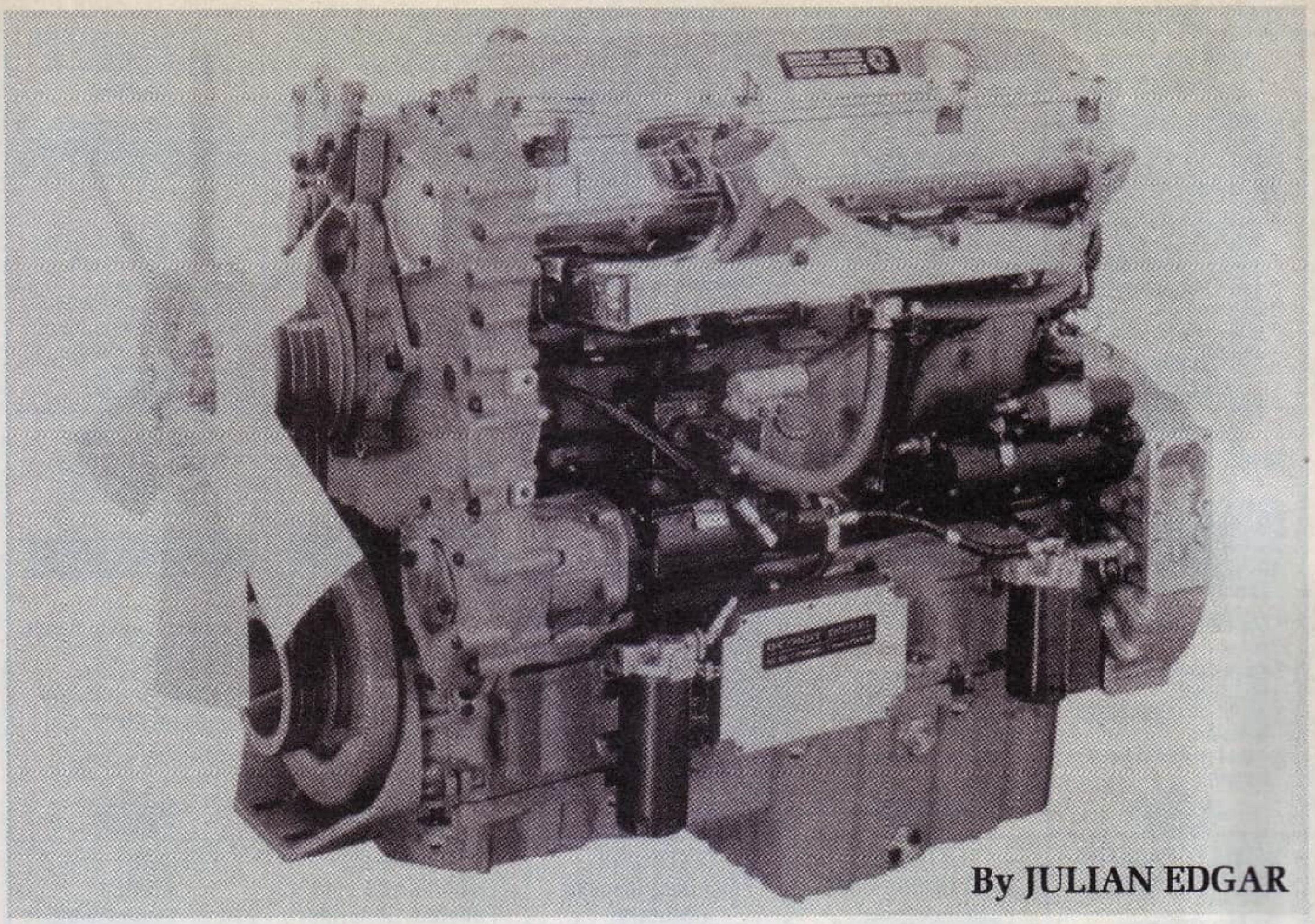


By JULIAN EDGAR

Electronic diesel engine management

Just as electronics has brought great strides in the performance & reliability of petrol engines, the application of similar techniques to diesel engines has led to improvements in fuel economy & a reduction in pollution. Here we examine the electronic control system used by Detroit Diesel on some truck engines.

