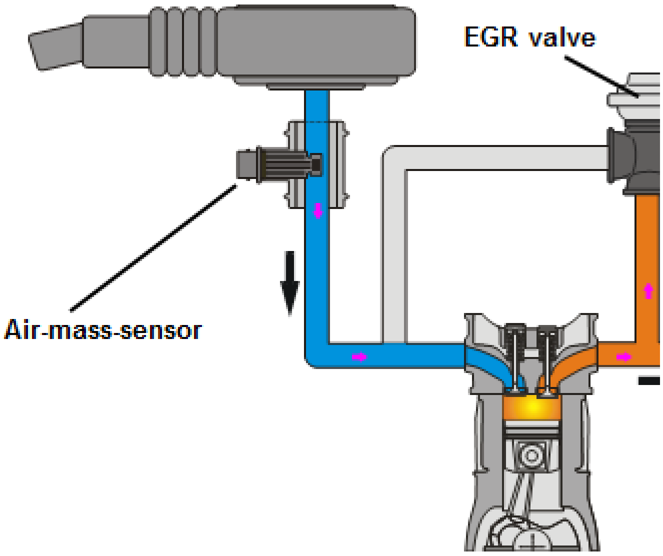
Secondly internal EGR will reduce HC emissions by burning the un burnt hydrocarbons that appear towards the end of the exhaust stroke.

Downsides of internal EGR arise when precise temperature control is required to reduce combustion temperatures. The systems are often very complex and so cost becomes high.

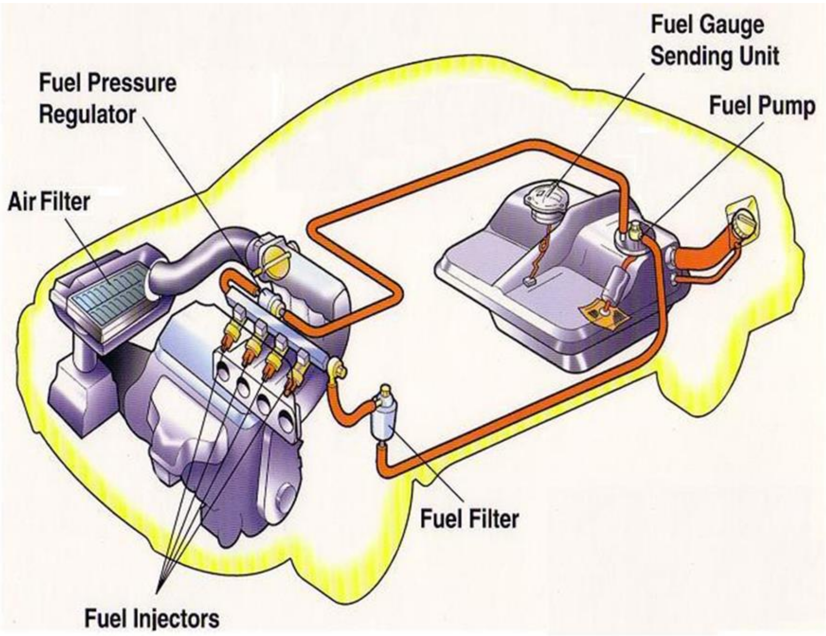
External EGR

This system has largely become the industry standard. It takes exhaust gas and re introduces it into the intake manifold. The major benefit of this system is increased efficiency in temperature reduction as the gas flows externally or through part of a cooling system heat exchanger resulting in a further reduction in NOx.





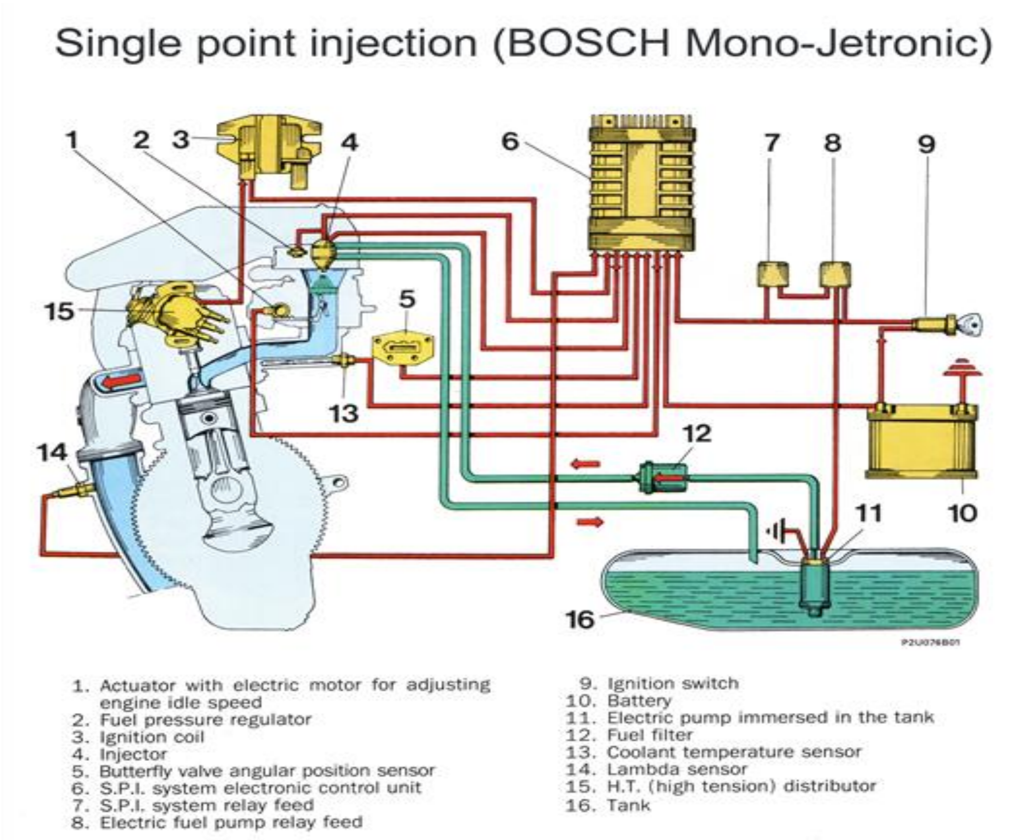
Fuel injection



Fuel injection systems ensure the precise amount of fuel enters the combustion chamber. Generally, there are two systems used.

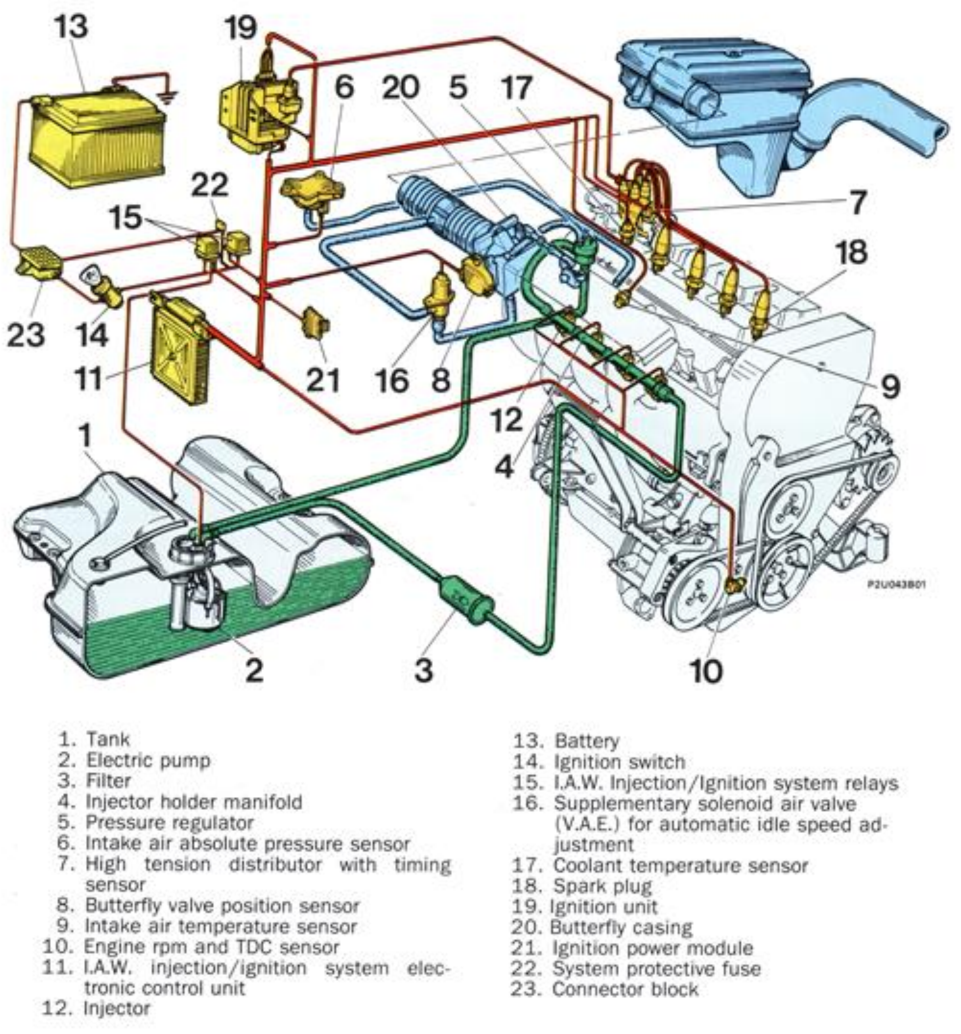
- Single point injection
- Multi point injection

Single point injection



Single point injection systems were the first real efficient alternative to carburettor. The system was similar to a carburettor, because the fuel enters the engine intake system from a single point in the throttle body. There is an injector housing with the injector screwed into it. The fuel injector has constant pressure behind it, and receives a signal from the electronic control unit (ECU, also known as the electronic control module ECM) as and when to open and spray fuel into the airflow. For the ECU to know when to tell the injector to open it needs information about the engines operating conditions. The main inputs the ECU receives are engine speed, manifold pressure, throttle valve position, engine temp, air temp, and battery voltage. The idle speed of the engine is also controlled by this system; by varying the amount of air getting into the engine the idle can be controlled. The amount of air able to get to the engine is electronically controlled by means of a servomotor operating the throttle valve. As the air fuel ratio can be so carefully monitored with this system it can be used with a catalytic converter and lambda sensor. If a catalytic converter is fitted the ECU will also receive a signal from the lambda sensor describing the oxygen content in the exhaust before the cat. This will allow the ECU to constantly make slight fuelling adjustments to keep the exhaust gas emissions suitable for a cat to deal with them.

Multi point fuel injection



The term multipoint injection derives from the fact that the fuel is injected into the inlet air using multiple injectors. This insures more accurate fuel metering and additionally ensures equal quantities of fuel are delivered to the individual cylinders. Currently this is the most common type of fuel injection fitted to modern petrol engined small vehicles. In some systems, the fuel is injected out of the injectors continuously and on other systems the fuel is injected in pulses. Continuous injected tended to occur on the earlier fuel injection systems, whereas now the injection is pulsed. With pulsed fuel injection, the injectors are opened by an earth signal sent from the ECU once per engine revolution. The result is, an atomised fuel cloud hovering around the inlet valve ready and waiting to be drawn into the combustion chamber.

Operation

Air enters the engine through the air induction system where it is measured by the air flow meter. As the air flows into the cylinder, fuel is mixed into the air by the fuel injector.

Fuel injectors are arranged in the intake manifolds behind each intake valve. The injectors are electrical solenoids which are operated by the engine control unit.

The engine control unit pulses the injector (pulse width modulation) by switching the injector ground circuit on and off.

When the injector is turned on, it opens, spraying atomised fuel at the back side of the intake valve.

As fuel is sprayed into the intake air stream, it mixes with the incoming air and vaporises due to the low pressures in the intake manifold. The engine control unit pulses the injectors to deliver enough fuel to achieve the ideal air/fuel ratio of 14.7:1 (stoichiometric).

The precise amount of fuel delivered to the engine is controlled by the engine control unit. The engine control unit determines the basic injection quantity based upon measured intake air volume and engine rpm. Depending on the operating conditions, injection quantity will vary. The engine control unit will monitor variables such as, coolant temperature, engine speed, throttle angle and exhaust oxygen content. The engine control unit will then make injection quantity corrections.

Advantages of Electronic fuel injection systems:

Uniform air/fuel mixture distribution

Each cylinder has its own injector which delivers fuel directly to the intake valve. This eliminates the need for fuel to travel through the intake manifold, improving cylinder to cylinder distribution.

Accurate air/fuel ratio control throughout all engine operating conditions.

EFI supplies a continuously accurate air/fuel ratio to the engine no matter what operating conditions are encountered. This provides better driveability, fuel economy and emission control.

Superior throttle response and power.

By delivering fuel directly at the back of the intake valve, the intake manifold design can be optimised to improve air velocity at the intake valve. This improves the torque and throttle response.

Increased fuel economy/ emission control.

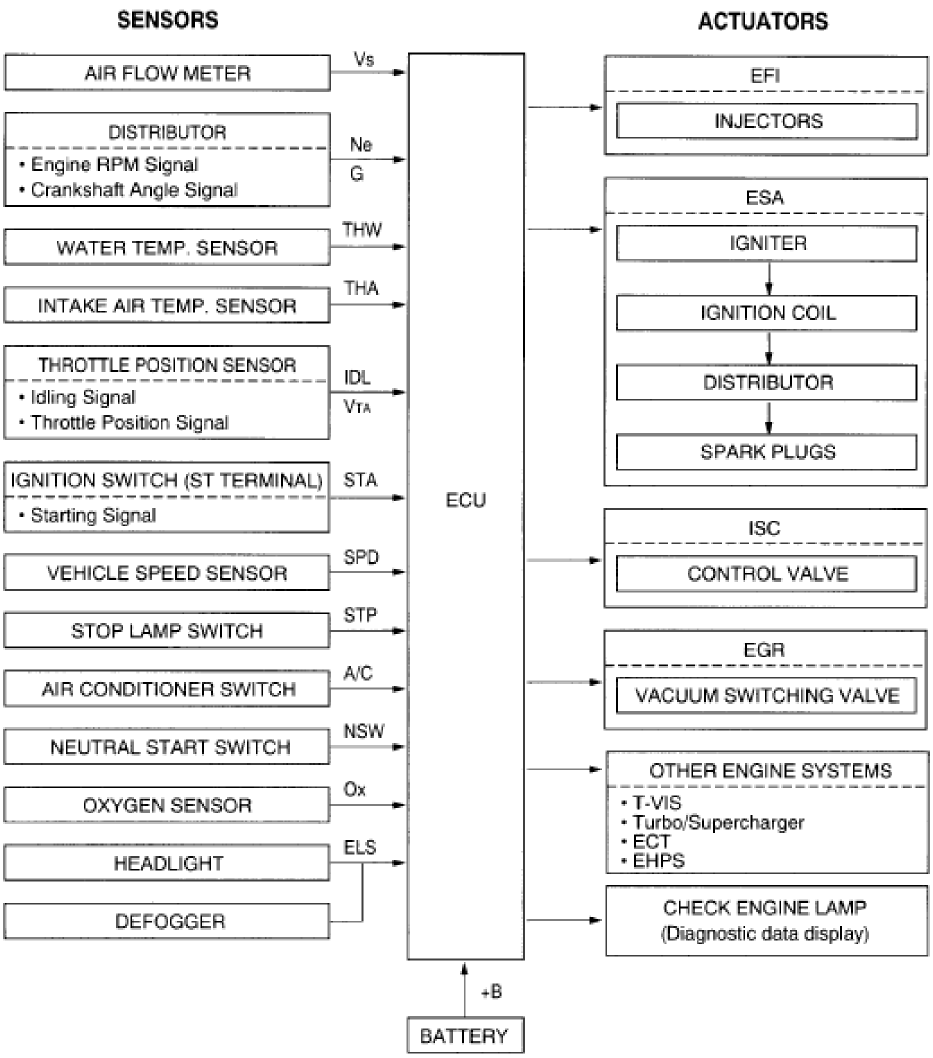
Cold engine and wide open throttle enrichment can be reduced with EFI engine because fuel condensation in the intake manifold is optimised. This results in better overall fuel economy and emission control.

Improved cold start.

The combination of better fuel atomisation and injection directly at the intake valve improves the engines ability to start and run a cold engine.

Reduced maintenance

The EFI system does not rely on any major adjustments for cold enrichment or fuel metering. Due to the system being mechanically simple, maintenance requirements are reduced.

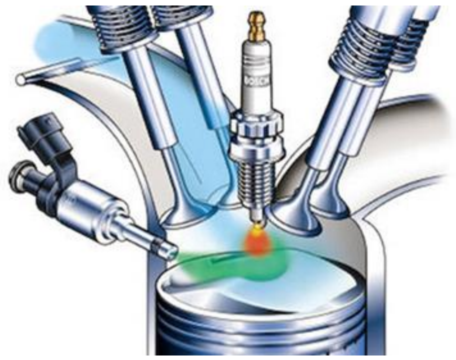


Evolution of the EFI system

The EFI system has evolved from a simple fuel control system to a fully integrated engine and emissions management system. Although the fuel delivery system operates the same as a conventional EFI system the engine control unit also controls the ignition spark angle. Additionally, the engine control unit also regulates an idle speed control device, an exhaust gas recirculation (EGR) system and depending on application any other related system.

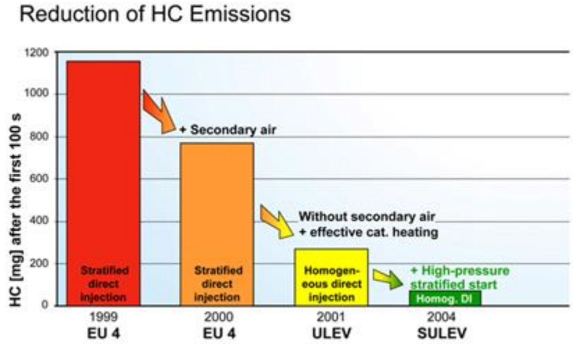
Direct fuel injection

In internal combustion engines, Gasoline Direct Injection (GDI) or sometimes known as Fuel Stratified Injection (FSI) is an increasingly popular type of fuel injection system employed in modern four- and two- stroke petrol engines. The petrol/gasoline is highly pressurized, and injected by high voltage driven injectors via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional single or multi-point fuel injection that happens in the intake manifold tract, or cylinder port. In some applications, gasoline direct injection enables a stratified fuel charge (ultra-lean burn) combustion for improved fuel efficiency, and reduced emission levels at low load.



Basic theory of operation

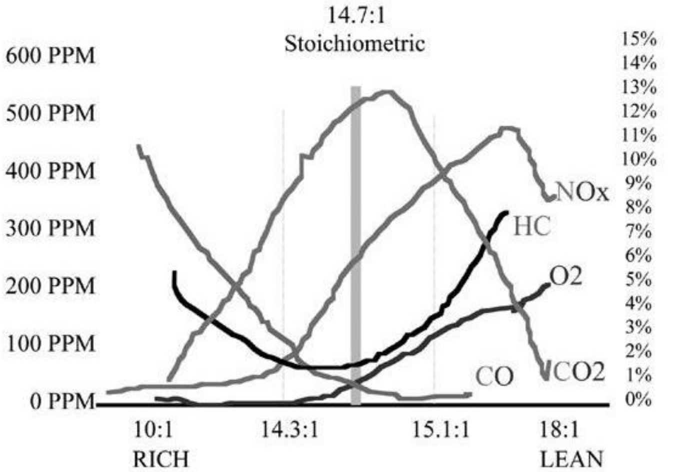
The major advantages of a GDI engine are lower emission levels, increased fuel efficiency and higher engine power output. In addition, the cooling effect of the injected fuel and the more evenly dispersed combustion mixtures and temperatures allow for improved ignition timing settings which are an equally important system requirement.



Emissions levels can be more accurately controlled with the GDI system. The lower levels are achieved by the precise control over the amount of fuel, air and ignition settings which are varied according to the engine load conditions and ambient air temperatures.

In addition, there are no throttling losses in some GDI designed engines, when compared to a conventional fuel injected or carburetted engine, which greatly improves efficiency, and reduces 'pumping losses' in engines without a throttle plate. Engine speed is controlled by the engine management system which regulates fuel injection and ignition timing parameters, instead of having a throttle plate which restricts the incoming air supply. Adding this function to the engine management system requires considerable enhancement of its processing and memory, as direct injection plus other engine management systems must have very precise mapping for good performance and driveability.

The engine management system continually chooses among three combustion cycles: ultra-lean burn, stoichiometric, and full power output. Each cycle is characterized by the air-fuel ratio. The stoichiometric air-fuel ratio for petrol (gasoline) engines is 14.7:1 by weight, but the ultra-lean cycle can involve ratios as high as 35:1 (or even higher in some engines, for very limited periods). These mixtures are much leaner than in a conventional fuel injected engine and reduce fuel consumption and certain levels of exhaust emissions considerably.



Ultra-lean burn cycle is used for light-load running conditions, at constant or reducing road speeds, where no acceleration is required.

The fuel is not injected at the intake stroke but rather at the latter stages of the compression stroke, so that the small amount of air-fuel mixture is optimally placed near the spark plug. This stratified charge is surrounded mostly by air which keeps the fuel and the flame away from the cylinder walls for low emissions and heat losses. The combustion of the fuel takes place in a toroidal (donut-shaped) cavity on the piston's surface designed to improve air swirl and delivered by a specially designed injector nozzle, this allows successful ignition without misfire even when the air / fuel mixture is very lean

Stoichiometric cycle is used for moderate load conditions. Fuel is injected during the intake stroke, creating a homogenous fuel-air mixture in the cylinder. From the stoichiometric ratio, an optimum burn results in a clean exhaust emission, further cleaned by the catalytic converter.

Full power cycle is used for rapid acceleration and heavy loads (as when climbing a hill). The air-fuel mixture is homogenous and the ratio is slightly richer than stoichiometric, which helps prevent knock (pinging). The fuel is injected during the intake stroke.

Direct injection is supported by other engine management systems such as variable valve timing (VVT) with variable length intake manifold (VLIM) or acoustic controlled intake system (ACIS). A high-performance exhaust gas recirculation valve (EGR) will almost certainly be required to reduce the high nitrogen oxides (NOx) emissions which will result from burning ultra-lean mixtures.

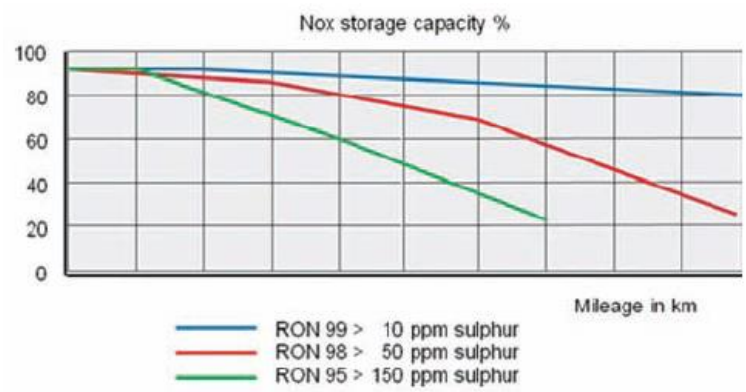
Conventional fuel injection engines could inject fuel throughout the 4-stroke sequence, as the injector injects fuel onto the back of a closed valve. In earlier designed direct injection engines, were the injector injects fuel directly into the cylinder, was limited to the induction stroke of the piston. As the RPM increases, the time available to inject fuel decreases. Newer GDI systems have sufficient fuel pressure to inject more than once during a single cycle. Fuel injection takes place in two phases. During intake stroke, some amount of fuel is "pre-injected" into the combustion chamber which cools the incoming air thus improving volumetric efficiency, and ensuring an even fuel / air mixture within the combustion chamber. Main injection takes place as the piston approaches top dead centre on the compression stroke, shortly before ignition.

Why GDI

The primary objective for the introduction of Gasoline Direct Injection is to reduce fuel consumption and exhaust gas emissions. Current closed-loop catalyst exhaust systems can reduce the emission of hydrocarbons (HC), nitrogen oxides (NOx) and carbon monoxide (CO) by up to 99% however the reduction of carbon dioxide (CO2) a major greenhouse gas can only be lowered by a reduction in fuel consumption. GDI systems have the potential to achieve a 15- 20% reduction in fuel consumption and a 20-30% reduction in exhaust gas emission of carbon dioxide (CO_2). The reduction in fuel consumption enables vehicle operating costs to be reduced and a reduction in road tax due to the lower emissions.

Late introduction of Gasoline Direct Injection (GDI) systems

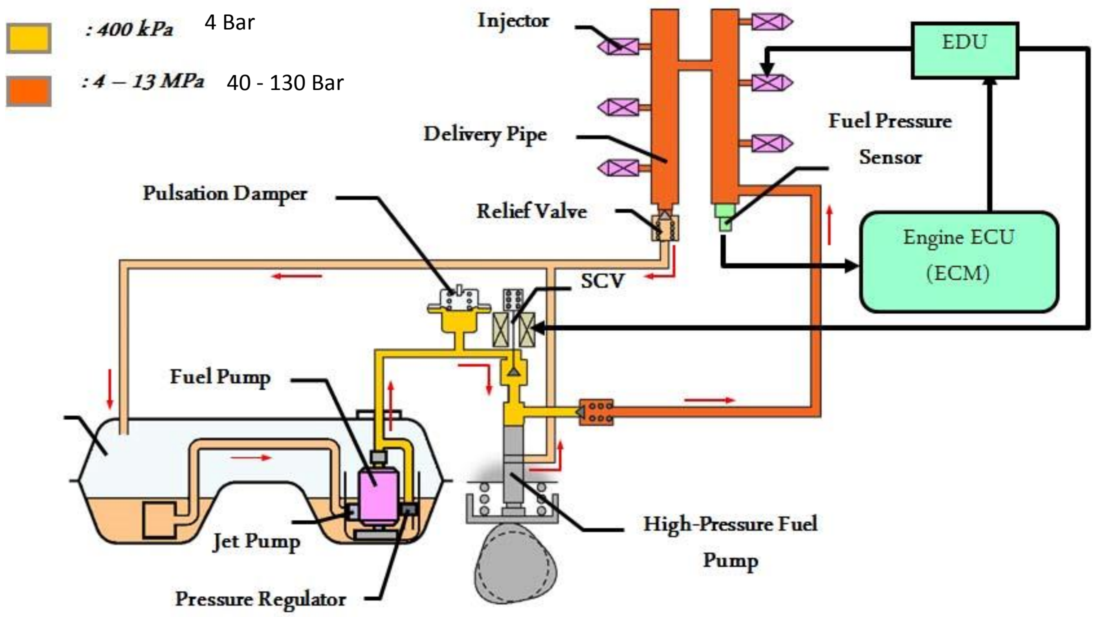
One of the major reasons why car manufacturers were slow to introduce GDI was the problem of exhaust gas after treatment in both the stratified and homogeneous charge modes, a standard closed-loop catalyst exhaust system cannot reduce the higher levels of nitrogen oxides (NOx) produced by GDI systems quickly enough. However, with the development and introduction of the NOx storage and reduction catalyst system it is now possible to convert the higher levels of NOx into nitrogen (NO) and meet the current EU emission standards.



The other reason for the late introduction of the GDI system was the high levels of sulphur contained in petrol prior to their reduction some years ago. The problem with the previous high level of sulphur was its chemical reaction within the catalyst which was similar to nitrogen oxides which resulted in the sulphur occupying the storage within the catalyst which was intended for the nitrogen oxides, the higher the sulphur content within the fuel, then more often the NOx storage catalyst has to be regenerated which results in a higher fuel consumption, which why super unleaded fuel with a RON 98 rating was used in earlier systems due to its ⅔ reduction in sulphur content when compared to standard unleaded fuel with a RON 95 rating. The virtual removal of sulphur will improve the efficiency and prolong the life of exhaust catalysts. Additionally, sulphur-free petrol is required for the efficiency of GDI petrol engines to improve fuel efficiency and reduce emissions of carbon dioxide when combined with NOx reduction exhaust catalysts. The UK has now moved to sulphur-free road fuels (sulphur content not exceeding 10 parts per million or 0.001% by weight).

System overview

Mainly consisting of a fuel pump (high pressure), delivery pipe, and slit nozzle type injectors, this system effects optimal control for combustion by controlling the fuel pressure, injection volume, and the injection timing via the Engine ECU and EDU (Electronic Driver Unit).



