Diesel Electromotion?

Cars with the acceleration of a gasoline engine and the fuel economy of a hybrid, all with an almost classic oil-hammer engine. What's the drama?

(Hint: You already know most of the cast!)

The subtle control circuits are too bad, in a way, because the traditional, non-electronic Diesel engine was so simple: If you didn't run out of fuel or oil pressure and if you didn't overheat or lock up, your Diesel engine kept running. Period. Now with the new electronic Diesels, if certain electronic sensors or actuators fail, you might find your engine in one or another limp-home mode, stuck in idle or even shut down altogether. Nonetheless, the new changes are worth it: On the one hand, electronics have become almost as dependable as mechanical systems; and no new car on the road, including the gas-electric hybrids, comes close to the one-tank range of the TDI Passat. With its 18-gallon tank and some careful, steady speed-limit cruise-controlling, you could drive beyond 1000 miles on a single fill-up! On a long trip you'd slump into snoring, swoon from hunger or burst your bladder first. Let's see how it works and get a few ideas what to look for some day when the first TDI that doesn't run rolls into your shop on a hook. The same engine, by the way, is available on the Jetta and even on the New Beetle. A structurally similar TDI system comes on some six-cylinder engines as yet available only in Germany but highly regarded there for Autobahn performance. No doubt we'll see them in time.

The Mechanicals

Turbocharger

First, this is a *t*urbocharged *d*irect-*i*njection (thus TDI) Diesel engine. The power and efficiency a turbocharger brings to a Diesel engine are well known: Recapturing residual heat energy otherwise just blown out the exhaust to compress the intake air instead, each fresh cylinderful contains a significantly higher amount of oxygen than it otherwise could. The VW TDI system includes an intercooler as well, so the compressed intake air can reach higher levels of oxygen density as it cools and shrinks (the fast spin through the turbocharger can heat it several hundred degrees).

Intercooler

While an intercooled turbocharger is largely a WOT power-increaser on a gasoline-fueled engine, on a Diesel the pair work together for both power and efficiency any time the engine is running. It does take more energy to compress the additional air during each compression stroke, but you get that energy right back in the next power stroke output, as if you just stored it briefly in a pneumatic spring.

When the driver puts the pedal to the floor, there is always plenty of oxygen available to burn all the fuel; when he doesn't, the extra oxygen just transits through the system at negligible loss of efficiency beyond the smidgen of extra heat drifting into the waterjacket. The abundant oxygen insures a complete fuel burn, particularly with the TDI system's feedback controls we'll describe later. As on most Diesel engines, the turbocharger is free to increase the intake manifold absolute pressure up to a specific amount any time there's enough exhaust flow to spool the turbo fast enough; there's no reduction of boost at partial throttle (after all, there's no throttle!). By the way, the turbocharger housing and the exhaust manifold are one and the same casting, so a penny-wise motorist skipping VW TDI oil changes to save money today can put one on his wish list for tomorrow.

No Prechamber

Direct injection means the fuel sprays immediately into the combustion chamber rather than into any sort of divided- or pre-chamber. Earlier VW Diesels use a Ricardo- or swirl-prechamber design, with a small, removable pocket in the cylinder head and an air passage between it and the main combustion chamber. Both the fuel injector nozzle and the glow plug tip of the earlier VW Diesels are in the prechamber.

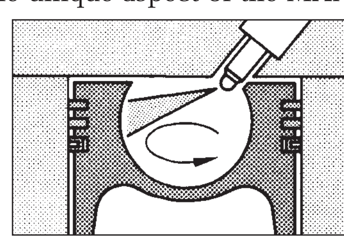
A prechamber Diesel has two advantages: It's easier to start when cold because of the generally higher compression ratio (22 or 23 to one, rather than the 16 or 18 to one common on DI's), and the power-stroke pressure builds more gradually, making it easier to minimize 'Diesel clatter.' The disadvantages are that when you increase the surface area in the combustion chamber, you increase the amount of that surface transmitting heat into the waterjacket — energy you'd rather use pushing pistons and cylinder heads apart. And the energy required to squeeze the charge air into the prechamber and to spigot the burning fuel and air back out into the combustion chamber are also wasted from the point of view of moving the vehicle. So a direct-injection Diesel will invariably be more fuel-efficient than an equally advanced prechamber version. Sometimes a prechamber design is called a *swirl-chamber* design, reserving the first term for the kind of prechamber with a diffuser-pin and multiple flame-output channels Daimler-Benz uses in their cars.

