Electronic Unit Injectors & Unit Pumps  
(*EUI’s & EUP’s*)

**Introduction**

The demands for cleaner engine emissions, improved power, quieter operation and better fuel economy has helped inspire the development of even more efficient fuel injection systems. The unit injection system integrates the injection pump and nozzle into a single module. This means the functions of fuel pressurization; injection timing, atomization and fuel distribution are accomplished using one single component.

**Description and advantages**

Unit injectors are installed directly into the cylinder head above each combustion chamber. The injector is driven by the engine camshaft, most often directly through only a rocker lever as in the case of an overhead camshaft. This configuration is one of the most efficient hydraulic and mechanical fuel system arrangements providing the low parasitic losses. Actuating the injectors using an overhead camshaft permits the least amount of injection lag since there are no push-tubes to bend, injector lines to swell or delivery values to lift. The short distance pressurized fuel travels means an absence of injection lag due to high-pressure fuel wave propagation found in PLN systems. Eliminating injection lag provides for precise injection timing and facilitates the most valuable attribute of these injectors - the highest spray in pressures of any fuel injection system.

Presently, the highest injection pressures are only available from unit injectors. The largest injectors currently pressurize to over 30,000-psi. This is about 20% higher than current common rail injection systems. Unit injection systems with 33,000-psi pressures
are planned. However, these high spray–in pressures are dependent on engine speed. Plunger velocities must be at their fastest to achieve these pressures. Specialized construction features in the smaller automotive injectors provide good spray-in injection pressures during low speed operation. In older, heavy-duty diesel engine applications, electronic unit injector may be driven through a pushrod type actuating mechanism. Push rods will solid and short to minimize bending and flexing causing injection lag and timing variations.

The extremely fine spray produced by unit injectors results in the best combustion chamber atomization and fuel distribution. Conditions like this is permits more effective and leaner upper-cylinder combustion. Consequently, unit injectors can produce more power and torque for a given quantity of fuel without a penalty to fuel consumption and emissions. For example, Volkswagens 2004 100 hp 1.9 litres TDI unit injected engine delivers 10 per cent more power and 13 percent more torque over the electronically controlled radial piston distributor pump system it replaced. Even better is fuel economy increases 9% in city (46 to 50-mpg Imperial 6.2 l/100 km to 5.6 l/100 km) and 3-mpg highway (61 to 64-mpg imperial 4.6 l/100 km to 4.4 l/100 km).

Fuel droplet sizing of less than 20 microns allows for improved emissions characteristics. This includes less particulate matter (PM) hydrocarbons (HC) and carbon monoxide (CO). Finer atomization promotes tolerance of EGR flow into the combustion mixtures and the use of retarded engine timing for NOx reduction.

**EUI SYSTEM FEATURES**

**FEATURES**
- Virtually Adjustment Free
- Dealer Serviceable Components:
  - Injectors
  - Electronic Sensors
  - Harnesses
  - Connectors
  - Electronic Control Module

**BENEFITS**
- Faster Repair Turnaround Time
- No Reliance on Fuel System Shops

**Advantages of EUI’s**

Finer atomization produces better fuel economy and lower particulate emissions.
Construction of EUI's

Electronic unit injectors are mechanically pressurized using electronic control of governing, timing and metering functions.

A unit injector consists of several basic elements.
1. The spring-loaded plunger and barrel assembly to pressurize fuel inside the injector.

2. A poppet valve, known also as a spill control valve or solenoid needle valve that regulates the build-up of pressure inside the injector.

3. An electric solenoid or cartridge valve that actuates movement of the poppet valve or needle valve. Linkage such as a stator or solenoid pin may also directly connect the solenoid to the poppet valve in some injectors.

4. Fuel inlet and return passageways. The fuel inlet is supplied low-pressure fuel by the transfer pump. The return passageway permits fuel which has circulated through the injector to flow back to the supply tank. Since the injector is located in the cylinder head, and pressurization of fuel creates heat, it is important that a steady circulation of fuel passes through the injector removes heat.