System components

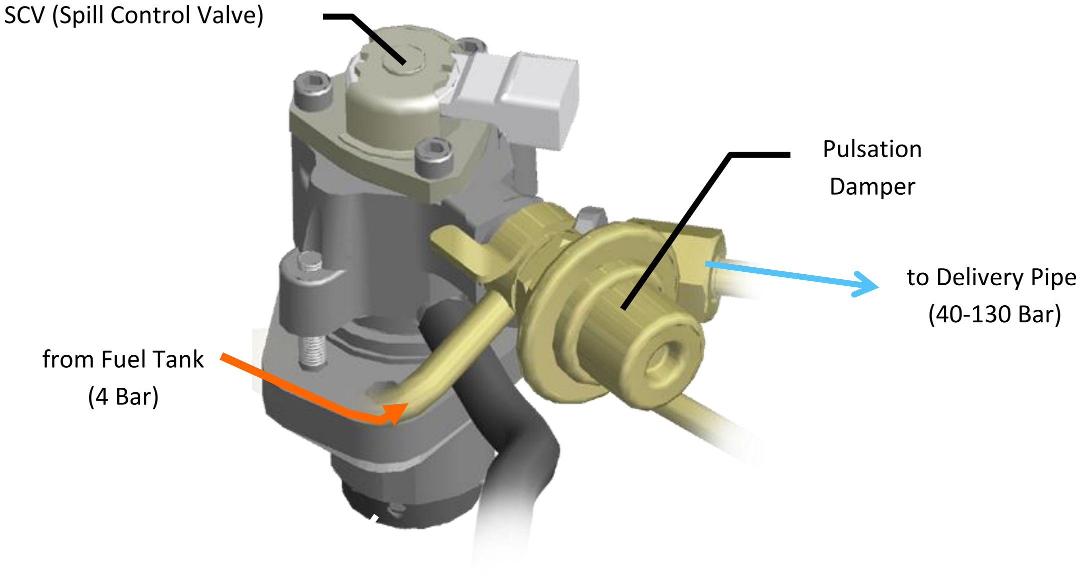
Fuel Delivery System

We will now look at the system components in more detail, starting with the fuel system. The fuel system is divided into two systems a low-pressure system and a high-pressure system.

Low pressure pump

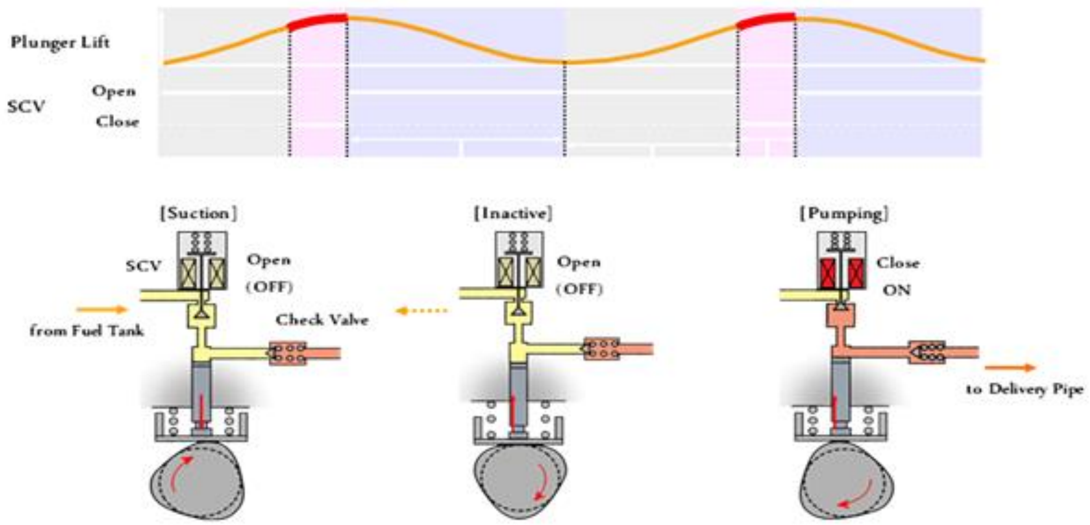
The low-pressure fuel pump is an electric pump located in the fuel tank. The fuel pump pressurizes the fuel from the fuel tank and sends the fuel to the high-pressure fuel pump.

High pressure pump

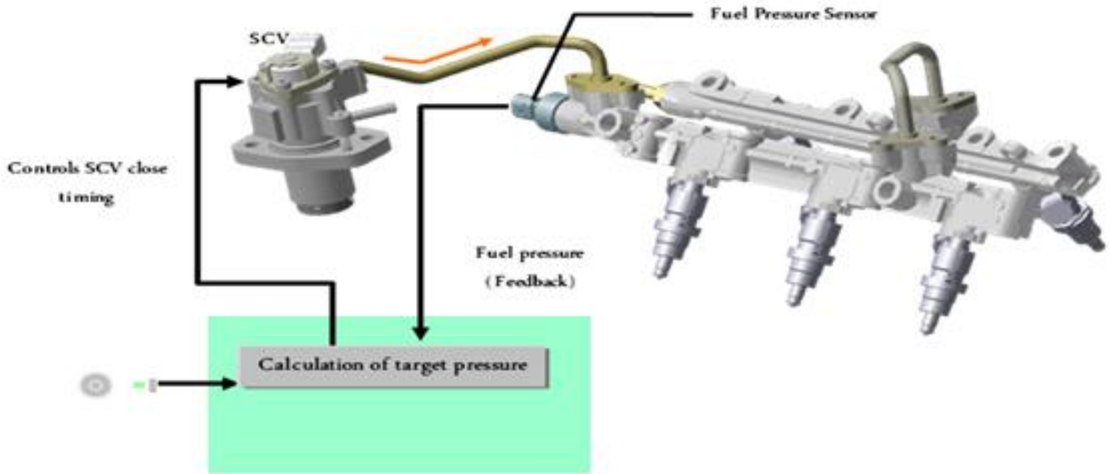


The high-pressure fuel pump which is normally driven by a lobe on the camshaft consists of a plunger, spill control valve and a check valve. A pulsation damper is also installed at the fuel inlet. The plunger is moved up and down by the camshaft lobe. The camshaft has three protrusion 120 degrees from each other on the same camshaft lobe. This lobe causes three strokes of the pump piston to occur for each camshaft revolution. A spill control valve is used to control the pump discharge pressure. The spill control valve is located is the inlet passage of the pump. It is electrically operated by the electronic driver unit (EDU) based on values sent from the engine ECU. A check valve is located in the outlet of the pump. As the pressure in the outlet of the pump rises, and becomes high enough to push the check valve off its seat, fuel will begin to flow to the delivery pipe.

Suction control valve operation

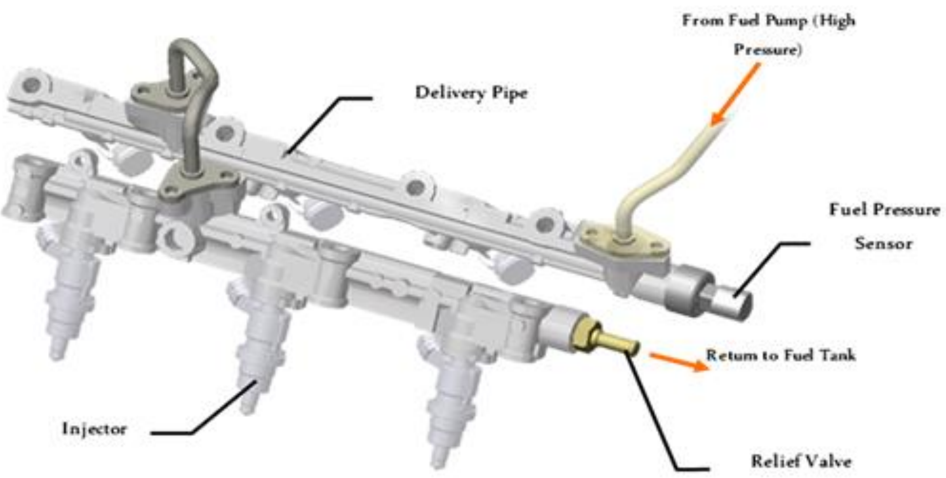


During the intake portion of the pump cycle, the spill control valve is opened, and the pump plunger (piston) is moved downward by a spring force. This allows fuel to be drawn in to the cylinder of the pump. If the spill control valve has not been closed yet, when the cam forces the plunger to move upward, the fuel in the pump cylinder (this fuel is not pressurized) will be pushed back to the pump inlet (fuel tank side).



In order to close the spill control valve as the piston is moving upward, the Engine ECU sends a signal to the valve via the EDU. When the spill control valve is closed, and the plunger is moving upward, the pressure in the pump cylinder will rise. As this pressure rises above 60 kPa (or the pressure of the delivery pipe, whichever is higher), the fuel will begin to flow to the delivery pipe. The Engine ECU calculates the target fuel pressure based on driving conditions. The Engine ECU controls the pressure by operating the spill control valve via the EDU. The timing and duration of the spill control valve closing is varied to cause the pump pressure to meet the target pressure.

Delivery pipe

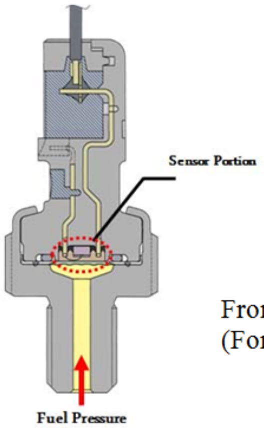


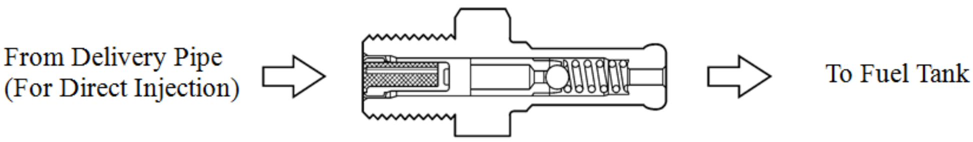
An aluminum alloy fuel delivery pipe is used. A fuel pressure sensor and a pressure relief valve are installed on the fuel delivery pipe. An injector clamp is provided for each area of the fuel delivery pipe where a high-pressure fuel injector is installed. This clamp applies a constant spring force to the injector to prevent the injector from moving when the combustion pressure is applied to the injector while the engine is being started, during which the fuel pressure is low. As a result, it increases the sealing performance of the injector, while reducing vibration and noise.

O-rings and backup rings are used in the areas in which the high-pressure fuel injectors and high-pressure fuel delivery pipes are joined. This reduces the transmission of the operating sounds of the high-pressure fuel injectors, enhances quiet operation, and ensures the sealing performance of the joined areas.

Fuel pressure sensor/Pressure relief valve

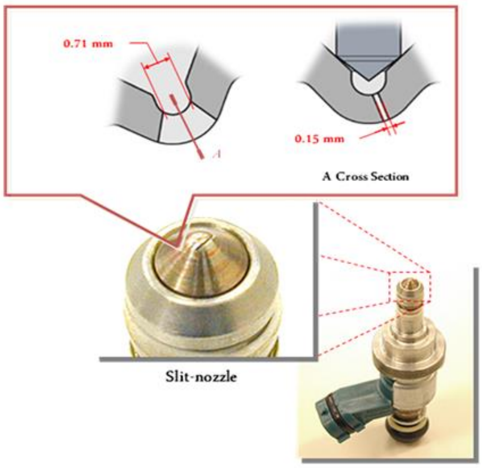
The fuel pressure sensor, which is mounted on the delivery pipe, outputs a signal to the Engine ECU that represents the fuel pressure in the delivery pipe in order to allow the constant regulation of the fuel at an optimal pressure.

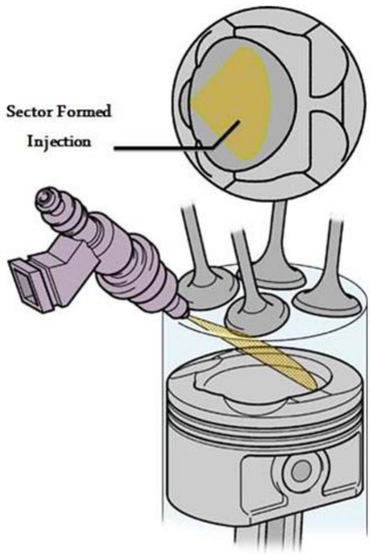




A relief valve is provided in the fuel delivery pipe. When the fuel pressure in the fuel delivery pipe rises above (153 Bar), the relief valve limits the pressure by returning fuel to the fuel tank.
High-pressure, slit-nozzle type injectors are used in most GDI systems. Each injector, based on signals from the Engine ECU, meters the flow of high pressure fuel. The fuel is injected as a fine-grained mist in a fan shaped pattern, directly to the combustion chamber, via a slit type nozzle. Sector formed injection increases air mixture, improving atomization and providing a highly uniform mixture.

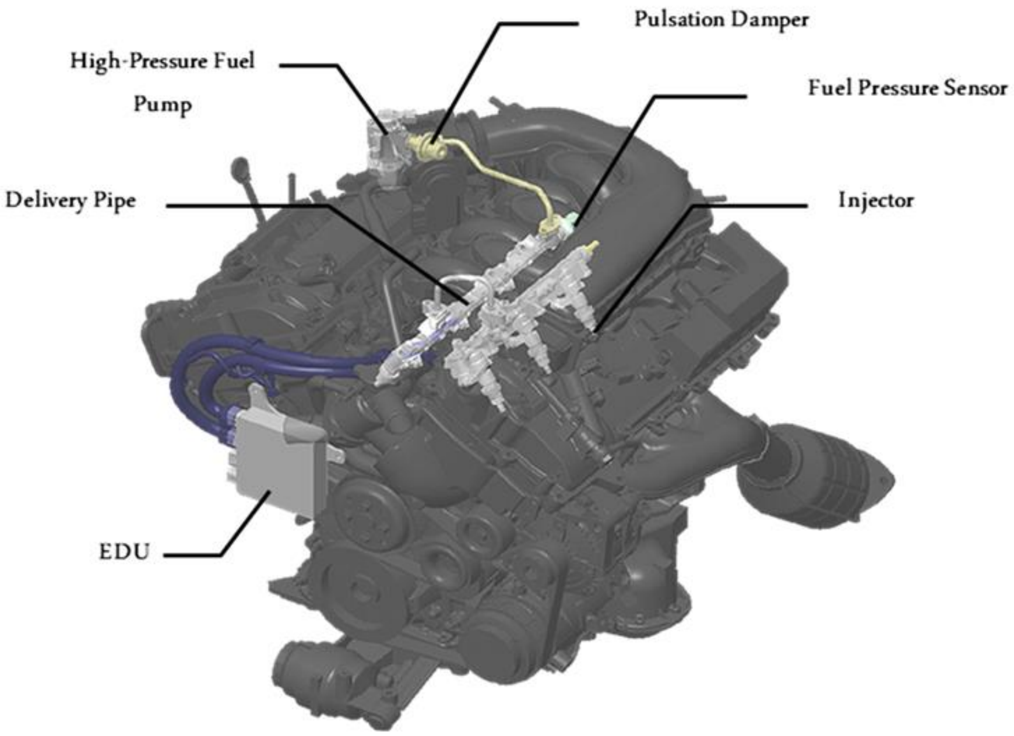
An insulator is used in the area in which the injector comes in contact with the cylinder head, and a Teflon shaft seal is used to seal the injector against the combustion pressure in the cylinders in order to reduce vibration and noise and to enhance sealing performance.
Each nozzle hole is coated to reduce the adhesion of deposits.
The injectors are actuated by the EDU using high-voltage and a constant-current control based on instructions from the Engine ECU. This control allows the injectors to inject high-pressure fuel in a short time.





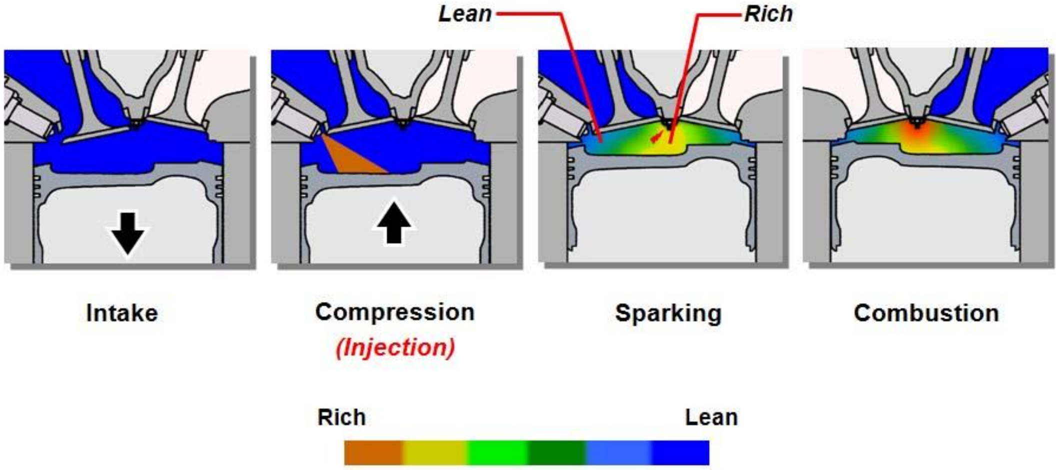
EDU
(Electronic Driver Unit)

This type of system uses an EDU, it is used to drive the injectors at high speeds. The EDU has the ability to operate the fuel injectors under high fuel pressure conditions through the use of a DC/DC converter that provides a high-voltage, quick-charging system. (“Quick charging system” refers to the ability of the EDU to “recharge” its internal high voltage power source).
The engine ECU constantly monitors the EDU and stops the engine in the event an abnormal condition is detected.



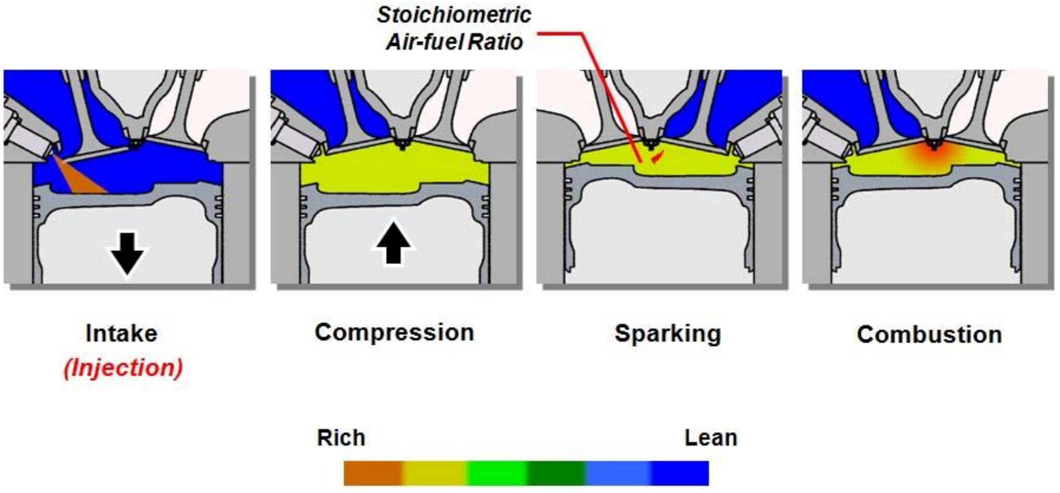
Fuel Charge Modes

Stratified charge mode



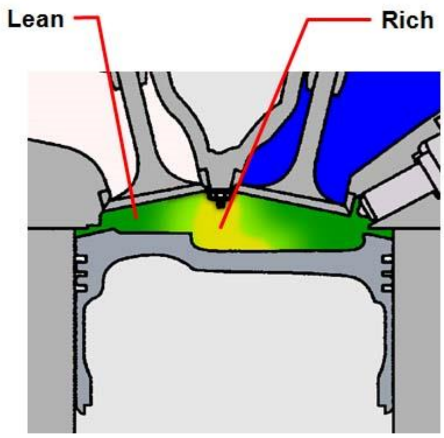
The meaning of the term, Stratified charge is the layering of the fuel/air mixture inside the combustion chamber. A GDI engine generally runs in a stratified charge mode from the small and up through to the medium engine load and speed range by the fuel/air mixture stratification in the combustion chamber. A highly ignitable mixture is injected directly into the combustion chamber during compression and forms around the spark plugs at the centre of the combustion chamber where it burns quickly and smoothly, as the combustion continues, it advances into a very lean mixture where the flame propagation cools rapidly as it reaches the outer layer which is comprised mostly of fresh air.

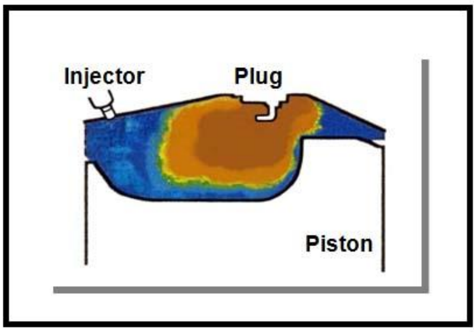
Homogeneous charge mode



The meaning of the term, Homogeneous charge is a thorough mixing of the air/fuel mixture throughout the combustion chamber equal to lambda 1. This thorough mixing of the charge occurs before the onset of ignition. This homogeneous charge is designed to create an easily ignitable combustion mixture that burns evenly and smoothly across the whole combustion chamber. However, this combustion process burns more fuel and creates a higher level of CO2 and NOx.

Homogeneous lean charge mode

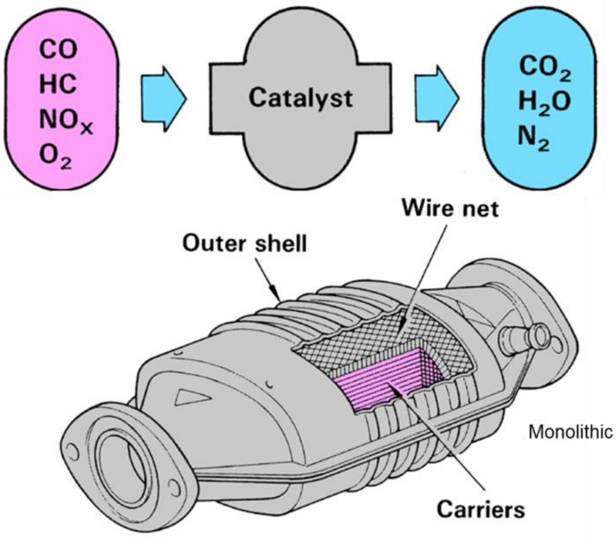




Is a transition period between the homogeneous and stratified charge mode where the engine runs in a homogeneous lean charge mode. The lean mixture is distributed evenly throughout the combustion chamber. The air/fuel ratio in this mode is approximately lambda 1.55.

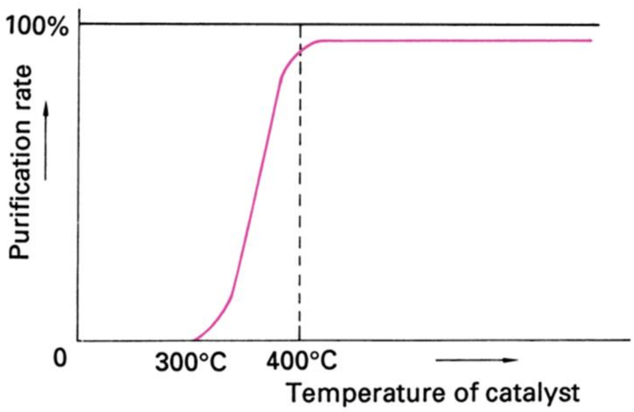
Catalytic convertor

Catalytic converters use heated precious metals and other materials (rhodium, iridium, platinum) to encourage a reaction to take place effectively converting the emission gases to less harmful ones.



The catalysing materials are applied as a coat to a 'monolithic substrate' - a porous sub-assembly having a very large surface area to reduce the inevitable exhaust back pressure that such a component in the exhaust pipe will cause. These materials are not chemically changed in any way during the reaction in the gases, hence the name catalyst.

'Cats' are only effective when hot, so they are often placed very close to the exhaust manifold. The catalytic convertor is very sensitive to oxygen content in the exhaust gas and requires constant monitoring in order to maintain efficiency.

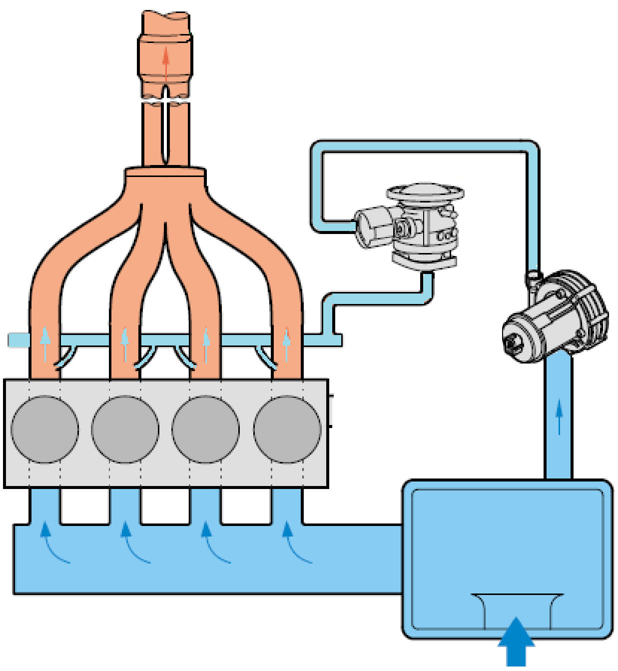


'Cats' are easily damaged. Under no circumstances must conditions be brought about where prolonged exposure to unburnt fuel occurs (push starting, disconnecting plug leads etc.). If this does happen, the fuel will accumulate in the cat and could ignite destroying it.

Secondary air injection

During warm up periods even the most efficient modern engine will require some fuel enrichment. Extra fuel is required to overcome condensing of the fuel on the intake and the cylinder walls. This ensures that the fuel will be able to vaporise in cold environments.

A rich mixture as we know will cause an excess amount of CO and HC to be created. These levels are above the legally permitted level and therefore must



be controlled. The problem lies with the catalytic convertor not being able to react with the high levels of CO and HC due to its own warm up period. To overcome this problem air can be injected into the exhaust manifold which will enable the O2 to combine with the CO and HC because of the temperature. The air injection process is only used for a short period of time after the engine is started but is sufficient enough to reduce the CO and HC levels during this period. The added bonus is that the combustion of the gasses in the manifold also creates heat which in turn can assist with the catalytic convertor warm up enabling quicker operation.

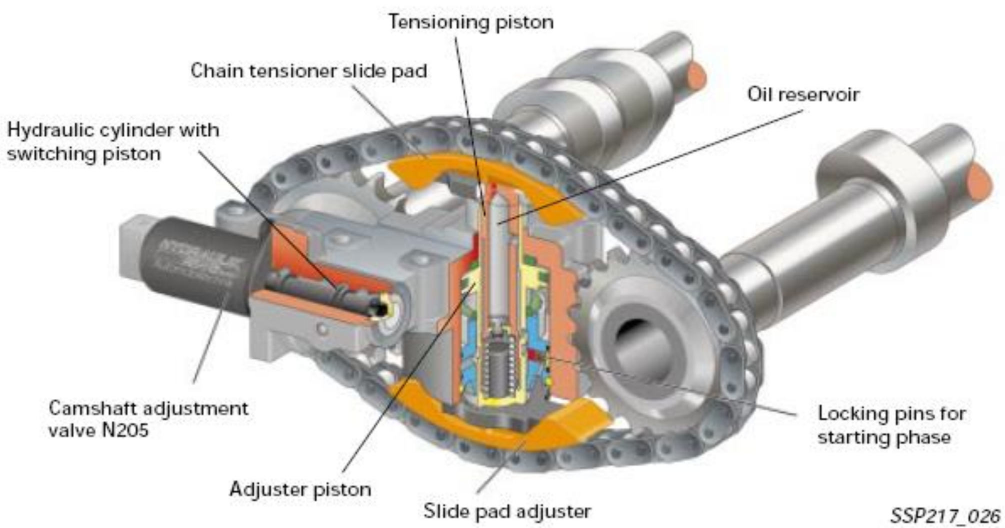
Variable valve timing

The dynamics of airflow through an engine combustion chamber changes dramatically over an engine range of 2000 to 6000 rpm. Using a standard valve drive arrangement is a compromise, which allows the engine to start, run and provide strong acceleration with good cruising speeds, but engines are rarely ever in the ‘sweet zone,’ which results in wasted fuel, reduced performance, and excess exhaust emissions.

Inertia forces apply when trying to get air to move, it is hard to get moving and once moving is hard to stop. It is well understood that the intake valve opens before the piston reaches the top of the cylinder and closes after the piston reaches the bottom. The exhaust valve begins to open as the piston reaches the bottom of the cylinder and begins to close after the piston reaches the top.