Diesel engines are widely used in railway locomotives, ships, heavy industry and trucks. Although of a similar age to the spark internal combustion engine, the diesel engine has not been widely adopted for use in passenger cars. However, just as electronic engine management has been widely adopted to improve the performance of cars, similar techniques have been applied in diesel engines for trucks, particularly those used for long distance haulage. As a result, typical electronically controlled diesel engines are as much as 20% more fuel efficient than their predecessors.

Although the basic design of petrol and diesel engines is similar (both are two or four-stroke designs which use reciprocating pistons driving a crankshaft), a diesel engine does not ignite its fuel charge by the use of a spark plug. Instead, only air is compressed on the compression stroke. The fuel charge for the power stroke is accurately metered and pressurised by a fuel injection pump, of which there is one for each cylinder. It then passes to the high pressure injector and is sprayed into the combustion chamber, where it mixes with the hot compressed air and self-ignites.

In a petrol engine (even one using fuel injection), the fuel and air are mixed prior to entry to the combustion chamber. The fuel/air mix is drawn into the cylinder on the intake stroke and so the injectors or carburettor need only mix the fuel and air at close to ambient air pressures. On the other hand, diesel injectors must operate at pressures of over 20MPa (3000 psi) and inject minute quantities of fuel at a rate of 2.5-25Hz.

In order that the air in the diesel's cylinders becomes hot enough for combustion to occur, the compression ratio is much higher than in a petrol engine. Compression ratios of 14:1 to 24:1 are commonly used, giving a cylinder pressure when the air is compressed of up to 3800kPa (560 psi). At a compression ratio of 16:1, the air temperature will theoretically be at 525°C, with actual temperatures being around 425-550°C in working diesel engines.

Table 1 gives a summary of some of the differences between petrol and diesel engines.

Because no throttling of the intake air occurs in a diesel engine (load changes are catered for by changing the mass of fuel introduced), a diesel engine needs to be governed to limit maximum engine speed. In comparison to petrol engines, the maximum engine speed of a diesel is quite low, typically 2500 to 5000 RPM.

This is because of the inertial loadings created by the heavy internal components which are required to absorb the very high cylinder pressures created during the power stroke. In order that the correct amounts of fuel are introduced to the combustion chamber at the right time, a complex mechanical system is usually employed.

Mechanical fuel delivery

The mechanical delivery of fuel to a diesel engine is complicated because of the high fuel pressures and short delivery times available. In fact, the processes occurring during injection are more akin to acoustic principles than geometric laws of displacement.

In a mechanical system, an engine-driven camshaft drives an injection pump's plunger which feeds a high-pressure gallery. The delivery valve opens and a pressure wave proceeds toward the injection nozzle at the speed of sound (approximately 1400 metres per second under these conditions). When the injection nozzle's opening is reached, the needle valve overcomes the force of the injection nozzle spring and lifts from its seat so that fuel can be injected from the spray orifices into the engine's combustion chamber.

