Optimizing split fuel injection strategies to avoid pre-ignition and super-knock in turbocharged engines

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Abstract

Fuel injection strategies often have a considerable impact on pre-ignition in high specific output gasoline engines. Splitting the injection event into two or more pulses has been widely explored as one means of reducing pre-ignition. As effective as these strategies can be with respect to pre-ignition suppression, they often introduce other compromises into the combustion process, e.g., reduced indicated mean effective pressure (IMEP) or greater cycle-to-cycle variation. This study examines a split injection strategy with up to three injection pulses for suppressing pre-ignition, while optimizing the start of injection (SOI) and duration of injection (DOI) to minimize the associated compromises on the combustion process. The results demonstrate that splitting the injection event generally lowers the in-cylinder temperature and reduces the fuel mass that reaches the cylinder liner. This leads to a lower probability of creating fuel-oil droplets, which may act as a precursor for pre-ignition. The split injection strategy with a late injection when the piston is close to top dead center (TDC) is shown to perform even better in terms of pre-ignition suppression, while providing comparable IMEP and cycle-to-cycle variation to the baseline case with a single injection pulse. Finally, the injection pressure is varied to establish an optimal combination of operating parameters for avoiding pre-ignition in high specific output gasoline engines.

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1. Introduction

Regulators around the world are calling for reductions in CO$_2$ emissions from passenger and commercial vehicles. To limit the global average temperature rise to 2°C above pre-industrial levels, the lifecycle CO$_2$-equivalent (CO$_2$-e) emissions of light-duty vehicles will need to be reduced to 121 g CO$_2$-e/km by 2040, and 50 g CO$_2$-e/km by 2050 [1-4]. From an engine perspective, this can be achieved using a range of technologies [5]. However, the incremental cost of different technologies often varies significantly. For example, downsizing a gasoline engine is one of the most cost-effective strategies for improving efficiency [6, 7]. For the same engine torque, a downsized engine has lower throttling losses than a larger displacement naturally aspirated engine, thereby providing higher part-load efficiency [8-11].

At higher loads, downsized engines operate with indicated mean effective pressures (IMEPs) exceeding 20 bar [12-14]. Operating at such high loads makes the engine susceptible to abnormal combustion phenomena, such as pre-ignition [15, 16]. This is considered a premature ignition of the fuel-air mixture before the spark plug discharges. This often leads to high knock intensity events referred to as super-knock or mega-knock (Figure 1), which can result in catastrophic engine failure. At higher engine speeds, pre-ignition has mostly been attributed to surface ignition from hot engine components, including the spark plug or exhaust valves [17, 18]. However, the mechanism responsible for pre-ignition at lower engine speeds, which represents most urban driving, is thought to be quite different. Although there is no single source of pre-ignition at low engine speed, many studies often point towards ignition of oil-fuel droplets [19, 20]. Other commonly cited theories include deposit and unburned hydrocarbon induced ignition [21-24].

Dahnz et al. studied all possible sources of pre-ignition, concluding that the likely cause in their specific engine was from the ignition of oil-fuel mixture droplets [19]. As the injected fuel mass increases with the amount of intake air boosting, the fuel spray can impinge on the cylinder liner at higher loads [25]. This can dilute the lubricating oil, and the resulting fuel-air mixture can land on the piston ring crevice. As the piston decelerates near top dead center (TDC), the inertial forces may cause the droplet to be ejected into the combustion
Calcium-based detergent additives in the lubricant oil may undergo exothermic reaction to form an ignition source [28].

Figure 1: Pre-ignition cycle (leading to super-knock) and normal combustion cycles. Combustion starts much earlier than the spark timing, and generally leads to high frequency pressure oscillations inside the combustion chamber. The grey region represents the range of normal combustion cycles.

Given the importance of the fuel spray in forming pre-ignition precursors, several studies have attempted to split the fuel injection event into multiple pulses to avoid pre-ignition. Lv et al. showed that injecting an equal mass of fuel across several pulses can drastically reduce the pre-ignition tendency [29]. Similarly, Wang et al. varied the mass of fuel in the second injection pulse by up to 50% along with the timing of the two injection pulses, achieving complete super-knock suppression. This was attributed to reduced fuel spray impingement, owing to the shorter fuel penetration length. Toyota’s 1.2L ESTEC engine also uses a triple injection strategy (with equally distributed pulses) to avoid potential damage from pre-ignition [30]. Hu et al. demonstrated a triple injection strategy could be effective at suppressing pre-ignition at low engine speeds [31]. Nevertheless, Luo et al. suggested even multiple injection pulses may not be sufficient to avoid wall wetting under all engine operating conditions, depending on the amount of intake tumble [32].
Amann et al. studied the comparison between port-fuel injection and direct injection, along with a split between the two. The authors reported more pre-ignition events from the port-fuel injection configuration.

Minimal pre-ignition events were observed when up to 80% of the fuel mass was delivered via direct injection. This study also identified an underlying sensitivity to injection timing. Pre-ignition tendency was shown to decrease as the start of injection (SOI) was progressively retarded to 120 crank angle degrees before top dead center (-120 CAD aTDC), but increased thereafter [33]. Similar benefits may also be possible using the Octane-on-Demand concept, which leverages two different fuels (delivered from two different fuel injectors) to suppress conventional engine knock [34-37].