As engine speed increases air will gain inertia force and even when the piston reaches the bottom of the cylinder air will want to keep flowing in, thus to obtain as much air as possible without causing inefficiencies from these inertia forces, the best solution would be to have the valve timing change as engine speed changes.

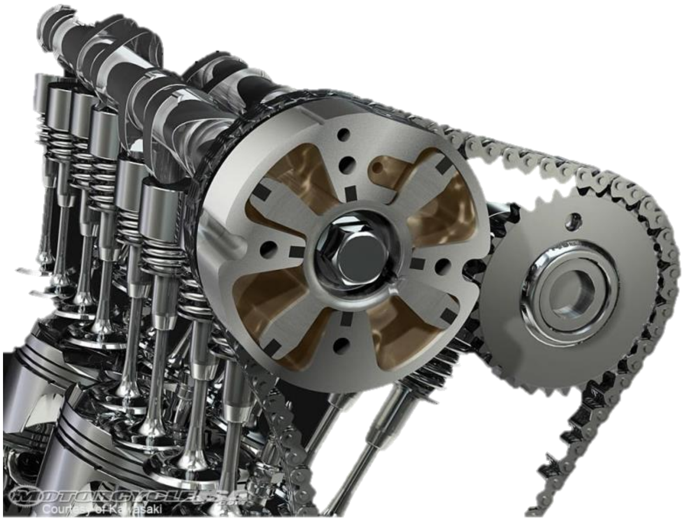
Variable valve timing has been developed to increase engine performance, improve fuel economy and reduce exhaust emissions throughout all the engines operating range.



One of the main factors influencing engine performance is the amount of valve overlap. The duration of valve overlap determines the amount of exhaust gas left in the cylinder when the exhaust valve closes.

At higher engine speeds a longer inlet valve-opening period would increase the power developed, but this will cause an increase in valve overlap and at idle would greatly increase hydrocarbon emissions.

To overcome these and other problems variable valve timing is used.



VVT-i, VVC and VTEC are all acronyms, which embrace a range of engine design enhancements.

There two basic methods of valve timing, cam-changing and cam-phasing. Cam-changing (VTEC) provides different cam profiles allowing earlier opening of the inlet valves and later closing including greater valve lift at high engine speeds. Cam phasing is described below.

During idling

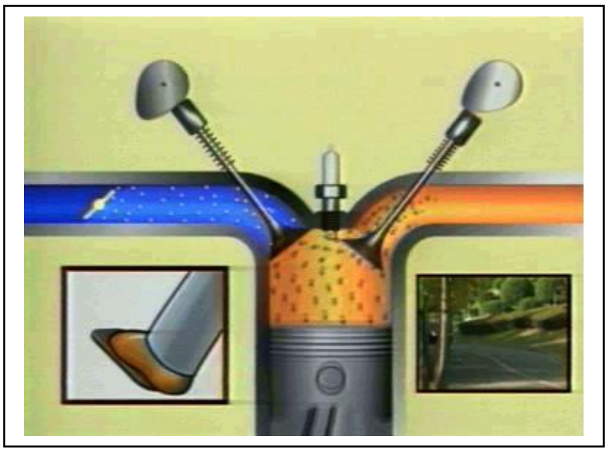
Timing is retarded which prevents exhaust gas intermixing with the intake air-fuel mixture.

It provides stable combustion and engine idle speed can be lowered, which improves fuel economy.

It provides stable combustion and engine idle speed can be lowered, which improves fuel economy.

During normal driving

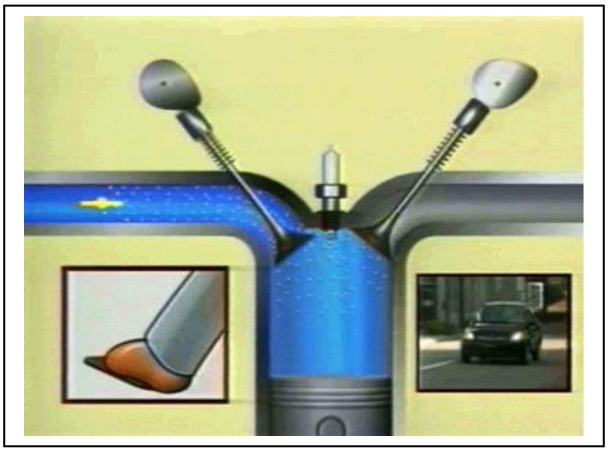
Timing is advanced re-burning a portion of exhaust gas, which minimises emissions.



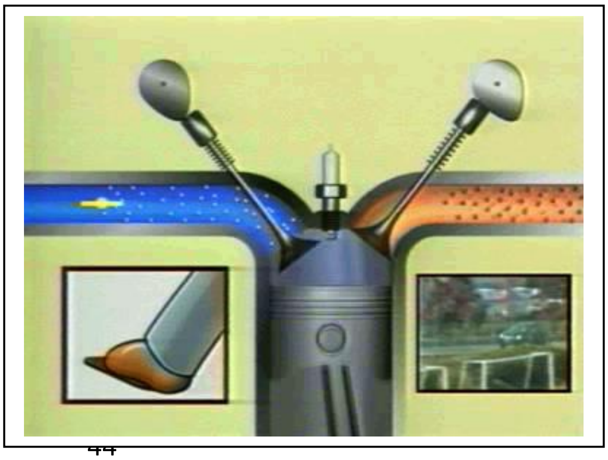
During full acceleration

Timing is retarded which delays the closing of the intake valve this

allows a greater amount of air-fuel mixture to be drawn in.



Produces higher torque and improved acceleration.



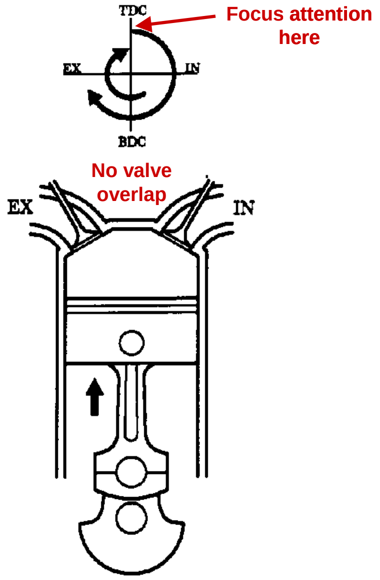
During full power

Timing is advanced thus preventing intake lag associated

with high rpm.

Allows greater amounts of
air-fuel mixture to be drawn in improving output power.

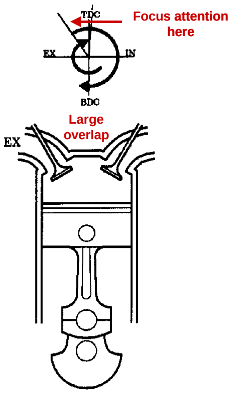
Varying the valve timing



No valve overlap

Exhaust gas moving into the intake side is prevented by delaying inlet valve opening.

Large valve overlap



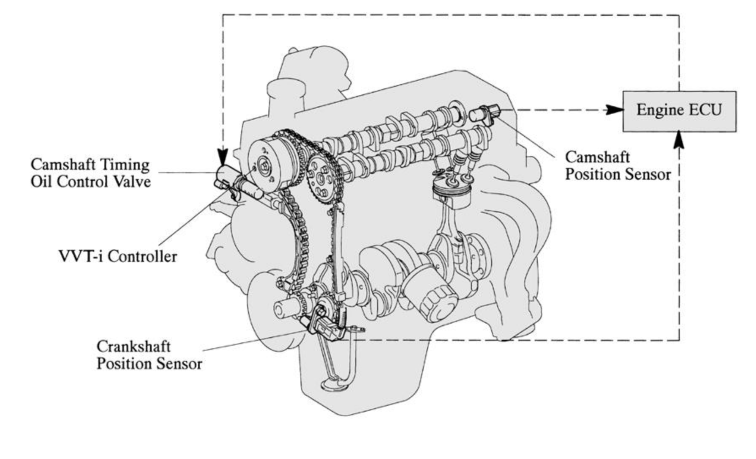
As a result of increasing the valve overlap – inlet and exhaust valves are open at the same time the inlet and exhaust gases mix and re-burning takes place.

Intake valve closes quickly

By closing the inlet valve early, fuel air mixture is prevented from being discharged from the cylinder therefore maximum acceleration is produced.

Operation of VVT - i

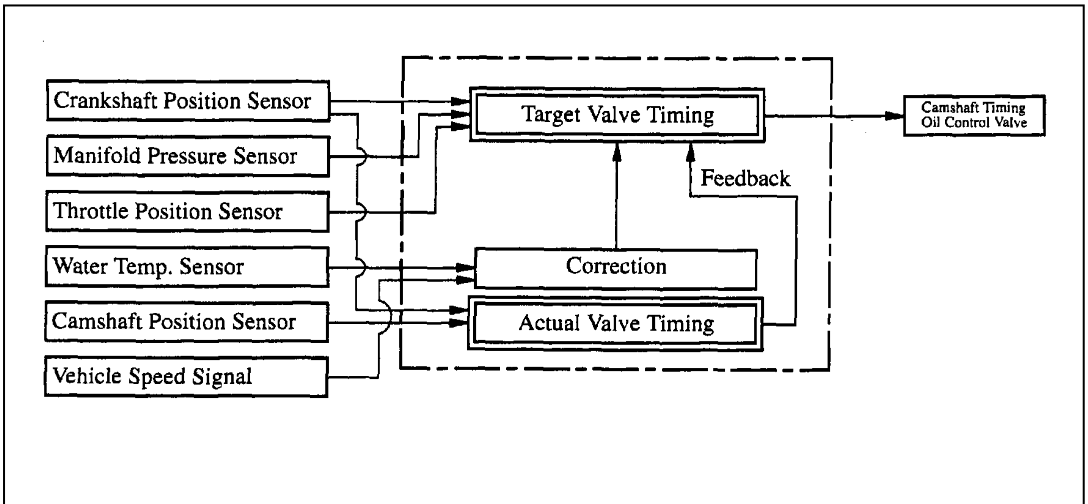
The VVT-i is designed to control the inlet camshaft over a wide range of around 60 degrees of crankshaft angle, which provides valve timing that is most suited to the demands of the engine.



Designed to control the intake camshaft within a wide range of 60° of crankshaft angle

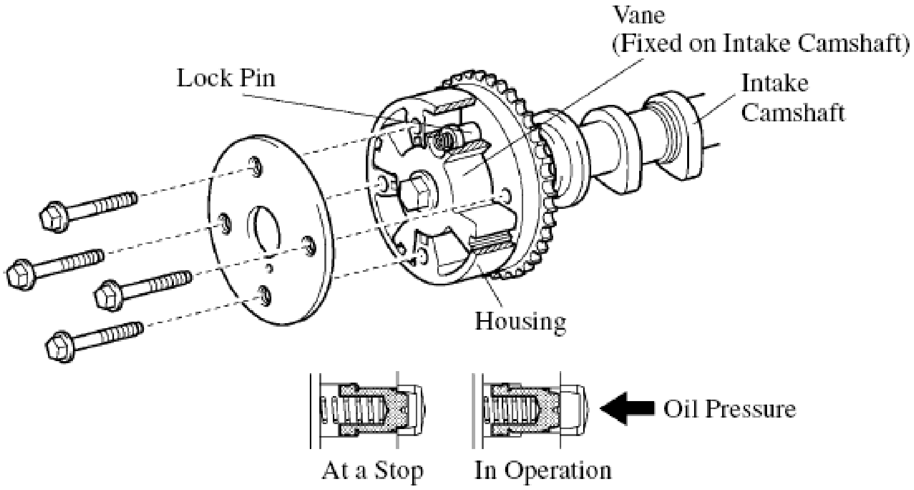
The actual inlet valve timing is fed-back to the ECU from the camshaft position sensor to control the target valve timing.

Management of the VVT - i system



The engine ECU calculates the target-timing angle according to the travelling state and sensor inputs.

Reason for the lock pin



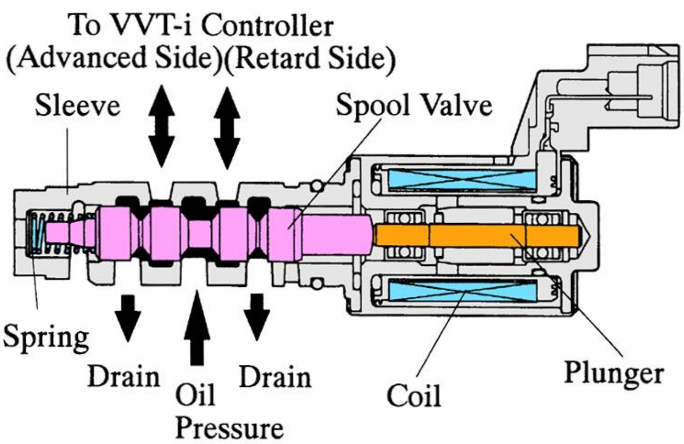
Lock Pin

Improved starting is achieved when the valve spring force rotates the inlet cam to the fully retarded position when the engine is stopped.

The spring-loaded lock pin locks the vane and housing together. After the engine starts the lock pin is released by engine oil pressure. The lock pin prevents a knocking noise due to lack of hydraulic pressure being applied to the controller immediately after the engine has started. When the engine starts the lock pin is released by hydraulic pressure.

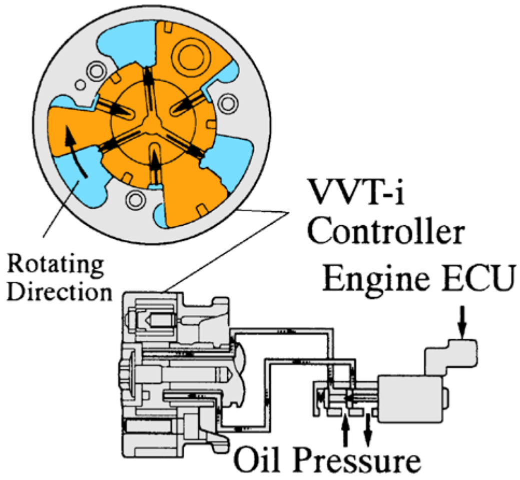
Timing oil control valve

The camshaft timing oil control valve selects the path to the VVT - i controller according to the advance, retard or hold signal from the ECU. The intake camshaft is rotated by the VVT - i controller to advance, retard or hold the



valve timing, these positions are governed by the oil pressure applied.

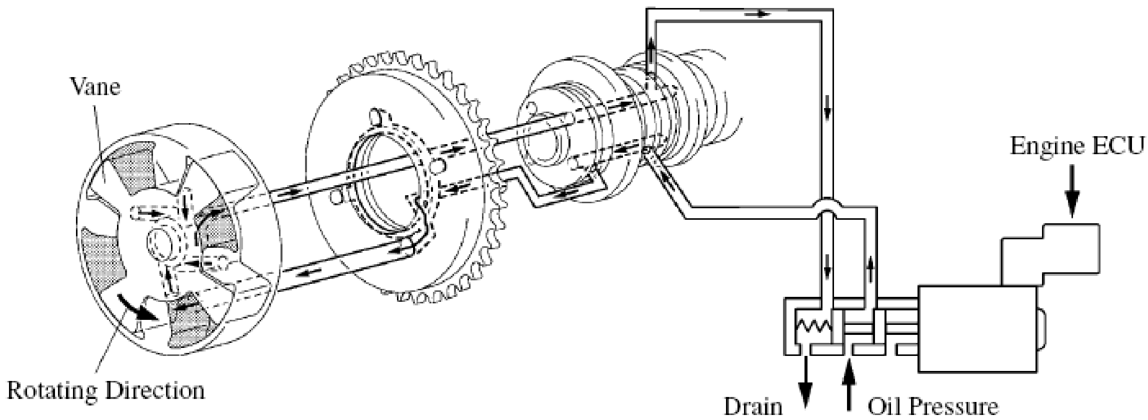
- **Operation**



Oil pressure causes the controller vane to rotate, therefore varying the valve timing continuously.

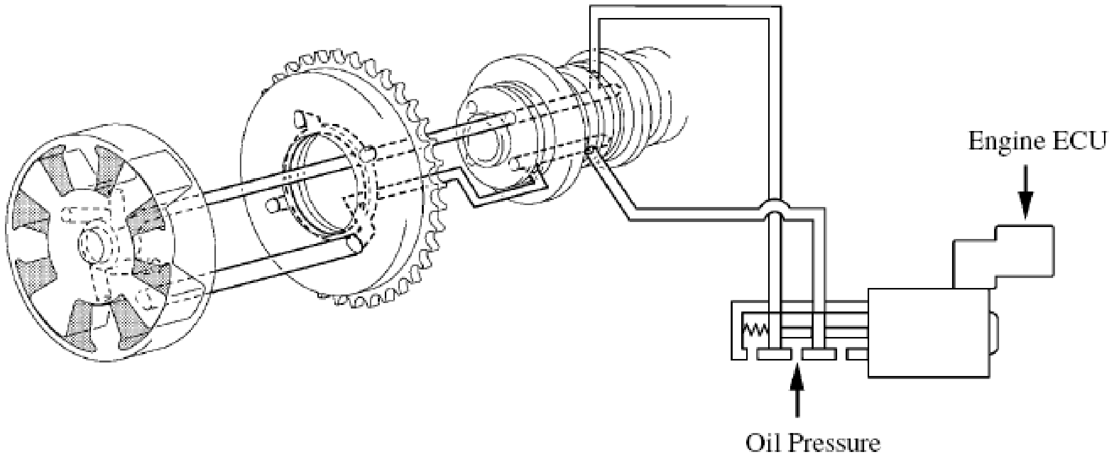
When the engine is stopped, the camshaft is in the most retarded position due to the external force such as valve spring force.

Retard



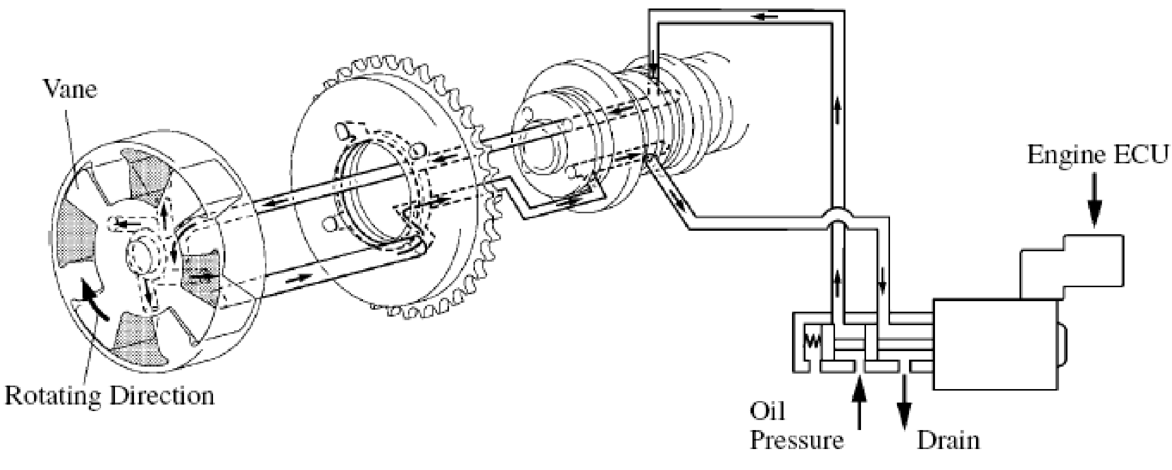
When the camshaft timing oil control valve is positioned as illustrated above by the retard signal from the engine ECU, the resultant oil pressure is applied to the timing retard side vane chamber to rotate the camshaft in the retard direction.

Hold



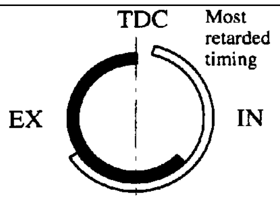
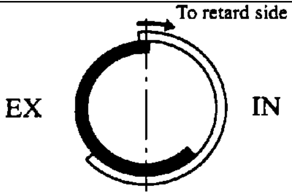
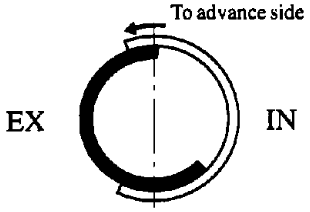
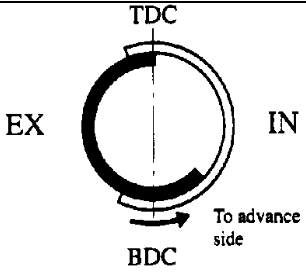
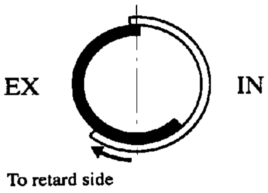
After setting to the target timing, the valve timing is held by keeping the camshaft timing oil control valve in the neutral position unless the travelling state changes. This adjusts the valve timing to the desired target position and prevents the engine oil from running out when it is unnecessary.

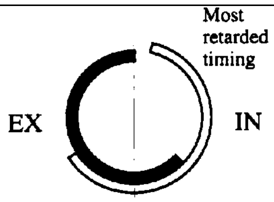
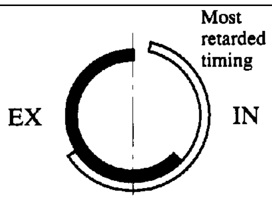
Advance



When the camshaft oil control valve is positioned as shown by the ECU advance signal, oil pressure is applied to the timing advance side chamber to rotate the camshaft in the timing advance direction

Valve timing varied

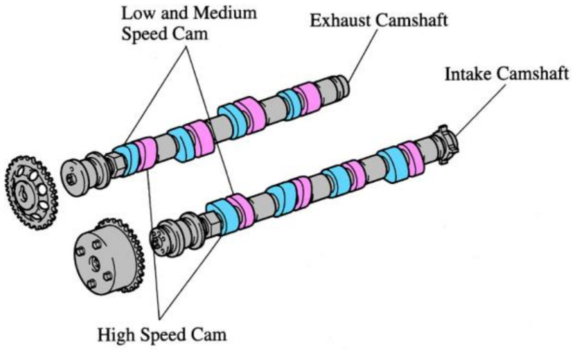
Operation state	Valve timing	Objective	Effect
Idling		Most retarded timing which reduces blowback into intake	Stabilized idling speed and improved fuel economy
Light load		Less overlap eliminates blowback into intake	Greater engine stability
Medium load		Overlap increases causing an internal EGR (exhaust gas re-circulation) which eliminates pumping losses	Improved fuel economy and emissions
Low to medium speed with heavy loads		Advancing intake valve closing to improve volumetric efficiency	Torque is improved in the low to medium engine speed range
High speed range with a heavy load		Inlet valve is retarded which improves volumetric efficiency	Increase in power output

Low engine temperature		Very retarded valve timing to prevent blowback into the intake leading to lean burn also engine fast idle speed is stabilized	Fast idle rev/min is stable and improved fuel economy
Starting or stopping the engine		Very retarded valve timing minimising blowback into the intake	Improved starting

Cam change over (VVTL – i the L is for lift)

Operation of the cam change- over system Both intake and exhaust camshafts have low and medium speed cams and high-speed cams.

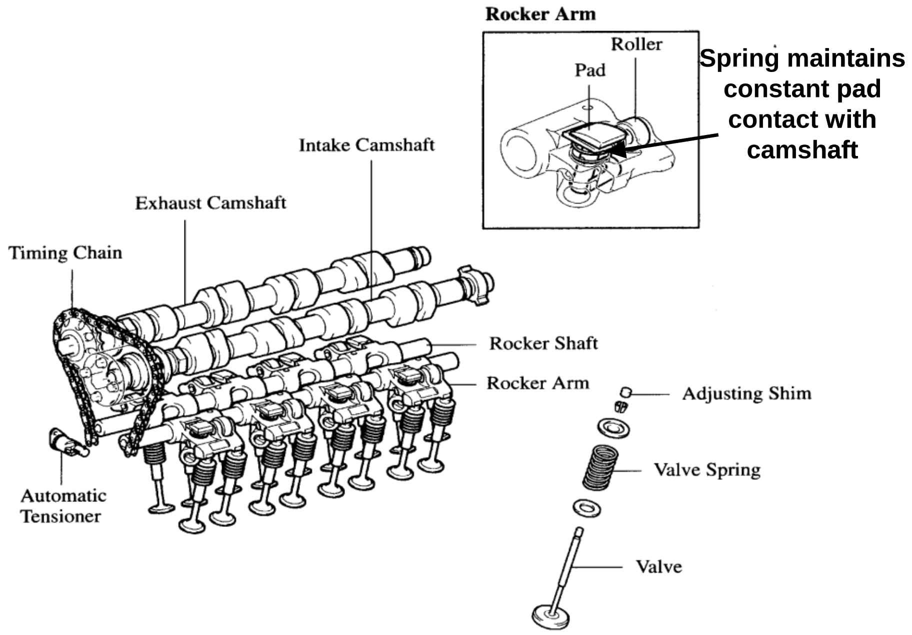
This system not only changes the valve timing but also alters the amount of valve lift.



The cam change over system varies the extent of inlet and exhaust valve lift, this causes high power output without affecting fuel economy or exhaust gas emission performance

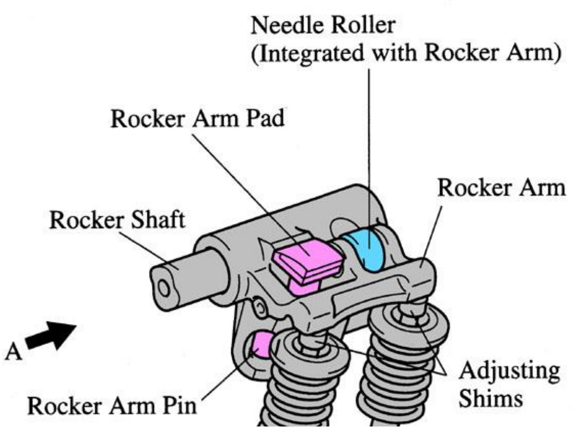
Signals are collected from the water temperature sensor and crankshaft position sensor by the ECU, which controls the oil control valve. The oil control valve switches the oil passages of the cam change over mechanism causing the inlet and exhaust valve lift to change.

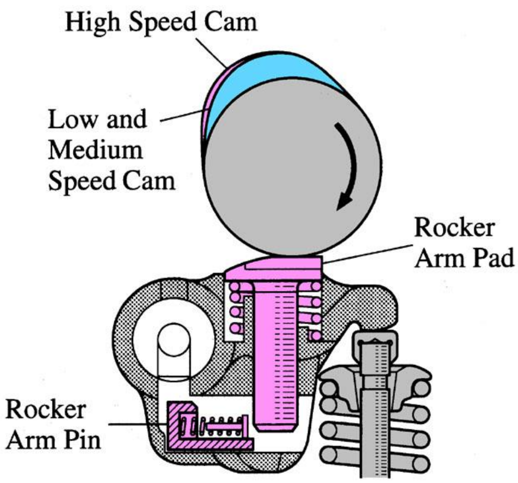
Valve arrangement



Operation

The rocker arm consists of a cam change over mechanism. The mechanism provides for both intake and exhaust valve lift change with each connected to its respective rocker arm.

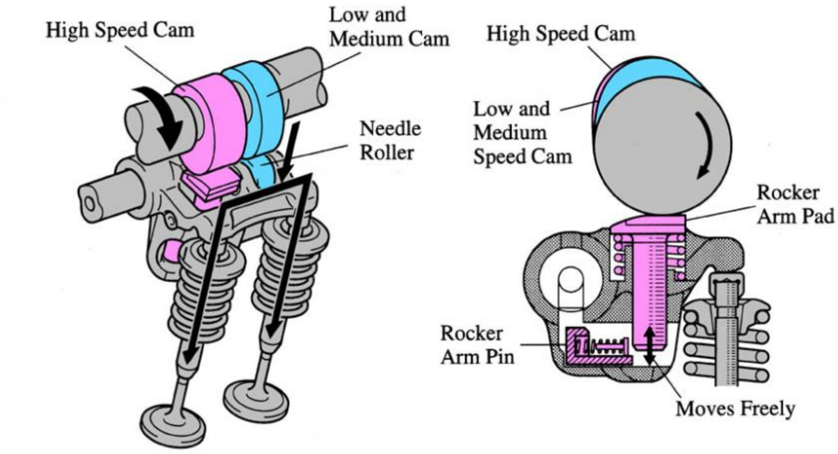




From the front view of the camshaft the low, medium speed and high-speed cam profile can be clearly seen.