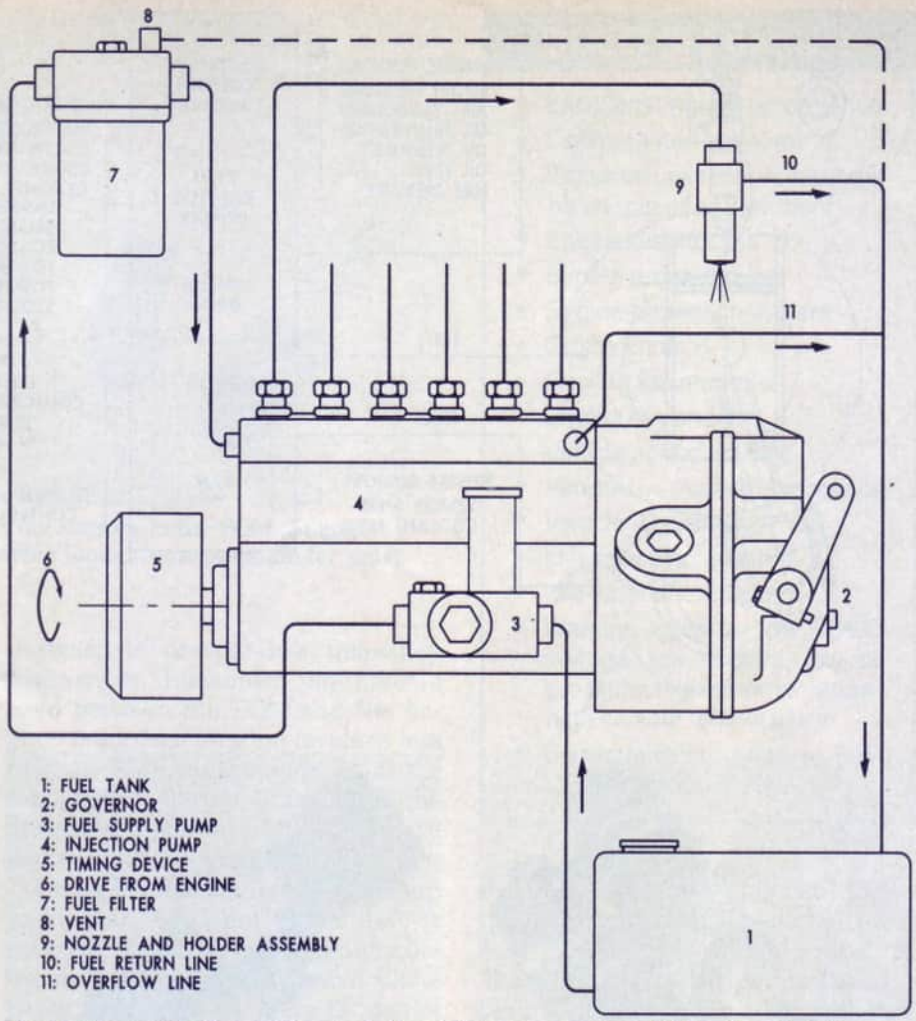


Fig.1: schematic of a mechanical diesel injection system: (1) Fuel tank; (2) Governor; (3) Fuel-supply pump; (4) Injection pump; (5) Timing device; (6) Drive from engine; (7) Fuel filter; (8) Vent; (9) Nozzle-and-holder assembly; (10) Fuel return line; (11) Overflow line.

Fig.1 shows a schematic diagram of an in-line fuel injection pump system with a mechanical governor.

The mechanical Detroit Diesel system differs slightly from this in that a combined plunger-type injection pump and hydraulically-controlled injector is used for each cylinder. The amount of fuel injected is governed by the period of injector flow. This is

Table 1: Diesel vs. Petrol Engines

Feature	High Speed Diesel	Petrol Engine
Admission of fuel	Direct from fuel injector	From carburettor via the manifold, or injected into the inlet port
Compression ratio	14:1 to 24:1	7:1 to 10:1
Ignition	Heat due to compression	Electric spark
Torque	Varies little throughout the speed range	Varies greatly throughout the speed range
Brake thermal efficiency	35-43%	25-30%
Compression pressure	3100-3800kPa	750-1400kPa
Compression temperature	425-550°C	Up to 230°

