

The Influence of Injection Strategy and Glow Plug Temperature on Cycle by Cycle Stability Under Cold Idling Conditions for a Low Compression Ratio, HPCR Diesel Engine

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ABSTRACT

Experimental studies have been undertaken on a single-cylinder HPCR diesel engine with a compression ratio of 15.5:1 to explore the effect of fuel injection strategy on cycle by cycle stability. The influence of the number, separation and quantity of pilot injections on the coefficient of variation of IMEP has been investigated at -20°C , 1000 rev/min, post-start idling conditions. Injection strategy and glow plug temperature trade-off has also been investigated at a range of soak temperatures. Up to four pilot injections have been used. For timing of the main injection near to the optimum, CoV_{IMEP} values of 10% or better can be achieved. Closer spacing of injections improved stability and extended the range of timings to meet target stability. The best combinations of pilot number and pilot quantity varied with total fuel delivered. For a 20 mg/cycle total, twin-pilot injections delivering a total pilot fuel of 4 mg/cycle, or three or four delivering a total pilot fuel of 4 mg/cycle or 6 mg/cycle, gave best stability, but at lower total fuelling (16 mg/cycle) stability was not so good and achieved by fewer combinations.

Target stability was not achieved through hotter glow plug temperatures alone; a multiple pilot strategy or an increase in total fuelling was necessary. Increasing the number of pilot injections and glow plug temperature produced a higher premix contribution and a following strong development of main combustion, which is generally consistent with better cycle by cycle stability. At high glow plug temperatures and using three and four pilot injections, stability improved with warmer soak temperatures. At -5°C , stability was particularly poor when single- or twin-pilot injections were used irrespective of glow plug temperature.

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INTRODUCTION

Recent designs of light duty diesel engines generally have lower compression ratios to allow high turbocharger boost to be used, increasing AFR, and limiting peak cylinder pressure. The NOx/PM trade-off at part load can be improved and specific torque and power at full load raised [1, 2]. This can enable engine downsizing, which tend to operate at higher specific engine loads in order to achieve lower fuel consumption [3]. In addition to decreasing CO₂ emissions, a fuel consumption reduction of 9% is possible with a displacement reduction from 2.0 l to 1.6 l [4]. The downside of reducing compression ratio is lower compression temperatures and higher propensity for poor cycle by cycle

stability during cold, post-start idling. At typical idle speeds under fully warm conditions, $\text{CoV}_{\text{IMEPg}}$ values are expected to be $<3\%$. At cold idle however, $<5\%$ is difficult to achieve and values can be higher, giving rise to the perception of poor performance and "rough" running [5].

Although cold start-up times are not generally extended by reducing the compression ratio [6], the deterioration in cold idling quality is receiving attention as an area of greater concern [7]. Multiple pilot injections to enhance heat release and ignition characteristics has been explored by [8] and [9] and shown to offset the effect of lower in-cylinder temperatures on ignition delay, as noted by Pischinger [10]. Okude et al [11] point out that dividing the pilots is necessary when an increase in total pilot quantity is required to avoid

liner impingement and to improve combustion. Tomoda et al [8] demonstrated the importance of injector design and multiple pilots. For an increase in number of injector holes for an equal nozzle flow rate, they observed a reduction in the amount of latent heat of vaporization per nozzle hole and consequently reduced the temperature drop inside the fuel spray. Air entrainment was also said to increase assisting with fuel air mixing. Whilst the multiple holes distributed the spray spatially, multiple injections were found to improve combustion attributed to the control over the fuel temporally within the cylinder. They concluded pilot combustion and hence total heat release can be greatly enhanced with the use of multiple injections.