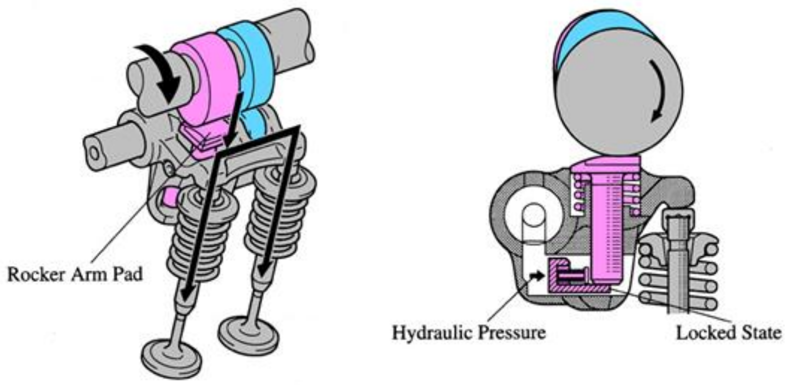
The rocker arm pin is shown inoperative therefore there is no increased lifting of the valve in this position.

Low and medium speed



When the engine is operating at a temperature below 60 degrees C and the engine speed is below approximately 6000 revs per minute, the low and medium speed cam pushes on the roller of the rocker arm and operates both valves. At the same time the high-speed cam pushes on the rocker arm pad, which is allowed to move freely and therefore the valve lift is unaffected and operates under normal conditions.

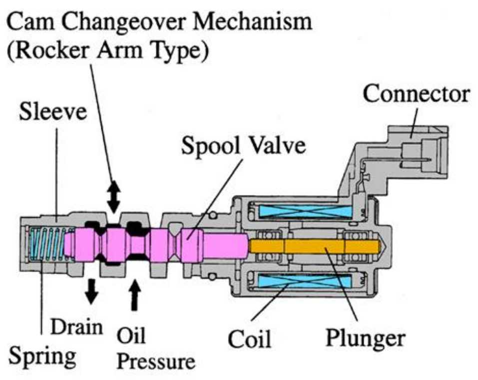
High speed



When the engine reaches approximately 6000 revs per minute (high speed), the hydraulic pressure from the oil control valve pushes the rocker arm pin to lock the bottom of the rocker arm pad.

The high-speed cam has a higher lift and therefore the two valves are lifted more they are operated by the rocker arm pad.

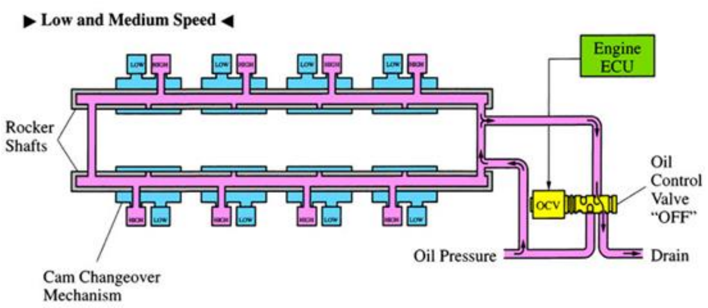
The oil control valve



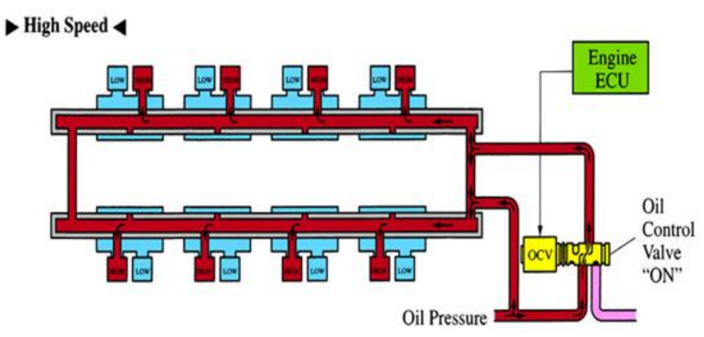
The ECU controls the position of the spool electronically (depending upon the duty cycle). Hydraulic pressure is applied to the high-speed cam of the changeover mechanism.

Oil pressure control

(low and medium speed)



During low to mid-engine speed, the oil control valve is open on the drain side therefore oil pressure will not be applied to the cam change over mechanism.



When the engine attains high speed, the oil control valve closes the drain side and thus applies oil pressure to the high-speed cam of the changeover mechanism

Electronic control

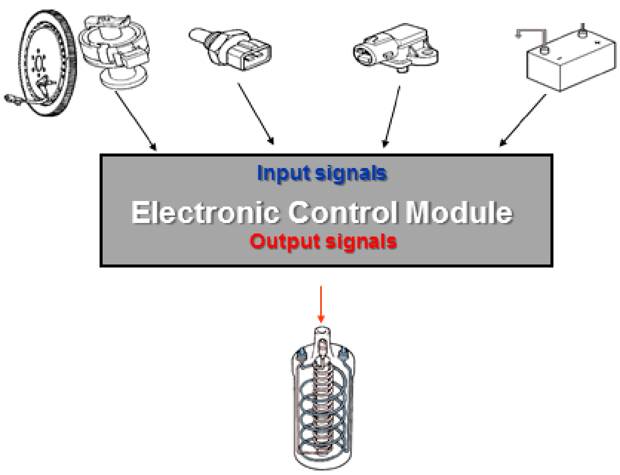
Electronic control systems consist of sensors (information gatherers), an ECU (Electronic Control Unit – the decision maker) and actuators (to carry out actions). It is a three-way process – the sensors gather the information and the ECU receives this information. The ECU processes the information and makes a decision based on what it has been taught. That decision is translated into an action by an actuator and something happens based on that action.

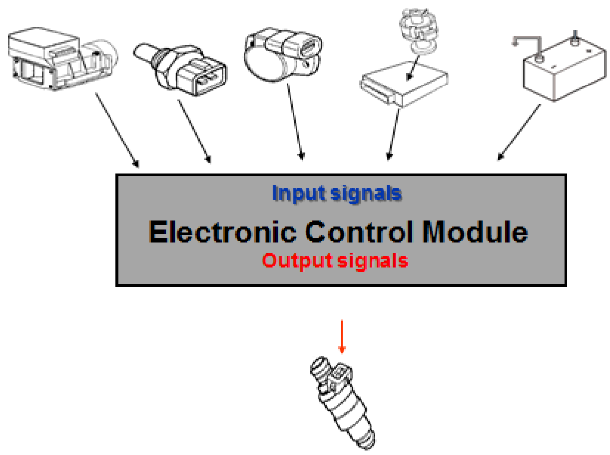
Electronic control systems are based on what is probably the most adaptable, intelligent thing on the face of the planet. Us!

Think about how we interact with the environment – we sense something (sight, sound, smell, taste, touch) using our sensors (eyes, ears, nose, tongue, nerve endings) and the information that we sense is sent to our brain (ECU) for processing. Our brain (ECU) makes a decision based on that information and controls our actuators to suit the situation (our muscles).

We pick something up, sense that it's too hot to touch, and drop it.

It should be noted that we are discussing the fundamentals of electronic control here. This same basic principle can be applied to any electronic control system – EFI, ABS, cruise control etc.





A fully integrated engine management system controls both the fuel injection and the ignition control system. Such integration allows the ignition and fuel injection programmes to interact with each other and therefore provide optimum control. The result is a reduction in emissions and an improvement in performance whilst maintaining fuel economy.

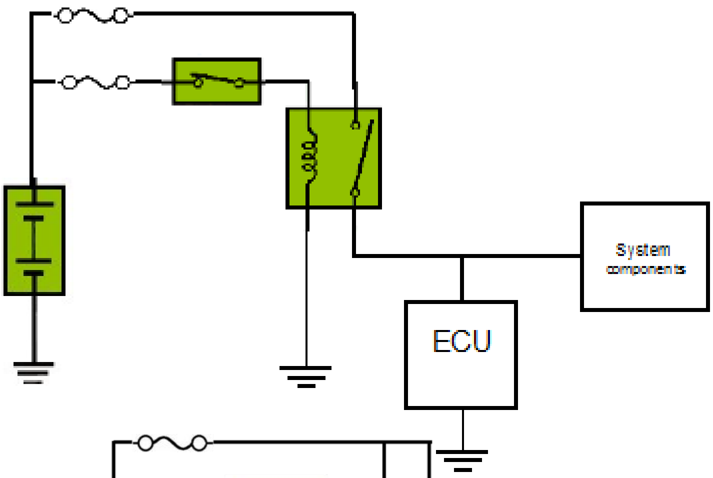
The electronic control unit (ECU)

The electronic control unit is often referred to by many names e.g. DME (digital motor electronics) or PCM (power control module). They all carry out the same role as the brain of the system and effectively make the decisions. In reality an ECU can only make decisions based on the information received from sensors and then performs a task based on the pre-programmed information. The ECU is limited in its decision-making process as it can only make decisions based on the programming it has been given.

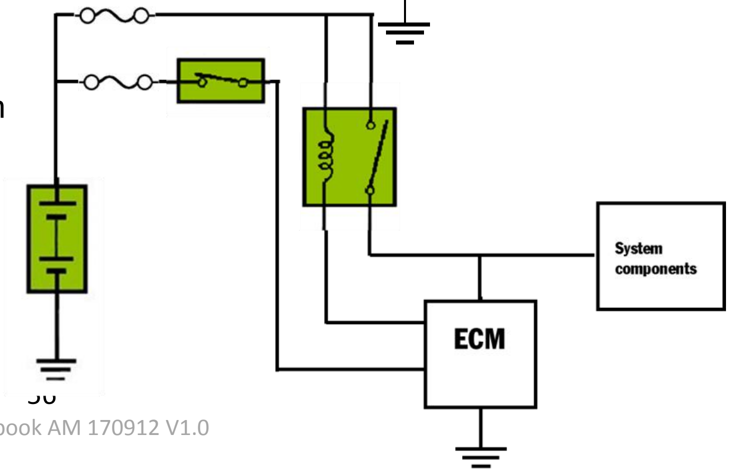
Power supply

In order for the ECU (ECM) to be able to process information, it requires a power supply. This is often supplied via a relay.

This relay is ignition controlled. Most modern vehicles are configured in this way.

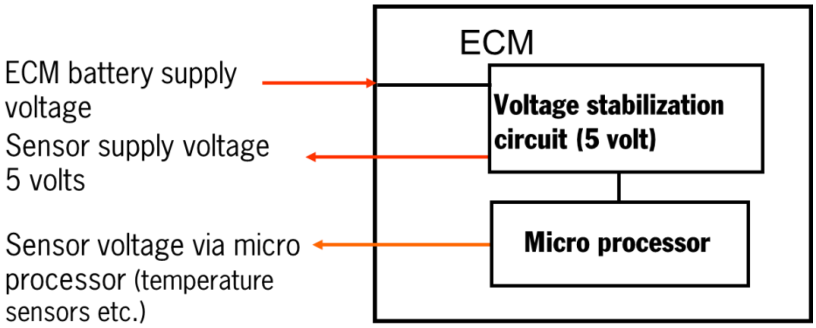


The diagram opposite shows a variation on this theme: the ignition switch provides only a signal to the ECU and the ECU then grounds the relay in order to control its own supply. This type of configuration is found on



any vehicle where continued control functions are required for a short time after the driver turns off the ignition.

Sensor power supply circuit



In the diagram above it shows the sensor power supply circuit.

Any active sensor (a sensor that experiences a change in resistance in proportion to changing conditions rather than one that generates its own voltage) must be supplied with a very closely controlled voltage. If we supplied unconditioned battery voltage to such a sensor, its signal voltage would fluctuate not only in accordance with changing sensed conditions but also in accordance with battery voltage.

Battery voltage is applied to the ECU and the ECU supplies 5v to each active sensor. An integrated circuit (IC) is used to achieve this effect, but it is primarily a Zener diode.

This 5v is also used by the ECU's microprocessor circuit to enable the ECU to fulfil its responsibilities.

Potential problems

Should the circuit open mid-harness, some or all of the sensors that depend on this 5v will fail. At best the engine will run badly, at worst not at all.

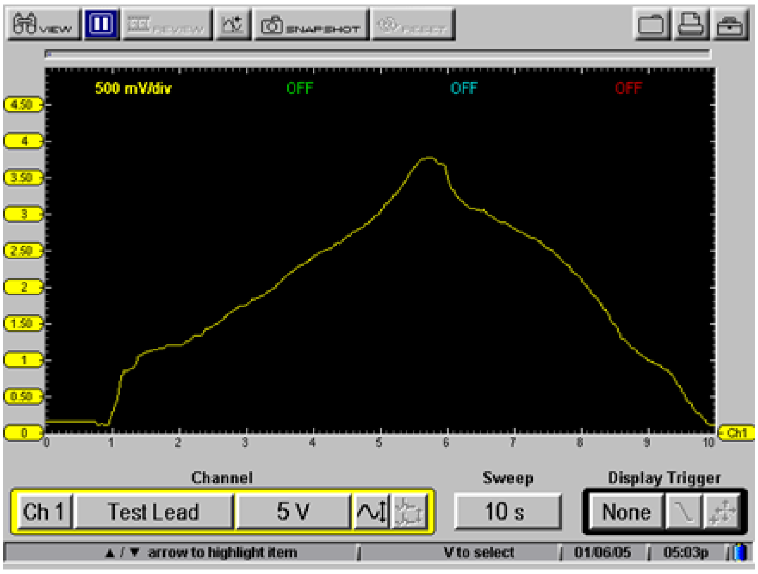
Should the circuit short to ground, we will have the same problem with the sensors but in addition to this, the ECU microprocessor will receive no voltage. A very good indication of this is that the check engine warning light (MIL or malfunction indicator light) will no longer illuminate when the ignition switch is turned on (this facility normally acts as a bulb check when all is well). The reason for this is that it is the responsibility of the ECU to ground the warning lamp when the ignition is turned on to carry out this bulb check; it cannot do this if the ECU microprocessor is effectively dead.

The signals

Two basic signal types are commonly seen on motor vehicle systems – Analogue and Digital. These can be divided into two groups – Alternating current (AC) and Direct Current (DC). Note: AC Digital signals are rarely seen outside the ECU.

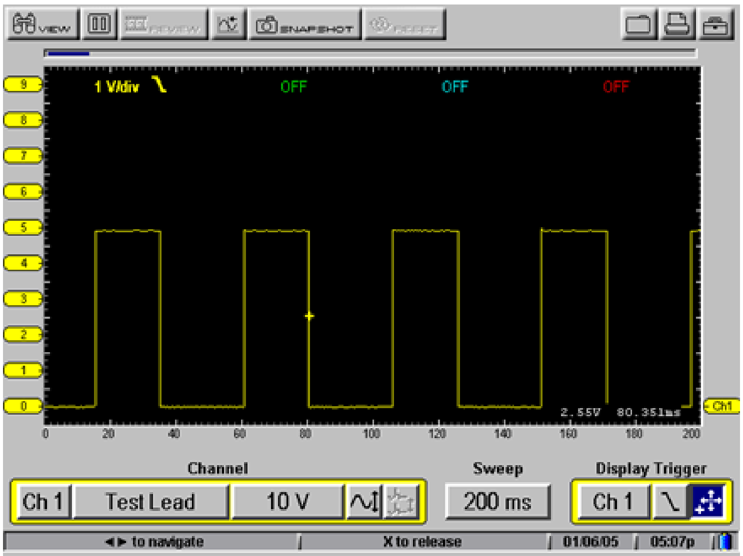
Analogue

An Analogue signal can be described as one in which the voltage varies up and down but is not seen as actually turning off or on but simply changing. An ECU will be looking for the voltage at any given time and in some cases, how fast it changes ("Rate"). An analogue voltage may change over very short or very long periods of time depending on the sensor and its intended use.



Digital

A Digital signal switches between zero volts and maximum supply voltage, effectively turning the circuit off and on rapidly. The ECU will be looking for a number of things, depending on the intended use of the signal:

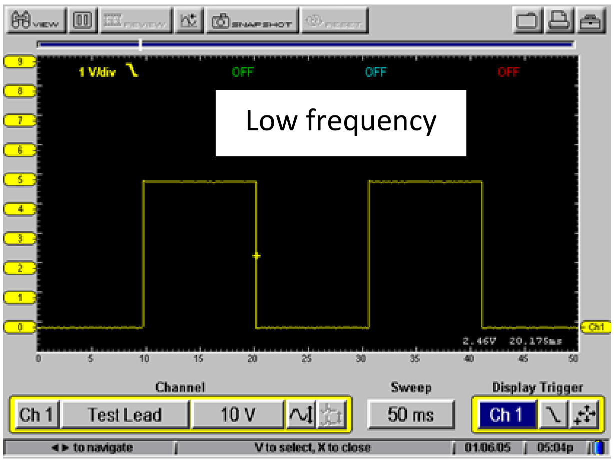


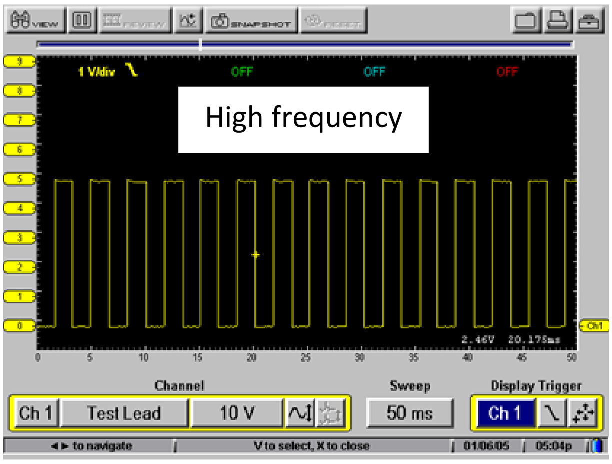
1. How fast the signal switches (Frequency).
2. How long the signal is low or high for (Duration).
3. How long the signal voltage is high for compared to how long it is low for (Pulse width modulation).
4. The average voltage resulting from any of the above.

Sensors can be designed to produce any of these variations in signal and measurements can be made to change by physical influences such as pressure, flow, speed etc. The ECU can also operate actuators by supplying changing frequency, duration, pulse width modulation or average voltage signals.

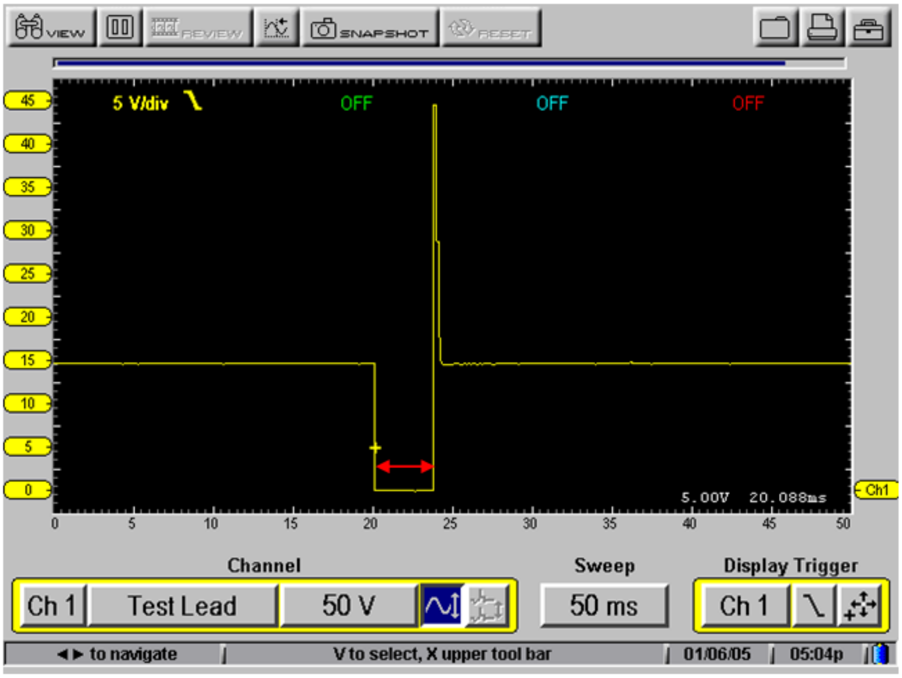
Frequency

Frequency is measured in Hertz (Hz), which is the number of repetitions or cycles that the signal occurs every second. 1Hz is equal to 1 cycle/sec.





Duration

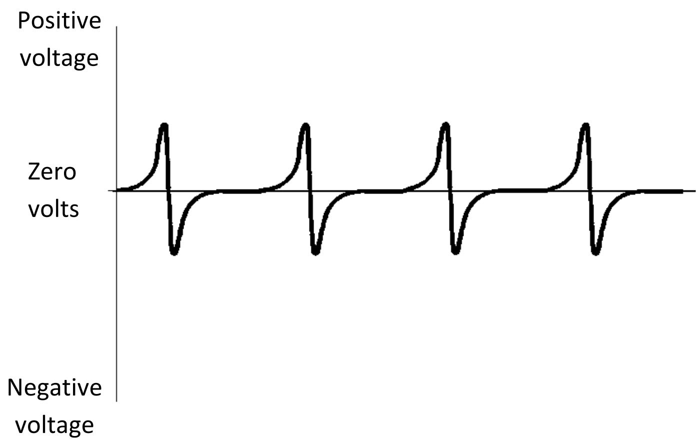


The duration or dwell time of a signal is usually the actual operating time of a sensor or actuator – how long it is switched ON for. This time is normally measured in Milliseconds (ms), where 1 ms is 1/1000th of a second.

In the example, (right), the arrow denotes ON duration. Which in this case would be 3.5ms.

Alternating Current (AC) signals

AC signals may be in analogue or digital form. In both cases the high voltage part of the signal will be above the zero line and the low voltage part will be below the zero line by an equal value.

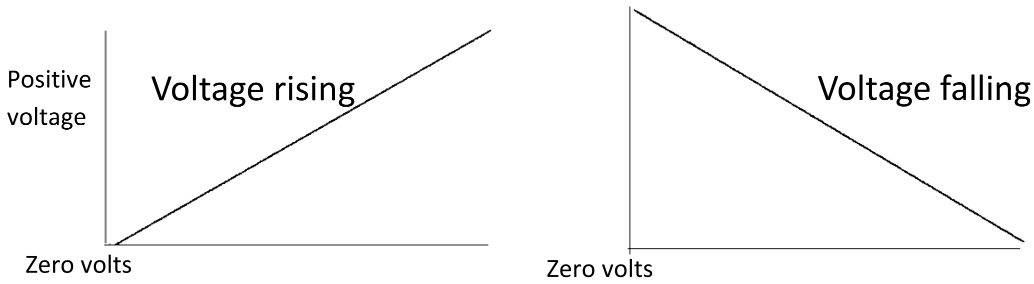


AC voltage

As an example, if the positive voltage (above zero) is + 5 volts then the negative voltage (below zero) will be – 5 volts. The total voltage change is therefore 10 volts and the average voltage will be zero. These signals are typically high voltage (positive) for the same time as they are low (negative).

It is unusual to see AC Digital signals on motor vehicles at present but AC Analogue signals are very common.

Direct Current (DC) signals



DC voltage

DC signals may also be analogue or digital. The voltage of these signals is always positive (Zero and above). The frequency and/or the duty cycle may change.

Electronic fuel injection systems provide an efficient method of controlling fuel delivery and quantity accurately. The result is improved combustion efficiency, improved engine performance, improved economy and reduced emissions.

A fully electronic fuel injection system also provides the facility of integration and communication with other vehicle systems, such as the ignition and emission control systems.

Sensors:

Engine temperature sensors

Oxygen sensors

Knock sensors

Airflow sensors

Mass air flow sensors

Manifold absolute pressure sensors

Air temp sensor

Throttle position sensor

Camshaft position sensors

Crankshaft position sensors

Control unit

Engine management power supply

Read only memory

Random access memory

PROM/EPROM

Keep alive memory

Limited operating strategy

Open and closed loop

Actuators

Idle speed actuators

Ignition coils

Fuel injectors

Throttle motors

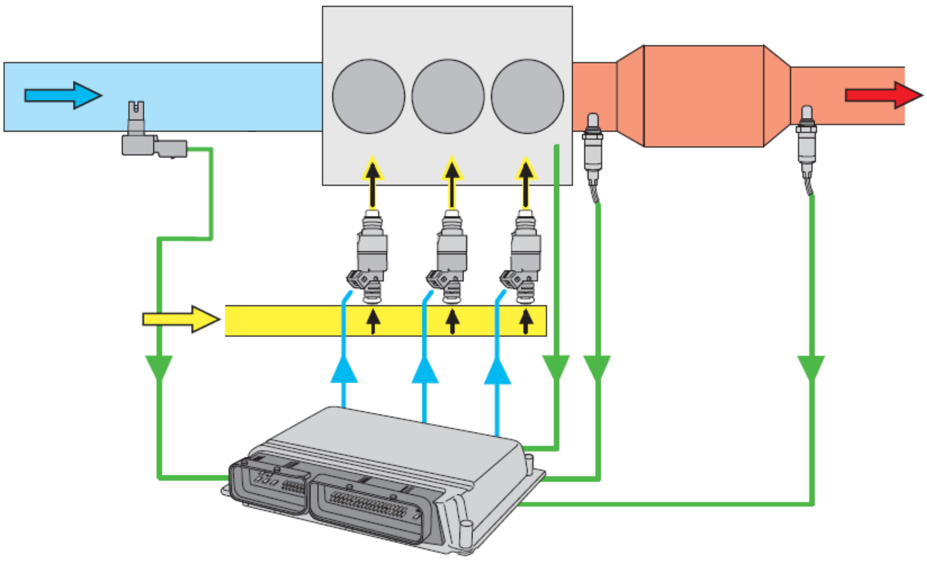
EGR control

EVAP control

Oxygen sensors

On a modern engine, oxygen sensors assume responsibility for the monitoring of the mixture strength.

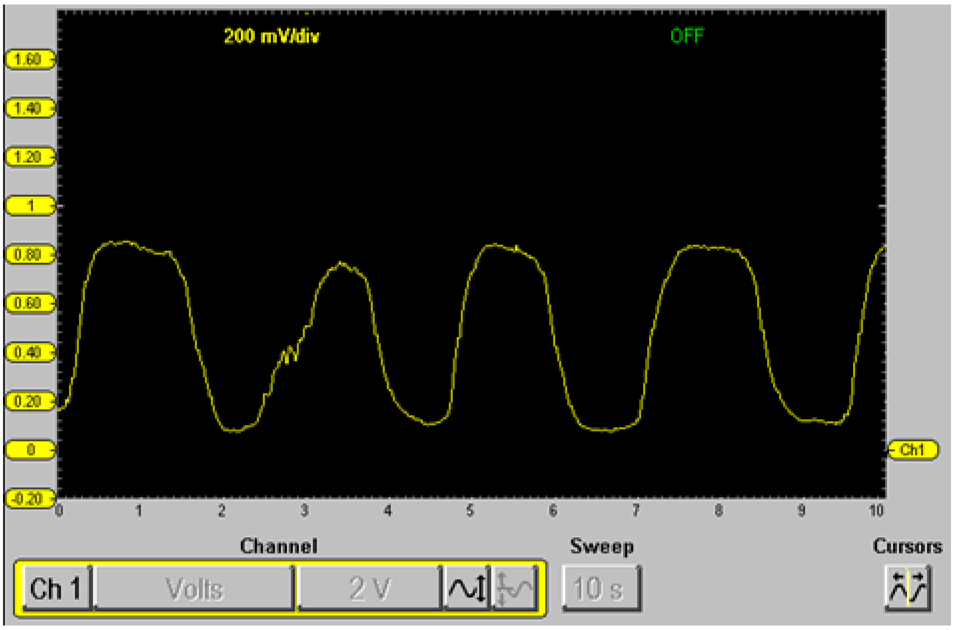
The lambda sensor is located in the exhaust pipe between the exhaust ports and the catalyst, normally in the exhaust down pipe. The lambda sensor signal is used by the ECU to



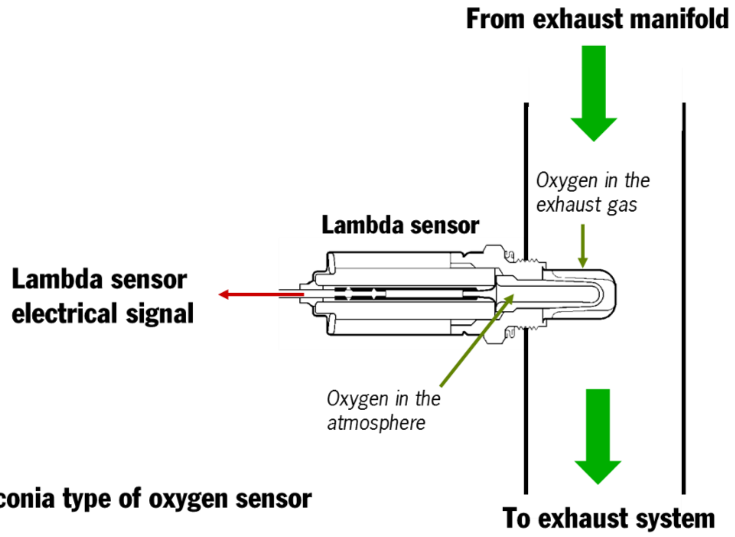
maintain the air / fuel mixture at the correct ratio.

