THE EXPERT
STEWART SANDERSON

Having worked as a tuner for 17 years, Stewart 'Stu' Sanderson is one of the most-respected names in the business. A Level 5-trained fuel-injection technician, Stu has worked for a Ford Rallye Sport dealer, a well-known fuel-injection specialist and various tuning companies.

Eight years ago he joined forces with Kenny Walker and opened up Motorsport Developments near Blackpool (01253 508400, www.remapping.co.uk), specialising in engine management live remapping, as well as developing a range of Evolution chips which are now sold all over the world.

He is the creator and administrator of www.passionford.com, which he started in 2003. It has grown rapidly from a few friends contributing, to one of the biggest Ford communities on the web.

Stu's enviable knowledge of the workings of modern-day Ford performance engines means that every month he's just the man to explain how and why things work, and importantly how they can be improved.

TECH

TURBO DIESELS

OFTEN OVERLOOKED WHEN IT COMES TO TUNING, STU WONDERS IF TURBO DIESELS ARE THE FUTURE..

There's a distinct lack of articles in the Ford press about diesel engines and I can't help wondering if it's because they are still viewed as old fashioned, dirty, loud rattling oil burners. However, for people in the know, this couldn't be further from the truth so I want to cover the basics of diesel engines and explain how they work, what changes they have undergone and why nowadays they are virtually all turbocharged and are definitely forces to be reckoned with.

The Mondeo 2.2TDCi for example has 172bhp as standard. This is only 32bhp short of the original Sierra Cosworth engine, and has far more torque than the Cossie at 400Nm. This is before we remap them to Stage 1 and give them 210bhp and 480Nm!

In order to understand the differences in operation between petrol and diesel engines, here's a quick refresher on the fundamental operation of a petrol engine.

THE PETROL ENGINE

Most of you will be familiar with the workings of a four-stroke petrol engine. You will know they suck air and fuel into a cylinder, close the cylinder, compress that mixture into a small space at the top of the cylinder, ignite it with a spark plug and then create a power stroke by forcing the piston back down the cylinder with the energy released by that burning mixture before finally using that pistons return up the cylinder to push the spent gasses out into the exhaust and starting again. So how does a diesel engine differ?

THE DIESEL ENGINE

A diesel engine still has a four-stroke cycle but its compression and ignition strokes are different to that of a petrol engine in as much as the compression stroke compresses the mixture far more than any petrol engine would, and the ignition stroke does not contain a spark from any ignition system.

A diesel engine doesn't actually have any ignition system at all because a diesel engine is what we call a compression ignition engine. This means that the fuel ignites as it is injected into the engine and not due to being ignited by a spark plug.

COMPRESSION IGNITION

Diesel is designed to be ignited in this way and the major mechanical difference between a spark ignition engine and a compression ignition engine is that the latter will normally have a very high mechanical compression ratio, typically between 15 and 20:1. It may surprise you to learn that a diesel engine is the most thermally efficient design, mainly because of this high compression ratio.

Diesel fuel vapour is ignited by heat and we generate that heat by first compressing air only in the cylinder into a very small piston cavity when the piston is at the top of its compression stroke. It's essentially the same as a petrol engine's combustion chamber, just smaller and usually built into the piston instead of the cylinder head.

When the piston is approaching top dead centre the compressed air will typically exceed 550 degrees Celsius. Around this point in the stroke the diesel is injected directly into this hot combustion chamber with a very high-pressure fuel injector. The vapour from the diesel is then ignited by the heat from the compressed air in the combustion chamber. The droplets of diesel continue to vaporise from their surfaces and burn, getting smaller and smaller until all the fuel in the droplets has been burnt.

The start of vaporisation causes a delay period during the ignition phase, and the characteristic diesel knocking sound is caused as the vapour reaches ignition temperature and causes an abrupt increase in pressure above the piston. The rapid expansion of combustion gases then drives the piston downward, supplying

Modern diesel systems include lots of complex parts power to the crankshaft and the rest of the cycle is the same as a spark ignition petrol engine.

It is important to note that since diesel fuel has a higher molecular weight than petrol it vaporises and burns far more slowly, which limits the speed the piston can ultimately be pushed down by the combustion process. This is the main reason diesel engines don't rev as high as their petrol counterparts.

FUEL INJECTION

On older diesel systems, the injection system typically consisted of a diesel supply to a pump that collected the fuel and delivered it at a much increased pressure. This pump was usually connected directly to the injectors and was designed to distribute the fuel to each cylinder. This type of pump is often known as a distributor or inline system.

These pumps were normally cam driven and the injection pressure was directly related and proportional to engine speed. This typically meant that the highest injection pressures could only be achieved at the highest engine speeds, and conversely the maximum achievable injection pressure decreased as engine speed decreased.