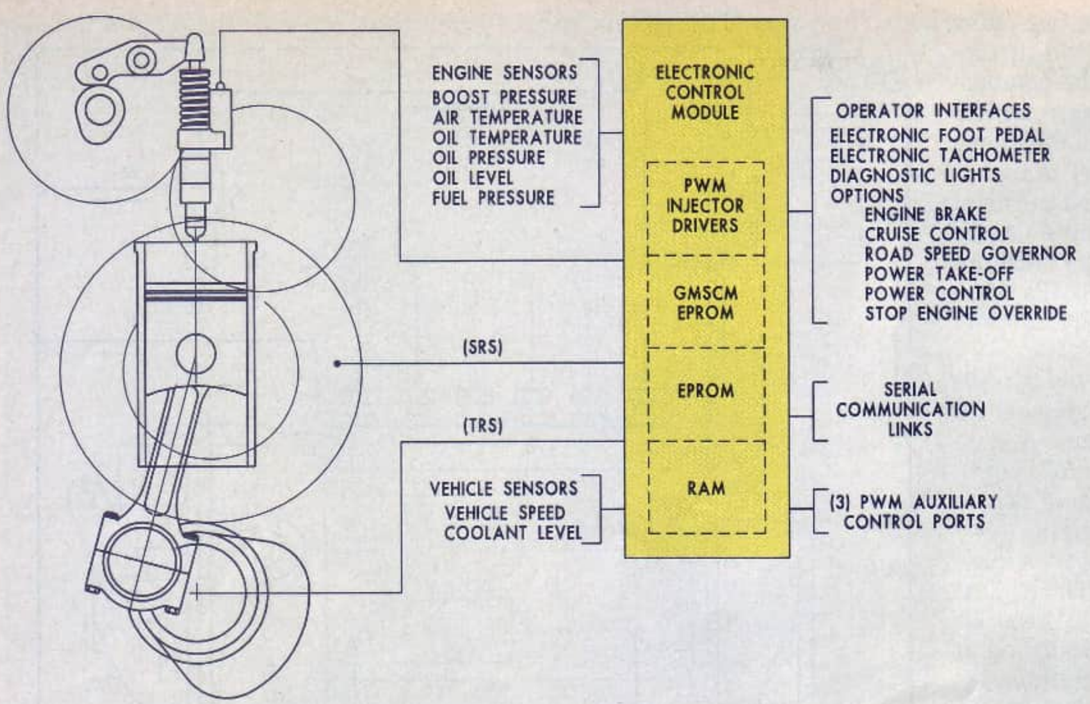
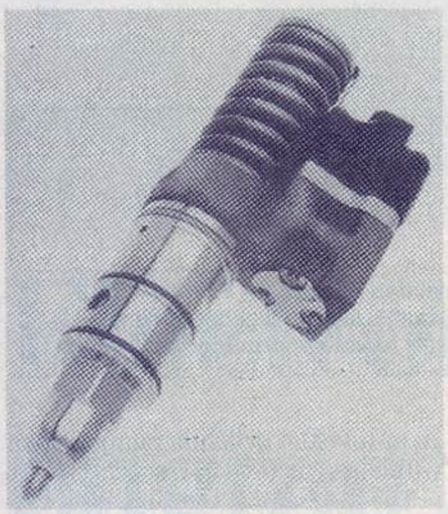
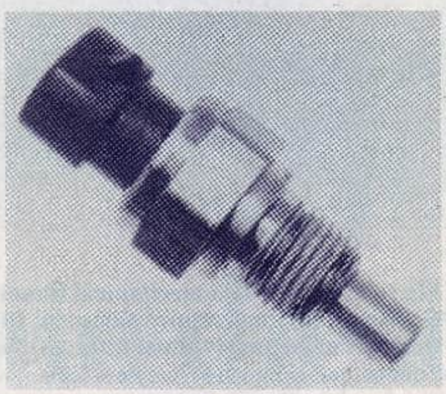


Fig.2: the DDEC-II system uses a large range of sensors to set the engine operating conditions. In addition, there is an engine protection system which is activated when the ECM receives an out-of-specification signal from the oil or coolant temperature sensors, the oil pressure or coolant level sensors, or two additional sensors which can be specified by the truck manufacturer.



The electronic unit injector incorporates a solenoid-operated poppet valve which performs the injection timing & metering functions.



Oil & fuel temperature sensors are also used. The oil temperature is used as part of the engine protection system incorporated into DDEC-III, while fuel temperature is monitored to aid in the calculation of fuel economy.

The air temperature sensor is used to provide one of the ECM's inputs. White smoke suppression & improved cold starting result from the use of this sensor. Other sensors monitor the intake manifold temperature & the oil temperature

dictated by the opening and closing of ports within the injector body itself, which in turn are dependent on mechanical linkages to the governor mechanism and the throttle.