The lambda sensor measures the oxygen content in the exhaust gas and passes an electrical signal to the ECU. The ECU is then able to provide the correct control signals to enable the engine management system to maintain the correct air / fuel mixture.

The lambda sensor signal operates between 0.1 volts and 0.9 volts. When the oxygen content in the exhaust is high (weak mixture), the lambda sensor voltage is low (0.1 volts), when the oxygen content is low (rich mixture) the signal voltage is high (0.9 volts).



The oxygen sensor is coated with a special material called Zirconia. Zirconia has a special property where when exposed to two areas of differing oxygen content, a small voltage is produced. If the engine is running rich, there will be an excess of fuel. This will result in the majority of oxygen being burnt. We then configure the sensor so that one side is in direct contact with the exhaust gas and the other atmospheric air. The greater the difference in oxygen across the sensor, the higher the voltage. The smaller the difference, the lower the voltage. Working range is 0.1v to 0.9v.



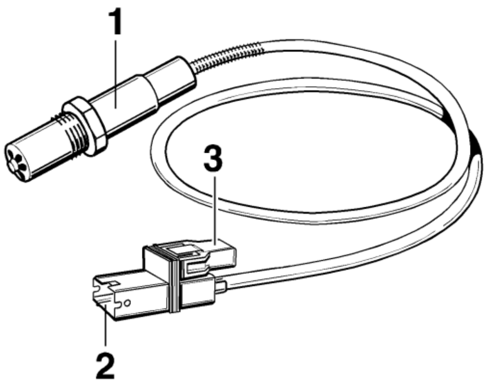
Zirconia type of oxygen sensor

The value ‘Lambda’ is used to describe how rich or lean an engine is running. It is calculated by dividing the actual A/F ratio by the ideal (14.7:1). If an engine is running at the ideal A/F ratio, it can therefore be described as running at Lambda 1 (14.7:1 divided by 14.7:1 equals 1). From this simple equation, it can be seen that if an engine is running rich, the Lambda value will be less than 1 and if it is running lean, greater than one. Lambda is also sometimes described as Excess Air Factor.

An oxygen sensor will only start to produce a decent signal when hot. As the majority of emissions are produced by a vehicle when cold, it is important to assume control based on an oxygen sensor signal as soon as possible. To help the sensor to heat up quickly, two things are done: the sensor is positioned very close to the exhaust ports and sometimes an electrical heater element is also provided. The ECU controls the flow of current through this.

Wide band oxygen sensors

An LSU4 wide-band oxygen sensor is installed for each cylinder bank upstream of the catalytic converters. In the engine compartment a sensor-specific, laser calibrated trimmer resistor is attached to the plug connection of these oxygen sensors. This resistor is specially calibrated for each individual sensor during production.



1 – Wide-band oxygen sensor LSU4

2 – 6-pin plug connector of oxygen sensor

(on left and right-hand side of engine compartment)

3 – Integrated trimmer resistor

(to compensate pumping current)

Advantages of wide-band oxygen sensor LSU4

• Constant characteristic curve

• Precise measurement in broad lambda range

from > 0.7 (rich mixture)

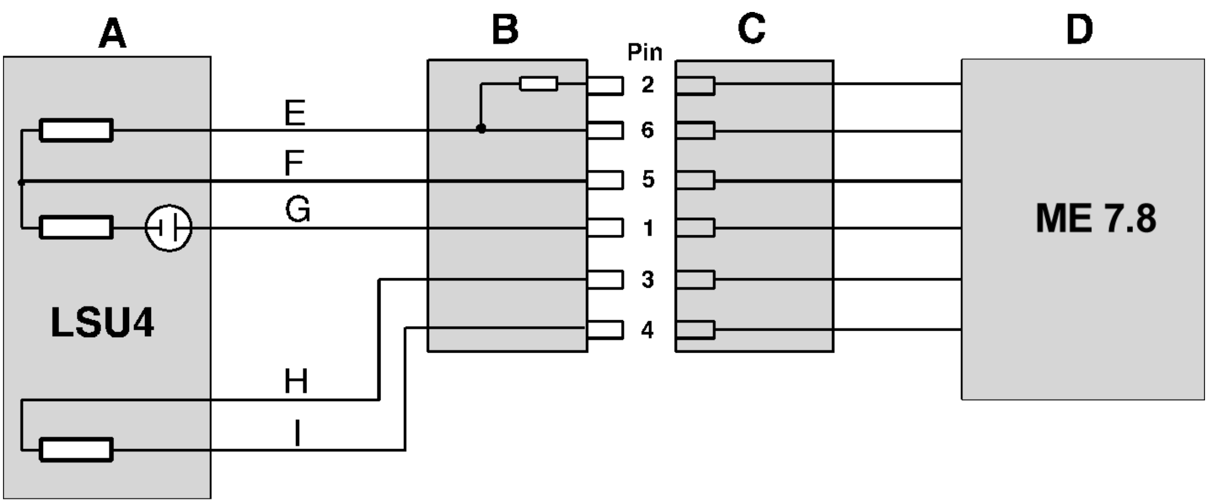
to < 4 (pure air)

• Short response times < 100 ms

• Fast availability

Six cables lead off from the ME 7.8 control unit to the plug connectors in the engine compartment.

Five cables then lead off from the plug connectors to the LSU4 wide-band oxygen sensors.



A – Wide-band oxygen sensor LSU4

B – Plug connection (oxygen sensor) with integrated

trimmer resistor for pump current

C – Plug connection (engine wiring harness)

D – ME 7.8 control unit

Cables for:

E – Pump current (0 mA ±)

F – Virtual earth

G – Sensor voltage signal (Nernst voltage UN)

H – Sensor heating (U Battery)

I – Earth for sensor heating (regulated via ME 7.8

control unit)

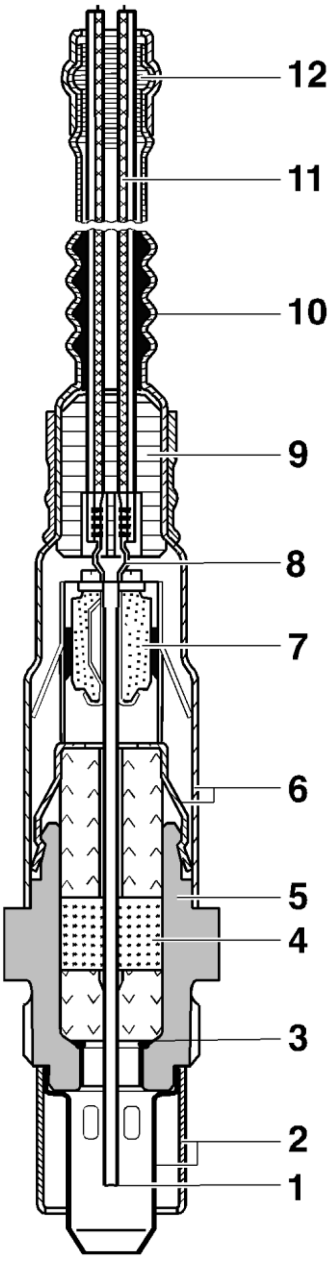
Wide-band oxygen sensor LSU4

The sensing element of the LSU4 wide-band oxygen sensor is a combination consisting of a zirconium dioxide sensor***** (or offset oxygen sensor with Nernst concentration cell) and the lean sensor****** which functions following the limit current principle. Used as a two-cell sensor in conjunction with regulating electronics in the DME control unit, it supplies a clear and linearly ascending signal across a broad lambda range (from lambda 0.7 to lambda 4). Accurate measurement is thus possible in both the rich and lean range. To reduce emissions, the engine is run with a stoichiometric air/fuel mixture of lambda 1 as soon as the operating behaviour of

the engine and the temperature of the components permit this. However, the LSU4 wide-band oxygen sensors used in this stereo oxygen sensing system allow the air/fuel mixture to be adjusted in both the warm-up phase and the full-load range to a certain set point value (determined by the DME control unit) which may deviate from lambda 1. As a result, the exhaust gas and running behaviour fluctuate only slightly since these ranges are also regulated by the ME 7.8 control unit.

The pump cell and concentration cell are coated with ZrO_2 and each have two porous platinum electrodes. The cells are arranged in such a way that there is a measuring gap of 10...50 µm between them. A gas inlet in the solid electrolyte forms the connection between the measuring gap and the surrounding gas atmosphere. The measuring gap is also the diffusion barrier which determines the limit current. An electronic circuit in the DME control unit regulates the voltage applied to the pump cell (and therefore the pump current) so that the composition of the gas in the measuring gap remains constant at lambda 1. This corresponds to a voltage of UN = 450 mV at the concentration cell of the oxygen sensor. With lean exhaust gas, the pump cell pumps the oxygen out of the measuring gap.

With rich exhaust gas, however, the oxygen separated from the exhaust gas of the surrounding atmosphere (by decomposing CO_2 and H_2O) is pumped into the measuring gap and the direction of flow is reversed. The pump current is proportional to the oxygen concentration and the oxygen requirement. An integrated heating element ensures that the oxygen sensor does not drop below its minimum operating temperature of 600 °C.



***** Zirconium dioxide sensor (offset oxygen sensor) The offset sensor with Nernst concentration cell functions following the principle of a galvanic oxygen concentration cell with solid electrolyte. Its ceramic material is made of zirconium dioxide and yttrium oxide. This mixed oxide, a virtually perfect oxygen ion conductor, is able to separate exhaust gas from the surrounding air. An electric voltage corresponding to the Nernst equation is produced at the platinum/ cermet electrodes. With lambda 1, the curve for this sensor exhibits an offset characteristic (above or below 450 mV). The offset sensor can only be used for measurements close to lambda 1 since it is able to supply only limited information in the lean range.

Lean sensor

The lean sensor which functions following the limit current principle is used to measure values above lambda 1. O_2 ions (oxygen ions) are pumped from the cathode to the anode by applying an external electric voltage to two electrodes attached to a ZrO_2 ceramic element. Since a diffusion barrier prevents the O_2 molecules from the exhaust gas from flowing to the cathode, current saturation occurs above the threshold value for the pump voltage. The resulting limit current is approximately proportional to the oxygen concentration. This sensor principle is especially suitable for lean concepts. The wide-band sensor (LSU4) is, however, more suitable in the case of lean/mixed concepts where a set point regulation value of lambda 1 is frequently desired.

1 – Sensing element of LSU4
(combination comprising Nernst concentration cell and oxygen pump cell)
2 – Double protection tube
3 – Sealing ring
4 – Sealing package
5 – Sensor housing
6 – Protective sleeve
7 – Contact holder
8 – Contact clip
9 – Grommet
10 – Moulded hose
11 – Five connecting cables
12 – Seal

A special operating electronics system for each wide-band oxygen sensor is integrated in the ME 7.8 control unit. This system contains the regulating electronics for the oxygen pump cell and the Nernst concentration cell used to generate the sensor signal. In addition, it also includes the regulating electronics for keeping the temperature at the LSU4 wide-band oxygen sensor at approx. 750° C.

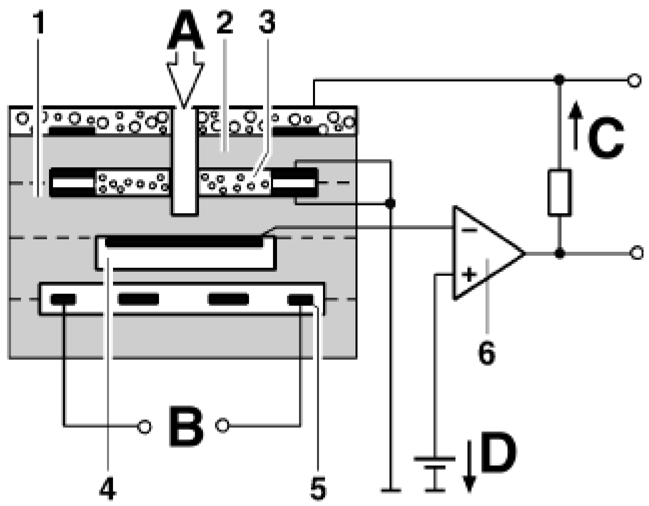
In the ME 7.8 control unit, the current for the oxygen pump cell is regulated to ensure that the composition of the gas in the diffusion gap of the oxygen sensor reaches the lambda value predefined by the DME control unit. The regulating system also compares the voltage signal from the oxygen sensor (Nernst voltage) with the setpoint value predefined by the DME control unit and adjusts the current for the pump cell so that the oxygen concentration (and thus the Nernst voltage) approximates the setpoint value.

With lambda 1, this corresponds to a voltage of UN 450 mV at the Nernst concentration cell. With lean exhaust gas, UN * is less than 450 mV. The oxygen pump cell is then actuated by the pump current so that oxygen is pumped out of the diffusion gap. With rich exhaust gas, UN is greater than 450 mV.

The direction of flow is then reversed so that the cell pumps oxygen into the diffusion gap.

UN * = Nernst voltage

The oxygen sensor voltage upstream of the catalytic converter for bank 1 and 2 can be read out from the actual values stored in the DME control unit using the Porsche System Tester 2. The displayed voltage is recorded in the DME control unit after it has been processed by the regulating electronics. With lambda 1, the displayed voltage is approx. 1.5 Volt. With a rich mixture, the voltage drops to approx. 1.0 Volt. In the lean range, the voltage may increase to approx. 5 Volt.



A – Exhaust gas

B – Heating current

C – Pump current

D – Sensor voltage/reference voltage

1 – Nernst concentration cell

2 – Oxygen pump cell

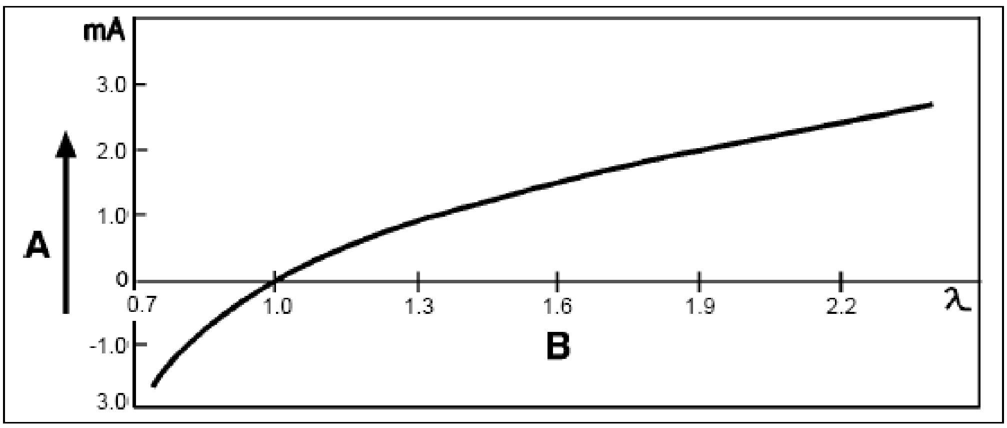
3 – Diffusion gap (10...50 μm)

4 – Reference air channel

5 – Oxygen sensor heating element

6 – Regulating circuit (in DME control unit)

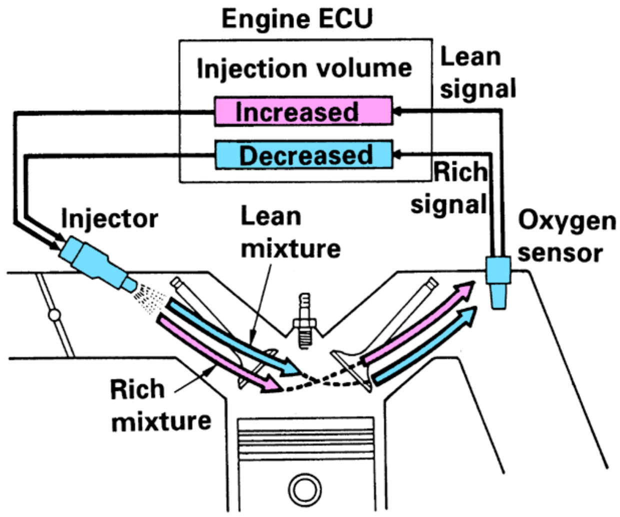
LSU4 pump current

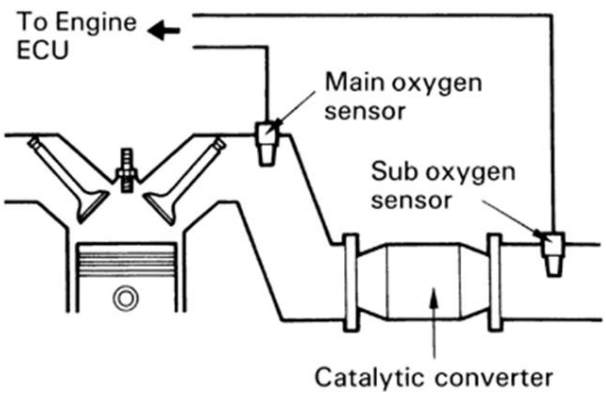


A – Pump current (mA)

B – Lambda value (air/fuel ratio)

Open loop/closed loop control





An oxygen sensor is always used in conjunction with a catalytic converter as the converter only works effectively at stoichiometric ratio (or lambda 1). When the ECU is monitoring mixture strength through the use of the oxygen sensor, this is known as closed loop control. The term is derived through the fact that the ECU decides what to put into the engine based on what it knows is coming out (like a loop).

When the driving conditions dictate that the air/fuel ratio is outside the lambda window i.e. warm up, full load, the lambda sensor signal is ignored (open loop). The fuel injection quantities are then based on information from other sensors and the pre-programmed values inside the ECU. The ECU will always revert back to closed loop as soon as conditions dictate.

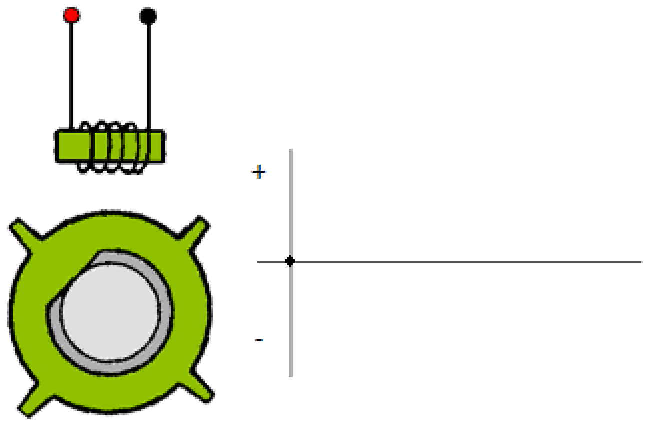
Speed sensors

In order for the ECU to inject into the correct cylinder at the correct time, it must be able to sense the position of the engine. With any increase in engine speed we have less time to introduce the fuel via the injector (the intake valves are open for a far shorter period) but the reaction speed of the injectors remains constant (the amount of time it takes for the injectors to open and close that is. If the ECU has a means of sensing engine speed then it can compensate for this by providing current to open the injector slightly earlier.

Operation

If we change the strength of a magnetic field in the presence of a coil of wire, current will flow in that coil.

This is the fundamental underlying principle of electrical generation.



Crankshaft position sensor

It can be seen above that the sensor consists of a coil of wire wrapped around a magnet (inductive pickup) placed close to a toothed wheel (the rotor or reluctor).

The rotor (toothed wheel) is connected to the crankshaft and therefore rotates as the engine rotates. When the rotor tip passes near to the coil, an AC current is produced which is sensed by the ECU. When the air gap is large, there is little influence on the magnetic flux around the pickup and therefore signal voltage is low. When the rotor tip approaches the pickup, the tip increases the strength of the magnetic flux and produces a positive voltage from the pickup. When the rotor tip leaves the pickup, the tip reduces the strength of the magnetic flux and produces a negative voltage. The rotation of the rotor near to the pickup therefore causes an AC current to be produced.

The rotor in figure 29 has 4 teeth on it. This indicates that it will generate 4 AC pulse per revolution of the crankshaft. If we program the ECU with this information, it can calculate engine speed by simply counting the pulses.

Example:

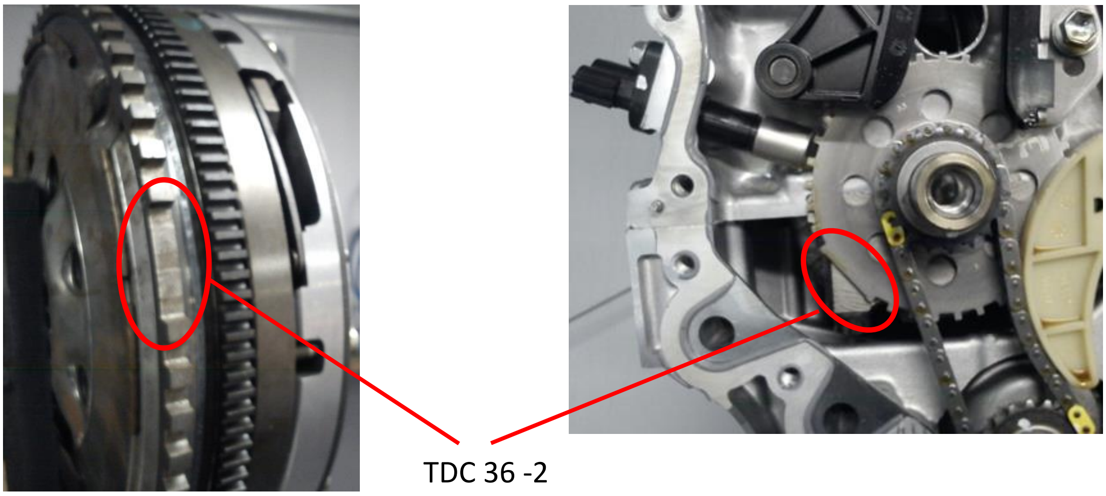
100 pulses received every second

4 pulses per revolution

25 revolutions per second (100 divided by 4)

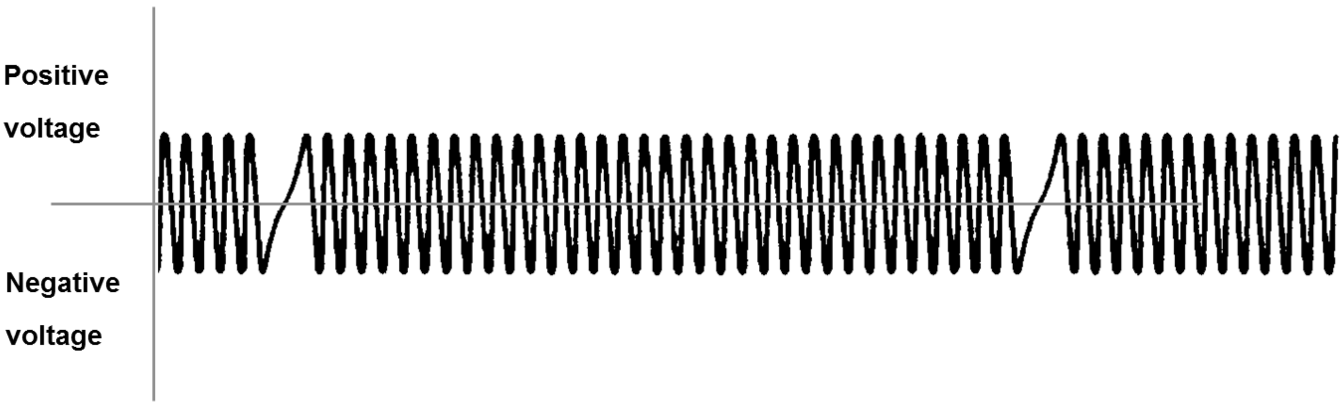
1500 revolutions per minute (RPM). (25 multiplied by 60 seconds)

In reality the crankshaft rotor has more than 4 teeth. The more teeth that it has, the more accurate the ECU's speed calculation will be at any given point.



TDC 36 -2 mark

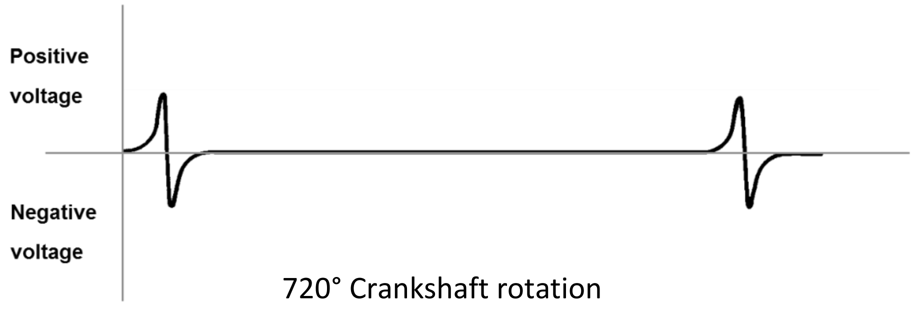
Crankshaft position sensor

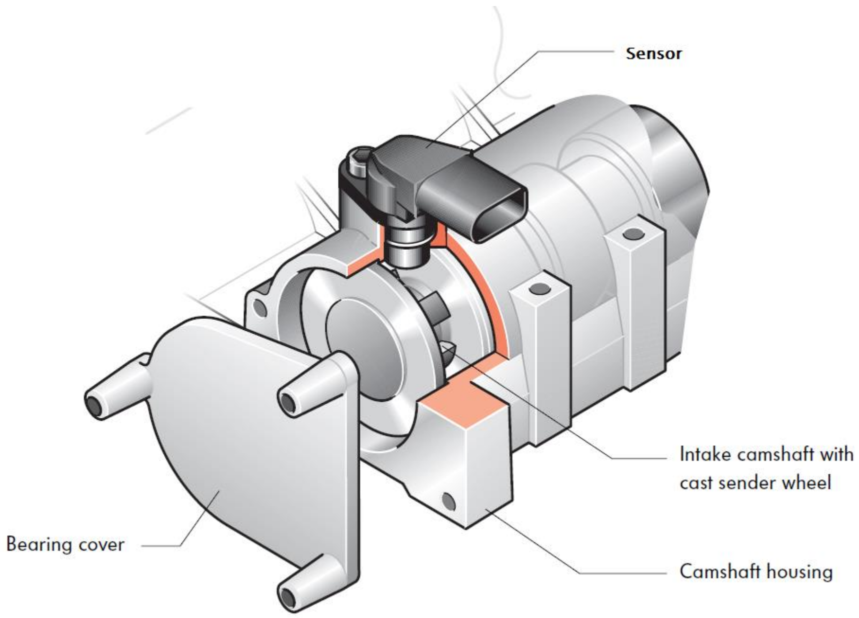


It has been seen that an engine speed sensor can be used to calculate engine speed. The diagram above shows the signal generated by a crank sensor with a 36-2 rotor. The minus 2 part of the rotor provides positional information (normally TDC). However, as the engine is 4 stroke, this could indicate TDC compression No1 cylinder *or* TDC valve overlap. For correct control of the fuel injectors', clarification of this is important. The camshaft position sensor provides definitive positional information because it is positioned on the camshaft, which only rotates once per engine cycle.

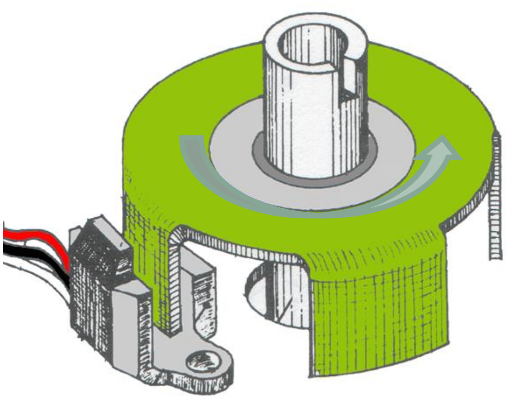
Camshaft position sensor

To confirm TDC compression, the ECU monitors the 36-2 crank sensor as well as the camshaft position sensor. When it receives the minus 2 flat line and the single pulse from the camshaft position sensor it knows exactly where the engine is within the 4-stroke cycle. This ensures that fuel is injected into the correct branch of the manifold on the induction stroke.