In other studies, Mayer et al. observed a 65% reduction in pre-ignition using a twin pulse injection strategy with 30% of the total mass injected in the second pulse [38]. Similarly, Xu et al. observed optimal pre-ignition suppression with equally split injection pulses, with the SOI of the first pulse maintained at -275 CAD aTDC [39]. Split injection strategies have also been shown to improve engine efficiency [40]. Mercedes-Benz used a triple injection strategy that provided one-fifth of the wall wetting of a more traditional single injection strategy. The last pulse is injected when the piston is close to TDC to increase turbulence levels close to the spark plug, and achieve more stable combustion [41].

Despite the well-established benefits of splitting the injection into multiple events, there remains a gap in the literature surrounding the other compromises associated with adoption of such strategies. This is in addition to the reasoning behind the adoption of one particular split ratio or start of injection timing over another. This study presents a comprehensive set of engine data which parametrically tests and optimizes a range of fuel injection strategies to alleviate the compromises associated with splitting the injection into multiple pulses to suppress pre-ignition. More effective charge cooling, increased turbulence, improved combustion speed, reduced wall impingement, and a richer mixture closer to top dead center all appear to contribute towards pre-ignition suppression to some extent. This study also guides further improvements in engine efficiency that can be obtained from leveraging such combustion strategies.
2. Methodology

2.1 Engine and testbed

The experiments were conducted in an AVL single cylinder research engine (Table 1). The engine is equipped with a centrally mounted six hole (0.18 mm diameter) direct injector, which has a spray cone angle of 65° and bend angle of 15°. The combustion chamber features a pent-roof cylinder head with a centrally mounted spark plug. The spark plug is located between the exhaust valves, and the injector is located between intake valves. An electrically driven supercharger is used to boost the intake pressure.

<table>
<thead>
<tr>
<th>Specifications of the single cylinder research engine.</th>
</tr>
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<tbody>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td>Bore</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Cylinder head</td>
</tr>
</tbody>
</table>

A high-pressure pump is used to supply fuel to the direct injector at up to 170 bar. The in-cylinder, intake and exhaust pressures are measured with piezo-electric pressure transducers. The signals are sampled in increments of 0.1 crank angle degrees (CAD). The in-cylinder pressure data is used to calculate knock intensity (KI) and heat release information. The latter is used to determine the combustion phasing (CA05), which is defined as the crank angle at which 5% of the total fuel mass is burned. A static temperature measurement is also made with a high response thermocouple, which is flush-mounted in the cylinder head. The intake air is maintained at 30°C, while the fuel mass flow rate is measured using a Coriolis-type flow meter.

2.2. Test procedure

The engine tests were performed with Coryton Gasoline (RON 97.5). This fuel is representative of a Euro-V gasoline and is composed of 5% (v/v) oxygenates. The key fuel properties and measured distillation characteristics are presented in Table 2 and Figure 2, respectively.
Table 2. Key fuel properties of the Coryton Gasoline.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research octane number (RON)</td>
<td>97.5</td>
</tr>
<tr>
<td>Motor octane number (MON)</td>
<td>86.6</td>
</tr>
<tr>
<td>Specific Gravity (SG)</td>
<td>0.7485</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>42.4</td>
</tr>
<tr>
<td>Energy density (MJ/L)</td>
<td>31.7</td>
</tr>
<tr>
<td>Aromatics (% v/v)</td>
<td>30.5</td>
</tr>
<tr>
<td>Olefins (% v/v)</td>
<td>8.2</td>
</tr>
<tr>
<td>Ethanol (% v/v)</td>
<td>5.0</td>
</tr>
<tr>
<td>H/C ratio</td>
<td>1.776</td>
</tr>
<tr>
<td>O/C ratio</td>
<td>0.015</td>
</tr>
</tbody>
</table>

All tests were performed with an air intake pressure of 2.1 bar and engine speed of 2000 rpm. These test conditions are similar to those used by automakers for pre-ignition testing [42, 43]. A data acquisition system was used to acquire 12,000 cycles for each operating condition (two sets of 6000 cycles). This number of cycles provides statistically significant data, and all trends were well captured [43]. Table 3 summarizes the critical control parameters monitored in the tests. The spark timing was maintained constant to provide a common operating condition for comparison of the pre-ignition tendency. Some researchers have observed an increase in the pre-ignition tendency with retarded spark timing, and hence, fixed spark timing was chosen for the current study [42, 44-47].
The effect of injection strategy on pre-ignition has been investigated by splitting the injection event into two and three individual pulses. Thereafter, the start of injection (SOI) and duration of injection (DOI) of each pulse is parametrically varied so that the effect on the pre-ignition count (PI count), indicated mean effective pressure (IMEP), coefficient of variation (CoV) of IMEP and the in-cylinder temperature can be quantified. In cases where the DOI is varied, the injection duration is provided.

