Common Rail Injection Systems.

As always emission control legislation is the driving force behind all injection system innovations and one of the latest of these is high pressure common rail injection systems. One inherent problem with most injection systems is the lack of control of injection pressures. For years injection pressure has been tied to engine and by extension pump plunger speed or velocity. The faster the pump plunger moves the higher injection pressure will become. The beginning and ending of the injection pulse was also a concern. With NOP values of approximately 4,000 PSI and nozzle closing values of approximately 3,000 PSI injected droplet sizing at the start and end of the injection event tend to be larger and harder to burn completely causing more particulate matter and VOC emissions. Ideal injection pressures of approximately 25,000 to 35,000 PSI produce very small droplets which are much easier to burn completely. In conventional systems these pressures were only achievable at certain times such as when delivering large quantities of fuel at relative high plunger velocities usually somewhere near peak torque. Just as the HEUI systems before them have done Common rail systems separate injection pressure from engine speed allowing optimum injection pressures for any given engine operating condition. Common rail goes further than the HEUI however by using Electro-Hydraulic injectors that do not have fixed opening and closing pressures, all but eliminating the larger droplet sizing at the beginning and ending of the injection pulse.

The common rail system is also one of the simplest systems available, easily adapted to any OEM engine and the components needed for any installation are the same, they are; the high pressure pump, the Accumulator Rail, the rail pressure sensor, the rail pressure control valve and the injectors.
There are two types of pumps in use: the radial piston style pump and the inline multi-plunger pump. The radial piston type pump has three ceramic pumping elements evenly spaced at 120 degrees apart around an eccentric cam shaft as the shaft rotates driven by the engine timing gear train. Each element is actuated once during one revolution. The pump is designed to be able to create maximum rail pressure approximately 22,500 to 26,700 PSI at speeds just off low idle and therefore its capacity far exceeds engine requirements at higher speeds. In order to reduce parasitic losses, one of the elements can be shut by holding open its one-way check valve when it is not needed.

When the pump plunger moves downwards, the inlet valve opens and fuel is drawn into the pumping-element chamber (suction stroke). At bottom dead center (BDC), the inlet valve closes and the fuel in the chamber can be compressed by the upwards moving plunger.
The second type of pump is an inline plunger style pump so far two piston models are being used by CAT International and in the Bosch FACR systems, (Fuel Amplified Common Rail), more on this later. Again the pump is driven off the engine timing gear train and can be driven at engine speed or at camshaft speed depending on the system. The inline multi-plunger pump has a gear type supply pump coupled to it and driven by the plunger pump drive shaft.

The accumulator rail is the receiver that the pumps unload to. It holds fuel at injection pressures that are commanded by the engine ECU. At idle this pressure may be as little as 8,000 PSI but can be increased to as high as 27,000 PSI in some systems when the engine is under load. The rail operates as an accumulator meaning that its volume is much greater than it needs to be so that when fuel leaves the rail for an injection event the amount is small enough compared to the total rail volume that rail pressure holds relatively constant.
The rail pressure sensor is a variable capacitance sensor that measures actual rail pressure. It is one half of a closed loop feedback system to the engine ECM. The other half of this feedback loop is the rail pressure control valve.

The rail pressure control valve is a pulse width modulated control valve that the ECM uses to control rail pressure. The valve consists of a linear proportioning solenoid, the strength of which is varied by the ECM by precisely controlling current flow through its coil with pulse width modulation. That means that the ECM manages the duty cycle or on time of the solenoid current to control rail pressure. The closed loop cycle is as follows: the ECM commands a certain desired rail pressure by sending a given PWM signal to the rail pressure control valve then reads the signal from the rail pressure sensor. If actual rail pressure doesn't match desired rail pressure, the ECM alters the PWM signal until it does. This closed loop gives the ECM absolute control over rail pressures.
The Caterpillar inline pump system uses a slightly different method to control rail pressures. A solenoid on the top of each pumping plunger is controlled by the ECM to direct pump fuel either to the low pressure return line system to the tank or to the high pressure rail. By monitoring rail pressure and controlling the solenoids, precise control over rail pressure is achieved.

Electro-hydraulic injectors were first controlled by solenoids but in the latest generation they are controlled by piezo-electric actuators, more on the actuators later. Electro-hydraulic injectors are injectors that use hydraulics to control the opening of the needle valve and therefore do not rely on spring pressure to set NOP. The needle valve in these injectors is held closed by a combination of spring and hydraulic forces. When the needle valve is closed the pressure that exists in the common rail is present in a control chamber above the nozzle. This pressure acts on a control piston that physically holds the needle in the seated position.
The rail pressure is also acting on the needle valve annular area in an attempt to open it however the surface area of the control piston is much larger that the valve annular area so the needle remains closed.

When injection is desired the ECM sends control voltage of approximately 100 volts to the injector actuator which in turn controls a very small orifice drain for the fuel pressure above the control piston. Opening this drain allows the pressure above the control piston to drop allowing the ever present pressure pushing the needle valve to open the valve and injection begins at whatever pressure there is in the rail at that moment. When injection is complete the ECM stops the signal to the actuator and the drain closes. Pressure immediately builds up on the control piston which drives the needle valve shut so injection ends without the characteristic pressure drop and droplet sizing remains optimum.