Hall Effect sensors

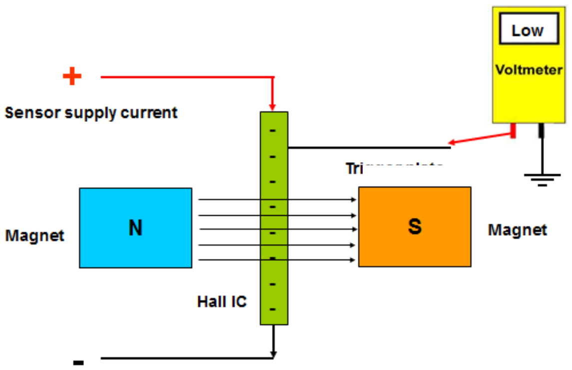


The Hall switch is an integrated circuit (IC), which is affected by magnetism. The Hall switch receives a power supply at the “+” terminal. The “-” terminal is connected to earth (usually via the ECU). The ECU passes a signal voltage to the sensing terminal of the Hall switch typically between 5 - 10 volts. The

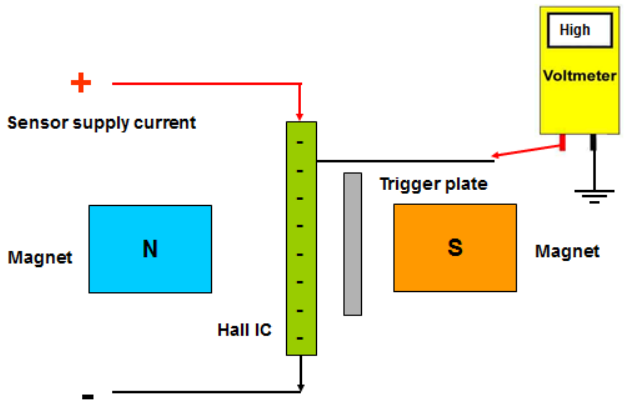
ECU uses any changes experienced in this voltage as positional / speed information.

When the solid section of the drum passes between the magnet and the Hall switch, magnetism cannot influence the Hall switch. If magnetism cannot influence the Hall switch, the Hall switch will be open. When the switch is open, the signal current cannot flow to earth, therefore the signal voltage at Hall switch terminal will be high (and also at the corresponding ECU terminal.)

When the cut-out section of the drum passes between the magnet and the Hall switch, magnetism can influence the Hall switch. If magnetism influences the Hall switch, the Hall switch will close. When the switch is closed, the signal current can now flow to earth. The signal voltage at the Hall switch terminal will be zero (and also at the corresponding ECU terminal).

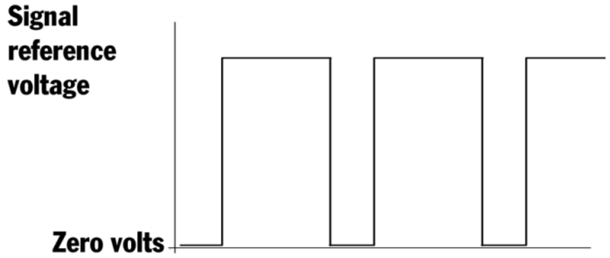


Current can flow across the hall switch



Current can NOT flow across the hall switch

Scope pattern

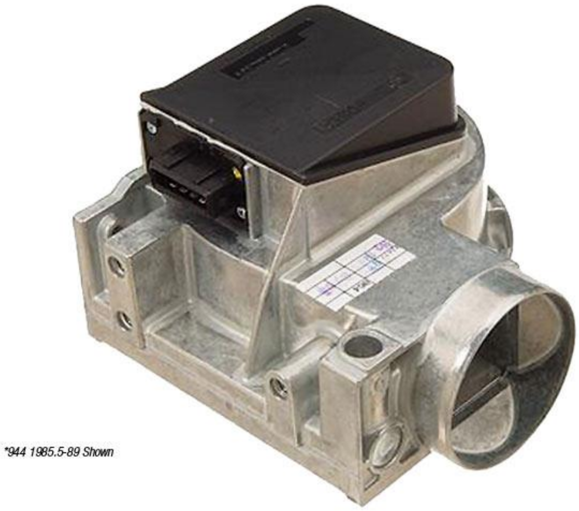


Air flow sensors

Airflow is measured either directly through the use of an air flow meter or indirectly through the use of a manifold pressure sensor.

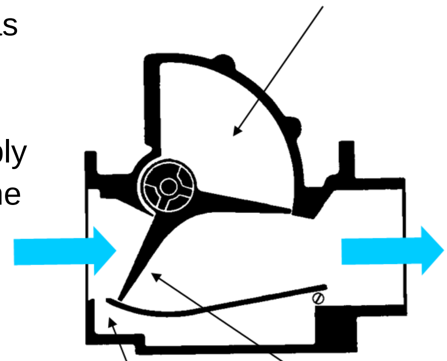
Vane type air flow meter

Manifold pressure sensor



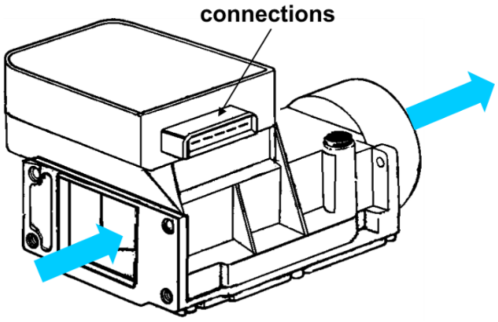
Vane type air flow meter

The position of the vane plate is influenced directly by the airflow volume, as the deflecting force will be proportionate to this. Mounted on the same axis as the vane plate is a potentiometer (mechanically varied resistance – see throttle position sensor) and its value is therefore changed by the rotation of the vane. If we supply the potentiometer with a closely regulated voltage (5v) the voltage returned by the potentiometer to the ECU will alter proportionately in accordance to the vanes position.

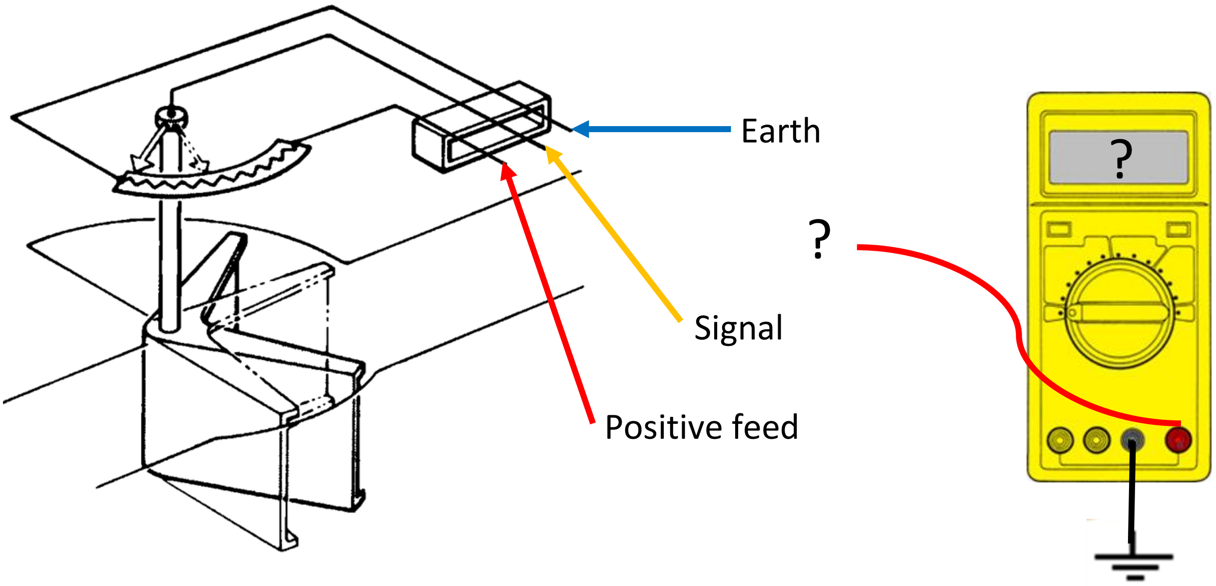


An example of a potentiometer that most of you will identify with is a Scalextric hand controller!

The damping chamber prevents natural turbulence in the airflow (created by the internal pumping effect of the cylinders) from setting up a frequency. This would make the engine hunt badly (the engine revs would fluctuate up and down).

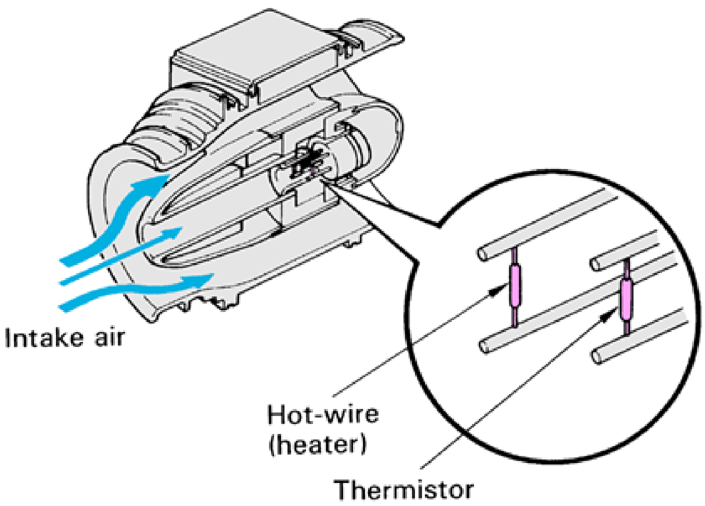


The electrical circuitry for the vane type airflow meter can be seen below.

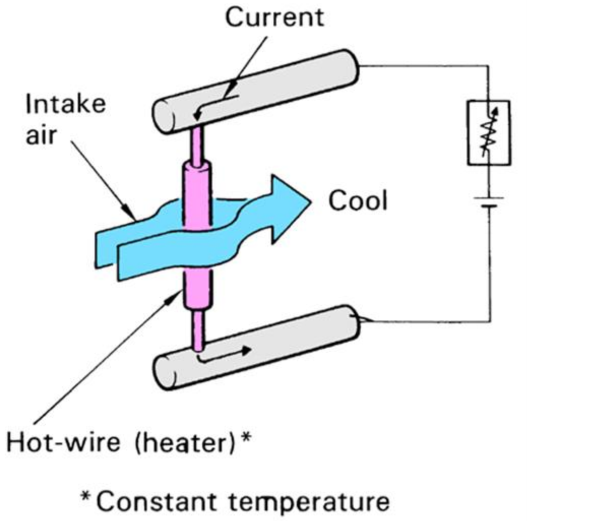


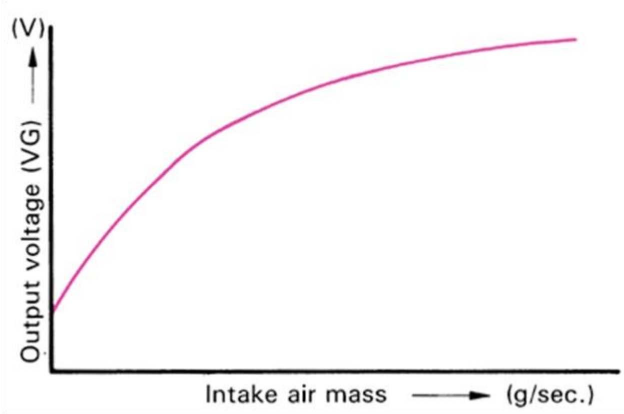
An oscilloscope is ideal for checking the serviceability of such a sensor as any worn parts of the potentiometer track will create dips and spikes in the signal voltage. Use of an Ohmmeter is limited to checking only the sensor and not the circuitry.

Hot wire type air flow meter



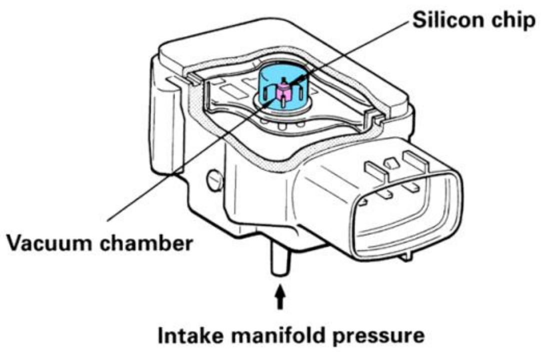
This clever sensor features a platinum wire suspended in the flow of air and a voltage applied to it by the ECU. The resulting current flow heats the wire. A thermistor (temperature sensor) is used to sense the temperature of the wire and when the target temperature is reached the voltage is maintained. The flow of air across the wire cools it, and the ECU has to apply a higher voltage to achieve its target wire temperature. The degree of cooling created by the air flow is in direct proportion to the amount of air flow, and the voltage required to achieve the target temperature is therefore also in direct proportion to this. The ECU interprets the voltage as airflow volume. Here's the clever bit; on a cold day, the cooling effect will be greater for a given amount of air flow, therefore the required voltage will be higher. The ECU interprets this as an increase in airflow and will increase fuel injection volume correspondingly. This is just what we want as cooler air is denser and therefore each cylinder will receive a greater amount of oxygen per intake stroke. This sensor is therefore a true air mass sensor.





Manifold pressure sensor (MAP)

Analogue type



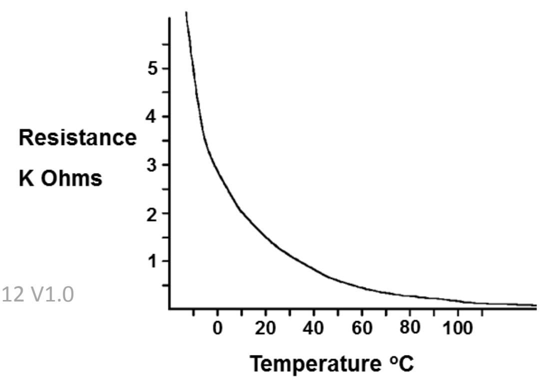
Changes in engine load will create changes in intake manifold pressure. The MAP (manifold absolute pressure) sensor detects these pressure fluctuations and converts them into a language that an ECU can understand-voltage. An integrated circuit called a piezoelectric element is mounted on a small diaphragm. This diaphragm is influenced directly by the pressure in the manifold. As the diaphragm flexes, the resistance of the piezoelectric IC alters. We apply 5v to the IC and the voltage from it alters in proportion to the degree of flex on the diaphragm. The lower the pressure, the greater the flex the higher the resistance the lower the signal voltage the shorter the fuel injection duration required.

Digital type

The operation of this sensor is identical to the analogue type with one exception; the signal is converted into a digital signal within the sensor and supplied to the ECU as such (the analogue sensor's signal is converted to digital inside the ECU). Both types of sensor can be checked using a scope and a source of vacuum such as a Mityvac pump. The digital type can also be checked using frequency.

Temperature sensors

A material that experiences a change in resistance in proportion to a change in temperature acting upon it is referred to as a thermistor (thermal resistor). There are two

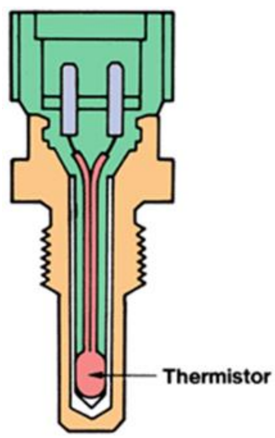


categories of thermistor-NTC (negative temperature coefficient) and PTC (positive temperature coefficient). Silicon is a good example of an NTC thermistor, and most metals are PTC. How an NTC thermistor behaves can be seen from the graph opposite.

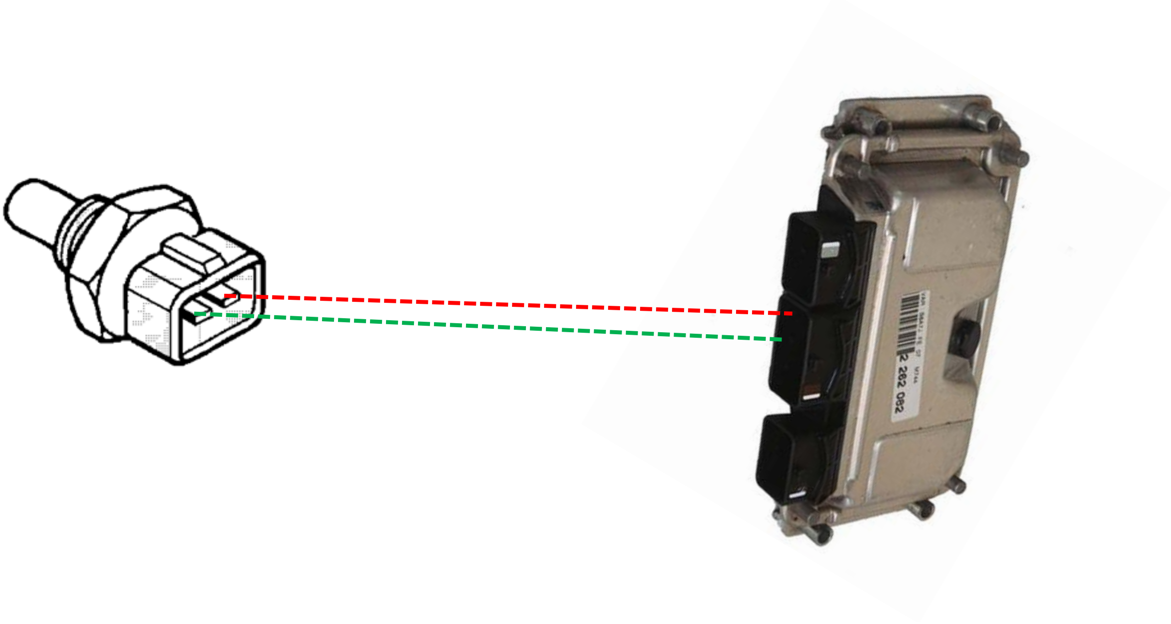
NTC = Sensor resistance decreases as the temperature increases

PTC = Sensor resistance increases as the temperature increases

NTC thermistors are commonly used to sense temperature, as they tend to experience a very large resistance change for a relatively small temperature change. This leads to greater accuracy.



The ECU applies 5 volts to the series circuit which consists of a fixed resistance (inside the ECU) and a variable resistance-our thermistor. If the engine temperature is low, the resistance of the sensor will be high (NTC) and therefore the sensor will have greater resistance influence on the circuit comparatively (that is compared to the fixed resistance). The voltage in between the two resistors will therefore be high. The ECU monitors the voltage at this point and compares its value to programmed temperature equivalents mapped to its memory. A high voltage means a cold engine and the injection duration will be long to compensate. As the temperature of the engine increases, the resistance of the sensor will reduce (NTC) and the fixed resistance will now have a greater effect on the voltage. The voltage in between the two resistors will now be lower. This is interpreted by the ECU as a higher engine temperature and the fuel injection duration will be reduced.



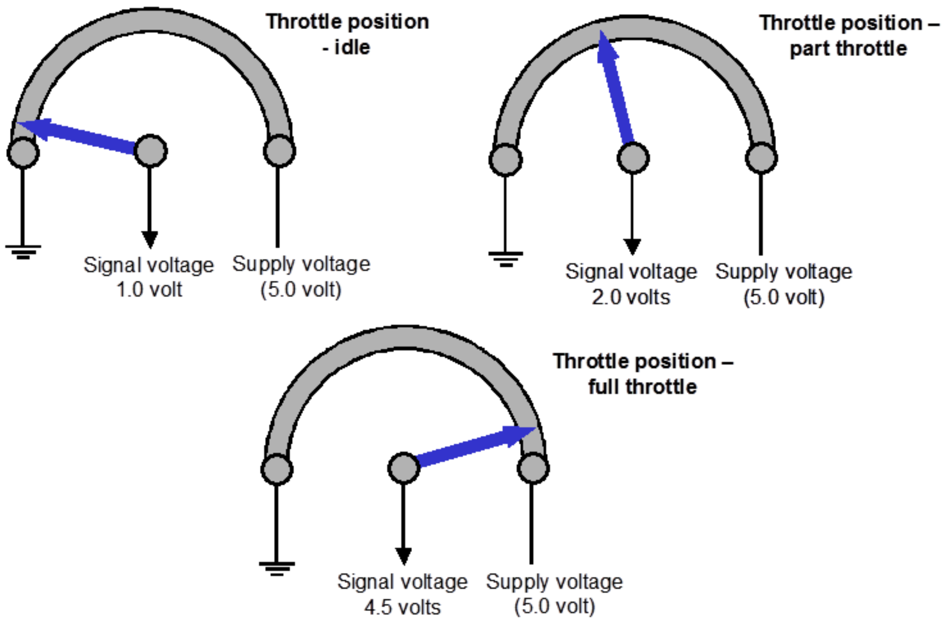
Why sense temperature?

An engine's temperature must be sensed due to the differing fuelling characteristics required of engines at different temperatures. This is because fuel tends to condense onto the inside of manifolds and onto the back of intake valves when the engine is cold. Therefore, the amount of fuel that reaches the cylinders is reduced. The ECU must compensate for this tendency by injecting more fuel (and vice versa).

The temperature of the air induced into the engine must also be sensed by the ECU as the density of the air will vary in accordance with this (very cold air is considerably more dense than hot air and therefore the cylinders are receiving more oxygen per intake stroke). More fuel required preventing lean running when the air is cold, less fuel required to prevent rich running when the air is hot.

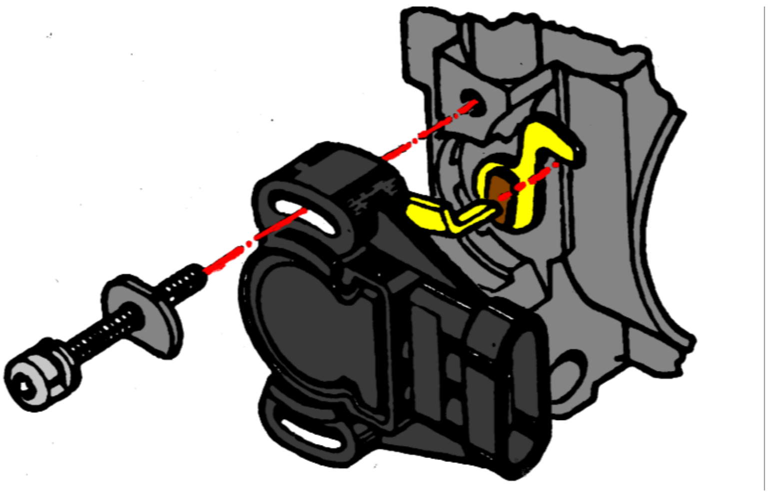
Throttle position sensor

The ECU needs to know the position of the throttle for one overriding reason – acceleration enrichment. When the driver presses hard on the accelerator pedal, the throttle opens fully. The air will increase in volume with very little delay, but the fuel being heavier is slower to react. This creates a momentary lean period, which often manifests as a flat spot (hesitation). You have seen that a carburettor overcomes this problem through the use of an accelerator pump. EFI has no such pump, only the injectors. The ECU senses that the driver has moved the throttle to the fully open position by monitoring the throttle position sensor. This enables the ECU to increase the quantity of fuel injected to prevent the generation of a flat spot.



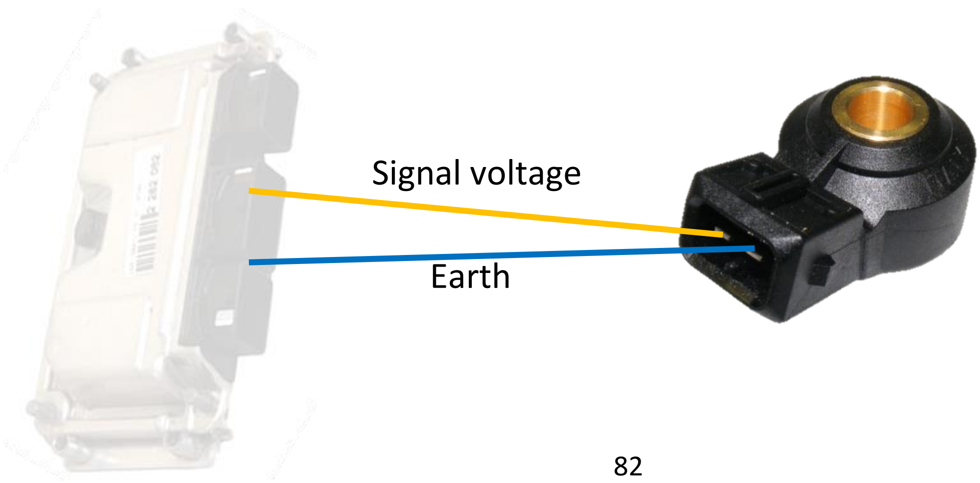
The diagram on the previous page shows the principle behind the throttle position sensor. The ECU applies 5v to the resistor track. The moving contact (in blue) effectively divides the resistor track into two resistors wired in series with one another. As the moving contact moves (it's connected to the throttle linkage) it will adopt a position that dictates the comparative length of the two resistors. If they are the same length, then the voltage will be half supply (2.5v) in the middle where the moving contact is. The moving contact is connected to the ECU via the harness and the ECU senses 2.5v. This it interprets as 50% throttle opening. All voltages sensed in between fully closed and fully open represent a known throttle angle to the ECU.

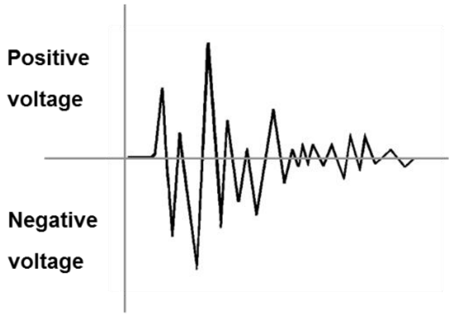
This type of sensor is often referred to as a 'potentiometer'. You have already seen this in use on the vane type airflow meter.



Knock sensing

A knock sensor is another example of a piezoelectric element being put to use on a modern engine (the other being the MAP sensor. Piezoelectric elements come in two main types: Those that experience a change in resistance and those that physically generate a voltage when deformed. The knock sensor is a good example of the latter category. When an engine starts to knock, the sensor vibrates and a high voltage is generated (this can vary between as much as 10v and as little as 1v dependent upon the manufacturer). This voltage indicates to the ECU that the engine is knocking and it will start to progressively retard the ignition timing. When the engine stops knocking, the knock sensor voltage will reduce to zero and the ECU will start to progressively re-advance the ignition timing until knocking is detected again. This type of closed loop control enables the ECU to keep the timing right on the threshold of knock therefore generating maximum power for minimum fuel consumption with low emissions.





Knock sensor signal

Actuators

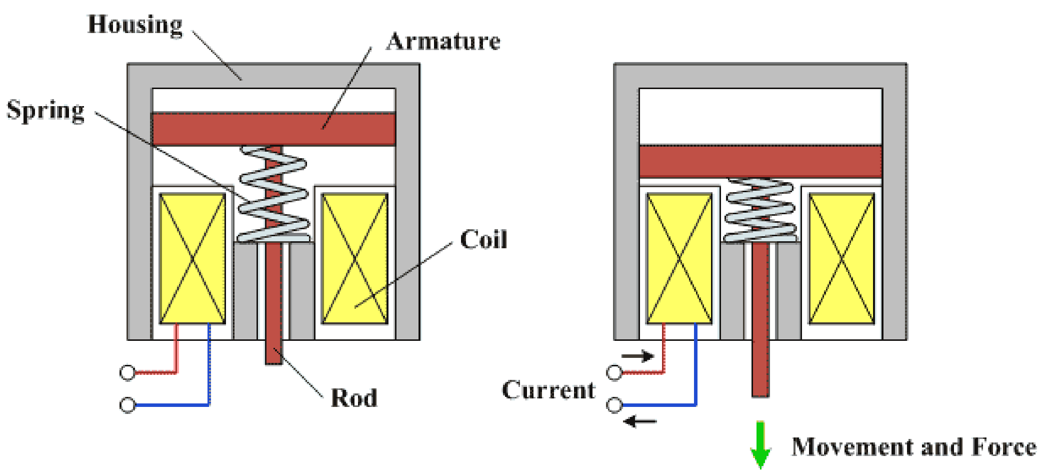
When the engine ECU receives its signals from the various sensors, the information can then be processed and a control signal generated in order to perform a task. The components that receive a control signal are referred to as actuators. The term actuator means to move and in the majority of cases this is true. There are control signals sent to actuators that have no movement such as, light bulb control or ignition control.