### Table 3. Engine operating conditions used in this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>2,000 rpm</td>
</tr>
<tr>
<td>Intake temperature</td>
<td>30 ºC</td>
</tr>
<tr>
<td>Coolant temperature</td>
<td>80 ºC</td>
</tr>
<tr>
<td>Oil temperature</td>
<td>80 ºC</td>
</tr>
<tr>
<td>Relative air-fuel ratio (λ)</td>
<td>1.00</td>
</tr>
<tr>
<td>Intake pressure</td>
<td>2.1 bar</td>
</tr>
<tr>
<td>Spark timing</td>
<td>0 CAD aTDC</td>
</tr>
</tbody>
</table>

#### 2.3. Pre-ignition and knock metrics

The peak in-cylinder pressure, start of combustion (CA02, CA05 or CA10) and knock intensity have all been used extensively in the literature to define pre-ignition events. This study uses CA05 as the metric to filter pre-ignition events. The algorithm uses a robust statistical method [48] that reduces the influence of outliers on the calculation of the mean and standard deviation of the data. For operating conditions where pre-ignition events are more frequent, the mean CA05 reduces and the standard deviation increases. This reduces the pre-ignition count for conventional filtering criteria such as \( \theta - 5 \sigma \), where \( \theta \) refers to mean value of CA05 and \( \sigma \) refers to standard deviation. Robust statistical tools are more effective at capturing all pre-ignition events [49]. This study therefore computes the pre-ignition count using \( R\theta - 5 * R\sigma \), where \( R\theta \) refers to robust mean and \( R\sigma \) refers to robust standard deviation. The number of pre-ignition events in any operating condition is presented as a percentage or the number of pre-ignition events per 100 cycles.

The \( R\theta - 5 * R\sigma \) algorithm separates the pre-ignition cycles using the methodology described above. The remaining ‘normal’ cycles are then analyzed for their average knock intensity. The KI value presented in the present study refers to the average knock intensity of the ‘normal’ cycles at any operating condition. Pre-ignition events may lead to super-knock, which can highly skew the average knock intensity. Hence, these
events are removed to give a more representative picture of the spark advance (and consequently the
efficiency improvement and increase in IMEP) that is possible at a given operating condition by suppressing
pre-ignition.

A flush-mounted, K-type thermocouple mounted in the cylinder head is used to measure the average in-
cylinder temperature. The thermocouple is embedded in a high response glow plug manufactured by Borg-
Warner. The specification of the thermocouple are provided in the Appendix. All subsequent data for the
combustion phasing and knock intensity (CA05 vs KI) is color-coded to represent the temperature reading
obtained from this thermocouple. A common scale is used for all the observations to allow for direct
comparison between different fuel injection strategies. This common scale is presented in Figure 3c.

Pre-ignition was a major limitation for enhancing the specific power of aircraft engines as early as the 1940s.
Researchers successfully tried to relate the pre-ignition tendency with the operational temperature of the
engine [50, 51]. Specific fuels molecules or operating conditions exhibiting higher operating temperature
were observed to exhibit lower pre-ignition ratings. An inverse relation was also observed between the
thermocouple temperature and the pre-ignition limited compression ratio [50]. There has been no evidence
of a similar methodology followed in modern form of pre-ignition. Previous research suggests that the pre-
ignition tendency of a given fuel injection strategy may correlate with the in-cylinder temperature close to
top dead center [25, 52]. A higher temperature (designated in this study by red symbols) may therefore lead
to a higher propensity for pre-ignition. However, once a pre-ignition event (followed by super-knock) occurs,
the in-cylinder temperature rises drastically, which may also lead to a higher average temperature. The
results of the present study are re-visited in terms of average thermocouple temperature over the entire
operating conditions in the Appendix.
3. Results and discussion

3.1. Baseline case: Single injection event

The first set of experiments consider the variation in the start of injection (SOI) timing from a centrally-mounted direct injector. The SOI was parametrically varied from -300 CAD aTDC to -210 CAD aTDC in increments of 30 CAD, with the fuel delivered via a single injection event. The operating condition corresponding to a SOI timing of -300 CAD aTDC is referred to as the ‘Baseline’ case in all subsequent discussions in the paper.

Figure 3 presents knock intensity (KI) as a function of the combustion phasing (CA05) as well as Knock Intensity (KI), indicated mean effective pressure (IMEP), pre-ignition count (PI count), average knock intensity (KI) and coefficient of variation (CoV) of IMEP as a function of the SOI timing. The different symbols in Figure 3a represent varying SOI timing. Each symbol has several data points, the color of which correspond to the average in-cylinder temperature (for that cycle). The average temperature for the whole operating condition is provided in the Appendix for reference. Two preliminary observations should be noted. Firstly, all pre-ignition events occur under ‘hot’ operation (refer to Figure 3). Secondly, the overall temperature reduces as the SOI timing is retarded. As an example, all data points for a SOI timing of -210 CAD aTDC are designated in green.

In Figure 3a, larger values on the y-axis represent high KI events that have been induced by pre-ignition. Conversely, lower values on the y-axis coincide with low CA05 values (CA05 < 10 CAD aTDC), and these represent pre-ignition events alone, i.e., the transition to super-knock has not occurred. Many pre-ignition events and high KI events can be observed when operating the engine with the SOI timing at -300 CAD aTDC. The number of pre-ignition events reduces considerably as the SOI timing is moved to -270 CAD aTDC, as does the KI. Further retarding the injection timing leads to zero pre-ignition events. These findings are broadly
consistent with other studies in the literature, and demonstrate that more retarded injection timing can be an effective strategy for reducing pre-ignition.

