# Combustion and EGR

In this first part of a series, the Institute of the Motor Industry (IMI) looks at the combustion process and emissions in petrol and diesel engines, the reasons behind the need for exhaust gas recirculation (EGR), EGR operation and what happens when things go wrong.

### Petrol engine combustion

A four-stroke petrol engine, running on ordinary petrol, will operate at its most efficient with an air/fuel ratio of 14.7:1 (14.7 kgs of air for every 1 kg of fuel). At this precise ratio, all of the fuel will be burnt and all of the oxygen in the air will be burnt, leaving nothing left to form unwanted emissions. This ratio is referred to as stoichiometric, a term borrowed from chemistry. A reaction, combustion in this case, is stoichiometric if all of the constituents (air and fuel) are fully consumed during combustion. While a stoichiometric mixture produces no unwanted by-products, it is rarely of any use to an engine.

### Inefficiency

The average 4-stroke petrol engine is less than 25% efficient. This means that for every four litres of fuel that you put in, less than one litre turns the flywheel! This inefficiency is mainly due to heat loss. 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). The great majority, more than 75% of this energy escapes through the exhaust pipe, into the cooling system, heating the engine etc. The theoretical maximum effeciency that a combustion engine could ever acheive, in a completly useless laboratory configuration, is only 37%.

Another area of inefficiency is in the mixing of the fuel and air. Oxygen is the only constituent gas in air that supports combustion, and it accounts for only 21% of air. So only one fifth of all the air drawn into the engine during the induction stroke is of any use.

The ideal is to ensure that the particles of fuel are mixed thouroughly with the air, to make best possible use of all of the oxygen. If some of the oxygen doesn't burn, the effeciency of the engine drops. There are numerous ways to ensure that thorough mixing does take place, but they can all be related to two techniques: creating turbulence (or swirl) in the induced air or introducing the fuel as a finely atomised (a very fine mist of microscopic droplets) state as possible.

### Emission gasses

Under perfect conditions, when petrol is burnt in air at a mixture strength of 14.7:1, nitrogen (N2), carbon dioxide (CO2) and water (H2O) are the only gasses produced.

In reality, an engine also produces the following gases, most of which are undesirable for many reasons:

- carbon monoxide (CO)
- hydrocarbons (HC)
- oxygen (O2)
- carbon dioxide (CO2)
- Oxides of nitrogen (Nox).

CO is produced by incomplete combustion of the fuel, which can be caused by poor mixing of the fuel and air at the time of combustion. This is a particular problem when the engine is cold and temperatures around the cylinder walls are low, which leads to "quenching" (figure 3). Quenching occurs when the relatively colder surfaces in the combustion chamber allows fuel to condense on the cylinder walls, just as steam will condense on a cooler surface. Fuel left unburnt in these quenching zones is then exhausted during the exhaust cycle as HC.

A rich mixture (excessive fuel or insufficient air) can also contribute to the production of CO. This happens when there is not enough oxygen to combine with the fuel during the combustion process.

A lean mixture (excessive air or insufficient fuel) burns slowly and the metal in the combustion chamber is exposed to the burning gas for longer and will absorb more heat, which can cause the engine to overheat. Excessively lean mixtures will extinguish as the piston moves down, causing a rise in HCs.

Carbon dioxide is the byproduct of complete combustion and peaks at or near stoichiometric ratios. (See figure 2).