Recent investigations of idle stability under cold conditions include those of Pacaud et al [12], MacMillan et al [6, 7], Payri et al [13], and Perrin et al [14] who signal the importance of cool flame and hot pre-mixed combustion in promoting rapid and reliable combustion of fuel delivered in the main injection. MacMillan et al [6, 15] concluded that although target stability at high compression ratio could be achieved through the optimisation of the injection strategy and modest glow plug temperatures, at low compression ratio, injection strategy optimisation alone was not sufficient to achieve target stability. At low compression ratio, the most effective strategy to improve stability combined pilot injection and the use of glow plugs operating at higher temperatures. Significant improvements were observed by raising glow plug temperature from typically standard values around 900°C-950°C to 1100°C. Beyond this the improvement was relatively small. The increase in glow plug temperature produced a reduced and less variable ignition delay, with an increase in peak rate of heat release. Further studies on glow plugs by Walter et al [16] have shown a similar strong influence on cold idling stability. In particular, reducing tip temperature and rotating the spray away from the glow plug tip had adverse affects on achieving adequate pilot combustion and then sustained main fuel combustion development. The study of the effects of glow plug temperature was however limited to a single-pilot injection strategy.

In the study reported here, the influence of the number and quantity of pilot injections and glow plug temperature trade-off on CoV_{IMEPg} under cold idle conditions has been explored using a single-cylinder variant of a Ford 2.2 l 4-cylinder DI diesel engine. This has 4 valves/cylinder, a swirl ratio of 1.5 and centrally mounted Continental piezo-electric, 8 hole injectors. The engine has a bore and stroke of 86 mm and 94.6 mm respectively, a swept displacement of 0.55 litres and a compression ratio of 15.5:1. Tests were carried out using a cold test reference fuel with a Cetane index of 54.7, $T_{90} = 330.5^\circ\text{C}$ and a cold filter plugging point temperature of -25°C .

TEST PROCEDURE

The engine is installed on a test bed with a motor/regenerator dynamometer. Chilled coolant can be circulated through the block and head to force-cool the engine. The engine is soaked for two to three hours to achieve a uniform engine target temperature; engine-out coolant temperature was used as the reference temperature defining the test temperature. For each test, the engine was started from stationary. The steel tip glow plug was turned on for a pre-glow period of 7.5 seconds, and remained on during the test. The engine was motored for 15 cycles, allowing the desired engine speed and rail pressure to be met and maintained. Injections would then commence on cycle 16 and remained for 40 consecutive cycles. This marked the end of the test, after which fuel injection stopped and the engine was motored for two minutes to draw air through the cylinder. Inter-conditioning tests were run to maintain repeatable cylinder conditions for subsequent tests.

One characteristic of lowering the compression ratio is the large variation in increasing IMEPg throughout a test from improvements in combustion efficiency as a consequence of warming up. To decouple this warming up effect from misfired cycles, a quadratic polynomial curve of best fit has been used to determine StD_{IMEPg} , as illustrated in [Figure 1](#). Low IMEPg cycles deviating from the moving mean in IMEPg could therefore be accounted for. The cycle by cycle stability over the 40 cycles and subsequently the quality of idle combustion is defined as

$$CoV_{IMEPg} = \frac{StD_{IMEPg}}{IMEPg_{40}} \times 100$$

The desired characteristic is a low CoV_{IMEPg} over a broad combination of number of pilots and pilot quantity at the IMEPg required to maintain target idle speeds. At -20°C , fuelling was chosen to achieve a target IMEP of ~ 5.5 bar, in line with FMEP values presented in [17]. At test temperatures of -5°C and 10°C , the corresponding targets were ~ 3.5 bar and ~ 2.5 bar respectively.

RESULTS AND DISCUSSION

Injection timing sweeps and separation

The compilation of data presented in [Figure 2](#) provides an overview of how pilot injection parameters influence the dependence of IMEPg and CoV_{IMEPg} on the timing of the main injection. Ideally, IMEPg should be high and insensitive to main timing; CoV_{IMEPg} should be low and insensitive. Results have been compared at two separations; 10° and 6° , defined as the crank angle between the start of two injections. The total fuel quantity was kept constant at 20 mg/cycle, and each pilot quantity 2 mg/cycle.