Figure 3. (a) Knock intensity plotted against start of combustion (CA05) for varying SOI. Symbols are representative of injection timing, colors represent the in-cylinder temperature, measured with a high response thermocouple. The different symbols represent the varying SOI timing. Each symbol has several data points, the color of each corresponds with the in-cylinder thermocouple temperature (average value for that cycle). (b) Knock Intensity (KI), indicated mean effective pressure (IMEP), pre-ignition count (PI count), average knock intensity (KI) and coefficient of variation (CoV) of IMEP at 2000 rpm. Data is for a single injection event with four different start of injection (SOI) timings. The operating condition corresponding to a SOI timing of -300 CAD aTDC, as shown in this case, is referred to as 'Baseline' case in subsequent discussions. (c) Scale for in-cylinder temperature measurements used throughout paper, (d) range of values in this methodology, which will be used in further discussions for comparison.

The corresponding IMEP, PI count, average KI of the normal combustion cycles, and CoV of IMEP is presented in Figure 3b. Although the pre-ignition count is reduced as the SOI timing is progressively retarded towards...
TDC, this also coincides with a reduction in the IMEP (~13%), and an increase in the CoV of IMEP. The latter exceeds 5% when the main injection timing is retarded to -210 CAD aTDC, which exceeds acceptable levels [35]. This demonstrates that there are two main disadvantages associated with reducing the pre-ignition count by retarding the SOI timing. Nevertheless, the reduced average knock intensity provides some potential to increase the IMEP by advancing the spark timing. Previous studies have shown that this can be attributed to enhanced charge cooling with retarded injection timing, which discourages successful triggering of pre-ignition event near TDC [25]. It can be noted that the Fig 3a and figures that follow are color coded to represent temperature reading from an in-cylinder thermocouple (details of which are provided in the appendix). The scale for the colors is provided in Fig 3c. Figure 3d provides the range of values of the four parameters shown in Fig 3b, which can be used for comparison with the subsequent pre-ignition mitigation strategies.

The lower pre-ignition count obtained from retarding the SOI timing can be exploited to offset the lower IMEP by increasing the intake pressure. An example of this is presented in Figure 4. To maintain a constant IMEP (equal to the baseline value), the intake pressure must be increased from 2.1 bar (SOI -300 CAD aTDC) up to 2.4 bar (-210 CAD aTDC). Figure 4b shows the compromises associated with this strategy. Although this is effective at maintaining IMEP same as baseline value, the CoV of IMEP still increases up to a similar value (~5%) as in the previous case (Figure 3b). This demonstrates the limitations of the single injection event. Although the IMEP can be maintained constant as the SOI timing is progressively retarded towards TDC, this strategy does nothing to address the higher CoV of IMEP, while also increasing the specific fuel consumption.
Figure 4. (a) Methodology followed to recover the IMEP by boosting the intake pressure for retarded SOI. IMEP reduction with retarded SOI and gained with subsequent increase in intake pressure is shown (b) Average knock intensity of normal combustion cycle (KI), coefficient of variation (CoV) of IMEP, pre-ignition count (PI count) and injection duration as a function of start of injection (SOI) timing at 2000 rpm. The lower pre-ignition count obtained from retarding the SOI timing has been leveraged to increase the intake pressure. Data is for a single injection event.

### 3.2. Two injection events

As discussed previously, several studies have demonstrated that splitting the single injection event into multiple pulses can be effective at suppressing pre-ignition. To establish the effectiveness of this strategy, the single injection event was split into two pulses, and a parametric sweep of the start of injection (SOI) and duration of injection (DOI) was conducted. The results are summarized in the following sections.

#### 3.2.1 Effect of SOI timing for second injection event

The first parametric sweep examined the effect of the SOI timing for the second injection pulse. The single injection event considered previously was split into two equal pulses. The SOI of the first pulse was maintained at -300 CAD aTDC, while the SOI of the second pulse was swept from -240 CAD aTDC to -90 CAD aTDC in increments of 30 CAD.

Figure 5a presents KI as a function of the combustion phasing (CA05). The case with the SOI timing for the second pulse at -240 CAD aTDC exhibits similar trends to the baseline case with the single injection pulse (SOI -240 CAD aTDC, refer to Figure 3d), with both cases exhibiting many high KI events. Further retarding the SOI timing for the second pulse towards -90 CAD aTDC results in zero high KI events. This indicates the split
injection strategy is more effective at eliminating high KI events when the two pulses are delivered further apart. The color of the scatter plots (Figure 5a) indicates that a cooler average in-cylinder temperature is also present when the two pulse are delivered further apart (refer to scale in Figure 3).