Prechamber and Ricardo-chamber Diesel engines are well suited to high-engine-speed applications, making them particularly attractive to carmakers, who can then use the same drivetrains, transmissions and differentials, as they use with gasoline engines, since the crankshaft to wheelspeed ratios are reasonably close to those of gasoline-fueled, spark-ignited engines.

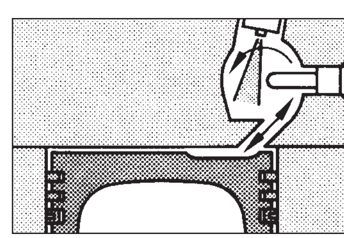
Direct-injection Diesels are the traditional design of choice for very large engines, for stationary powerplants, tugboats and over-the-road big trucks. The direct-injection Diesel's advantage over practically every other engine design is its fuel-efficiency. The simple, one-piece combustion chamber is entirely filled with compressed, superheated air when injection begins; and under most power settings the fuel burn takes place within an envelope of air that keeps any fuel from condensing on the combustion chamber walls or roof (pistons and valves stay hot enough to discourage fuel misting). Direct injection usually requires higher injection pressures than prechamber designs because the air is relatively still in a DI chamber, so the fuel particles atomize finer and blow through the air faster to oxidize properly. The VW TDI engine, however, uses swirl-port intake runners and a two-stage, fine-spray, five-nozzle injector, so this is less of a problem. That higher fuel pressure, of course, produces more injection pump noise. In industrial engines, the noise just happens, and you just deal with it; in the VW TDI the injectors have two separate needle springs, one for the low pressure initial injection for low power settings and the other for a higher volume delivery. Besides, there are enough sound baffles and insulation panels around the engine compartment that little injection pump sound escapes.

MAN-Pattern Pistons

A final mechanical feature of the VW TDI is its use of the MAN-pattern pistons. MAN builds large trucks and earthmovers in Germany, many of them used for military and heavy-industrial purposes like mines and quarries. The unique aspect of the MAN design is a steel-lined pocket or thimble around which each piston is cast. In this pocket is the space where the combustion actually occurs, as the injector sprays the fuel into that pocket. When there is a high enough injection quantity that not all the fuel burns at once, the residue strikes the hot, hollow surface of the piston, which boils it back into the combustion chamber's superheated air for complete burning.



Combustion chamber shape and nozzle location in the MAN system.



Combustion chamber shape and nozzle location for the swirl chamber system

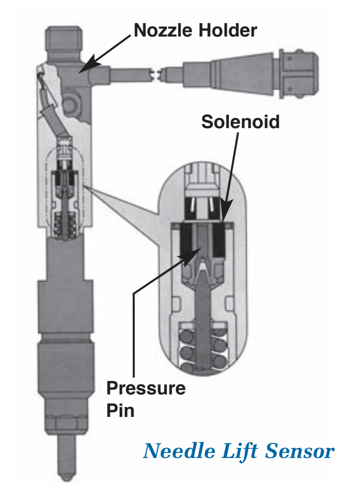
Part of the way a direct-injection Diesel achieves unparalleled fuel-efficiency is by turning more slowly than other engines, reducing friction and reciprocating losses, completely filling the cylinder during each intake stroke (remember, Diesel engines are unthrottled — they ingest as much air as they can take for every power stroke, regardless of the power output, which develops entirely from the *quantity* of fuel injected) and giving the fuel-air mixture a long time to burn as it's producing power and turning the crankshaft. Contrary to what happens in a gasoline engine, on a Diesel burn-time is not exclusively a chemical function of the fuel and air, but also depends on the rate and delivery of the injection spray: Fuel not yet injected can't yet burn.