Within the optimum timing region, between -10 and -8°ATDC , CoV_{IMEPg} is comparable for each of the multiple injection strategies, with twin-pilot having marginally higher

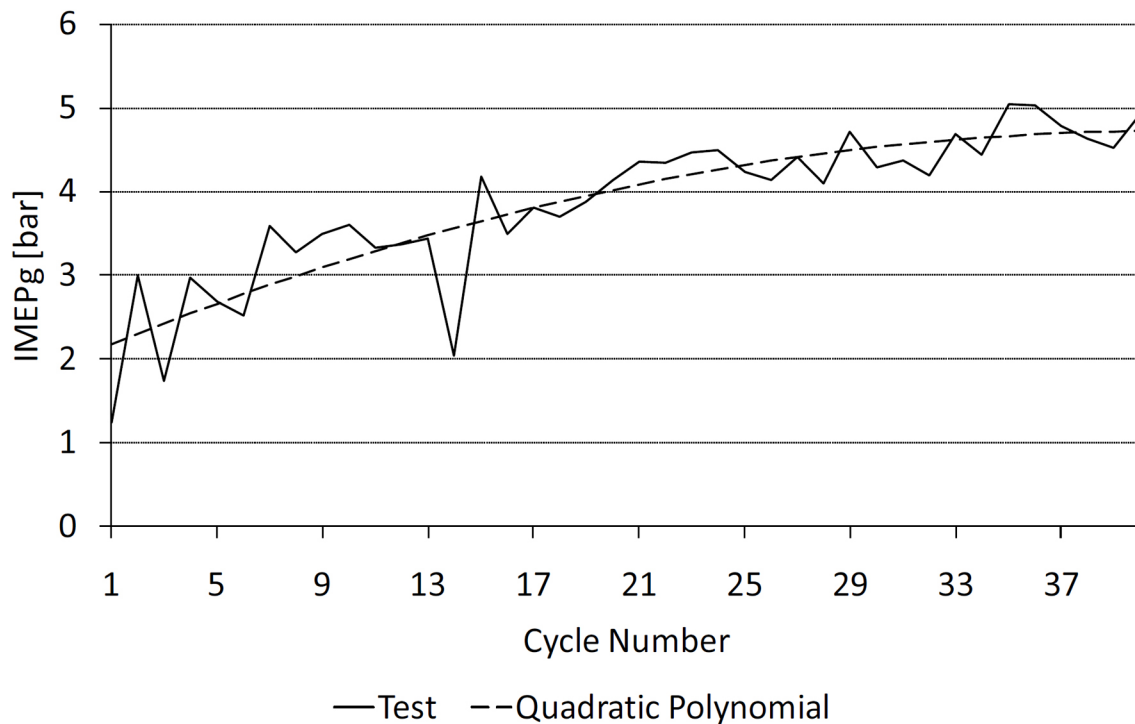


Figure 1. Quadratic polynomial curve fit through the IMEPg data to determine StD_{IMEPg}

IMEPg. This is largely dominated by improved combustion efficiency. At advanced timings, increasing number of pilots is detrimental to IMEPg and CoV_{IMEPg} because the early pilots deliver fuel into adverse cylinder conditions and is poorly utilised. Reducing separation from 10° to 6° improves CoV_{IMEPg} through the combination of raising IMEPg and reducing StD_{IMEPg} extending the range of advanced timings which can be used without performance deteriorating greatly. The benefit of increasing number of pilots to three or four is only observed at retarded timings, but fails to achieve comparable IMEPg and CoV_{IMEPg} obtained at optimum timings. Reducing separation at retarded timings shows less of an advantage compared to advanced and optimum, but does marginally improve CoV_{IMEPg} . The benefit again stems from improvements in both IMEPg and StD_{IMEPg} . In general, both combustion and thermal efficiencies increase around optimum timings and worsen at advanced and retarded timings. Reducing separation marginally reduces ignition delay and increases combustion efficiency with small observable changes in thermal efficiency. Ignition delay generally reduces with increasing number of pilots, and further reduces with retarding main injection timing but is offset by poor combustion phasing late into the power stroke.