Electronic management

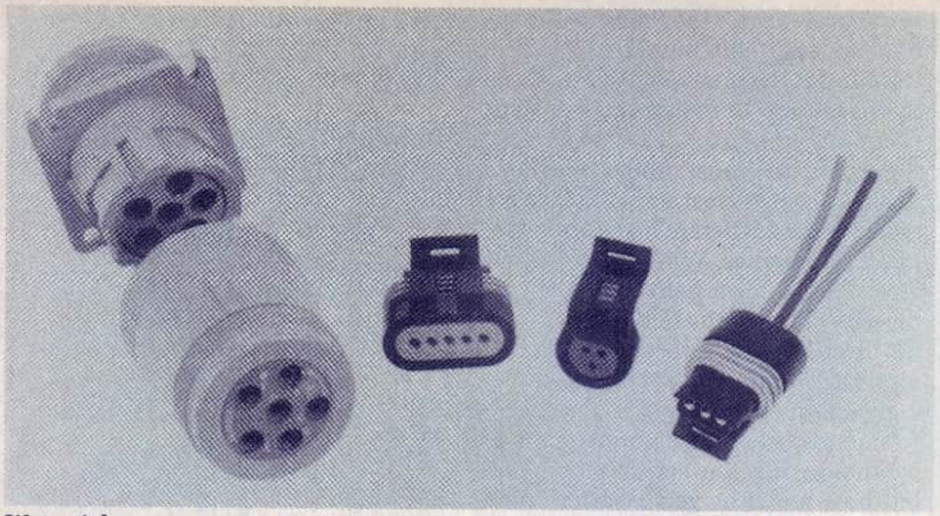
Detroit Diesel Electronic Control (DDEC – pronounced 'Dee-Deck') was introduced in September 1985. DDEC-II was released in 1986 and the system currently in use is DDEC-III, released in 1994. The major subsystems of DDEC are the electronic injectors, the electronic control module (ECM) and the sensors. Fig.2 shows a schematic diagram of DDEC-II. Fuel is delivered to the cylinders by the electronic injectors which are cam-driven for pressurisation of the fuel and controlled by solenoid-operated valves to give precise fuel delivery.

DDEC electronics

The DDEC-II system uses a microprocessor designed by General Motors (Detroit Diesel Allison is a subsidiary of General Motors Corporation). Similar to the Motorola MC68-HC11, its features include 2Kb of EEPROM and 256 bytes of static RAM. DDEC-III has a much improved microprocessor which runs eight times faster, has seven times more memory and is 50% smaller.

Electronic injectors operate on a similar principle to DDA mechanical injectors but a solenoid-operated control valve performs the injection timing and metering functions. Unlike a petrol EFI system, it is the closing (rather than opening) of the solenoid valve which initiates the beginning of injection. A bypass for the fuel is blocked when the valve closes, forcing the fuel to pass through the injector nozzle and into the combustion chamber. Conversely, opening the valve causes pressure decay and the end of injection.

A pulse width modulated (PWM) driver pulses the current to the injector solenoids at about 10kHz during the injection phase. Fig.3 shows the sequence of events during injection.



Watertight connectors are used to connect the sensors to the ECM. In engine management systems, connectors & the wiring loom are responsible for most of the faults which occur.

DDEC III Features

- Excellent engine performance
- Optimum fuel economy
- Emission laws met without exhaust gas after-treatment
- Engine diagnostics
- Simple programming
- Engine protection system
- Cruise control
- Cooling fan control
- Engine fan braking
- Vehicle speed limiting
- Vehicle over-speed diagnostics
- Vehicle ID number
- Idle speed adjustment
- Idle timer shutdown
- Warning lights for low DDEC voltage, low coolant, low oil pressure, high oil temperature, high coolant temperature
- Communication links – SAE J1587, J1922, J1939

When voltage is applied to the injector solenoid, current begins to flow through the coil. The current increases until the magnetic field creates enough force to move the armature and valve assembly against the return spring force. Once a preset current flow is reached, the driver circuitry regulates the voltage and monitors the current. A detection circuit is used to monitor the time at which the valve closes and injection actually starts; this is critical in maintaining injection timing and fuel quantity control.

After the detection circuit signals that the valve is closed, the current passing through the coil is set to a level sufficient to keep the valve closed. At the end of the command pulse, the low inductance coil design promotes rapid current decay and fast valve opening. During the first portion of the command pulse, the time needed for the valve to close is dependent on the rate at which energy is supplied to the magnetic field. This is highly dependent on battery voltage and the feedback signal supplied by the detection circuitry is used to compensate for this variable. Fuel injector timing of better than ±0.25 crankshaft degrees is obtained with this system.

Engine control module

Unlike the electronic engine management systems employed in cars, the DDEC system uses an engine-mounted ECM and the circuit boards are designed to withstand the rigours of vibration, heat and dust. Large components are hot-melt glued to the boards and the board supports are designed to prevent low frequency resonances. Elastomer mounts are used between the ECM and the engine, reducing vibration levels to less than 1G RMS for the majority of the frequency spectrum. Fig.4 shows the measured vibration of the ECM with and without the isolation mounts.