Solenoid operated actuators were used in the first generation of these injectors. They were capable of split shot injection to reduce engine noise and in some cases multi-pulse injection. Actuator speed was limited however by self induction of the coil when the actuator was turned on by the ECM. Self induction means that as the magnetic field is building in the coil its lines of force are cutting through the coil winding until the coil is saturated. This induces a current in the coil whose direction of flow is opposite to the flow that created the magnetic field so this current opposes the actuation current and delays coil saturation and actuator functioning.

Second generation electro-hydraulic injectors now use piezo-electric actuators. These actuators work on the principle of piezo-electricity. A piezo electric crystal when subjected to pressure creates an electric current you have seen this effect if you have ever used a B-B-Q lighter that you click and a spark is created. Researchers have found that this effect is reversible that is if a current is applied to a piezo crystal that it is deformed slightly. Piezo-electric actuators consist of a stack of hundreds of crystal wafers that hold the drain valve closed in the electro-hydraulic injector when the ECM commands injection it sends a 100 volt signal to the actuator and the stack deforms enough to open the drain causing injection to begin. At the end of injection the current is removed and the stack returns to its normal shape closing the drain and allowing the pressure to build on the control piston slamming the needle valve shut.
Piezo-electric actuators do not build a magnetic field and therefore have no self induction delay as the solenoid actuators do. This increases actuator speed and allows the ECM to break the injection pulse into as many as seven separate injections during one cylinder firing cycle. This gives the ECM the power to precisely control combustion chamber pressure during the injection event to optimize engine and fuel efficiency.

There several other components on common rail systems most are the same as found on other Full Authority controlled engines such as sensors and actuators etcetera however two important extras are found on most common rail systems. Number one is a rail pressure limiter basically a high pressure relief valve should rail pressure exceed the pre-designed maximum pressure this valve will open and return excess fuel to the tank.

The second item is a flow limiter to limit maximum fuelling to any injector. Should something happen to cause the injector to stick open the engine would potentially over fuel that cylinder causing an engine runaway. Flow limiters are installed between the rail and the injector lines that function in such a way that if the fuel flow to any one injector exceeds a maximum limit the flow limiter will close and flow to that injector will stop.
One problem associated with common rail systems is that the constant high pressure that is present in the system can lead to leaking. Also twin actuator EUI systems are boasting injection pressures of 32,000 to 35,000 PSI and are the large bore highway engine system of choice for today, for common rail to increase to those pressures would necessitate much more robust components. A new development to address this problem has recently been developed however and that is Fuel Amplified Common Rail or FACR.
Fuel amplified common rail systems use a hydraulic amplifier to double injection pressures compared to rail pressure that is a rail pressure of 15,000 PSI will be injected at 30,000 PSI without subjecting the entire system to the higher pressure.

The drawing below is from a patent application for an FACR System the amplifiers are item 16 in the drawing.
Detroit Diesel Corporation is boasting injection pressures of up 45,000 PSI using FACR with plans for pressures to increase to as high as 60,000 PSI in the future. The FACR amplifier is a completely hydraulically operated system that is that it only functions when fuel is actually flowing from the injector. When the injector actuator opens and fuel starts to flow the fuel rushing through the amplifier through the high pressure passage 74 and then 95 in fig. 3 it is communicated to passage 110, Fig 4. The flow area represented by the clearance between piston 84, (Fig 4 and 5) and passage 112, (fig 5) creates a desired drop in pressure in passage 108, (fig 5) and the outlet passage 68 (fig 3). This passage is communicated by passage 111, (fig 4) to the top of piston 86, (fig 4). The higher pressure at the bottom of piston 84, (fig 3,4 and 5) forces piston 84 upwards seating the ball 82, (fig 4) in the up position.
When the ball is in this position it exposes the lower end of the amplifier piston 90, (fig 3) to passage 105 which is communicated to the fuel return passage 62, (fig 3) this causes rail pressure to force the amplifier piston downwards. This motion pressurizes the fuel in the High pressure chamber 74, (Fig 3) to be amplified by a ratio of two to one. The upward motion of piston 84 also opens the flow gap 112, (fig 5) to remove restriction to flow. When the injection ceases the pressure equalizes on the top of piston 86 and the bottom of piston 86, (fig 4) and the larger surface area of piston 84 causes the ball 82, (fig4) to return to its lower seat. This allows rail pressure to once again occupy the area beneath the intensifier piston 91, (fig 3) and with the pressure above and below the piston equal the return spring moves the piston up to its starting position.

These systems are touted to be the injection system of choice for OEMs in the future however as with any emerging technology the proof will in the pudding so to speak so time will tell if they are the answer to our latest efforts at gaining more control and efficiency from the diesel engine.

**NOTE:** Engines are either equipped with an air cooled or fuel cooled ECM. If an air cooled ECM is used, the fuel enters the engine from the OEM connection at the gear pump inlet.