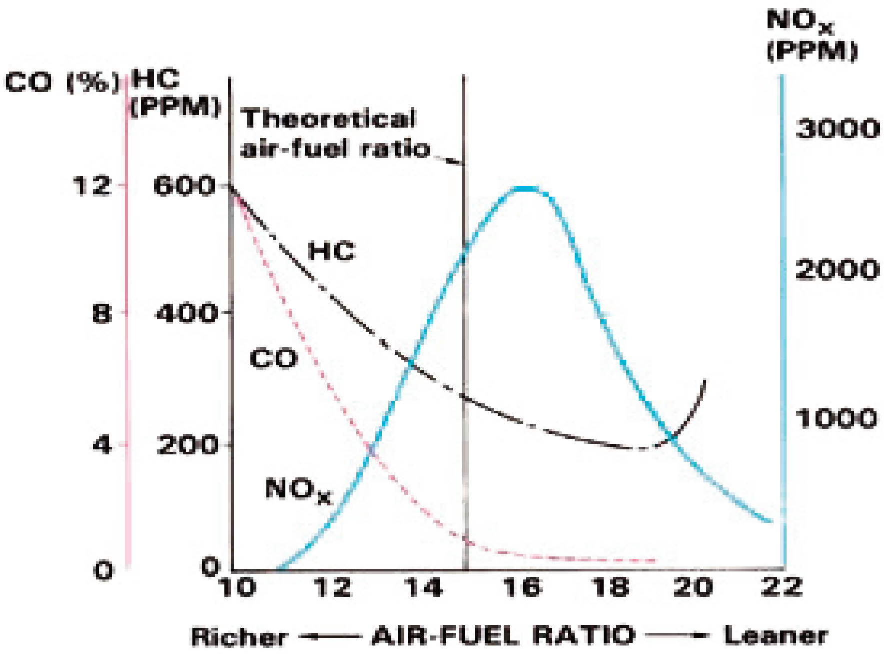


**Figure 2 The effect of air-fuel ratio and CO (red line), HC (black line) and NOx (blue line)**

### Hydrocarbons

HC is raw, unburnt petrol emitted from the engine. It comes from the following sources:

- raw blow-by of gas caused by overlapping of intake and exhaust valve timing (figure 5).
- raw gas remaining near the walls of the cylinder after burning, and exhausted during the exhaust cycle quenching zones (see figure 3).
- Low compression during coasting or deceleration which casues incomplete combustion of fuel, resulting in raw HC gas in the exhaust.

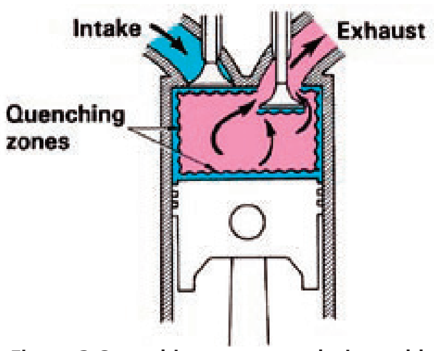


**Figure 3 Quenching can occur during cold engine start-ups. Some of the air-fuel mixture may condense on surfaces inside the combustion chamber.**

## Oxides of nitrogen (NOx)

Oxides of nitrogen, NOx, are gases formed by Nitrogen and Oxygen during combustion if the combustion temperatures become excessive. They are NO nitric oxide, NO2 nitrogen dioxide, 2NO nitrous oxide, and so on. In general terms, the higher the temperatures during combustion, the higher the levels of NOx. A figure of around 1,800 degrees Celsius is often quoted as a temperature above which excessive levels of NOx are formed. The type of NOx depends on the length of time the high temperature prevails.

## The NOx effect

NOx is a colourless gas, which can cause paralysis if it enters the bloodstream. NO2 can cause respiratory irritation and can damage lungs. Additionally, oxides of nitrogen, combined with hydrocarbons, can form photochemical smog. Hence legislation requiring vehicle manufacturers to fit additional equipment to aid NOx reduction.

## NOx formation reduces engine efficiency

The reaction between oxygen and nitrogen is endothermic, it takes an external heat source to make it happen. This takes energy out of the expanding gas, robbing the engine of power. NOx formation also steals oxygen away from the fuel, producing incomplete combustion, lower combustion pressures and higher CO and HC output, so it's all round pretty undesirable.

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

## EGR to the rescue

Inventors of EGR were looking for a way to reduce temperatures in the combustion chamber so NOx would never form. A compromise was reached where the EGR system allows a percentage of the exhaust gas to be fed back into the intake system. Exhaust gas is mostly non-combustible; therefore, if a small amount of exhaust gas is mixed with the fresh fuel/air mixture, it occupies a portion of the mixture that would otherwise be combustible and less heat will be produced.

The recirculated exhaust gas absorbs some of the heat produced during combustion, by increasing the heat capacity of the mixture in the cylinder. Exhaust gas has a higher heat capacity than the fresh air fuel mixture, so diluting the intake charge with exhaust gas causes the heat energy from combustion to have less effect in raising the in-cylinder temperature.The combustion temperatures are reduced, thus reducing the formation of NOx.