Under-bonnet temperatures can run as high as 150°C but the module is protected from these extremes by being mounted on a fuel-cooled plate. Using the fuel to keep the ECM cool might seem odd but water cooling would not be suitable since the temperature is too high, at above 120°C (due to pressurisation of the cooling system). The diesel fuel, on the other hand, is normally at ambient temperature and so the ECM is kept considerably cooler than engine block temperatures. In addition, all electronic components in the ECM are rated for operation at up to 125°C.

Sensors & engine protection

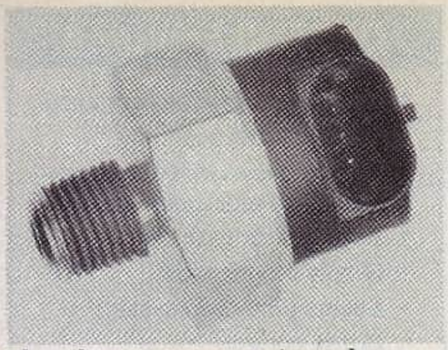
As with cars, lots of sensors are used in the DDEC-III system. Some are used to adjust the engine operating conditions while others can bring the engine protection system into play. The engine protection system is activated when the ECM receives an out-of-specification signal from the oil or coolant temperature sensors, the oil pressure or coolant level sensors, or two additional sensors (which can be specified by the truck manufacturer).

Each of the above sensors can be programmed to cause one of two results. The first is complete engine shutdown, 30 seconds after a dash warning light comes on. This could happen, for example, after loss of oil pressure. The second possible result is "Ramp Down" which illuminates a yellow dash warning light and cuts the engine power to 70%, then a red dash light comes on and the power is reduced to 40%. Alternatively, any of the sensors can illuminate warning lights on the dash.

Both the Ramp Down and Shut Down modes can be overridden by the driver if a switch is operated every 30 seconds, allowing a return to 70% of operating power. This could allow a driver to proceed safely to his destination, or at least to a safe position by the roadside.

Engine fuel control

There are sensors for air temperature, intake manifold temperature, and for oil temperature. Both are used to adjust the idle speed and fuel injection, to reduce white smoke emissions and improve cold starting. As well, there is a coolant temperature sensor which allows the ECM to measure engine temperature and also to trigger an over-temperature alarm. The fuel temperature sensor does not affect engine running but does provide an input in the calculation of fuel consumption. Similarly, the fuel pressure



The oil pressure sensor is used as an input to the engine protection system.

This sensor is designed specifically for fire truck operation & measures fire pump water pressure. The engine speed is then adjusted by the ECM to give a constant water pressure.

sensor provides an input for consumption calculations.

Fire pump pressure sensor

As you might imagine, this facility is only used on fire trucks, to monitor water pressure for the Pressure Governor System. This signal causes the ECM to set the engine speed to allow the fire pump to maintain a constant pumping pressure.

Perhaps the most crucial sensor is that for throttle position and this is a major area of difference to the control of petrol engines. Whereas the accelerator pedal for a petrol engined car directly controls the butterfly valve in the throttle body, the accelerator pedal for a DDEC-fitted diesel has no direct connection to the engine. The driver "demands" a certain amount of power by depressing the accelerator pedal but how much he gets is determined by the ECM.

In effect, this is a "fly-by-wire" system. One of its beneficial effects is that it stops the emission of clouds of smoke as a diesel truck accelerates – because the fuel is always precisely controlled, it can never be over-rich and therefore, smoke is minimised.

Timing sensors

Two timing sensors are used to control the fuel injection. The "SRS" – synchronous reference sensor – provides a 'once per cam revolution' signal, while the "TRS" – timing reference sensor – provides 36 pulses per crankshaft revolution. Both sense the rotation of a toothed cog (called a "pulse wheel") on the crank shaft. Working together, these sensors allow the ECM to sense which cylinder is at Top Dead Centre. Precise monitoring of piston position allows optimum injection timing.

