Effects of pilot injection timing and EGR on a modern V6 common rail direct injection diesel engine

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Abstract. Nitric oxide and smoke emissions in diesel engine can be controlled by optimising the air/fuel mixture. Early injection produces premixed charge resulted in simultaneous NOₓ and smoke emissions reduction. However, there could be an increase in hydrocarbons and CO emissions due to fuel impinged to the cylinder wall. The focus of the present work is to investigate the effects of a variation of pilot injection timing with EGR to NOₓ and smoke level on a modern V6 common rail direct injection. This study is carried out at two different engine load conditions of 30 Nm and 55 Nm, at constant engine speed of 2000 rpm. The results show that the early pilot injection timing contributed to the lower smoke level and higher NOₓ emissions. The higher level of NOₓ is due to higher combustion temperatures resulting from the complete combustion. Meanwhile, the lower smoke level is due to complete fuel combustion and soot oxidation. The early pilot injection timing produces an intermediate main ignition delay which also contributed to complete combustion. The formation of smoke is higher at a high engine load compared with low engine load due to the higher amount of fuel being injected.

1. Introduction
In direct injection diesel and compression ignition engines, the start of fuel injection (SOI) influences the fuel-air reaction rates and combustion behaviour [1-2]. A number of studies have been carried out aiming to promote premixed lean charge and minimise diesel engine emissions [3-7]. This is due to the improved premixed combustion leading to low combustion temperatures and condition favourable for low NOₓ and PM emissions. Several studies have revealed that the pilot injection strategy produced a shorter ignition delay on the main injection thus contributing to the lower emissions [8-12] and cleaner combustion process [13-14].

In diesel and compression ignition engines, ignition delay and combustion phasing are amongst the main parameters influencing emissions formation and engine performance. Long ignition delay
promotes premixed uncontrolled combustion which can lead to knocking and high combustion noise [15-19]. Murari Mohon Roy and Hideyuki Tsunemoto studied the effects of injection pressure (200 - 1200 bar) and split injection on emissions and engine noise using a common rail four-stroke multi cylinder 7.7 L direct injection diesel engine. The results showed that the proper post-pilot injection strategy has a significant improvement in the emissions and engine noise [20]. Keiichi Okude et al. investigated the effect of multiple injections of engine performance and emissions using a single-cylinder engine 0.744 L. The results showed that the multiple pilot injection substantially reduced HC and CO emissions [9]. A. Vanegas et al. used a 4-cylinder common-rail diesel engine to study the effect of multiple injection on emissions. The overall results showed that the NOx emissions from the split injection strategy were significantly lower compared to the single injection strategy [14]. D. T. Hountalas et al. demonstrated that the cooled EGR is favourable for NOx reduction [21]. Siddappa et al. utilised a single cylinder direct injection engine to study the performance and emissions at different injection pressures and injection timing fuelled with diesel and biodiesel. According to their experimental results the higher injection pressure produces improved engine performance and emissions in terms of smoke, HC and CO but NOx emissions were slightly increased [19].

From the literature review, it was concluded that the effects of variation of pilot injection timing on engine performance and emissions of a diesel engine can be further investigated. Moreover, the influence of the pilot injection timing on the main ignition delay has not been extensively discussed. A number of research programs have been carried out at the University of Birmingham to investigate diesel engine performance and emissions [22-31]. In present study, the variations of pilot injection timing were performed in order to investigate their effects on the emissions of NOx and smoke level by using a common rail direct injection V6 diesel engine equipped with variable turbine geometry (VTG) turbochargers and cooled EGR. The pilot injection has a potential to control the pressure rise during the main combustion through a shorter main ignition delay. This experiment run with a split injection consists of 10 % pilot injection and 90 % main injection fuel quantity. The use of 10 % pilot fuel quantity is due to the large amount of pilot injection tends to increase the NOx emissions due to higher rate of heat release [32].

2. Experimental Setup
The experiments were carried out on a fully instrumented multi-cylinder V6 diesel engine, common rail multiple direct fuel injection system, twin water-cooled variable geometry turbochargers and cooled EGR. The engine specification is shown in table 1. An eddy-current dynamometer type Schenck W230 and an engine starter motor, are used to load and start the engine respectively. The Schenck series 2000 controller is used to control the dynamometer.

The exhaust gas of the engine is passed through the gas analyser via a sample line and NOx and smokes were measured. The exhaust sample acquisition time is approximately 10 seconds at an operating temperature of 28 to 30 C and the relative humidity is approximately 40-50 percent. The emissions presented are an average value from 10 reading samples. The smoke emissions were measured by using an AVL 415S smoke meter which provides results directly as a Filter Smoke Number (FSN) unit. Main injection quantity, timing, pressure and EGR rate were held constant throughout the experiment. The amount of fuel injected for both pilot and main injection was at a constant ratio of 10:90 for pilot and main respectively. All the tests were performed with ultra low sulphur diesel (ULSD) and the fuel properties are given in table 2. The effects of pilot injection timing on the emissions of NOx and smoke level were examined. These experiments consisted of three different regions of pilot injection timing (early, middle and late) at two different engine loads (30 Nm, 55 Nm) operating with a constant speed 2000 rpm. The details about the experimental conditions have been summarized in table 3.
Table 1. Engine Specifications.

| Property                    | Value       |
|-----------------------------|-------------|
| Bore                        | 81.0 mm     |
| Stroke                      | 88.0 mm     |
| Displacement Volume         | 2720 cm³    |
| Maximum Torque              | 435 Nm @ 1900 rpm |
| Maximum Power               | 152 kW @ 4000 rpm |
| Compression Ratio           | 17.3 : 1    |
| Connecting Rod Length       | 160.0 mm    |

Table 2. Fuel Properties.