These systems while widespread and very reliable did have their limitations and their fundamental design had various drawbacks that limited diesel engine technology from moving forward for a number of years. The main drawbacks were:

- On a typical distributor/inline system, the start of injection occurred at a predetermined pressure, often referred to as the pop off pressure, and the end of injection was also determined by pressure.
  This old style of mechanical injector fired off as the fuel pressure overcame the spring pre-load that is applied to the plunger inside the injector. Once the pressure in the injector reached a predetermined level, the plunger would lift and injection would start. As pressure fell, the plunger closed and injection ended – simple, but very reliable. If you're thinking that sounds a little like Bosch K and KE, you're right, it's a very similar system of injection.

"COMMON RAIL SYSTEMS CAN POTENTIALLY FIRE MULTIPLE TIMES PER STROKE."

- The number of injection events they could command during a single combustion event was limited, as was the physical timing of those injection events.
- Fuel droplet size is limited due to the design, and in modern terms the old droplet sizes are huge.


Common rail diesels are very efficient, and have ample power too

COMMON RAIL

In common rail systems a very high pressure pump stores a reservoir of fuel at extremely high pressure. This pressure can exceed 2000bar (29,000psi).

The term 'common rail' refers to the fact that all of the fuel injectors are supplied by a common fuel rail which is nothing more than a pressure accumulator where the fuel is stored at high pressure. This accumulator supplies multiple fuel injectors with the fuel. This simplifies the purpose of the high pressure pump in that it only has to maintain a commanded pressure which is either mechanically or electronically controlled.

The diesel fuel injectors are piezoelectric and under complete ECU control. The fuel injectors are electrically activated and contain a hydraulic valve consisting of a nozzle and


Piezoelectric injectors allow the ECU to have complete control of the injection process

plunger which is mechanically or hydraulically opened and the fuel is sprayed into the cylinders at the desired pressure.

Since the fuel pressure energy is stored remotely and the injectors are electrically actuated the injection pressure at the start and end of injection is very near the pressure in the common diesel supply rail regardless of engine speed. This is one of the major advantages over the old systems and gives the injection system a virtually square injection rate. If the accumulator, pump and plumbing are sized properly the injection pressure and rate will be the same for each of the potentially multiple injection events per stroke.

BENEFITS OF COMMON RAIL

You'll have noticed I mentioned that the common rail system can potentially fire multiple times per stroke. Well, this is in fact one of the most important features of common rail and one of the reasons that the system scores over the old fashioned type.

The common rail system with its piezoelectric fuel injectors gives the vehicle's ECU the ability to control each injector individually and allows it to fire more than one injection of fuel per engine cycle. There can be five events per stroke but usually there will be three.

PIEZOELECTRIC INJECTORS

Piezoelectric technology is the energizing of a stack of electrodes and ceramic wafers, producing an extension that lifts the injector needle. This technology has a very fast response time for the fine control of injected fuel.

Piezoelectric injectors however are proving to be invaluable in modern, clean diesels because of their extremely quick switch on and off ability. The multiple aperture injectors atomize the fuel through a disk with six to 10 holes at its tip. The geometry of these openings can be altered to work with multiple cylinder designs, which should make it relatively easy to adapt this combustion technology to any engine.

Also, the combination of multiple holes and magnetic actuation makes it possible to produce compact, ultra-fast injectors that are relatively small and have incredibly small fuel droplet sizes. The capability to emit a much finer spray of diesel than has ever been possible before has led to the improved burn speeds and even greater engine efficiency and power.

COMMON RAIL DIESEL INJECTION STRATEGY

The way a common rail diesel system injects fuel is not quite as simple as a petrol engine, in fact it's far more complex. To increase the diesel engine's power, torque and operating range, designers have had to find more and better ways to burn the fuel more quickly and efficiently. In doing so have they ended up with a complex sequence of events, as follows:


Injectors deliver the fuel multiple times per engine cycle

Pilot injection or pre-injection

With this system the ECU can inject a small amount of diesel just before the main injection event. This is called pilot injection and it performs many roles including the reduction of noise and vibration, as well as optimizing the cylinder temperature for the following main injection event. It also has some great benefits for cold starting etc. The pilot injection feature alone has been proven to decrease an engine's sound output by up to 3dB.

The main injection event

This is the main power producing event and is triggered at optimum engine angle in order to produce maximum power or best emissions, depending on what the ECU requires at that particular time. This may be split into two injection events.