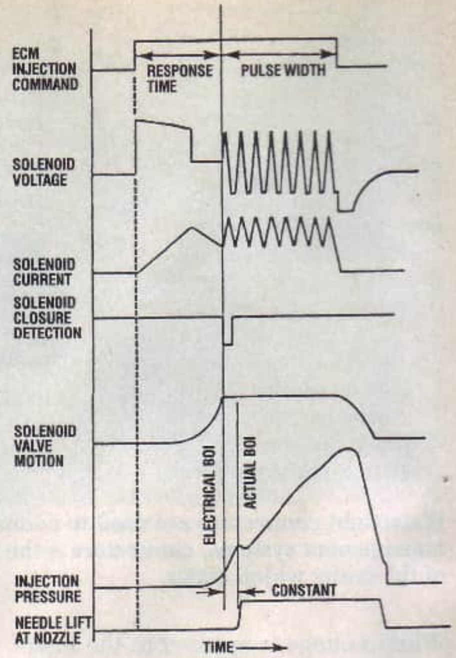


Fig.3: the relationship between the electrical events & injection. BOI indicates the Beginning of Injection.

Other sensors include those for **(1) vehicle speed** (for use with cruise control, vehicle speed limiting, and progressive engine braking); and **(2) turbo boost** (for monitoring the compressor discharge pressure, for smoke control during engine acceleration).

Control functions

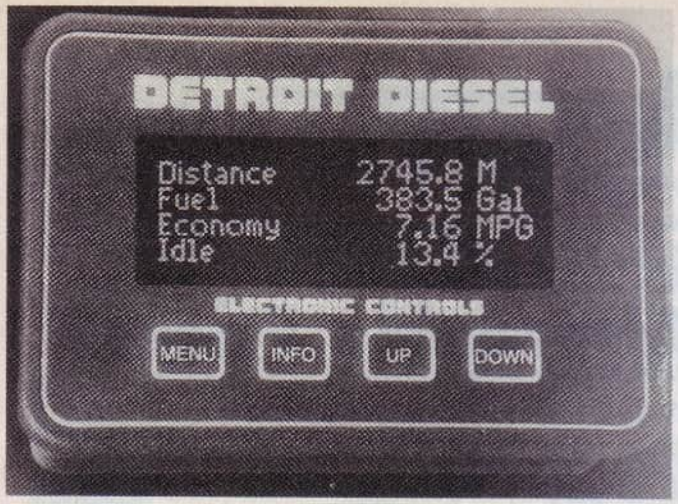
The fundamental variable controlled by the DDEC system is the engine fuel input. This is accomplished by the fuel pulse width and timing signals applied to the injectors. The ECM calculates a desired torque level based on the driver's throttle position and the engine RPM. The basic torque request and injection timing are modified during transients to control smoke and noise emissions.

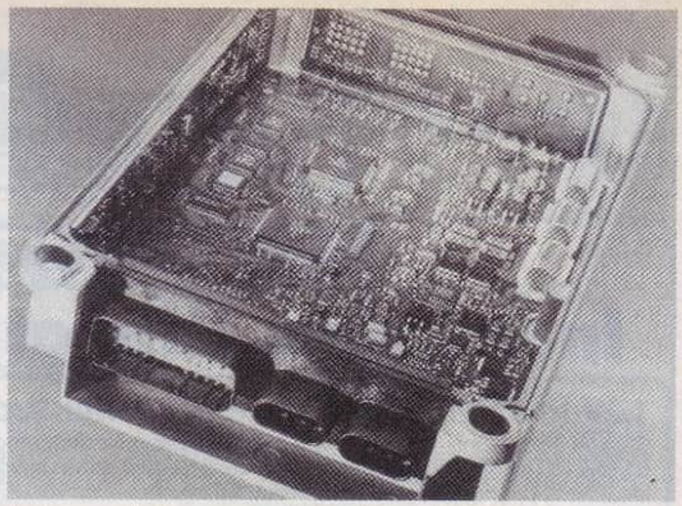
Several governing modes which modify the basic torque request are available to control engine and vehicle speeds. These are as follows:

(1) The **idle governor** – this provides fixed speed control over the whole of the torque capability of the engine. The idle speed is set as a function of engine temperature to provide optional cold idle boost. This controls cold white smoke suppression and provides faster engine warm-up.