The corresponding IMEP, PI count, average KI of normal combustion cycles and CoV of IMEP is presented in Figure 5b. In this case, the data is presented as a function of the SOI timing for the second injection pulse. Similar to the baseline single injection case, the IMEP is again shown to gradually decrease as the SOI timing for the second injection pulse is retarded towards -90 CAD aTDC. The opposite trend is observed with the CoV of IMEP, which progressively increases up to its maximum value of 3.5%. However, the data suggests the presence of a “sweet spot” when the SOI timing for the second injection pulse is at approximately -150 CAD aTDC. After this point, the CoV of IMEP decreases and average KI increases, while the IMEP remains approximately constant. Nevertheless, the CoV of IMEP remains higher than the 2% threshold used in this study. As such, the split injection strategy with the SOI timing for the second injection pulse at -120 CAD aTDC appears to be a more optimal operating condition, with less compromise on IMEP and CoV of IMEP, while still resulting in a pre-ignition count of zero.
3.2.2 Effect of injection duration

Parametric sweeps were next conducted for the injection duration (DOI). The SOI for the first and second injection pulses were fixed at -300 CAD aTDC and -210 CAD aTDC, respectively, while the ratio of fuel delivered in the two injection pulses was varied.

Figure 6 presents KI as a function of CA05 as well as the IMEP, PI count, average KI of normal combustion cycles and CoV of IMEP as a function of the DOI for the second injection pulse. The pre-ignition count initially reduces as the fraction of fuel delivered in the first injection pulse (SOI -300 CAD aTDC) is reduced. The pre-ignition count reaches its minimum value at the DOI corresponding to 50% fuel (by mass) from the first injection pulse. Thereafter, the pre-ignition count marginally increases as the fraction of fuel delivered in the second injection pulse increases. The average in-cylinder temperature is also lower as the fraction of fuel delivered in the second injection pulse increases. All cycles with pre-ignition correspond to higher average in-cylinder temperatures (designated by the red color, refer to Figure 3c). When the mass of fuel delivered by the second injection pulse is greater than 50%, the pre-ignition cycles correspond with lower average in-cylinder temperatures (designated by the yellow color), as well as low KIs. Additionally, the IMEP decreases as the second injection pulse width increases, while the CoV of IMEP increases as the mass of fuel delivered by the second injection pulse increases (Figure 6b). But in this case, these two parameters are partially decoupled from the PI count, which obtains its minimum value at approximately 50%, i.e., when the fuel mass is equally split between the first and second injection pulses. Eventually, a PI count of zero is obtained as more fuel is delivered in the second injection pulse. The average KI also decreases with increasing fuel fraction in second injection pulse. This demonstrates there is potential for improving the IMEP when using the split injection case, with a higher fuel fraction in second pulse.
Figure 6. (a) Knock intensity plotted against start of combustion (CA05) for varying DOI of the second injection pulse. Symbols are representative of injection timing, colors represent the in-cylinder temperature, measured by a high response thermocouple. (b) Indicated mean effective pressure (IMEP), pre-ignition count (PI count), average knock intensity (KI) and coefficient of variation (CoV) of IMEP at 2000 rpm. The SOI of for the first and second injection pulses are maintained at -300 CAD aTDC and -210 CAD aTDC, respectively, while the ratio of fuel in the two pulses is varied.

3.3. Three injection events

Based on the earlier observations and literature data, splitting the injection event into three separate pulses would be expected to lead to a further reduction in the PI count. To this end, a methodological approach to parametrically sweep the SOI timing for the second and third injection pulses (at fixed injection duration) is considered. To accommodate the large number of test variables (three SOIs and DOIs), a design of experiment (DOE) approach with three different injection split ratios has been adopted (Figure 7). In the first case, equal amounts of fuel are delivered in the three injection pulses (33:33:33), while the second and third cases examine smaller amounts of fuel in the later injection pulses (50:25:25 and 50:40:10, respectively). These are referred to herein as Case 1 (33:33:33), Case 2 (50:25:25), and Case 3 (50:40:10). Within each of these cases, the SOI timing is varied for either the second or third injection pulse. The SOI timing for the first injection event is maintained at -300 CAD aTDC in all tests.
As an example, the SOI timing for the second injection pulse in Case 1 (33:33:33) was examined at -240 CAD aTDC, -210 CAD aTDC and -180 CAD aTDC, while maintaining the SOI timing for the third injection pulse at -120 CAD aTDC. Additionally, the SOI timing for the third injection pulse was examined at -150 CAD aTDC, -120 CAD aTDC and -90 CAD aTDC, while maintaining the SOI timing for the second injection pulse at -210 CAD aTDC.

### 3.3.1 Case 1 (33:33:33)

Figure 8 presents KI as a function of combustion phasing (CA05) for Case 1 (33:33:33) with the SOI timing varied for the second and third injection pulses. Despite splitting the mass of fuel equally between the three injection pulses, pre-ignition is still observed when the SOI timing for the second pulse is -240 CAD aTDC. This is similar to the twin injection strategy considered previously, and is likely due to the close proximity of the first injection pulse to the second injection pulse (-300 CAD aTDC and -240 CAD aTDC). This results in a similar mixture formation process as the single injection event case (-300 CAD aTDC). Nevertheless, the PI count is still lower since the amount of fuel delivered in the first two injection pulses is only 66% of the total fuel mass, i.e., the remaining 33% is delivered at -120 CAD aTDC via the third injection pulse. This suggests that moving the SOI timing for the second or third injection pulses closer to TDC (and further away from the first injection pulse) is effective at reducing the PI count.
Figure 8. Knock intensity plotted against combustion phasing (CA05) at 2000 rpm for Case 1 (33:33:33). The start of injection (SOI) for the second (a) or third (b) injection pulses is varied while holding other test parameters constant (refer to Figure 7).