5. The nozzle valve at the injector tip is like a conventional nozzle valve opening at 4,500-psi to 5000-psi in most injectors. This provides for improved atomization and crisp beginning and end of injection characteristics.

Below- Simplified operation of EUI's. An electromagnetically controlled spill valve opens and closes to determine the beginning and end of injection.
EUI Operating Principles

Injection metering and timing
Regardless of the type of unit injector, EUI’s share common operating principles. An electrical signal is sent to the unit injector’s solenoid-actuated spill/poppet valve system to deliver the correct quantity fuel at the precise time required to by ECM algorithms and fuel maps. Injection is accomplished by switching an integrated solenoid valve on and off. Injection delivery quantity is a function of both electrical signal time and plunger velocity. The time or duration the injector solenoid is electrically actuated is one factor determining the injection quantity. This means the longer a signal is applied to the solenoid, the greater the quantity of fuel injected. However, the faster the engine rotates, the greater the distance of plunger travel per unit of time. Consequently, more fuel is injected at higher engine speed if the time the solenoid is electrically actuated remains constant.

Above - Fuel is supplied to EUI's through drilled passageways in the cylinder head known as fuel galleries of rails.

The point when the injector solenoid is energized also determines the beginning of injection. Since injection timing is controlled electronically, the beginning and ending is completely variable.
Shown here is the unit injector in extremely simplified form. However, it is easy to understand how the injector works.

In this position, the piston is at its highest and the valve is open. Fuel flows through the injector and all of the spaces are filled with fuel.

The camshaft has pushed down the piston and the inlet is plugged. No injection will take place due to the fact that the valve is open. Fuel is forced out only through the piston outlet.

The solenoid is energized and the valve closes rapidly. The piston is still traveling downwards and the fuel pressure is rising rapidly. The injector needle opens at 4,350 psi, then the pressure increases still further to more than 22,000 psi. The fuel is injected in the form of tiny droplets or mist.

The injector must be relieved from the pressure of the fuel so that injection is discontinued very quickly and definitely. This is what happens when the solenoid is not energized and the valve opens again.

**Trigger pulses**

As you can see, the position of the valve determines whether injection will take place or not. Open valve - no injection. Closed valve - injection.

The position of the valve is determined in turn by whether or not the solenoid is energized. The valve is opened and held open by the solenoid. Power is supplied to the solenoid for only a few milliseconds. This short power feed is known as the trigger pulse.

The pulses determine two things:

- When injection should start (how many degrees BTDC).
- How long injection lasts, and how much fuel should be injected.
Overhead cam actuated unit injector and high-mounted cam actuated unit injector. The least amount of injection lag and highest pressurization is produced by overhead cam engines.

Major EUI Components

UNIT INJECTOR ACTUATION

- Electronic controlled unit injector
- Rocker Arm
- Push Rod
- Oil Passages
- Swing Arm Roller Follower

Cartridge Assembly

- Solenoid
- Armature
- Poppet Spring
- Poppet Valve
**Suction (Fill) Stroke**
Fuel passages integrated into the cylinder head supply low-pressure fuel from the supply/transfer system to each injector. Supply circuits are arranged to ensure consistent fuel temperature between injectors.

Fuel flows into internal passageways and the pressure chambers within the injector to cool the injector and purge any vapour from the fuel circuits.

The injector plunger, driven by the camshaft, moves through a stroke fixed by the injector plunger travel adjustment. On its upward stroke, the low-pressure fuel supplied to the injector fills the cavity created beneath the plunger. Fuel can enter this cavity through the open spill, poppet or needle valve.

**Main Injection**
The injector plunger will begin its downward stroke and fuel below the injector plunger will be forced out of the injector through the fuel return passageway. Without a signal from the ECM to the solenoid the plunger will bottom out it stroke and the suction cycle will repeat with no pressurization or delivery of fuel.