The VW TDI, for instance, develops its best torque output and thus best fuel economy at 1900 rpm, so VW tailored the drivetrain to it. Perhaps this combination of high torque and low rpm is what gives some people the impression the engine is quicker than the gasoline engine mated to the same vehicle — people are generally reluctant to wind the gas engine all the way to redline.

The Electricals

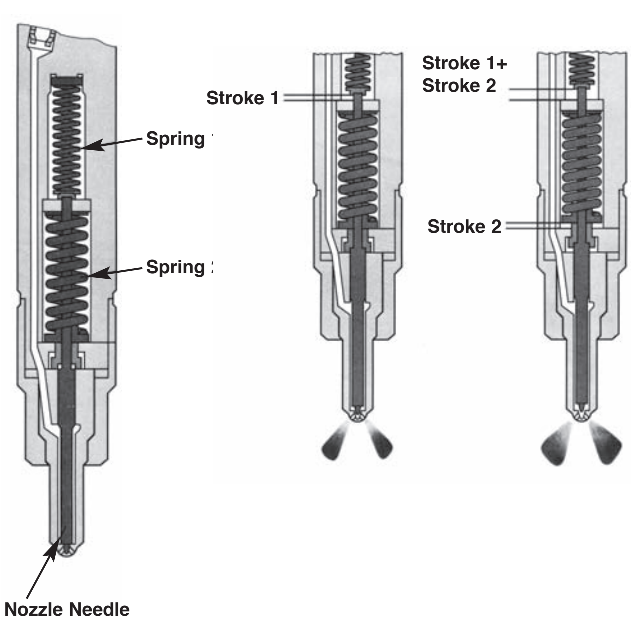
Sensors

But now TDI electronics complete the picture started with those clear and simple mechanicals. On gasoline engines, the major purpose of electronic controls is to keep the fuel-air mixture at just the stoichiometric ratio that best allows the catalytic converter to render the exhaust innocuous. On Diesel engines, the purpose is also to keep the exhaust emissions as clean as possible, but it can't be done by fine-tuning mixture. Diesel engines run superlean almost all the time, but all over the superlean landscape, not at any ideal fuel-to-air ratio. The fuel quantity and injection timing determine engine output as well as exhaust quality, including smoke; the engine always ingests as much air as it can swallow, regardless of how much power it will produce on the next combustion stroke. So what the electronic system controls are the *volume* and the *timing* of the injection, both previously mechanical/hydraulic functions. By limiting the quantity of fuel to only what the engine can actually burn completely with no residue, the computer controls hydrocarbon emissions, especially soot particulates. By modulating the operation of the EGR valve, it resists the formation of oxides of nitrogen, just as on a gasoline-fueled, spark-ignition engine.