Similar trends are also observed when the SOI timing for the third pulse is varied from -150 CAD aTDC to -90 CAD aTDC, with the SOI timing for the first and second injection pulses maintained at -300 CAD aTDC and -210 CAD aTDC, respectively (Figure 8b). The reduction in the average in-cylinder temperature is expected since the SOI timing for the second and third injection pulses occurs progressively later in the cycle. However, the reduction in the average in-cylinder temperature is greater when the SOI timing for the third injection pulse is varied. For example, a SOI timing for the third injection pulse at -90 CAD aTDC results in lower average in-cylinder temperatures (refer to scale in Figure 3c). The PI count at this operating condition generally coincides with low KIs.

The corresponding IMEP, PI count, average KI of normal combustion cycles and CoV of IMEP is presented in Figure 9. Varying the SOI timing for the second injection pulse (with the SOI timing for the first and third injection pulses fixed at -300 CAD aTDC and -120 CAD aTDC, respectively) provides similar results to the previous two injection strategies, i.e., reduced IMEP and increased CoV of IMEP (left side of Figure 9). This is not the case when the SOI timing for the third injection pulse is instead varied (with the SOI timing for the first and second injection pulses fixed at -300 CAD aTDC and -210 CAD aTDC, respectively). In this case, the IMEP marginally increases and the CoV of IMEP marginally decreases (right side of Figure 9). The left side of Figure 9 has the SOI timing for the third injection pulse maintained at -120 CAD aTDC. Previous observations
with the twin pulse split injection strategy showed an increase in IMEP when the SOI timing for the second injection pulse was at -120 CAD aTDC. The same trend can be observed in Figure 9. Higher IMEPs are observed on the left side since the SOI timing for the third injection pulse is maintained at -120 CAD aTDC. When the SOI timing for the third pulse is maintained at -120 CAD aTDC (right of Figure 9), the IMEP is higher compared with the other two cases. The SOI timing for the case with the third injection pulse at -150 CAD aTDC also shows lower KIs, and therefore more potential for higher IMEP via increased intake boosting or spark advance.

Figure 9. Variation in indicated mean effective pressure (IMEP), pre-ignition count (PI count), average knock intensity of normal combustion cycles (KI) and coefficient of variation (CoV) of IMEP for Case 1 (33:33:33).

3.3.2 Case 2 (50:25:25)

Figure 10 presents KI as a function of combustion phasing (CA05) for Case 2 (50:25:25). The first set of experiments were performed by varying the SOI timing for the second injection pulse, while keeping the SOI timing for the first and third injection pulses fixed at -300 CAD aTDC and -120 aTDC, respectively (Figure 10a). As in Case 1 (33:33:33), the PI count is extremely sensitive to the SOI timing for the second injection pulse. For example, several pre-ignition events are observed when the SOI timing for the second injection pulse is at -240 CAD aTDC. But the PI count can be reduced to zero by retarding the SOI timing for the second injection.
pulse to -180 CAD aTDC. This indicates the PI count may be more sensitive to the SOI timing than the mass of fuel (DOI) delivered by the injection event.

The SOI timing for the third injection pulse was then varied from -120 CAD aTDC to -60 CAD aTDC, while keeping the SOI timing for the first and second injection pulses fixed at -300 CAD aTDC and -210 CAD aTDC respectively (Figure 10b). In this case, the most retarded SOI timing for the third injection pulse (-60 CAD aTDC) results in a PI count of zero. The PI count decreases as the SOI timing for the third injection pulse is retarded towards TDC. Locating the SOI timing of the third injection event close to TDC would be expected to be effective at reducing the average in-cylinder charge temperature.

Since the mass of fuel delivered in the third injection pulse in Case 2 (50:25:25) is lower than Case 1 (33:33:33), this provides greater flexibility to study the sensitivity of the PI count to the SOI timing for the second injection pulse, while maintaining the SOI timing of the third pulse at -60 CAD aTDC (which was previously shown to provide a very low PI count). Figure 10c demonstrates that no pre-ignition events were observed in this set of experiments, even for the case where the SOI timing for the second injection pulse was at -240 CAD aTDC (a case previously shown to result in a high PI count). This suggests a late injection pulse delivered with the piston close to TDC can be particularly effective at suppressing pre-ignition. Previous studies have shown the effectiveness of charge cooling increases as the injection timing is retarded, and this may be a likely contributor to the observed behavior [25]. For example, blue markers (refer to scale in Figure 3c) can be observed for all cases in both Figures 10b and 10c when the SOI timing for the third injection pulse is at -60 CAD aTDC. Even in Figure 10c, where the majority of the fuel mass (75%) is delivered early in the cycle, the average in-cylinder temperatures are still comparatively low due to the late injection pulse when the piston is close to TDC.
Figure 10. Knock intensity plotted against combustion phasing (CA05) at 2000 rpm for Case 2 (50:25:25). The start of injection (SOI) for the second and third injection pulses is varied while holding other test parameters constant (refer to Figure 7).
The corresponding IMEP, PI count, average KI of normal combustion cycles and CoV of IMEP is presented in Figure 11. The key trends are similar to the previous cases, where the PI count correlated closely with IMEP, and inversely with the CoV of IMEP. Among the three subsets of Case 2 (50:25:25), the best overall trade-off is achieved by maintaining the SOI timing for the third injection pulse at -120 CAD aTDC (middle of Figure 11). This is consistent with the previous observations at -120 CAD aTDC. Nevertheless, this configuration shows a slightly higher PI count than could otherwise be achieved, i.e., the PI count is zero when is the SOI timing for the second injection pulse is -180 CAD aTDC. Locating the SOI timing for the first, second and third injection pulses at -300, -180 and-60 CAD aTDC, respectively, provides the best overall trade-off in terms of IMEP (25 bar), CoV of IMEP (2.1%) and PI count (zero). The IMEP for these cases is comparable to the baseline case with the single injection event at -300 CAD aTDC (refer to Figure 3d) with the added advantage of a negligible PI count. Moreover, the reduction in IMEP is almost consistent with the reduction in KI, and hence the spark timing could be advanced to recover the IMEP back to the level observed in the baseline case.