When the ECM does send an electrical signal to the solenoid, the poppet, spill or needle valve will close the fuel return passageway causing trapped fuel to pressurize beneath the injector plunger. As the plunger continues its downward stroke, fuel pressure builds in the high-pressure passages, the nozzle valve opens and fuel injection begins. Maximum injection pressures occur near the end and not the beginning of the plunger travel, this point usually coincides with the time the solenoid valve is de-energized.
**Residual Stroke**
Injection will continue until the solenoid is de-energized. This will allow the spill control valve to open thus, causing the pressure to collapse beneath the plunger. Fuel beneath the plunger vents to the return passage, consequently, the nozzle valve will close abruptly, terminating injection.

**EUI Adjustment**
Adjustment of plunger travel is required for EUI’s. The adjustment ensures the plunger travel is almost bottomed out when the camshaft is on its outer base circle or crown. Adjustment procedures vary between manufacturers. Adjustment is performed according to a maintenance schedule. Newer linkage designs connecting the plunger to the rocker lever minimizes wear leading to adjustments that are more frequent. Rather than have a rocker arm slide across the face of a plunger, linkage is designed to pivot with a minimum amount of friction.

---

Above – Adjusting plunger travel is a critical adjustment made to EUI’s.

**Safety of unit injection**
Unit injection systems are not likely to be involved in run-away engine operation like mechanically governed systems are. In the event of an injector malfunction, only one
uncontrolled injection can happen. For example, if the solenoid valve remains open, no injection can take place since the fuel flows back into the fuel return circuit. Since the valve is open, it is also impossible to cause pressure to build below the plunger. If the solenoid or poppet valve is stuck closed, no fuel can enter the high-pressure chamber. In this instance, only a single injection can take place.

**Electrical signal processing**

The EUI with the ECM achieve precise injection timing and fuel quantities using principles of electronic signal processing. Sensors collect data regarding engine position and operating conditions (i.e. intake, fuel, oil, and coolant temperatures, boost pressure engine speed and others), as well, driver demand. The ECM collects and processes the data based on operating algorithms and fuel maps stored in memory to decide what the exact injection timing and fuel quantity are necessary to realize optimal performance, emissions and fuel economy.

**Pulse width modulation (PWM)**

There is a variety of output signals produced by the ECM but, the signal operating the EUI’s is especially unique. Driving the injector solenoids is a signal type known as a pulse width modulated (PWM) signal. This refers to a pulsing DC voltage signal that either is on or off which gives it a digital characteristic. However, unlike digital signal which are only in one of two states (on or, off, yes or, no, hi or low, one or zero), PWM signals vary in the amount of time they are on or off. This means current to the solenoid will be switched on and then off for varying amounts of time, typically measured in milliseconds.
Current Ramping and Injector Response Time.

Another feature of the PWM signal is the use of a peak and hold current shaping strategy to operate the solenoid. This is necessary to accommodate the electrical characteristics of the solenoids. When coils are energized to produce magnetic fields, the expanding magnetic field induces current flow in the opposite direction of current producing the magnetic field. Consequently, injector solenoids exhibit high resistance during magnetic field build-up when current is initially applied. This resistance is known as reactive resistance or inductance. Reactive inductance refers to the high electrical resistance of a coiled wire when current is initially applied. High resistance to the ECM electrical signal is meaningful because it causes a delay in poppet valve closing or the beginning of injection (BOI). Slow poppet valve response to the electric signal results in injection delay, injection timing variations between cylinders and shot-to-shot delivery quantity variations. The delay can be easily as much as 15 milliseconds, which at high engine RPM, can cause substantial discrepancy between calculated and actual injection timing.

![Diagram](image)

Until the magnetic field is stationary, the solenoid coil will have significant resistance. To overcome this, higher voltage shortens the time required to build and stabilize the magnetic field. After the magnetic field has stabilized, less current is required to overcome injector coil resistance and keep the poppet valve closed. Maintaining the current at high levels after the magnetic field is stabilized would only overheat the coil. Therefore, the ECM will drop the current flow to the injector.