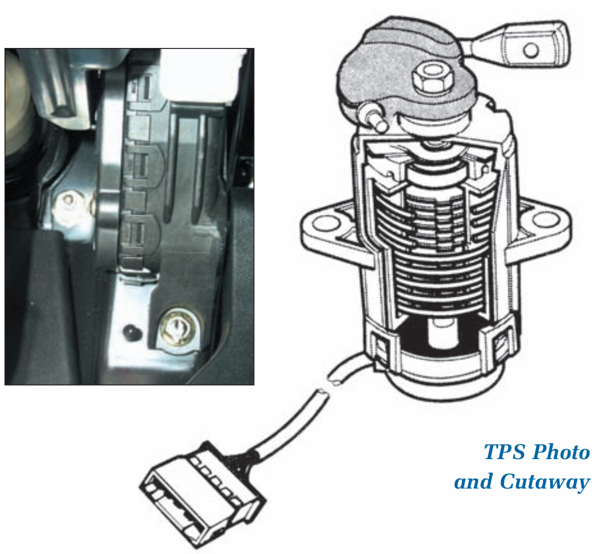


Needle Lift Sensor

Dual Spring Injector



Let's start right on the ground floor, or at least on the driver's-side bulkhead. The first control of fuel injection comes not through a cable or mechanical linkage but electronically, through a drive-by-wire system. Just on the firewall by the pedal hinge is a throttle-position sensor (except it should be called the *fuel-pedal position sensor*, of course). Because of its importance in the system – you certainly don't want any electrical design such that a short or open could drive the system into uncontrolled full power. That could reawaken the whole 'unintended acceleration' scam! The sensor is multiply redundant and sends simultaneous different output signals (some increase voltage as the pedal moves to the floor; others decrease; some seem to change capacitance; all of them must present the same information simultaneously, but coded in different electrical forms). If the sensor fails, the computer sets the engine speed to a fast idle to enable the driver to keep moving in limp-home mode. Fast idle on a Diesel, you'll recall, is actually usable for transportation since the engine develops very high torque at low rpm, so a driver could engage at least the middle gears. VW says to test the sensor with a scan tool, but several experienced VW mechanics told me you can learn what the signals look like by experimenting with 'known-good' sensors, tracking the several channels, before you run into one that's failed.



TPS Photo and Cutaway

In addition to the TPS, the TDI system has an air-mass sensor, the same kind of hotwire sensor used in VW gasoline cars. If the computer knows exactly how much air has entered the combustion chambers, it can set a maximum fuel quantity it will inject, regardless of where the driver puts the fuel pedal. You're not likely to get exhaust smoke from a clean Diesel except by overfueling, and the MAF sensor locks that one out.

The system includes several other sensors related to the gasoline engine's. There is a MAP (manifold absolute pressure) sensor, and a temperature sensor in the intake channel, and a BARO (barometric pressure) sensor in the computer itself. Why would you need such sensors in an unthrottled Diesel engine? Because of changes in intake air volume resulting from altitude, accumulated dirt on the air filter, temperature and the like. The system even uses a fuel temperature sensor: After all, the viscosity and density of the fuel varies with its temperature; the spray quantity varies with the viscosity; and the power output varies with the density.

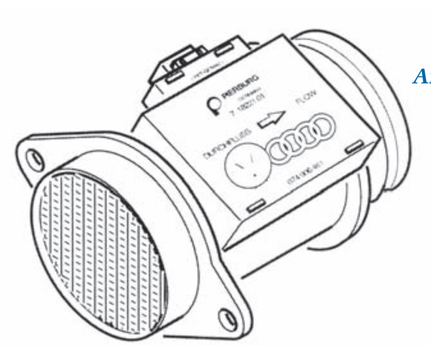
Actuators

The function of all of the sensors we've considered so far is to calculate the quantity of fuel to inject on the next combustion sequence. The power to force the fuel through the injectors, of course, comes mechanically from the crankshaft timing sprocket, through the toothed timing belt and into the injection pump. It takes considerable power to inject the fuel, much more than is required for gasoline fuel injection, because the injection force must drive the fuel into the cylinder over and above the pressure of the combustion itself before and during the power stroke. This is several thousand psi and far beyond the capacity of an affordable or currently practical electric pump.

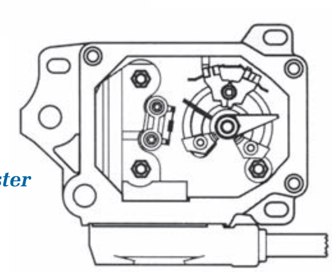
But while the crankshaft provides the injection muscle, the computer controls the quantity and timing with two separate actuators inside the injection pump. On the old VW Diesels, the fuel pedal cable pulled a bellcrank that turned the shaft that varied the fuel quantity by changing the effective stroke of the pump plunger. On the TDI, the quantity adjuster, a rotary magnet (essentially an angular electric motor) performs the same task. The computer controls injection timing, the beginning of injection, by a duty-cycle modulated pulse it sends to the peculiarly named "cold start injector," which doesn't inject fuel at all, but functions as a bypass valve to hydraulically modify the position of the injection timing piston in the injection pump. Pressurized fuel, vented through the cold start injector, works against a spring to set the timing piston position. The computer determines this timing to begin with according to an injection advance map stored in its memory.