There are generally two types of mechanical actuators used:

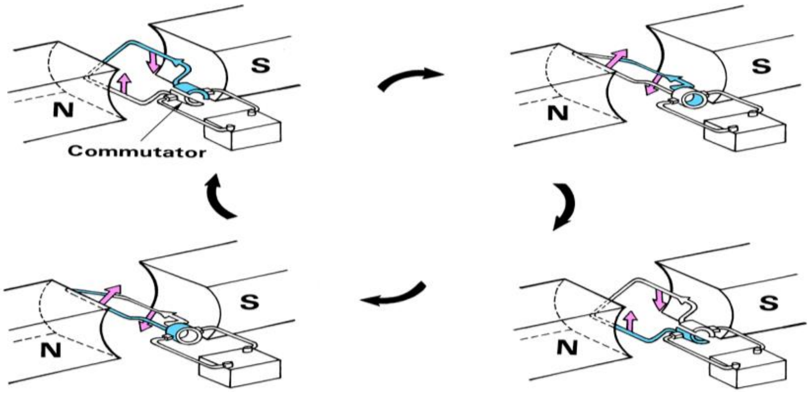
- Solenoid
- Electric motor

Solenoids

Solenoids are generally used to achieve some sort of linear movement. During operation, a current is passed through the coil of wire and a magnetic field is created. The field causes the plunger to be attracted to the coil and move towards it. When the current is switched off the plunger will then return to its original rest position.



Electric motors



A simple electric motor operates on similar principles to the solenoid, but instead of the magnetic field causing the plunger to move, the magnetic force causes the shaft to rotate.

Duty cycle/ pulse width modulation (PWM)

When something is switched ON and OFF repeatedly it is normally possible to compare these times in percentage terms. One complete cycle, from ON to OFF and ON again is 100%. The ON time is when the component is actually working or when it is “On duty”. If a component is switched ON (on duty) for the same time as it is switched OFF, it is said to have a duty cycle of 50%. A circuit which is ON for less time than it is OFF has a duty cycle of less than 50% and one which is ON for more time than it is OFF has a duty cycle of more than 50%. This type of signal can be used to control motors and solenoid valves very precisely. Some ‘oscilloscopes can calculate the duty cycle automatically but for those that do not, the following formula can be used:

$$\text{Duty cycle \%} = \frac{\text{On time}}{(\text{On time} + \text{Off time})} \text{ X } 100$$

Example:

On time 5ms

Off time 3ms

$$\frac{5}{(5 + 3) = 8} \text{ X } 100$$

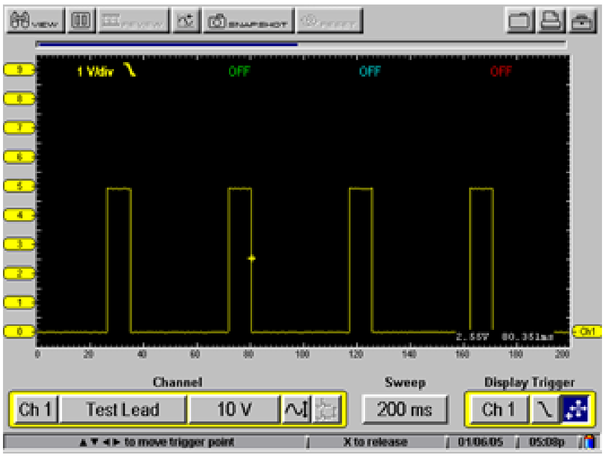
Duty cycle % = 62.5%

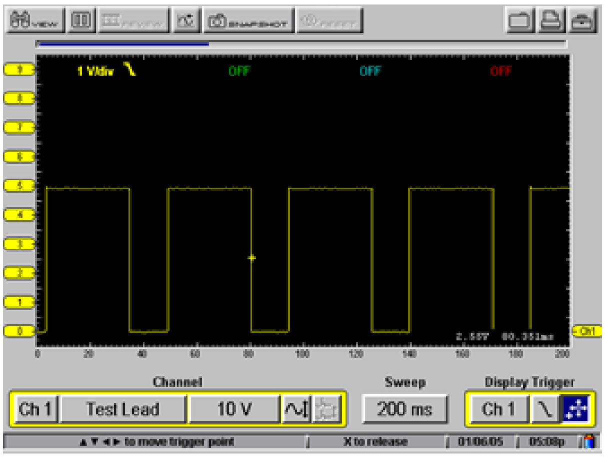
Average Voltage

The average voltage of a signal is related to its duty cycle/pulse width modulation and whether the circuit has a switched earth or switched supply.

Switched earth system - If the duty cycle is 50% the average voltage will be half the supply voltage. If the duty cycle is less than 50% then the average voltage will be more than half of the supply voltage. If the duty cycle is more than 50% the average voltage will be less than half the supply voltage.

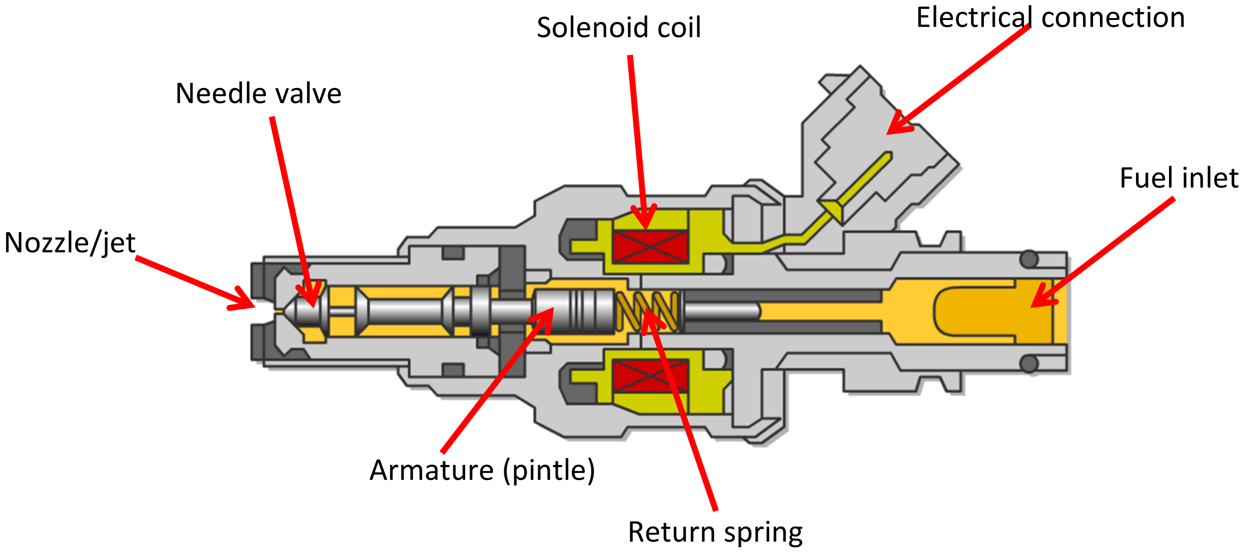
Switched supply system - If the duty cycle is 50% the average voltage will again be half the supply voltage. If the duty cycle is less than 50% then the average voltage will be less than half of the supply voltage. If the duty cycle is more than 50% the average voltage will be more than half the supply voltage.





For a positively switched circuit the example to the left would a low duty cycle value and the example to the right would be a high duty cycle

Fuel injectors



Fuel injectors are used to control the flow of fuel into the engine. The injectors of a multi-point fuel injection system are commonly located in the intake manifold and inject fuel into the individual region of the inlet valves.

The injector is a solenoid-operated valve. The injector requires a power supply and an earth connection in order to operate. Most systems will supply a constant power supply to the injector and switch the injector ON / OFF by switching the injector earth circuit, although there are a few systems which switch the power supply circuit. The injector is opened electromechanically and closed by spring pressure acting on the injector pintle.

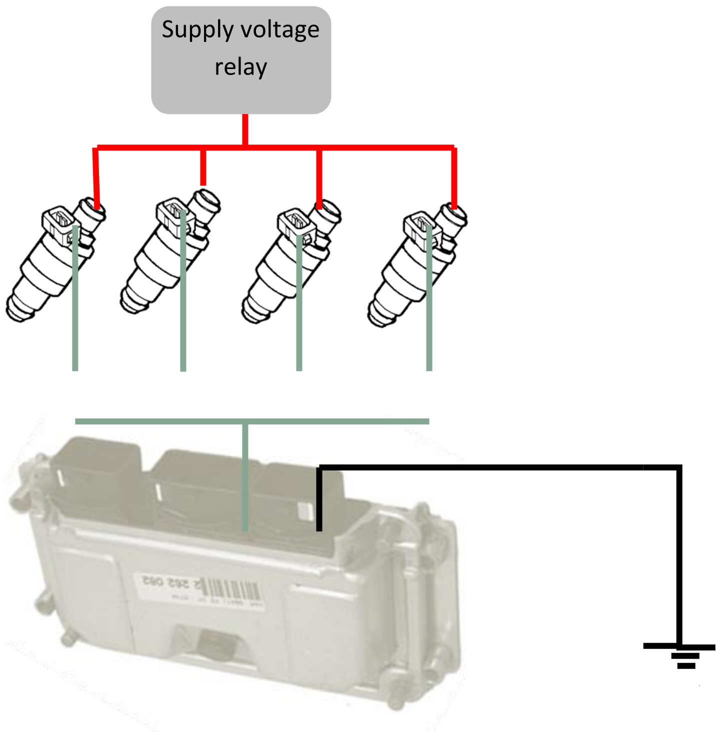
Injectors are commonly used with ether a high resistance of 13 - 18 Ohms or a lower resistance injector of 1.5 - 3.0 Ohms. A ballast resistor may be fitted in series with a low resistance injector. The resistor limits the current flow in the circuit when the circuit is switched on. Initially when the temperature of the circuit is low the ballast resistor resistance is low, when the resistor heats up, the resistor resistance becomes higher lowering the current flow. Later systems can normally limit the current flow through the injector circuit (also refer to injector signals).

A lower resistance injector will initially allow a higher electrical current flow through the injector circuit, which will allow the injector to open quicker. A lower resistance injector will also reduce the induced voltage generated during the injector operation. The reduction in EMF will allow the injector to open and close quicker giving precise fuel injection control.

Injector control

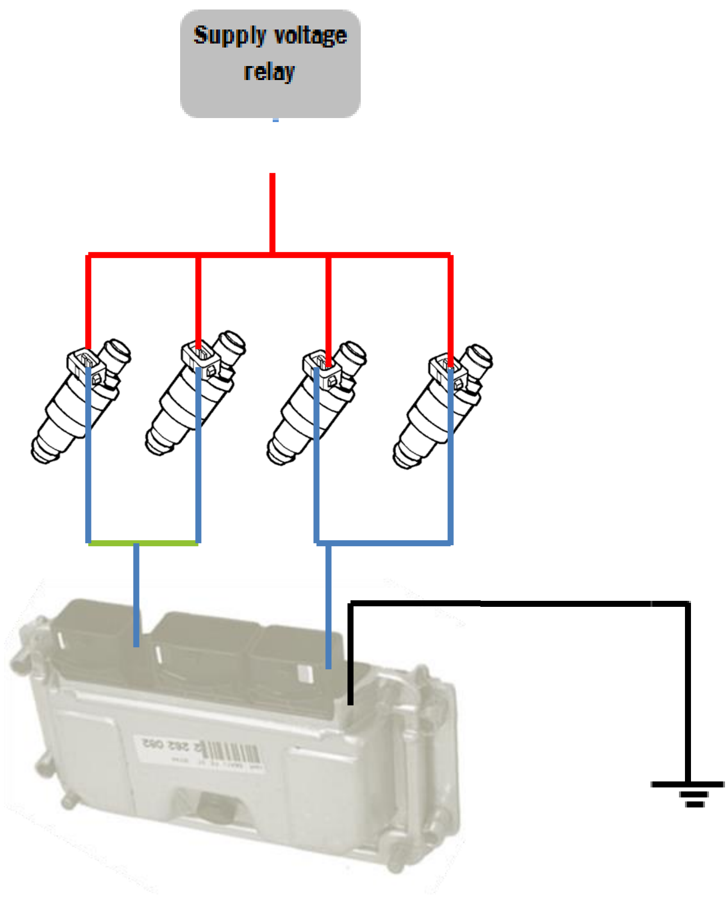
Simultaneous injection

The majority of injection systems produced during the 1980's were simultaneous systems. This is especially true of 4 cylinder engines. All 4 injectors are opened and closed at the same time. All four injectors are opened twice in every engine cycle i.e. twice for every two engine revolutions. The ECU will use ignition pulses as a reference or, if the ECU controls ignition, it will rely the master reference from the crankshaft position sensor and internal references. The disadvantage of this system is that fuel has to effectively wait for a short period of time before it can be drawn into the cylinder.



Grouped injection

Grouped injection is sometimes referred to as “semi sequential”. This method, when related to a 4 cylinder engine, provides injection operation in two groups of two injectors. The advantage is that it is possible to avoid injection when an inlet valve is open. The ECU must therefore have two power stages plus other components / circuits, in order to handle the two groups of injectors. The injectors only open once for each engine cycle. This method of injection was used on some Bosch systems.

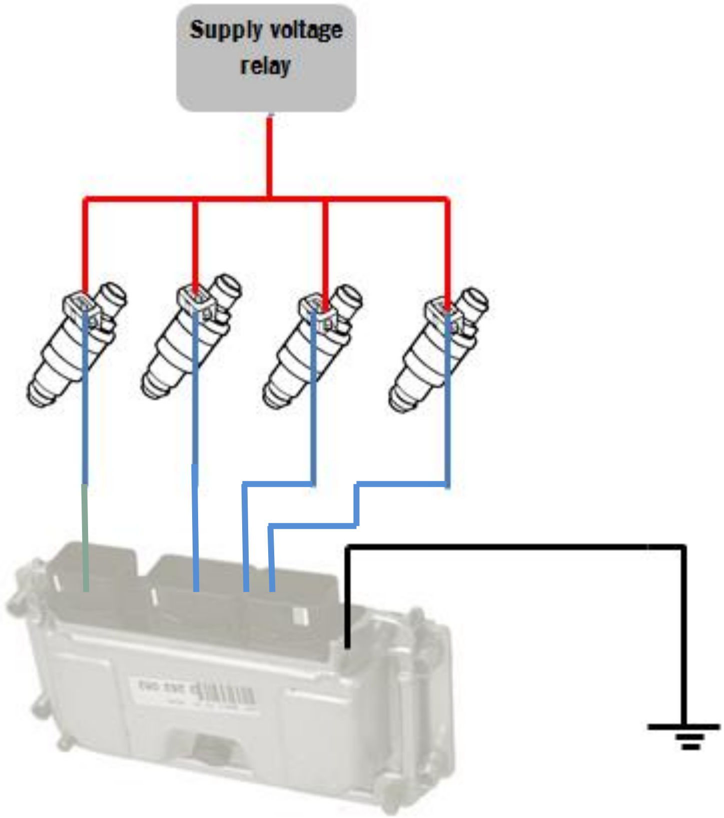


Sequential injection

Modern injection systems usually have individual control of the injector operation and can open in the correct sequence (firing order). The injectors typically inject fuel just as the intake valve is about to open.

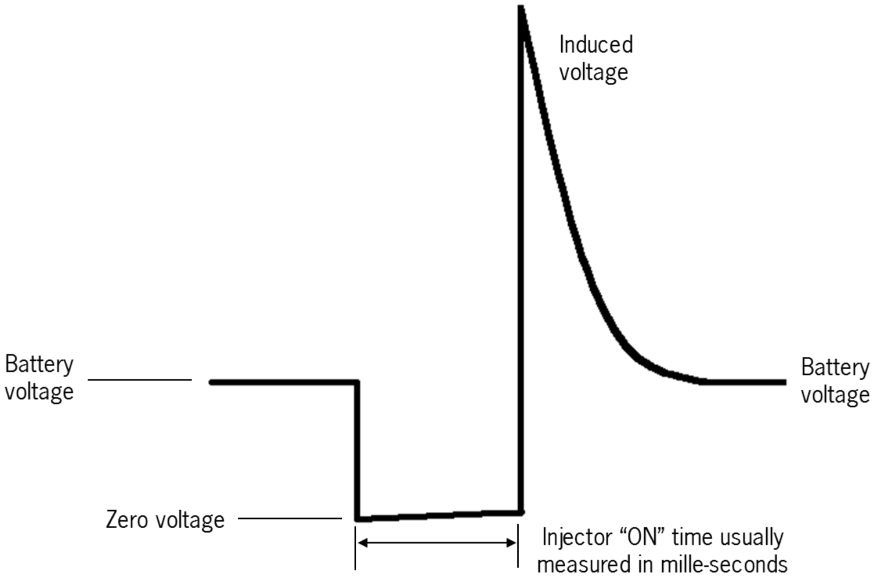
The ECU requires information on the engines exact position (firing order) in order to operate the sequential injector operation. The engine speed / position signal will only contain information on the crankshaft position, not the cylinder firing order. The cylinder recognition sensor signal provides the ECU information on the exact engine position and therefore the firing order of the engine. The ECU can therefore provide the injector control signal to the correct cylinder at the correct time.

If the cylinder recognition sensor signal is not available, the ECU will usually operate the injectors in a simultaneous mode.



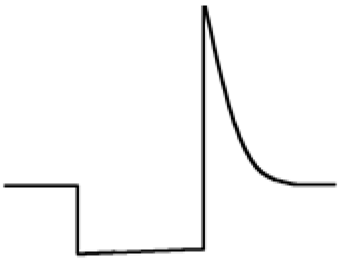
Injector control signal

An injector control signal waveform is shown above**.** When the injector is inoperative, the supply voltage is available. When the injector is operated, the supply voltage reduces to virtually zero volts. The earth circuit voltage may not reduce to completely zero, as the earth path will usually have a slight resistance. When the injector circuit is switched off, the voltage will rise. The period of when the injector opens until the period when the injector closes is referred to as the injection duration. Notice from the injector waveform, that the closure of the injector induces a high voltage into the circuit, typically 40 - 60 volts. The induced voltage can be used to diagnose dirty / sticking injector solenoids. The voltage will then reduce to the supply voltage again.

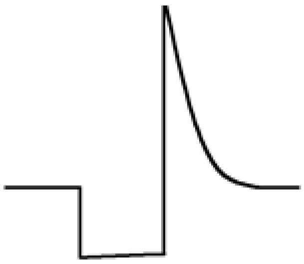


The control signal "ON" time (injection duration) will alter dependent on the ECM input signals – engine temperature / engine load / throttle position etc.

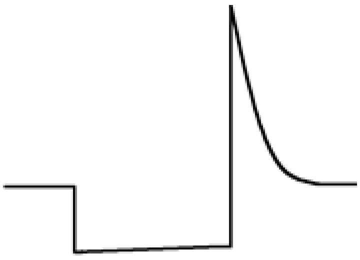
The length of the injection duration will depend on the ECU input signals. When the engine is cold, the engine requires more fuel and so the injector duration is long (approximately 7 - 15 milliseconds). As the engine warms up and therefore requires less fuel, the injection duration shortens. When the engine is at idle and at the correct operating temperature, the injection duration is typically 2.0 - 3.0 milliseconds. During high load (wide open throttle, acceleration) more fuel is required and the injection duration lengthens, dependant on the ECU input signals. During vehicle deceleration (overrun situations), fuel is not required and therefore under certain conditions (engine speed above 1500 rpm and the throttle closed) the injection duration will be very short or with some EFI systems, disappear completely (only the supply voltage is available). The waveforms and duration figures are only guidelines. They will differ for system to system and therefore always refer to vehicle specific information before checking any signals etc.



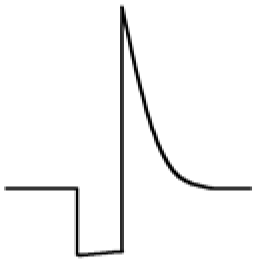
Engine cold – long injection duration



Engine at idle speed – short injection duration

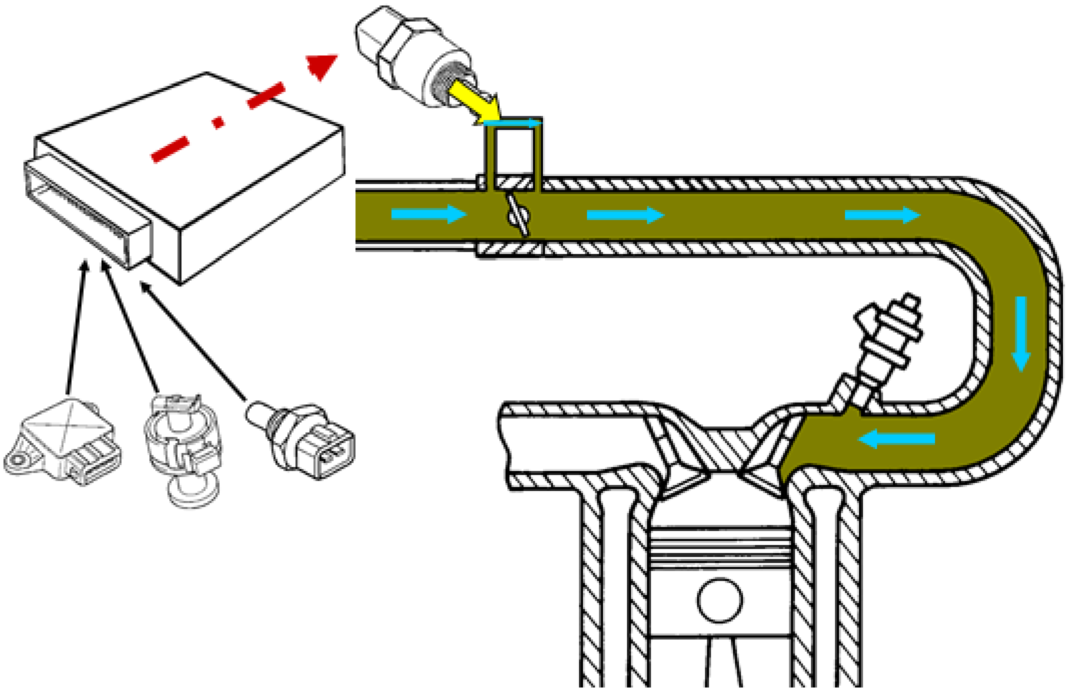


Engine under high load - long injection duration



Engine deceleration – very short injection duration

Idle speed control

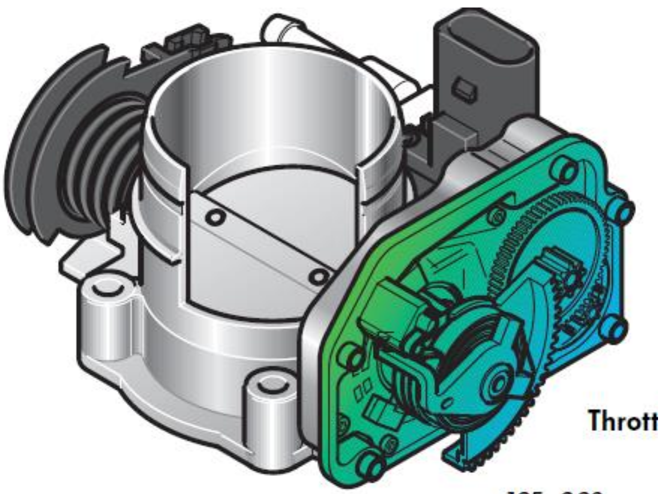


The diagram above shows the idle speed control valve altering the engine idle speed by varying the air bypassing the throttle butterfly. The ECU controls the position of the idle speed control valve. The ECU stores the engine idle speed information in its memory; this is often referred to as the engine idle target speed.

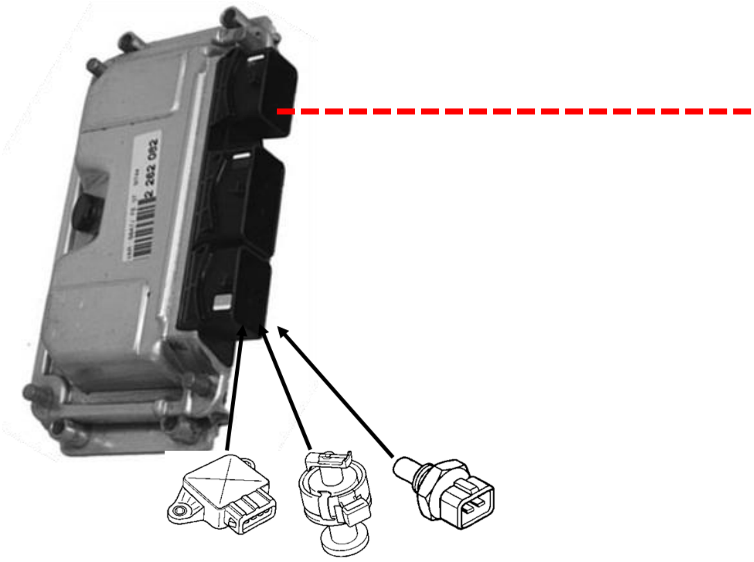
The ECU receives an engine speed sensor signal. When the throttle is in the idle position (the ECU receives an idle position signal from the throttle position sensor) the ECU controls the engine idle speed to the target speed. Note that the ECU may vary the target speed dependant on additional sensor signals i.e. engine temperature.

The idle speed control actuator illustrated is a rotary type idle speed control valve. The valve is supplied with battery voltage from the system relay. The ECU controls the position of the valve by switching the actuator earth circuit ON / OFF (similar to other actuators such as the injector). Most idle speed control actuators operate in a similar manner although the control signals will vary from system to system.

Most modern idle speed is controlled using a duty cycle/ PWM signal from the ECU to an idle control solenoid valve inside the throttle housing.



EGR control



One of the most effective ways of reducing NOx emissions is by reducing the combustion temperature. As mentioned earlier an EGR system passes a percentage of exhaust gas back into the combustion chamber where it mixes with the fresh charge entering the cylinder. It is possible to reintroduce approx. 10-15% of the exhaust gas back into the cylinder. This percentage has very little effect on fuel consumption and overall power, but is sufficient enough to have an effect on lowering the combustion temperature. In general, EGR is only operated during part/medium load conditions but not when the engine is at idle or at full throttle.

It can be seen from the diagram above that the ECU controls the EGR valve. The ECU decides when it is acceptable to recirculate (not when the driver is demanding power) and also when Nox is most likely. At this point it controls the lifting of the valve through the use of a duty cycle/PWM signal and solenoid.

Diagnosis

Overview of EOBD (European onboard diagnostics)

The visible elements of EOBD are the self-diagnosis fault warning lamp and the diagnosis interface (16 pin diagnostic link) in the cabin. The engine control unit performs all other functions and diagnostic operations automatically. The driver does not notice the on- going checks on the systems in his vehicle which are relevant to exhaust emissions. This means that not much changes for the driver of a vehicle with EOBD, however service personnel will be required to familiarise themselves with new automotive technologies and the associated procedures.

Malfunction indicator light (MIL)

If a fault impairing exhaust gas quality occurs on board the vehicle, the fault is saved to the fault memory and the self-diagnosis fault warning lamp is activated. If there is a risk of catalyst damage due to misfiring, the self-diagnosis fault warning lamp flashes.

Diagnostic interface

Stored EOBD data can be read out via the diagnosis interface. The fault codes are standardised so that data can be acquired using any Generic Scan Tool (OBD visual display unit). The diagnosis interface must be within easy reach of the driver's seat.

EOBD checks:

- The electrical functions of all components which are important for exhaust gas quality.
- The functioning of all vehicle systems which have a bearing on exhaust gas quality (e.g. lambda probes, secondary air system).
- The functioning of the catalyst.
- For misfiring.
- The CAN data bus.

- Operation of the automatic transmission (if fitted)

Comprehensive Components Monitoring (Line-conducted faults)

This diagnostic routine monitors the functioning of all sensors, actuators and output stages that are relevant to exhaust emissions within the framework of the EOBD.

Components are tested according to the following criteria:

- Check of input and output signals (plausibility)
- Short circuit to earth
- Short circuit to positive
- Open circuit

Lambda probe

Voltage curve shift diagnosis and adaption of the probe before the catalyst ageing or poisoning can cause a shift in the voltage curve of the probe before the catalyst. This shift is detected by the engine control unit and can be compensated (adapted) within defined bounds. The diagnosis sequence is basically the same despite the new broadband lambda probe.

Lambda probe heater diagnosis

By measuring the probe heating resistance, the engine control unit checks the heat output of the lambda probe heater for correctness.

Fuel tank purging system Flow rate diagnosis

When the fuel tank purging system is activated, the fuel/air mixture changes. If the activated charcoal canister is full, the mixture will be rich. If the activated charcoal canister is empty, the mixture will be lean. This change of mixture composition is registered by the probe before the catalyst and serves as confirmation that the fuel tank purging system is functioning properly.