Manufacturers monitor response time to injectors in order to make adjustments to timing for each cylinder. To accomplish this, a couple of techniques are used. One involves the ECM measuring the time it takes for current to rise to its desired value. To do this, the ECM will monitor the voltage applied to the injector for instance, to the negative lead of
the injector and compare it to the return value on the positive lead as current returns to 
the ECM. In other words, the voltage drop across the injector is measured to learn when 
the coil is least resistive and the time it takes to arrive at this value. The delay factor 
between the time the electrical signal is applied to the injector coil and the time it takes to 
rise to the required value is the injector response time. When the voltage rises to a 
predetermined value, the ECM assumes the poppet valve has closed and injection can begin. Response time measured by the ECM is used to calculate the time when the next 
injection signal is applied to the solenoid in order to correct for the delay factor caused by 
reactive inductance. So, if the response time is 5-milliseconds of injection delay, the 
ECM will send the electrical signal 5-milliseconds sooner for the next injection.

Manufacturers typically use 70 -110-volts DC PWM current to operate the injector. 
While this voltage is not sustained for the duration of injection, it can reduce the length of 
response time. Injectors using 12-volts to operate have longer response time. Injector 
response time is an important piece of diagnostic information. If injectors have different 
resistances, bad connectors or become overheated, their response time will lengthen. 
Monitoring response time indicates whether there may be a problem with an injector 
circuit.

Injector response times are expected to vary from injector to injector at a given rpm. 
However, each individual injector response time should remain relatively consistent from 
one cylinder firing to the next. Wide variations in response time (typically ± 0.2 
milliseconds) for one injector, at a steady engine rpm may indicate an electrical problem. 
This could include a faulty alternator emitting excessive AC voltage ripple, poor or 
broken ground connections, or binding solenoid components.

Below - Detroit Injectors. The newer N3 has a faster response time due to a lower 
mass poppet valve, smaller coil windings and higher voltage.
Bosch UIS injectors have a different method to calculate response time. Their injection response is designated as the Beginning of the Injection Period, (BIP). This corresponds to the closing of the solenoid-valve needle. When the needle valve closes, it affects the magnetic field reluctance of the solenoid that in turn produces a slight change in coil resistance. The ECM can detect this change of current through the solenoid windings using a BIP detection circuit. Using this data, the actual start of delivery is corrected for timing the next injection event.

Bosch UIS Injector - VW TDI Pumpe-Duse The retractor piston creates special rate shaping capabilities by changing the needle valve spring tension. Fuel pressure is also used to hold the needle valve hydraulically onto the seat.

Rate shaping technology.
Rate shaping is easily accomplished electronically in the designs of the newest EUI’s injectors. The problem encountered to rate shaping using older injector technology was the size, weight and inertia of poppet valve and cartridges. Newer injectors use smaller, low mass, low inertia solenoids and poppet valves. This permits the solenoid and poppet valve to operate faster to achieve electronic control of rate shaping.

The electronic controls can now cycle the injectors up to 10,000 times a minute, completing a full cycle in 1 to 2 milliseconds. The actual injection of fuel takes approximately 10 micro-seconds (1/1000 of a milliseconds) The newest injectors can accomplish five separate injection events all controlled electronically. Not all of these however, will take place during one injection sequence. Two or three will normally take place in one injection sequence.
1. Pilot Injection
2. Main Injection Step One
3. Main Injection Step Two
4. Main Injection Step Three
5. Post Injection
Trim Codes
Since variations between flow rates of injectors can occur due to manufacturing tolerances, identical injectors can deliver different quantities of fuel despite using the same length of PWM signal. This produces emission problems and cylinder imbalance conditions. To correct this condition, manufacturers will flow test all injectors and compare them against a nominal standard value. Depending on whether the injector flows more or less fuel, an alphanumeric value is applied to the injector. This fuel trim code value is entered into ECM injector data where adjustments to fuel flow can be made electronically. The values can be very elaborate with some manufactures. Accompanying Caterpillar ACERT service injectors is a CD containing injector information. This data is entered into ECM computer memory when the injector is replaced to provide accurate fueling information which is unique to the injector.