Figure 11. Variation in indicated mean effective pressure (IMEP), pre-ignition count (PI count), average knock intensity of normal combustion cycles (KI) and coefficient of variation (CoV) of IMEP for Case 2 (50:25:25).
3.3.3 Case 3 (50:40:10)

For the first set of experiments in Case 3 (50:40:10), the SOI timing for the second injection pulse was varied from -240 CAD aTDC to -180 CAD aTDC, while keeping the SOI timing for the first and third injection pulses fixed at -300 CAD aTDC and -120 CAD aTDC, respectively (Figure 12a). Similar to earlier observations, positioning the SOI timing for the second injection pulse at -240 CAD aTDC is ineffective at suppressing pre-ignition. Additionally, 90% of the fuel mass is now delivered in the first and second injection pulses, which is likely to be a further contributor to the high PI count. Nevertheless, the PI count is reduced as the SOI timing for the second injection pulse is retarded to -180 CAD aTDC.

Figure 12b demonstrates the effect of varying the SOI timing for the third injection pulse, with the SOI timing for the first and second injection pulses fixed at -300 CAD aTDC and -210 CAD aTDC, respectively. No pre-ignition events are observed when the SOI timing for the third injection pulse is at -30 CAD aTDC. This is consistent with Case 2, where the PI count was lowest when the SOI timing for the third injection pulse was closest to TDC. Since only 10% of the fuel is delivered via the third injection pulse, this allows the SOI timing of the third injection pulse to be retarded much closer to TDC (SOI -30 CAD aTDC). Hence, for the next case, the SOI timing for the first and third injection pulses are maintained constant at -300 CAD aTDC and -30 CAD aTDC, respectively, while the SOI timing of the second injection pulse is varied (Figure 12c). This strategy is highly effective at suppressing pre-ignition. Two pre-ignition events are observed when the SOI timing for the second injection pulse is at -240 CAD aTDC, while no pre-ignition events are observed when the SOI timing for the second injection pulse is at either -210 CAD aTDC or -180 CAD aTDC.

Given that a SOI timing of -30 CAD aTDC for the third injection pulse has been shown to be effective at suppressing pre-ignition, this case is now examined using a twin injection pulse strategy. Only 10% of the total fuel mass is delivered at a SOI timing of -30 CAD aTDC, while the remaining 90% is delivered at a SOI timing of -300 CAD aTDC. Figure 12d indicates that only two pre-ignition events (without super-knock) were observed for this operating condition. This points to a greater benefit in terms of improved IMEP from the
early injection of 90% of the fuel, and reduced CoV of IMEP (from only 10% of the fuel being injected when the piston is close to TDC). The latter leads to less heterogeneity close to spark plug, which is a leading cause of cycle-to-cycle variation [52]. Once again, the closer the SOI timing for the third injection pulse is to TDC, the lower the average in-cylinder temperatures (Figure 12b).

Figure 12. Knock intensity plotted against combustion phasing (CA05) at 2000 rpm for Case 3 (50:40:10). The start of injection (SOI) for the second (a,c) and third (b) injection pulses is varied while holding other test parameters constant (refer to Figure 10). (d) represents injecting 10% of total fuel mass injected at -30 CAD aTDC.

The corresponding IMEP, PI count, average KI of normal combustion cycles and CoV of IMEP is presented in Figure 13. In general, the key outcomes are similar to the previous cases. In particular, as the SOI timing is retarded towards TDC, the PI count decreases. However, this comes at the expense of a lower IMEP and increased CoV of IMEP. Once again, a SOI timing for the third injection pulse of -120 CAD aTDC shows the
highest IMEP. The reduction in the IMEP is consistent with the reduction in the average KI. As such, the reduced IMEP could be recovered for these cases by advancing the spark timing. The PI count is also high, but reduces considerably as the SOI timing for the second injection pulse is retarded towards TDC.

