Injection Strategies for Compression Ignition Engines
Part II: Pilot, Split, and Interacting Sprays Injections

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In the first part of this series the basic operation and the logic behind the "common-rail injection" system were briefly discussed and advantages/disadvantages were listed. It was indicated that with this injection system pilot and split injection strategies can easily and efficiently be accommodated. In part II, the logic behind the pilot and split injection is described. However, before such a description it is useful to briefly discuss the three phases of the combustion process in a diesel engine.

The combustion process in a compression ignition engine starts with the beginning of the injection (BOI) process, see Fig. 1. This figure shows the rate with which the heat is released in the combustion chamber as a function of the crank angle. Because the fuel is injected into an air with a temperature (and pressure) above the ignition point of the type of fuel used, spontaneous ignition (autoignition) of the portion of the mixed vaporized-fuel and air occurs only after a delay period called "ignition delay" time. The mass of the charge ready to burn at the end of the delay period is important both for smooth operation and lower nitric oxides (NO_x) emission levels. Hence, it is highly desired to attain a short ignition delay period for the type of the fuel injected, an attribute to be avoided in homogeneously-charged spark-ignited gasoline engines due to the knock phenomenon. Immediately after the ignition delay period, all the fuel that was vaporized and mixed with the air burns in what is referred to as the "premixed burn phase" of the diesel combustion process. The remainder of the liquid fuel is consumed as it is being injected, atomized, vaporized and mixed. This phase of the combustion, being the major portion of the total, is controlled by the mixing process and is named as the "mixing-controlled combustion phase." Hence, the overall rate of combustion process is mixing-controlled in diesel engines. The higher the amount of the charge ready to almost-spontaneously burn at the end of the ignition delay period, the stronger the impact of this phase is felt by the engine. This is commonly referred to as "diesel knock," indicated by an audible sound and rough engine operation. Also, it is known that the amount of NO_x produced by the burned gases (primarily) depends on temperature and the time duration. Hence, the early burned charge masses have more time to produce NO_x than those that burn towards the end of the combustion process. Although further mixing of the burned gases with the available in-cylinder air blurs this logic to some degree, positive correlation between the tailpipe NO_x emission levels and the mass of charge ready to burn at the end of the ignition process has been observed. To have some degree of control over this early burned masses, variety of injection strategies such as fuel injection rate shaping, pilot injection, and split injection strategies are employed.

In essence, in pilit or split injection strategies, instead of injection of the total mass of fuel in one continuous event, it is divided into two or three isolated individual injections per cycle. In pilot injection strategy, there are only two injections and the quantity of the pilot is relatively small and the interval between the pilot and main injections is short. On the contrary, the quantity of the fuel to be injected is relatively larger and the interval between the injections is longer. Up to three individual injections per cycle have been used for split injection strategy. However, the distinction between the pilot and split injections is usually made by a relatively smaller amount of the fuel injected during the preinjection in the former case. Common-rail injection system (see Part I) combined with a suitably designed injector can easily accommodate both strategies. In the case of pilot injection scheme, the flame formed by the preinjection (i.e. first small injection) is explained to act as an ignition source for the succeeding main injection. In the split injection, the ignition caused by the preignition itself is believed not important but the activation in the environment of combustion chamber caused by the preinjection is.

The following advantages and improvements were observed by the use of multiple injections in advanced diesel engine:

- Dual fuel capability

- Eliminates diesel knock
- Improves cold startability and white smoke
- Systems at sufficiently high injection pressure combined with the pilot or split injection showed a potential for simultaneous reduction of NO_x , smoke and particulate with minimal adverse effects on brake specific fuel consumption (BSFC)

Table 1 shows numerical results in one case indicating the degree to which such improvements were achieved.

Finally, although most multiple injection studies were performed using a single injector, some recent works employed two to three separate injectors, strategically located in a cylinder of multi-valved diesel engines. These systems although expensive and complex, prove the concept that forcing individual fuel sprays and/or jets interaction or impingement can provide more flexibility in attaining additional benefit, for example see, interacting-sprays injection by *Chehroudi et. al*, SAE paper 960839, and its variations by *Nakagome et. al*, SAE paper 970898 and *Akagama, et. al*, SAE paper 1999-01-0183.

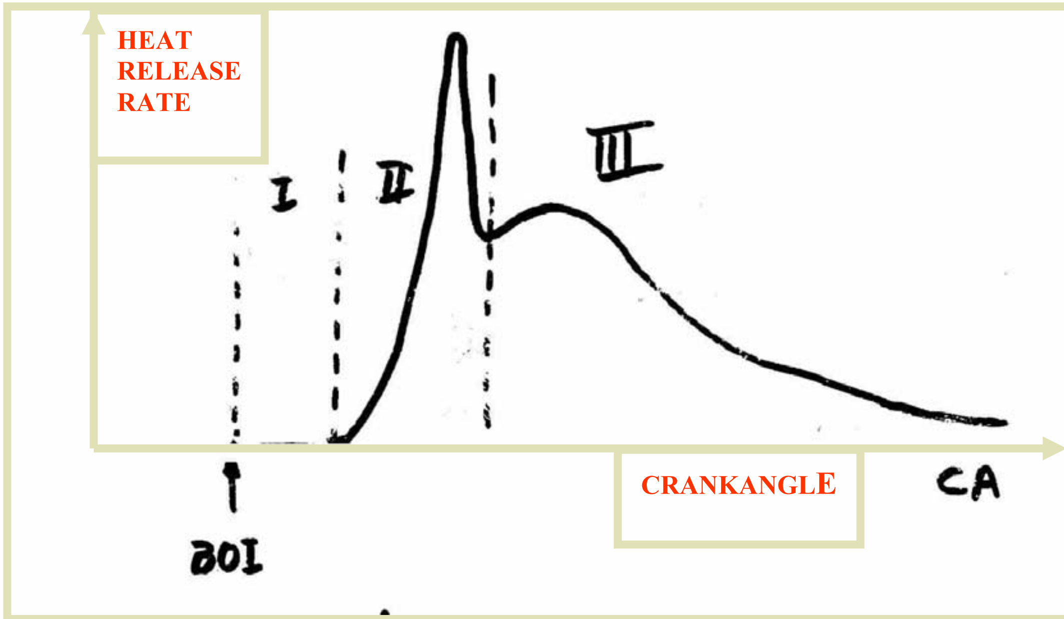

Figure 1. Three phases of the combustion in a direct-injected diesel engine. I. IGNITION DELAY PERIOD, II. PREMIXED COMBUSTION PHASE, III. MIXING-CONTROLLED COMBUSTION.

Item	Benefits
Combustion Noise Reduction	−4dB (Cylinder Pressure Level)
	90 dBA ➡ 81 dBA
NOx Reduction	Possibility to Reduce Certain Percent at Same BSFC
Cold Startability	25 sec ➡ 8 sec at −15°C
White Smoke Reduction	63 sec ➡ 5 sec (Fade Away Time at −5°C)

Figure 2. Improvements observed by multiple injections on engine noise, NO_x emission, cold startability, and white smoke. From *Osuka, et. al*, SAE Paper 940586.