Post injection

The post injection system sustains combustion in order to burn off the soot produced by burning diesel. It is also often used in a different role to raise exhaust gas temperatures even further to regenerate particulate filters at specific intervals. (See later description)

The vehicle's ECU is of course in full control of all the above injection events

TYPICAL DIESEL ECU INPUTS OUTPUTS

To give you an idea of how advanced a modern diesel engine is here are a list of the things likely to be monitored by the ECU. (The list is typical, but not definitive or exhaustive.)

Battery
Camshaft position sensor
Crankshaft position sensor
Vehicle speed sensor
Coolant temperature sensor
Air temperature sensor
Fuel temperature sensor
Fuel pressure sensor
Accelerator position sensor
Airflow and mass meter
Brake pedal position switch
Clutch pedal position switch
Turbocharger pressure sensor
Exhaust temperature sensor
Exhaust pressure sensor
Security signal Transponder

ECU OUTPUTS

This will give you an insight into just what the ECU has direct control over. (Again, the list is typical, not definitive or exhaustive)

Fuel injectors
Diesel pump's pressure
Diesel injection timing
Diesel injectors
Exhaust gas recirculation valve
Boost pressure control valve
Air conditioning compressor
Alternator
Control relays
Dashboard rev counter
Dashboard trip counter
Heating supply
Scavenge pump
Auto gearbox
Diagnostic connector
Diagnostic light
Diesel particulate feature regeneration control

DIESEL HISTORY TIMELINE

1892
The diesel engine is named after German engineer Rudolf Diesel, who invented it. This unit was limited to very low rotational speeds.

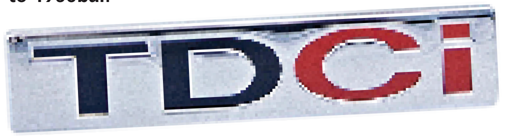
1927
The first high volume diesel production pump appeared enabling diesels to run at higher speeds.

1962
The distributor injection pump with automatic timing device was developed and gave the diesel engine a much needed additional boost.

1997
The first common rail diesel system in the world for passenger cars. This new system ran at extremely high pressure (up to 1450bar!) and brought massive benefits to the diesel engine in terms of economy and power.

2001
The 2nd gen common rail diesel system for passenger cars makes diesel engines even more economical, cleaner, quieter and more powerful than ever. These systems ran under even higher pressure than the original common rail system and could reach 1800bar.

2003
Third generation common rail diesel system for cars. This system is notable for using ultra high technology piezoelectric fuel injectors. Once again these systems run under even higher pressure than the previous common rail system and can now pressurise the fuel to 1950bar.



2009
Fourth generation common rail diesel system for cars. This system has a totally new style of injector and a pressure rating now up to 2100bar (61,000psi),

With all these developments, the aim has always been to lower fuel consumption, improve energy efficiency and decrease noise. Each time these aims have been met.

and it has complete control over not only the precise moment when the fuel is injected into the cylinder but also allows the pressure at which it does so. As a result, the fuel that is injected atomizes easily and burns cleanly, which both reduces exhaust emissions and increases engine efficiency.

Now most European and Japanese manufactures have common rail diesels in their model line-ups. Interestingly, the pre- and post-injection events are often so short that they are measured in microseconds, which is one thousand times shorter than a millisecond!

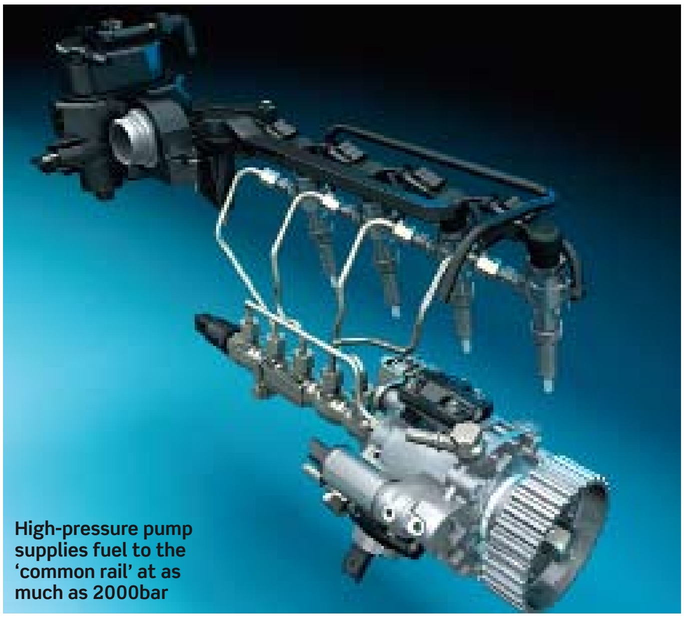
INJECTOR PROGRAMMING

Some of you out there may have heard of the term 'Injector Coding.' It's a very common procedure nowadays that is performed on a daily basis at most garages on all manner of vehicles, including the Ford TDCi range of systems.