Location of the calibration code for a DDEC injector. This information must be entered into the ECM when replacing or moving and injector. Rough running and low power complaints will result from incorrect trim code information.
Delphi EUI trim code (DDEC V)
Another example of electronic correction of response time and fuel flow factors is Delphi unit injectors. On top of their injectors is a five letter code. This code is used by the ECM to calibrate flow through the injector. Once again, each injector is tested after it is manufactured and is measured against a nominal start of injection point, end of injection point and an idle quality factor. (See graph depicting how this alpha code is used to change fueling data for the EUI).
The first two letters of the alpha code refer to the response time comparing a nominal injector to the measured injectors start point. The second two letters in the alpha code refer to the end of the injector’s response time. The tolerance band for the start and end of injection is ± 127mS (0.000127 seconds). The last letter in the alpha code is a measured variance in idle performance. The injector is given one of three idle letters: A, B or C to qualify idle performance.

The alpha codes used for both the start point and the end are not sequential, i.e. not AA through to ZZ. The codes have been picked at random to minimize the probability of intentionally over-fuelling of the engine to enhance power output.

The code does not indicate that one injector is better than another. The code simply provides the ECM with a mapping adjustment needed for that particular injector, enabling very precise fuelling and smooth idle performance.

It is critical that the injector code is programmed into the ECM if an injector is replaced, or reinstalled in another cylinder.

Injector Failures

Water contamination
Water contamination is the greatest concern because it is the most common form of contaminant. Water may be introduced into the fuel supply during fuelling when warm, moisture laden air condenses on the cold metal walls of fuel storage tanks or dissolve into the cooler fuel. The effects of water in diesel fuel can be serious. Since water cannot pass easily through nozzle orifices, water can accumulate, vaporize and then cause a tip to blow off an injector. Water causes galling and seizure of injector plungers since it disrupts the lubricating film strength of fuel. Water can combine with sulphur in the fuel to form corrosive acids.

Missing injector tip
Above - Seized injector plunger also caused by water contamination.

Above - Water causes plunger seizure by displacing the lubricating diesel film surrounding injector plungers.
Dirt
Dirt can cause premature wear and shortened injector life. The spill or poppet valve is easily scored, worn and damaged by the continuous abrasive action of dirt. While most filters can remove particles down to 10 microns in size, the most damaging dirt particles are between 6-8 microns in size. Micro-glass filters are the preferred filter medium for EUI’s. These filters have a nominal rating of 2 microns at 90% efficiency.
Worn poppets cause low-power and misfire complaints

Fuel temperature
Diesel fuel provides cooling of the injection system. However, the temperature of the fuel may vary considerably due to engine operating temperature. As fuel temperature increases, fuel viscosity decreases, along with the lubrication capabilities of the fuel. When the system is operated with elevated fuel temperatures, the injectors will operate at reduced internal clearances. As a result, dirt and smaller particulate material may cause
injection durability concerns. Installing a fuel cooler or operating with fuel tanks above half-full may also help eliminate concern. Maintaining proper fuel temperatures will help provide proper fuel injection system functioning.

**Testing EUI's**

Bench testing of EUI injectors is not practical in the field. If an injector is suspected defective, performing a cylinder cut-out or contribution test can identify the bad injector. Using manufactures diagnostic software, a cylinder cut-out/contribution test involves cutting out (removing an electrical signal to) one or, pairs of cylinders at a time to determine what difference is made to engine performance. If an injector is defective or a cylinder is making little contribution, the crankshaft speed as measured by the crank or cam position sensor will slow down during the power stroke of that particular cylinder. The value of the speed change is compared to other cylinders to calculate a percentage of cylinder contribution. 100% would be considered an ideal value. A cylinder contributing more than 100%, while not necessarily defective, is probably slightly over fueling. Cylinders contributing 0% or less may likely have a defective injector or some other mechanical defect.