(2) The **cruise control** – this in-

The Diagnostic Data Reader can be used to program factors such as the cruise control settings, vehicle ID number, engine power rating & vehicle speed limiting. It also can download engine faults logged in the ECM's memory.





Using the 'ProDriver' option, the DDEC system can also be interrogated via its dash-mounted data link. Fuel economy, trip distances & the number & status of logged faults can all be sourced from the engine management computer. The photo above shows the internal details of the electronic control module of the DDEC-III system.

cludes set, resume and coast features, as well as an acceleration mode which provides a fixed speed increase for each application.

(3) **Road Speed Limiting** – this enables the customer to determine the maximum vehicle speed attainable, independently from the engine-governed speed.

(4) **Engine Speed Limiting** – this provides a programmable maximum engine speed.

Once all of the modifications to the base requested torque have been calculated, a high precision torque to injector pulse width output calibration is performed to drive the injectors. The sensing of the beginning of injection interacts with the fuel rate algorithm to control noise and exhaust emissions. The fuel injection timing is carefully controlled during starting to reduce cranking times, allowing unaided starting down to ambient temperatures of -12°C.

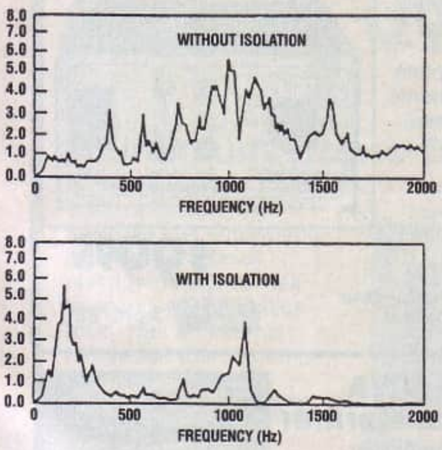


Fig.4: engine vibration spectrum, before & after the installation of elastomer vibration-suppressing mounts. The DDEC system is unusual in that the ECM is mounted on the engine.

User definable programming

Because the DDEC system is used on a variety of engines and trucks, the system must be programmed to suit each application. An EEPROM is located within the ECM and is programmed via the serial communication link. During engine assembly, and just prior to the final test, the ECM is interfaced to the factory scheduling computer to program the EEPROM to the specific sales order for the engine. Data such as the engine's horsepower rating, torque curve and maximum engine speed is downloaded.

Unlike any car engine management system, some aspects of the DDEC system can be reprogrammed by the customer, using a DDEC Diagnostic Data Reader, via a connector on the dashboard. This allows the following features to be customised: engine power ratings, variable speed governor, engine protection, cruise control, vehicle ID number, idle speed, engine braking and vehicle speed limiting.

Data logging

Part of the EEPROM is used for logging accumulated operating hours, fuel consumption, diagnostic codes and other cumulative information. By the use of an additional electronic module (dubbed 'ProDriver') and dedicated software, the SAE diagnostic data link can be used to extract information such as total distance travelled; average, shortest and longest trips; total fuel use and fuel used during idling, driving and cruising; and perhaps most importantly, the number and status of engine alerts.

The self-diagnosis function of the ECM can register intermittent and continuous faults and then display these via flashed codes on an in-cabin 'check engine' light. No less than 57 different fault codes can be registered, including any of the sensors being either too high or low in output, engine or vehicle overspeed, torque overload, slow injector response time, data link and EEPROM faults.

In short, while those large and imposing trucks and semi-trailers may seem like ponderous beasts, as indeed they are, underneath the bonnet they are often every bit as advanced as the best car engines. And, at least with the DDEC system, electronic circuitry plays an even greater role in providing information and control.

References

(1). Asmus, A. & Wellington, B., Diesel Engines and Fuel Systems, Longman Cheshire, 1992.

(2). Bosch Automotive Handbook, Third Edition, 1993.

(3). Detroit Diesel Series 60 – A Success Story, [pamphlet].

(4). Detroit Diesel Electronic Controls, [pamphlet].

(5). Electronic Diesel Engine Controls, SAE Collected Papers SP-819.

(6). Hames, R. (et al), DDEC II - Advanced Electronic Diesel Control, SAE Technical Paper 861110, 1986. **SC**