EGR does not make it so cool that no NOx forms at all, but it is a compromise that does enough to keep NOx formation below limits specified in government pollution regulations.

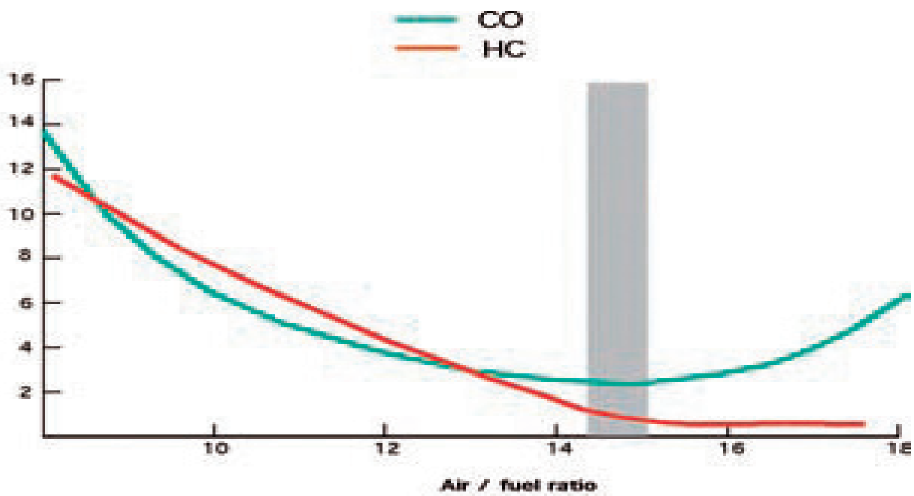


**Figure 6 The effect of air-fuel ratio and HC (red line) and HC (red line)**

## EGR and performance?

It is an ongoing myth that EGR reduces performance when operating correctly, it actually marginally improves fuel economy. The fuel economy benefits of EGR are made through a small reduction in pumping losses. With each rotation, the engine consumes a certain volume of air. This volume can be calculated based on the engine's displacement, RPM, and volumetric efficiency. Without EGR, the volume is filled with just intake air. This air has to be travel past the throttle valve, which is obviously a huge restriction when it is partly open. But with EGR active, some of that volume is filled with exhaust gas. This makes the engine more efficient through slightly increasing the pressure in the intake manifold, as if it had an increase in throttle opening, thus a reduction in pumping losses. The benefit to engine efficiency is that the engine wastes less torque drawing air into itself. This shows up as a small increase in fuel economy.

There is a fine line as to the efficiency improvement EGR offers, because once the optimum point has been passed, further increases in EGR result in poor combustion, increasing emissions of hydrocarbons (HC) and therefore excess fuel consumption. About 5% to10% per cent EGR appears to be the current maximum in spark ignition engines.

## Internal EGR

This method was realised once variable valve timing became a common application. At light loads, increasing valve overlap to retain or reintroduce exhaust gasses back through the exhaust valve that remains open longer, 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 unburnt hydrocarbons that appear towards the end of the exhaust stroke. The downside 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.

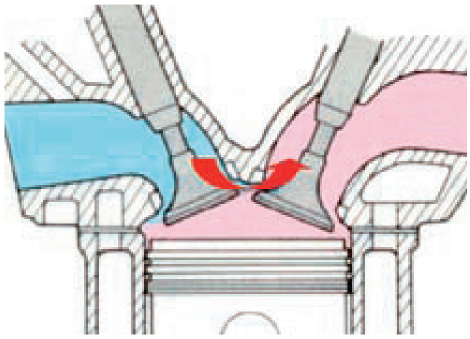

**Figure 5 Blow-by of the air-fuel mixture, red arrow, occurs when both the intake and exhaust valves are open**

## External EGR

This system has largely become the industry standard. It takes exhaust gas and reintroduces 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.

## The limits of EGR

Like all systems on vehicles, EGR has limits on its operation. During idle speed, the EGR system is disabled - after all, EGR is a controlled leak into the intake. Idle speed conditions become unstable because the engine is very sensitive to air fuel ratios and swirl conditions. Diluted mixture will have adverse effects on combustion.

During wide open throttle, the EGR system is also disabled, as maximum power and torque are required and need the engine's full volumetric efficiency.