Alternatively, software can measure the change in fueling to other injectors required to compensate for a cut-out cylinder. For example, a defective cylinder when cut-out would not require the ECM to increase fueling to the remaining injectors to maintain engine speed. However, a good cylinder, when cut-out, will require fuel compensation by the remaining cylinders to maintain engine speed. The software can measure the changes to fueling as each cylinder is cut-out to calculate the relative contribution each cylinder is making to engine output.

If no software or electronic service tool is available to measure cylinder contribution, an infrared, non-contact thermometer is a helpful diagnostic tool. After speeding the engine to mid throttle position or higher, (if practical and after following safety precautions), the temperature of each cylinder at the exhaust manifold is measured. Underperforming
cylinders will register lower temperatures in comparison to good cylinders. At least a 70-100 degree variation between cylinders should be observed before suspecting any defect.

An injector swap can be done between a suspected injector and a known good injector to differentiate between a defective injector or some other cylinder condition.

**Future - Variable nozzle unit injector**

Bosch is presently working on a further development of their unit injection system (UIS) called the Coaxial Variable Nozzle UIS. It promises to make the diesel engines even quieter and cleaner burning through enhanced abilities to rate shape injection over wider engine speed and load conditions. The arrangement, number, diameter and shape of the injection spray holes distinguish the variable nozzle from the conventional unit injector. The injector uses an electrically operated solenoid valve however, it operates two nozzle valves sharing a common axis or, coaxial. The nozzle valves open two rows of spray holes. A lower set of spray holes delivers fuel at a small injection rate at the start of the combustion process. Like pilot injection, this set of orifices produces a gentler, less noisy, combustion pressure rise. Under light load operation, mixture formation improves resulting in significantly reduced emission levels. Evaluation of emissions demonstrates particulate and nitrogen oxide reductions of between 25 and 40 %. A second row of spray holes with a higher flow rate are opened when injection delivery volume increases. This configuration permits the use of pre-injection over a wide range of engine speed and load conditions, resulting in lower particulate emissions.

**Electronic Unit Pumps (EUP’s)**

Also referred to as a unit pump system (UPS), unit injection pumps combine elements of pump line nozzle injection systems and unit injectors. Each cylinder will use a separate engine camshaft driven high-pressure pump to pressurize fuel for injection. Connecting the pump to the nozzle is a high-pressure fuel line. The pump operates using principles similar to the unit injector. A roller reduces friction between the pumping element and dedicated camshaft lobe. EUP injection systems have permitted the adaptation of high pressure electronically managed injection system to engines previously using inline pump injection systems without extensive engine modifications.

Control of the solenoid by the engine ECM is identical to the unit injector. Slightly lower injection pressures are used by EUP’s and the use of the line prevents the use of electronic rate shaping the unit injectors are capable of. Metering and timing of the fuel is regulated by the electronic engine management system, which actuates the solenoid poppet control valve to stop the free flow of fuel through the injector unit pump. When the solenoid poppet valve closes, fuel is trapped in the injector unit pump plunger.

Fuel supply to each EUP is provided by a low-pressure supply transfer system. The supply fuel pump delivers fuel at low pressure to the fuel filter, then to the individual fuel injection pumps. The continuous fuel flow through the injector unit pump
prevents air pockets from collecting in the fuel system and cools those injector unit pump parts subjected to high combustion temperatures. A fuel return line collects unused fuel circulating through the pumps and empties it back into the fuel tank.

The use of the flange mount on the side of the engine block above the camshaft provides for convenient of service or field replacement of pumps.

Electronic Unit Pump