Cylinder-selective misfiring detection system Irregular running method

The engine speed sender can recognise irregularities in engine speed caused by misfiring with the aid of the crank disk. In combination with the signal from the Hall sender (camshaft position), the engine control unit can locate the cylinder in question, save the fault to fault memory and activate self -diagnosis fault warning lamp

Electrical exhaust gas recirculation Pressure diagnosis

While exhaust gas is admitted into the intake manifold, the intake manifold pressure sender must register a rise in pressure (less partial pressure). The engine control unit compares the pressure rise in the intake manifold with the supplied exhaust gas quantity and can thus determine whether the exhaust gas recirculation (EGR) system is functioning properly. This diagnosis is only carried out in overrun mode, because injection is deactivated as a disturbing influence for measurement and the intake capacity of the engine is very high.

Electric throttle drive

The EOBD uses the electrical throttle control diagnostic functions which indicate a fault via the electric throttle control fault lamp. If these faults still exist during the next one or two driving cycles, the EOBD also activates the exhaust gas warning lamp.

The electric throttle drive checks:

- the function processor in the engine control unit
- the accelerator position sender
- the angle senders for throttle valve drive
- the brake light switch
- the brake and clutch pedal switch
- the vehicle road speed signal

CAN data bus Data diagnosis

Each engine control unit knows the electronic components which exchange information via the CAN data bus in the vehicle. If the minimum number of messages is not received from a component, a fault is detected and saved.

Further components which the CAN data bus uses include:

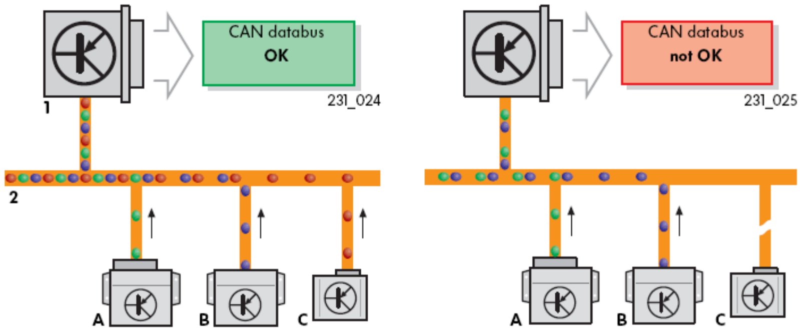
- Control unit with display unit in the dash panel insert
- ABS control unit/ESP
- Automatic gearbox control unit

CAN data bus in proper service condition

All connected components (in this case: control units) regularly transmit messages to the engine control unit. The engine control unit recognises that no messages are missing and data is being exchanged properly.

CAN data bus interrupted

A component cannot transmit information to the engine control unit. The engine control unit notices the missing information, identifies the component affected and saves a corresponding fault message to fault memory.



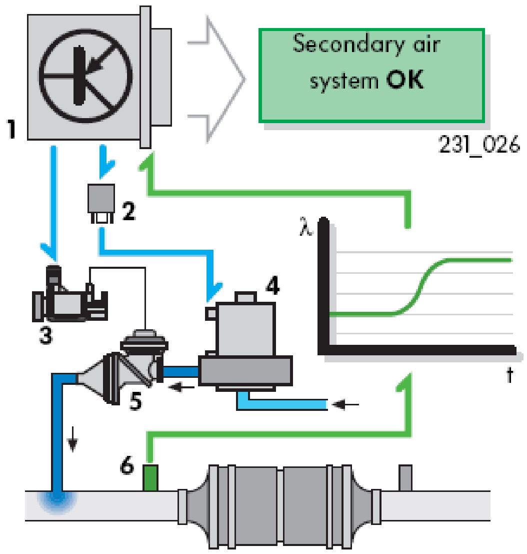
1 Engine control unit
2 CAN databus
A-C Various control units on board the vehicle

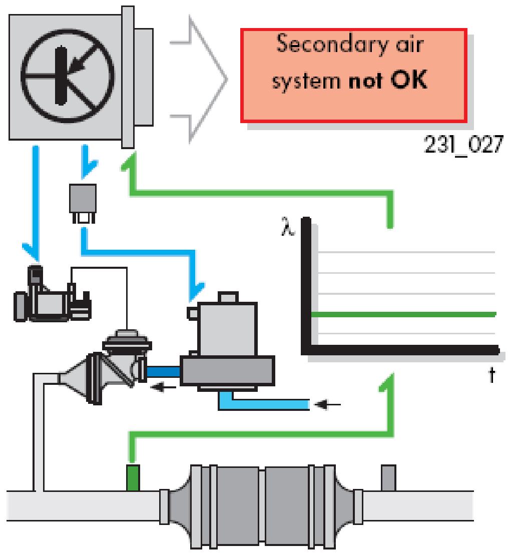
Secondary air system

The performance of the secondary air system was previously tested via the lambda control value.
This means that the voltage present at the probe before the catalyst must indicate a lean mixture during secondary air discharge (□>1) although the engine control unit is running the engine on a rich mixture.

Flow rate diagnosis

Since the introduction of the broadband lambda probe, the signal from the probe before the catalyst is used for diagnosis purposes, because the broadband lambda probe supplies more detailed measurement results than the step type lambda probe for example. The actual air mass flow is calculated and checked on the basis of the lambda differential (lambda value before and during secondary air discharge).





λ = lambda, t = time

1 Engine control unit
2 Secondary air pump relay J299
3 Secondary air inlet valve N112
4 Secondary air pump V101
5 Combi valve
6 Probe before catalyst

Charge pressure control

Charge pressure limits diagnosis

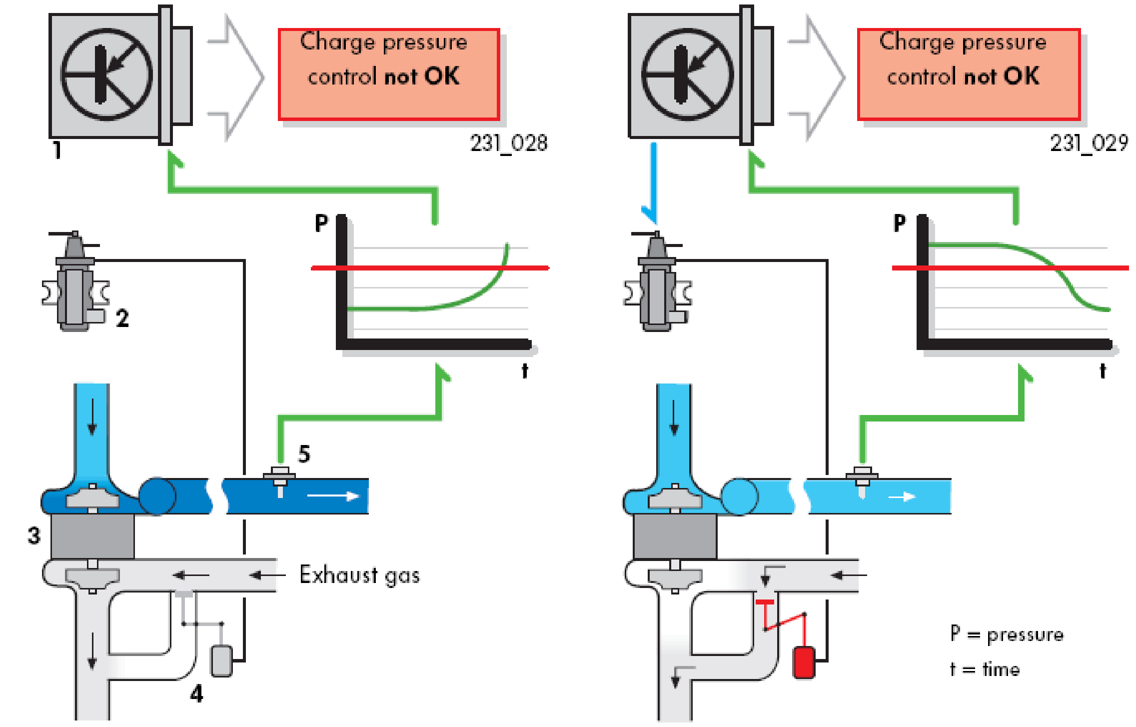
In turbocharged engines, charge pressure is checked for exceeding the maximum permissible value within the framework of the EOBD. The check also serves to protect the engine, which must not be overloaded by excessively high charge pressure.

The charge pressure limit is exceeded

The maximum permissible charge pressure is exceeded due to a fault in the charge pressure control. The intake manifold pressure sender signals the presence of charge pressure to the engine control unit, and the engine control unit detects the fault.

The protective function is initiated

In this case, it is not enough to indicate and save the fault. The exhaust gas turbocharger has to be deactivated in order to avoid damaging the engine. For this purpose, the "waste gate" of the turbocharger is opened and the driving exhaust gases are diverted through it.



1 Engine control unit
2 Solenoid valve for charge pressure control N75
3 Exhaust gas turbocharger with charge pressure control valve
4 Waste gate
5 Intake manifold pressure sender G71

Generic Scan Tool (OBD visual display unit)

It must be possible to read out emission-related faults and data acquired by the engine control unit within the framework of the EOBD using any OBD visual display unit. Therefore, the detected faults are saved using an SAE code. This SAE code is used by all OBD systems.

SAE code:

- P0xxx: Codes with set fault texts defined by the SAE (Society of Automotive Engineers) (same for all automobile manufacturers)

- P1xxx: Codes defined by automobile manufacturers which are required to be reported to the government (these codes are defined differently for different automobile manufacturers)

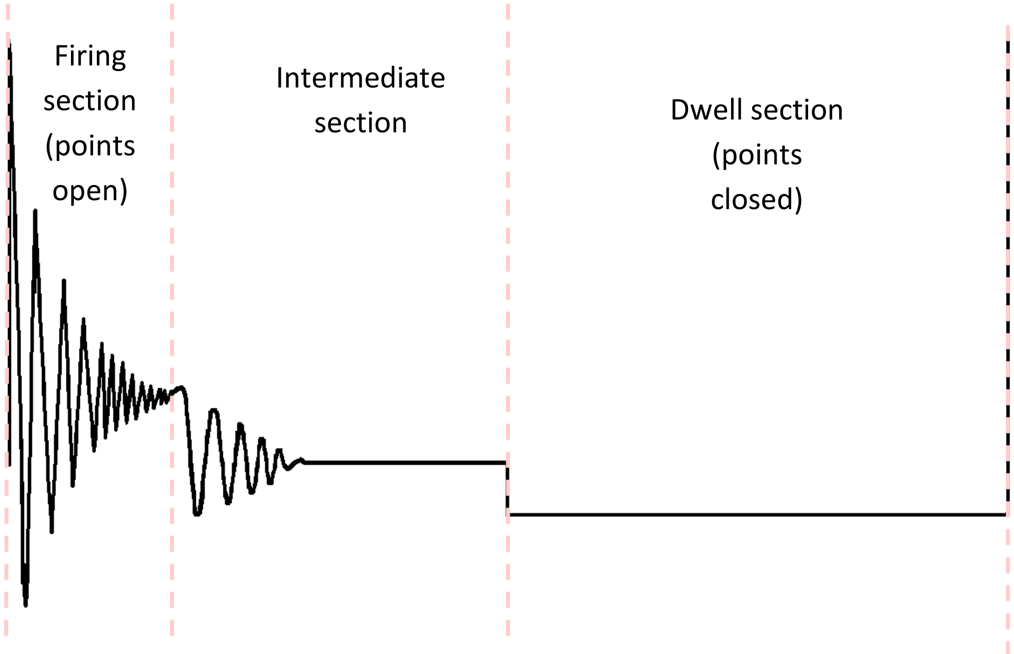
Ignition systems

The ignition system is needed to deliver a strong spark that will ignite the air fuel mixture within the combustion chamber. For the engine to run effectively three elements are needed.

- A good air fuel mixture
- High compression pressure
- Strong spark and correct ignition timing.

Due to the high compression pressure that is generated within the combustion chamber, the spark that is delivered needs to be strong enough to ignite the air fuel mixture. For this reason, the ignition system must deliver an appropriate voltage to the spark plug to allow this process to take place. The point at which the spark is delivered must also be adjusted to take into account engine rpm and load. This means the relationship between crankshaft angle and the spark plug firing is constantly changing. In order for the engine to run, the spark must be delivered at the correct time in the compression stroke for each of the pistons. For this reason, the ignition system needs to be reliable and able to operate under all engine conditions.

The primary waveform



The primary wave pattern is important when diagnosing problems on older ignition systems. It can be split into three sections:

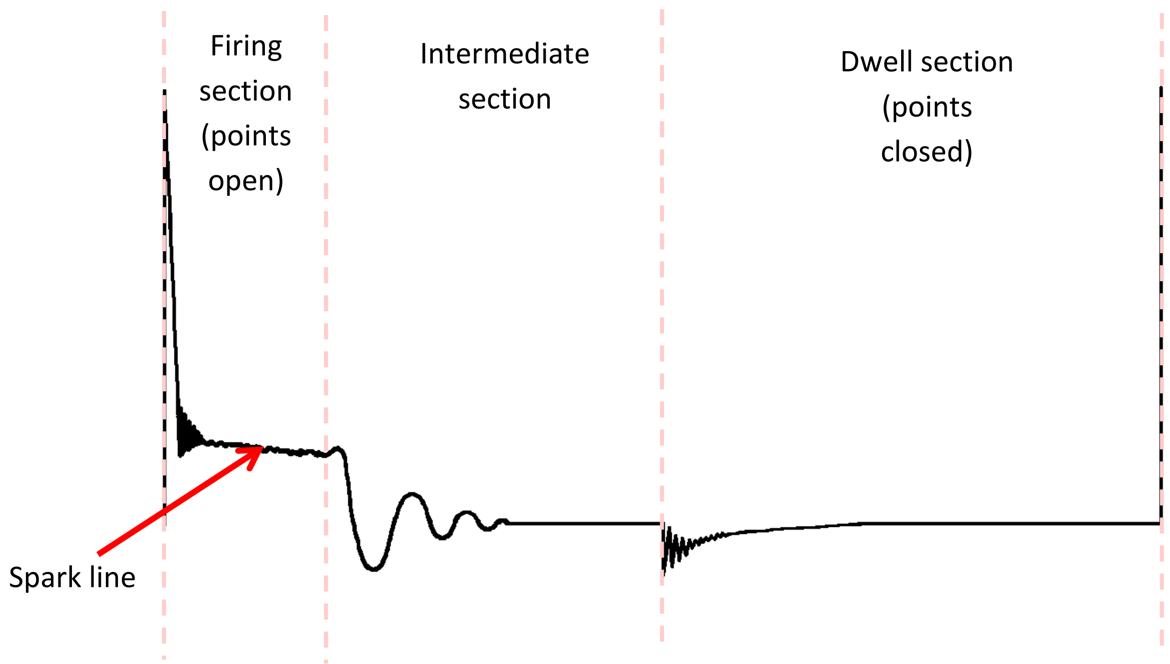
- Firing section
- Intermediate section
- Dwell section

The firing section shows the induced (back E.M.F.) voltage in the primary winding and may be as high as 200 volts. The oscillations are caused by coil energy being used up, jumping the spark plug gap. They reduce in size until enough stable energy is left to maintain the spark across the gap (primary spark line, at about 40 volts).

The intermediate section shows remaining coil energy being used up and oscillating away, due to interaction between the coil and the condenser (capacitor). There should be at least
four oscillations in a correctly functioning circuit.

The dwells section, or period, is the length of time that the contact breakers (or transistor switch) are closed, and the primary winding of the coil is energized. Current flow (therefore, magnetic field build up) is limited by the resistance of the primary winding, the closing and bouncing of the contact breakers and the dwell period determined by the distributor cam.

The secondary waveform



The firing section shows the firing line. High voltage produced by the coil to jump the spark plug (and rotor arm) gaps. The line should be vertical and for a contact breaker ignition system range from 5 to 15 kV (7 to 25kV for electronic ignition).

The spark line represents the voltage required to maintain the spark across the spark plug gap, after the spark has started. It should be a horizontal line that is approximately 25% of the height of the firing line. The length of this line is known as the duration of the spark. The length of the spark line and the height of the firing line are related (ratio) to the amount of available coil energy. When the firing line is high, the spark line shortens. When the firing line is low, the spark line lengthens.

Pre-ignition

Pre-ignition is a condition whereby combustion is initiated within the combustion chamber before the spark occurs at the plug. This results in uncontrolled ignition and combustion conditions.

If a spark plug operates at a temperature in excess of 1000 degrees Celsius for a prolonged period the electrodes can start to overheat. When excessively overheated, pre-ignition can occur, the electrodes and insulator tip may melt and piston damage may result.

Pre-ignition is usually caused by a temperature exceeding
850 degrees Celsius – 1000 degrees Celsius (1600 degrees Fahrenheit – 1800 degrees Fahrenheit)

Causes of overheating

- Over-advanced ignition timing
- Too lean fuel mixture
- Excessive deposits accumulated in combustion chamber
- Insufficient cooling
- Insufficient spark plug tightening or failure to fit gasket
- Too low octane gasoline
- Too hot a spark plug fitted

Overheated

The plug has been subjected to a relatively heavy load and evidence of overheating can be seen in the oxidized electrodes and melted deposits which have formed on the insulator surface.

Recommendation

Check for over-advanced ignition timing and too lean fuel mixture. Check spark plug tightening and gasket. If conditions recur, use plug one step colder in heat range.

Melted

Overheated plug with melted electrodes and blistered ceramic insulator surface.

Recommendation

Check for over-advanced ignition timing and too lean fuel mixture. Check spark plug tightening and gasket. If conditions recur, use plug one step colder in heat range.

Worn Spark Plug

A worn spark plug not only wastes fuel but also loads the whole ignition system because the expanded gap requires higher voltage.

As a result, a worn spark plug may also cause engine damage and increased exhaust emissions.

Recommendation

Spark plugs should be replaced.

Deposits

The accumulation of deposits on the firing end is influenced by oil leakage, fuel quality and engine operating period.

Recommendation

Check for excessive amounts of lubricating oil entering into the combustion chamber. High quality oil should be used.

Detonation

Detonation is the spontaneous combustion of the end-gas (remaining fuel/air mixture) in the chamber. It always occurs after normal combustion is initiated by the spark plug. The initial combustion at the spark plug is followed by a normal combustion burn. For some reason, likely heat and pressure, the end gas in the chamber spontaneously combusts. The key point here is that detonation occurs after you have initiated the normal combustion with the spark plug.

Unburned end gas, under increasing pressure and heat (from the normal progressive burning process and hot combustion chamber metals) spontaneously combusts, ignited solely by the intense heat and pressure. The remaining fuel in the end gas simply lacks sufficient octane rating to withstand this combination of heat and pressure.

Detonation causes a very high, very sharp pressure spike in the combustion chamber but it is of a very short duration. If you look at a pressure trace of the combustion chamber process, you would see the normal burn as a normal pressure rise, then all of a sudden you would see a very sharp spike when the detonation occurred. That spike always occurs after the spark plug fires. The sharp spike in pressure creates a force in the combustion chamber. It causes the structure of the engine to ring, or resonate, much as if it were hit by a hammer. Resonance, which is characteristic of combustion detonation, occurs at about 6400 Hertz. So the pinging you hear is actually the structure of the engine reacting to the pressure spikes. This noise of detonation is commonly called spark knock. This noise changes only slightly between iron and aluminum. This noise or vibration is what a knock sensor picks up. The knock sensors are tuned to 6400 hertz and they will pick up that spark knock. Incidentally, the knocking or pinging sound is not the result of "two flame fronts meeting" as is often stated. Although this clash does generate a spike the noise you sense comes from the vibration of the engine structure reacting to the pressure spike.

One thing to understand is that detonation is not necessarily destructive. Many engines run under light levels of detonation, even moderate levels. Some engines can sustain very long periods of heavy detonation without incurring any damage. If you've driven a car that has a lot of spark advance on the freeway, you'll hear it pinging. It can run that way for thousands and thousands of miles. Detonation is not necessarily destructive. It's not an optimum situation but it is not a guaranteed instant failure. The higher the specific output (HP/in3) of the engine, the greater the sensitivity to detonation. An engine that is making 0.5 HP/in3 or less can sustain moderate levels of detonation without any damage; but an engine that is making 1.5 HP/in3, if it detonates, it will probably be damaged fairly quickly.

Detonation causes three types of failure:

1. Mechanical damage (broken ring lands)

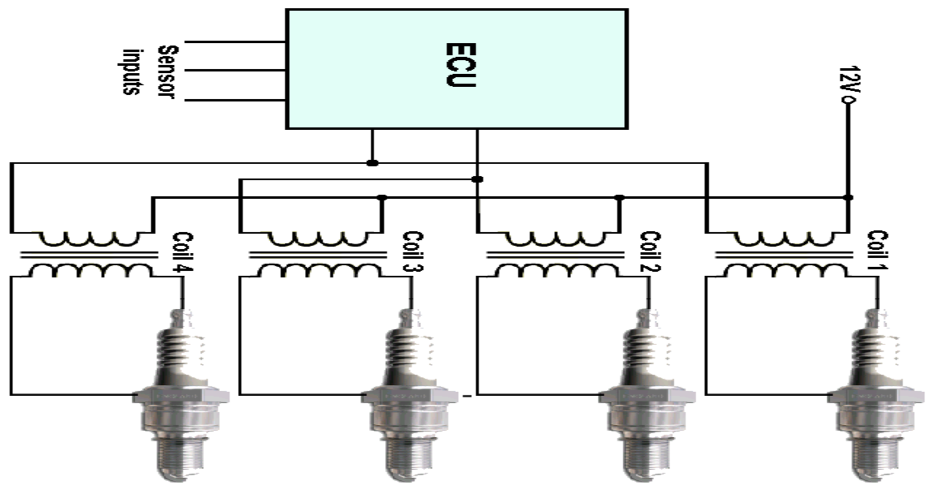
2. Abrasion (pitting of the piston crown)

3. Overheating (scuffed piston skirts due to excess heat input or high coolant temperatures)

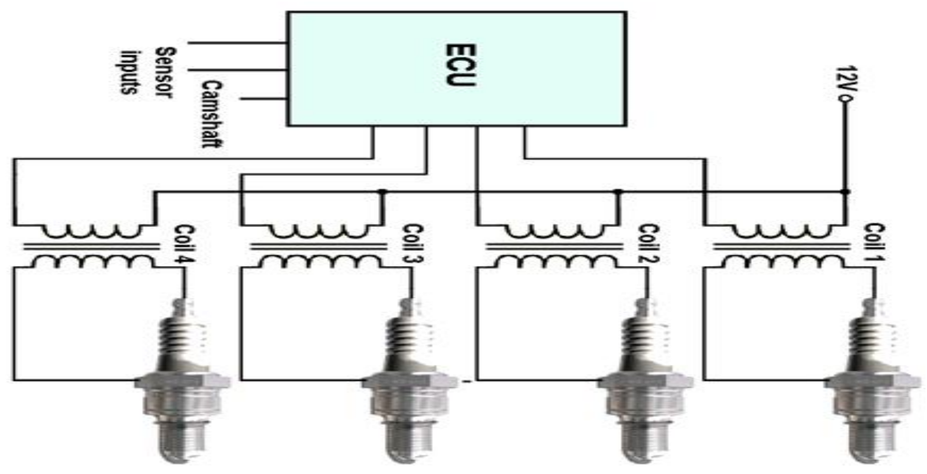
The high impact nature of the spike can cause fractures; it can break the spark plug electrodes, the porcelain around the plug, cause a clean fracture of the ring land and can actually cause fracture of valves-intake or exhaust. The piston ring land, either top or second depending on the piston design, is susceptible to fracture type failures. If I were to look at a piston with a second broken ring land, my immediate suspicion would be detonation.

Direct Ignition systems

The direct ignition system shown below is wired so that two coils are switched by one ECU output. The system functions using the 'waste spark' principle. This means that the ECU can control ignition timing using **crankshaft** and other sensor information

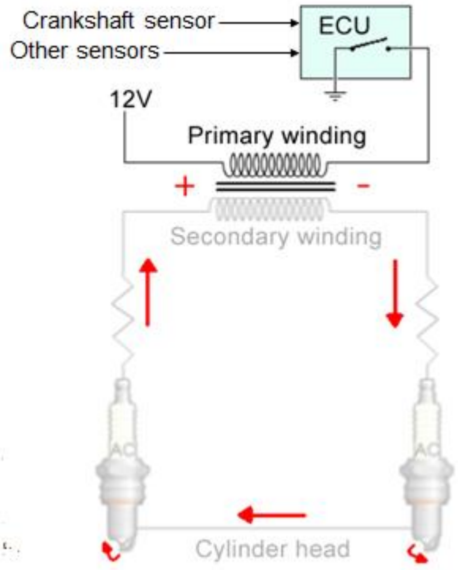


The direct ignition system shown below is wired so that coils are switched by individual ECU outputs. This means that the ECU has to know the position of cylinder 1, when it is on the compression stroke. It controls ignition timing using



camshaft, crankshaft and other sensor information.

DIS Primary Circuit



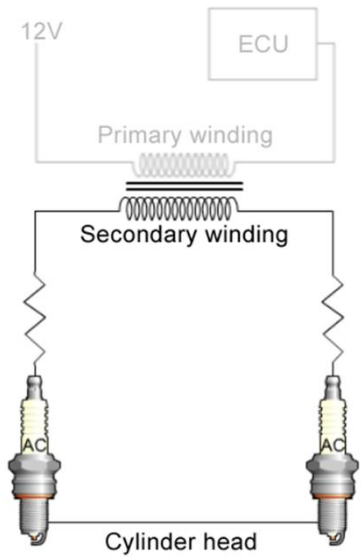
The primary winding is connected between 12 volts and an ECU output.

When an ECU output is turned on, current flows in the primary winding and the coil's magnetic field builds up.

When a spark is required, the ECU's output is turned off and the collapsing magnetic field produces a very high secondary voltage across both spark plugs.

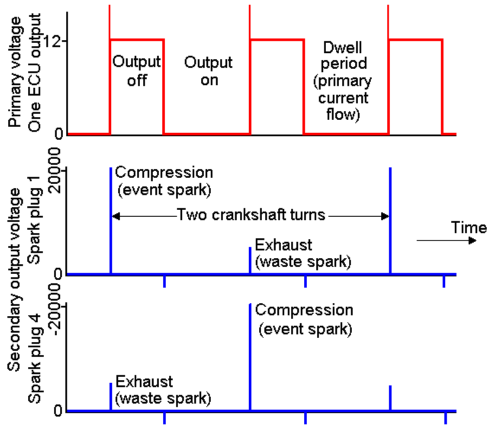
Because the ECU fires both plugs, this system does not need a method of determining which plug should be fired (distributor cap and rotor function). It just needs to know 'when' (crank sensor).

DIS Secondary Circuit



A spark plug is attached to each end of an ignition coil secondary. The two plugs are in companion cylinders that are cylinders whose pistons reach Top Dead Centre (TDC) at the same time, but on different strokes. The cylinder on the compression stroke is referred to, as the "event" cylinder while the cylinder on the exhaust stroke is the "waste" cylinder.

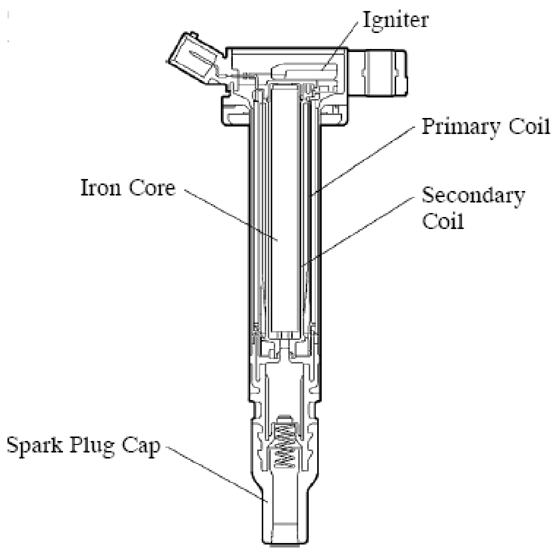
The cylinder head between the spark plugs is used as a conductor and completes the secondary circuit. The primary and secondary coil windings are not connected.



The diagram shows the relationship between the primary and secondary voltages for one coil.

Typically, the event spark will reach at least 20,000 volts.

Typically, the waste spark will reach 1000 volts.



Ignition Coil Cross Section

Effects in the event of failure

If a single-spark ignition coil fails, this is detected by the misfiring detection system. The corresponding injector is then no longer actuated.