Feedback and Closed Loop

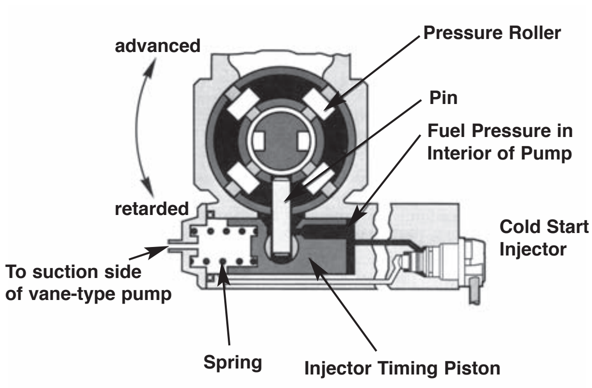
Control of the quantity of fuel also provides the major control of exhaust emissions. It would be misleading, though, to think of TDI feedback in terms of mixture, the key strategy with a gasoline engine. A Diesel engine runs far leaner than any gasoline engine can, but the actual mixture varies considerably, depending on the load. At hot idle there is so little fuel injected into the engine it may be quite difficult to even calculate the mixture. Even at full power settings, however, the Diesel's mixture will be much leaner than the 14.7 to one we think of as stoichiometry. The point of the control system's feedback is to reduce or eliminate exhaust smoke, and the key to that is feedback information about the injection quantity and timing.



Air-Mass Sensor



Quantity Adjuster



Cold Start Injector

The VW TDI produces so little waste heat it includes three electric heaters for coolant headed for the heater core.

How Much?

Injection quantity feedback comes from the modulating piston displacement sensor in the injection pump. This sensor is a contactless rotation angle measurement attached to the eccentric shaft of the quantity adjuster. An alternating voltage coil induces an alternating magnetic field in the sensor's iron core. The metal positioner that rotates with the eccentric shaft changes this magnetic field, and the change corresponds to the injection-quantity information reported back to the computer. Advantages of this design are: no wear from no contact, resistance to interference and relative immunity to temperature. This feedback sensor is so important, however, that the computer shuts the engine down if the signal is lost.

When?

Injection timing feedback information comes from cylinder number three's injector, which includes a needle-lift sensor to flag the movement at the beginning of injection. A direct current flows through a coil in a passive solenoid atop the injector (a passive solenoid reports movement by a change in the voltage through its coil). When the needle lifts, this changes the magnetic field generated by the current. That change tells the computer the injector has just begun to spray fuel. The computer calculates the injection advance by comparing this signal to the crankshaft position sensor signal. A failure of this sensor will leave the engine running, but the computer will reduce the maximum fuel quantity possible and light the indicator.

Particulate Trap

What looks like a catalytic converter on the TDI exhaust (and is sometimes misleadingly so described) is actually a particulate trap, almost a self-cleaning exhaust filter. When enough carbon builds up on the aluminum oxide substrate, it simply catches fire and burns off in the plentiful oxygen of the Diesel's exhaust.

I once had a Diesel Rabbit that lasted over 475,000 miles with no major work, almost all of those miles in and around, over and through the gaping Third-World potholes of Evil Gotham, New York City. I hated driving that car to the scrapyard under its own power, but even someone as safety-obtuse as yourstruly knew that when you could stab an index finger through the driver's-side A-pillar it was time to junk it. These new VW Diesels should last at least as long, and since they dunk the unibodies in zinc these days there won't be as much rust. A well-maintained TDI could be your last car ever! Better think about that color carefully, because if you don't want it, I do. ■

— By Joe Woods

"Save the Whales!"

Some people are superstitious about Diesel engines, and I don't just mean the testosterone-rich delusions tobacco-chewing OTR-truckers cherish. Some people don't like the smell of the fuel – does the occasional whiff of gasoline delight them? Some people think Diesels 'pollute more' because they see old Diesel trucks with puffs of exhaust smoke under load. Never mind the TDI's aren't those old trucks, anyone who in the name of clean air and environmentalism prefers 'good, clean, colorless, odorless' carbon monoxide to 'wicked, dirty' particulate soot is someone who should do a bit of reading. Unwanted emissions from Diesels are almost all visible particulates; unwanted emissions from gas cars are almost all invisible and toxic brain destroyers. This isn't the place to rant at length about ecology, but those who have strong views on the subject owe it to themselves (and to the rest of us) to learn more about the applied science. Introspectively judged good intentions are not enough.