Number of pilots and total pilot quantity optimisation

In the work presented above, each pilot injection was maintained at 2 mg/cycle and therefore the total pilot quantity and the main changed when varying the number of pilots. It is not clear from this whether the number of pilots, or the total pilot quantity, or a combination of the two has most influence on work output and cycle by cycle stability. To address the uncertainty, a series of tests were carried out covering four total pilot quantities: 2, 4, 6 and 8 mg/cycle. The main injection was reduced when total pilot quantity was increased to maintain constant fuelling. The fuel distribution of the pilot injections remain equal i.e. for a quad-pilot case with a total pilot quantity of 4 mg/cycle, the fuelling demand was [1, 1, 1, 1, main] mg/cycle. Tests were conducted at the optimum main timing of -8° ATDC and focused on 6° separation, for total fuelling levels of 20, 18 and 16 mg/cycle. Results for 20 mg/cycle are presented in [Figure 3](#) and results for 16 mg/cycle are presented in [Figure 4](#).

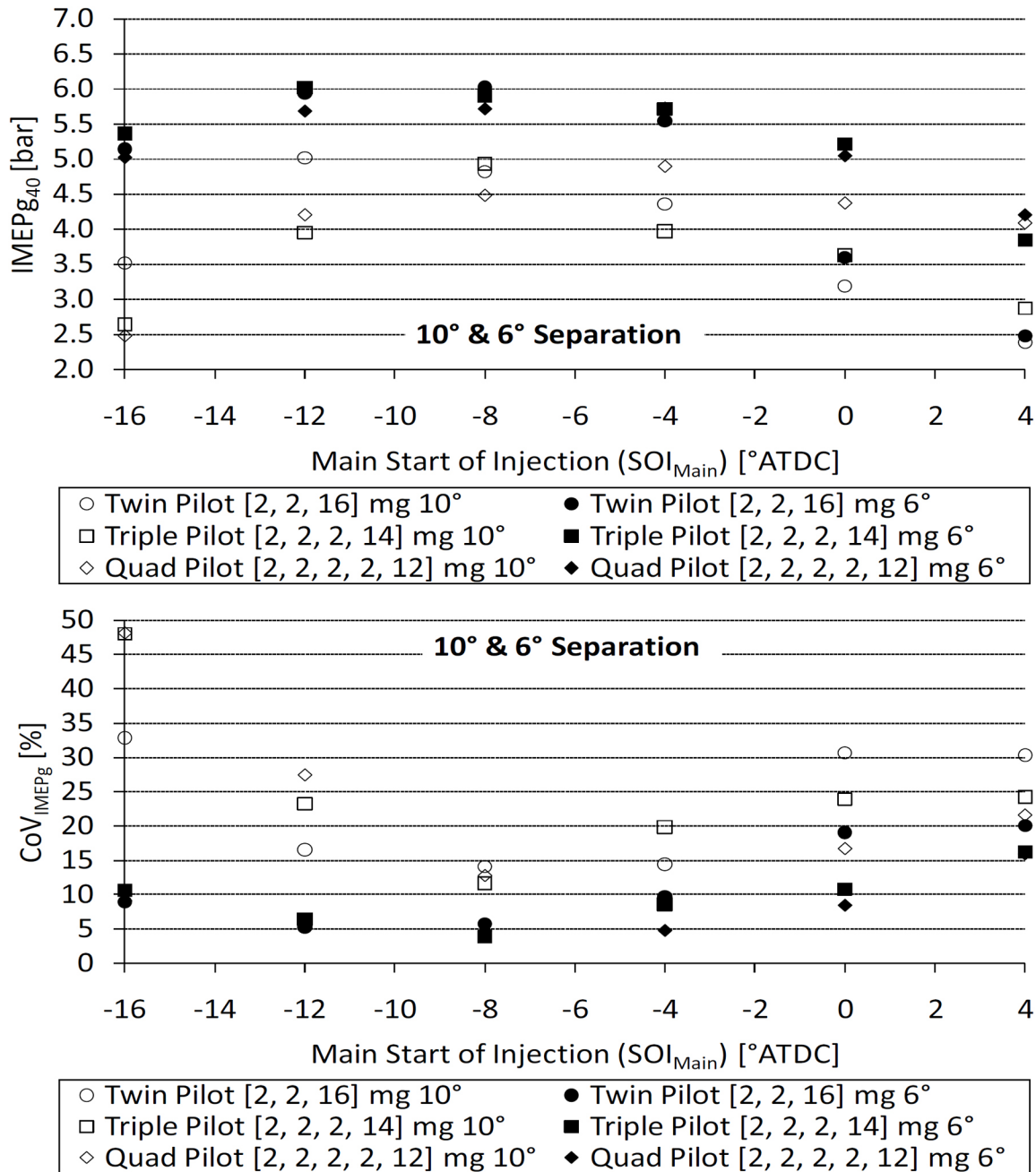


Figure 2. Effect of main injection timing on $IMEPg_{40}$ and CoV_{IMEPg} . Conditions: -20°C , 1000 rev/min, 400 bar rail pressure, 850°C glow plug, 20 mg/cycle total fuel