| Property                | ULSD       |
|-------------------------|------------|
| Cetane Number           | 53.9       |
| Density at 15 °C (kg/m³)| 827.1      |
| Viscosity at 40 °C (cst)| 2.5        |
| 50% Distillation (°C)   | 264        |
| 90% Distillation (°C)   | 329        |
| LCV (MJ/kg)             | 42.6       |
| Sulphur (mg/kg)         | 46         |
| Mano-aromatics (% wt.)  | 21         |
| Di-aromatics (% wt.)    | 3.1        |
| Molecular Mass (eq.)    | 209        |
| C (wt.)                 | 86.5       |
| H (wt.)                 | 13.5       |
| O (wt.)                 | -          |

Table 3. Summary of Test Conditions.

| Test | Injection Timing CAD Pilot Injection | Engine Load (Nm) | Notes            |
|------|-------------------------------------|------------------|------------------|
| 1    | 9 bTDC                              | 30               |                  |
| 2    | 12 bTDC                             | Fixed            | Late Injection   |
| 3    | 15 bTDC                             | Fixed            |                  |
| 4    | 19 bTDC                             | Fixed            | Middle Injection |
| 5    | 21 bTDC                             | Fixed            |                  |
| 6    | 24 bTDC                             | Fixed            |                  |
| 7    | 27 bTDC                             | Fixed            | Early Injection  |
| 8    | 30 bTDC                             | Fixed            |                  |
| 9    | 9 bTDC                              | 55               |                  |
| 10   | 12 bTDC                             | Fixed            | Late Injection   |
| 11   | 15 bTDC                             | Fixed            |                  |
| 12   | 19 bTDC                             | Fixed            | Middle Injection |
| 13   | 21 bTDC                             | Fixed            |                  |
| 14   | 24 bTDC                             | Fixed            |                  |
| 15   | 27 bTDC                             | Fixed            | Early Injection  |
| 16   | 30 bTDC                             | Fixed            |                  |

Constant Engine Speed: 2000 rpm
Constant Main Injection Timing: 1.4 CAD aTDC
Constant EGR Rate: 40%
3. Results and Discussion

The NO\textsubscript{x} emissions are mainly influenced by the peak in-cylinder pressure and high combustion temperatures. It can clearly be seen from figure 1 that the NO\textsubscript{x} concentration increases monotonically with early and late pilot injection timing. The early pilot injection timing tends to produce intermediate main ignition delay resulting in a complete combustion process due to long residence time for the reaction of fuel-air (Guntram A. Lechner, Timothy J. Jacobs et al. 2005-01-0167, 2005). As a result, the early pilot injection timing produces the higher in-cylinder pressures leading to the higher temperatures and NO\textsubscript{x} emissions (Cenk Sayin and Canakci 2009; Cenk Sayin, Murat Ilhan et al. 2009). The middle pilot injection produces longest main ignition delay that leads to the slower combustion and low NO\textsubscript{x} emissions (K.Verbiezen, A. J. Donkerbroek et al. 2007). Therefore, in general the reduction in NO\textsubscript{x} can be controlled through the reduction of peak in-cylinder pressure by reducing the main ignition delay, the air temperature and combustion duration (Mohammad Ghaffarpour and Noorpoor 2007). The overall results show that the NO\textsubscript{x} emissions increased with the early and late of pilot injection but decreased with the middle pilot injection timing in both engine loads.

The effect of pilot injection timing on the smoke number (FSN) is shown in figure 2 with the engine operating at two different loads at a constant engine speed of 2000 rpm. The amount of smoke formation is strongly related to the fraction of diffusive combustion phase (Ren, Huang et al. 2006). Smoke formation occurs at extreme local air deficiency. It increases as the air/fuel ratio decreases. The higher fraction of diffusive combustion phase will result in an increase in smoke formation due to insufficient of oxygen. The presented results are in a good agreement with Keiichi Okude et al. which showed that the smoke decrease as the pilot injection timing is advanced (Keiichi Okude, Kazutoshi Mori et al. 2007). It is strongly believed due to improvement in mixture formation with an early pilot injection. This in turn resulted in complete combustion due to better mixing process. The early pilot injection timing produces an intermediate main ignition delay which also contributed to complete combustion. The formation of smoke is higher at a high engine load due to the higher amount of fuel being injected, resulting in higher smoke formation. Complete combustion also resulted in higher combustion temperature leading to the higher soot oxidation during expansion and exhaust stroke (Nicolas Dronniou, Marc Lejeune et al. 2005). The most obvious finding to emerge from this study is that the early pilot injection timing is better for smoke reduction.
Figure 2. Smoke level (FSN) as a function of pilot fuel injection timings (-9 to -30 CAD) at two different engine loads (30 Nm and 55 Nm) and constant engine 2000 rpm, error bars represent 95 percent confidence.

4. Conclusion
In the present work, the emissions of NO\textsubscript{x} and smoke level were measured for various pilot injection timings, operating with two different engine loads at a constant engine speed. As accepted, the pilot injection favoured for the main combustion behaviour. It has been shown smoke level were increased with retarded pilot injection and then decreased after an injection timing of 19 CAD onwards. Both engine loads produced similar patterns. However, the NO\textsubscript{x} emissions were decreased with retarded pilot injection then increased after 19 CAD onwards in both engine loads. Therefore, it has been proven that advancing pilot injection timing of 24, 27 and 30 CAD are better for smoke. Conversely, the injection timings of 9, 12, 15, 19 and 21 are worse for this particular emission. In terms of NO\textsubscript{x} emissions, the injection timings of 19 and 21 CAD are the best. In summary, advanced pilot injection has promising emissions reduction associated with it in terms of smoke but not for NO\textsubscript{x}.

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