When we are opening injectors for only one millionth of a second, and the fuel is delivered in that time at 29,000psi, and we may deliver only $1mm^3$ of fuel (which is 30 times smaller than your average raindrop), it's fair to say that the flow rate of the injectors is not only important, it's mission critical.

Early on in the development of the common rail system, engineers realised that they couldn't trust a mass produced part like a fuel injector to be created to such incredibly fine tolerances with any degree of repeatability, so they introduced a testing system whereby each new injector is tested and its performance logged.

This performance is given a code which is usually stamped onto the injector itself. This code is programmed into the ECU and therefore the ECU now knows the exact flow rate of all the injectors and can compensate accordingly when delivering fuel pulses. Recoding usually needs to be done when new injectors are fitted or an ECU has its power or programming removed.



High-pressure pump supplies fuel to the 'common rail' at as much as 2000bar

"REGENERATION IS THE PROCESS OF REMOVING ACCUMULATED SOOT FROM THE FILTER."

EMISSION CONTROL.

Diesel combustion creates many residues, most of which are regarded as pollutants such as:

- Water (H_2O)
- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Unburnt fuel hydrocarbons (HC)
- Nitrogen oxides
- Sulphur dioxide (SO_2)
- Sulphuric acid (H_2SO_4)
- Soot particles

These pollutants need to be removed from the exhaust gas just as badly as we needed to remove them from a petrol engine's exhaust. So, nowadays all diesels have not only catalysts, but also particulate filters that will deal with the physical element, which is the soot.

PARTICULATE FILTER

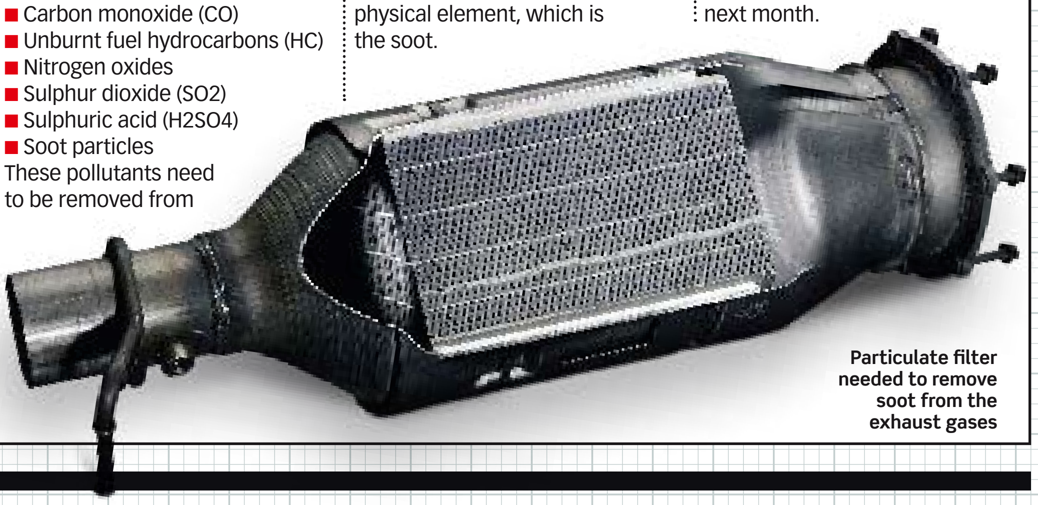
This is similar to a catalyst but it mechanically removes the soot from the exhaust gas. The main problem they face is that like any other mechanical filter; they eventually get clogged and require cleaning, or 'regenerating' as we call it in the diesel world. Regeneration is the process of removing the accumulated soot from the filter and it's normally done with heat automatically.

The filters are monitored using exhaust pressure sensors. The more pressure the ECU can see, the more clogged the filter, so when the time is deemed right the ECU can increase the exhaust gas temperature by increasing or adding to the post diesel injection pulse width which will in turn increase the EGT and start to burn the soot off. This can be triggered manually if required but is usually totally automated in one of the two following ways:

- By injecting fuel intermittently at cruising speed to increase the exhaust temperature using a separate reservoir. This is a service item on the Peugeot/Citroën range.
- Passively adding a catalytic converter oxidiser to increase the exhaust temperature.

Some vehicles' ECUs monitor the particulate filter and if it starts to build up it will give a post injection, and on some vehicles this can mean two post injections.

That is about all we have space for this month. I hope you now see modern diesels in a different light and will at least have some understanding why that diesel Focus or Mondeo has just left you for dead in the traffic light grand prix. See you next month.



Particulate filter needed to remove soot from the exhaust gases