At a fuelling level of 20 mg/cycle, $IMEPg$ values of around 6 bar and $CoV_{IMEPg} \approx 5\%$ were achieved across a combination of pilot quantities and number of injections provided a minimum of two pilots were used. A twin-pilot strategy with a total pilot quantity of 4 mg/cycle matched the best CoV_{IMEPg} achieved, with little or no discernible advantage gained using triple- or quad-pilot or a higher pilot quantity. At 18 mg/cycle, $IMEPg$ values around 5 bar were produced, but the best CoV_{IMEPg} values achieved were worse. A twin-pilot strategy gave no better than 10% or

higher; triple- and quad-pilot strategies gave 8% or higher. The results for 16 mg/cycle presented in Figure 4 illustrate a further deterioration in stability with reducing fuelling. The use of two pilots achieved CoV_{IMEPg} no lower than 27%. Triple- and quad-pilot stability also worsens through the combination of $IMEPg$ falling and StD_{IMEPg} increasing. At best, the triple-pilot strategy gave around 12% CoV_{IMEPg} ; the quad-pilot with a total pilot quantity of 8 mg/cycle gave 11%. Around 4 bar $IMEPg$ is achievable from both triple- and quad-pilot, with twin-pilot offering no higher than 3 bar.

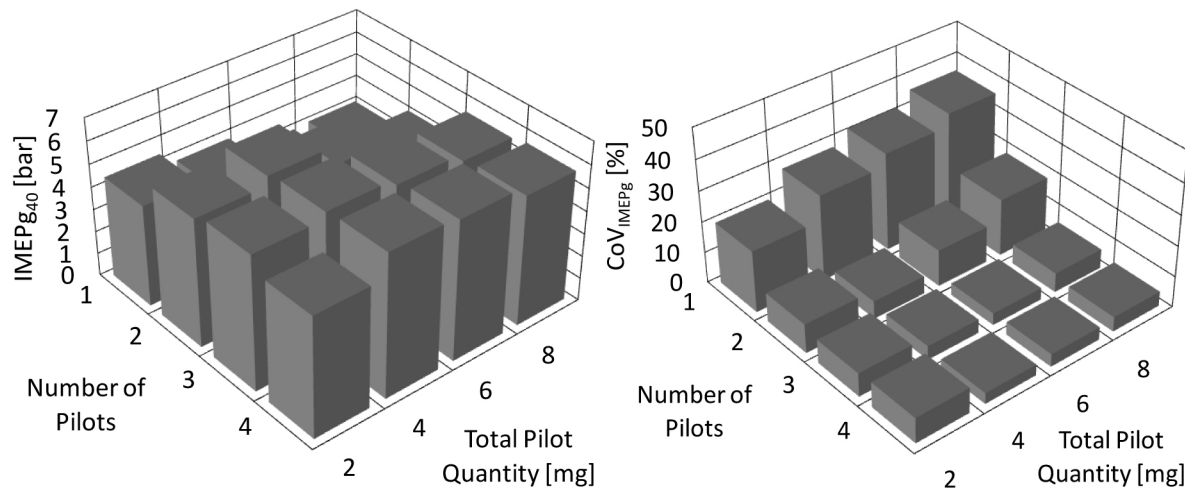


Figure 3. The effect of number of pilots and total pilot quantity. Conditions: -20°C , $\text{SOI}_{\text{Main}} = -8^{\circ}\text{ATDC}$, 6° separation, 1000 rev/min, 400 bar rail pressure, 850°C glow plug, 20 mg/cycle total fuel

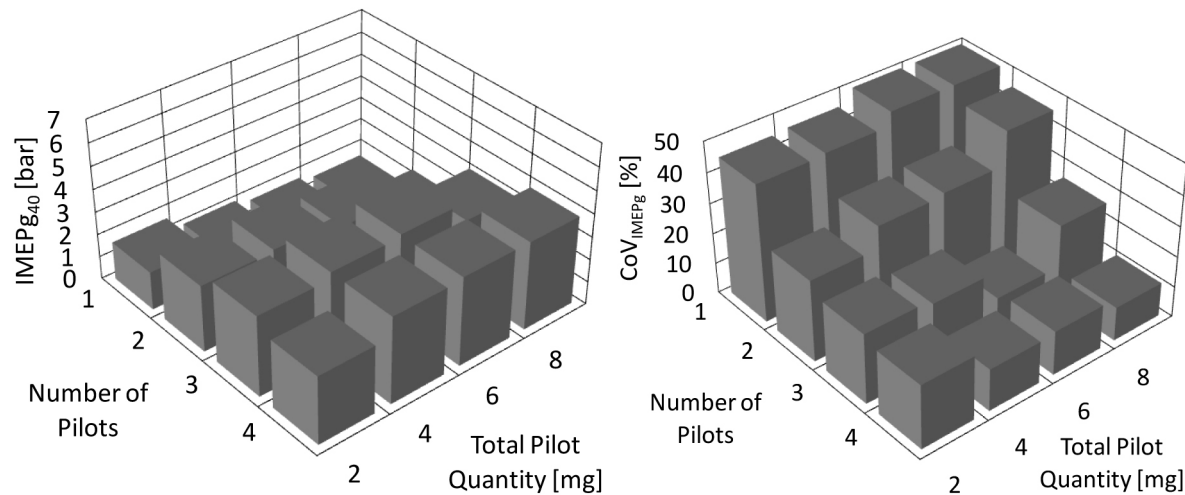


Figure 4. The effect of number of pilots and total pilot quantity. Conditions: -20°C , $\text{SOI}_{\text{Main}} = -8^{\circ}\text{ATDC}$, 6° separation, 1000 rev/min, 400 bar rail pressure, 850°C glow plug, 16 mg/cycle total fuel ($\text{CoV}_{\text{IMEPg}}$ scale has been capped at 50% to maintain clarity, single-pilot results are in the region of 45-90%)

Generally, improvements in IMEPg with increasing number of pilots are dominated by increasing combustion efficiencies. There are small improvements in thermal efficiencies associated with shorter periods of heat release occurring closer to TDC.

Influences on combustion development of the main

Indications of how pilot injection strategy influences the burn of fuel delivered in the main and the effect of premixed combustion on stability can be seen in Figure 5. A similar picture emerges for high and low total fuelling: Cycle by cycle stability improves as the maximum premixed value increases. A high premix is associated with a strong burn,

high combustion efficiency and good stability. For values of $\text{CoV}_{\text{IMEPg}}$ around 5%, the value of the maximum premixed combustion spike needs to be at least 30 J° . This is necessary and sufficient to achieve $\sim 5\%$. Further increases do not produce a further clear improvement in stability.

Injection strategy and glow plug temperature trade-off

The standard glow plug operates at a surface temperature around 850°C . This was replaced with a ceramic glow plug with a 3.3 mm diameter tip capable of internal temperatures of up to 1250°C . The ceramic glow plug protruded the same distance into the combustion system but had a slightly smaller diameter (3.3 mm compared to 4.5 mm) than the