Overall, the late injection strategy (third pulse with SOI timing at -60 CAD aTDC and -30 CAD aTDC for Case 2 and Case 3, respectively) is shown to be the most effective at reducing the PI count. Additionally, none of the pre-ignition events observed throughout these cases leads to super-knock. This may be due to the late injection event cooling the in-cylinder charge late in the cycle, i.e., close to TDC. As a result, pre-ignition inception can be avoided altogether, or any pre-ignition events in progress may be quenched. The broader results also demonstrate this strategy provides the best compromise in terms of both the IMEP and CoV of IMEP.

3.3.4 Comparison of triple pulsed injection strategy

The three cases considered in Figure 7 are compared at a common operating condition (with the same SOI timing for the three pulses) in Figure 14. This data therefore isolates the effect of the injected fuel mass in
each pulse on the critical combustion parameters. Several clear trends are evident in the data. For example, as the mass of fuel injected in the third pulse reduces (from Case 1 to Case 3), the IMEP also increases. This coincides with a higher mass of fuel injected earlier in cycle, providing a more homogeneous fuel-air mixture at spark discharge. Among the five strategies presented, insert (a) shows the highest IMEP. This is expected since almost all of the fuel is injection early in the intake stroke. As the fraction of fuel in the third injection pulse reduces, the IMEP also increases (Case 1 to Case 3 insert (a)). This coincides with a large reduction in the PI count. The CoV of IMEP is also lowest for insert (a). In general, for the same injection strategy, the PI count increases as the mass of fuel delivered by the third injection pulse decreases (Case 1 to Case 3). Case 2 and 3 are equally effective at maintaining a low CoV of IMEP from insert (a) to insert (e). Insert (c) shows the lowest PI count across all three cases, and provides the best combination for avoiding pre-ignition at any fuel mass split ratio. The KI is observed to follow the same trend as the IMEP. However, Figure 14 does not consider the injection strategies that have previously shown lower PI counts. Instead, only the injection strategies that are common to the three cases are presented.

Figure 14: Comparison of triple pulsed injection strategies for varying DOIs Case 1 (33:33:33) versus Case 2: (50:25:25) versus Case 3 (50:40:10) for common SOIs (designated in boxed text). Five different sets of injection timing of three pulses are shown (a) refers to split injections at -300, -240 and -120 CAD aTDC, (b) and (d) refers to split injection at -300, -210 and -120 CAD aTDC, (c) refers to split injections at -300, -180 and -120 CAD aTDC and (e) refers to split
injections at \(-300\), \(-210\) and \(-90\) CAD aTDC. (a), (b) and (c) are cases where the second pulse is varied, while (d) and (e) are cases where the third pulse timing is varied.

Figure 15a presents all the triple pulse injection strategies (Case 1, 2 and 3) that exhibit a PI count of zero. These strategies are broken down by case number in Table 4. The best overall scenario for Case 1, Case 2 and Case 3 are designated with red dotted rectangles (Figure 15a). The red marked points show maximum IMEP and the minimum CoV of IMEP, with a PI count of zero. The IMEPs are all in excess of 24 bar, while the CoVs of IMEP are less than 3%. Figure 15b is an inset of the three operating points with the minimum compromise on IMEP and CoV of IMEP (bracketed in the red dotted rectangle). It shows that Case 2 shows the highest IMEP, followed by Case 3, and then Case 1. The average KI value is indicative of the potential for further IMEP enhancement via spark advance. This is highest for Case 3, followed by Case 2, and finally Case 1.

<table>
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<tr>
<td>Case 2 (50:25:25)</td>
<td>-300, -210, 180 CAD aTDC, -300, -240, -60 CAD aTDC, -300, -210, -60 CAD aTDC, -300, -120, -60 CAD aTDC.</td>
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<tr>
<td>Case 3 (50:40:10)</td>
<td>-300, -180, -120 CAD aTDC, -300, -210, -30 CAD aTDC, -300, -180, -30 CAD aTDC.</td>
</tr>
</tbody>
</table>

Table 4. Summary of triple pulse injection strategies (Case 1, 2 and 3) that exhibited a PI count of zero.
3.4 Optimizing the late injection strategy

3.4.1. Optimization of injection duration (DOI) for the late injection pulse

The results presented in the previous sections indicate the use of a late fuel injection pulse can be an effective means of suppressing pre-ignition. However, the optimized quantity of fuel (DOI) and SOI timing for the late injection event is yet to be established. In the next set of experiments, these parameters are optimized to achieve a PI count of zero, while minimizing the compromises associated with the IMEP and CoV of IMEP.

First, the DOI for the late injection pulse is varied, while the SOI timing is maintained at -30 CAD aTDC (Figure 16). The PI count is zero when the DOI for the late injection pulse is large. However, with a DOI of 500 \( \mu \)s, the PI count is four, but none of these events led to high KI values. As the DOI is further reduced to 400 \( \mu \)s, both pre-ignition and super-knock can be observed. This again supports the earlier findings, i.e., a large mass of fuel delivered late in the cycle is very effective at cooling the charge, and suppressing any pre-ignition. However, below a certain threshold, the latent heat of vaporization from the injected fuel appears to be inadequate to suppress pre-ignition. Reducing the fuel mass further not only sees pre-ignition reemerge, but...
also causes this to transition to super-knock. Additionally, Figure 16 demonstrates that the greater the mass of fuel injected in the late injection pulse, the lower the average in-cylinder temperature (refer to scale in Figure 3c). At 5% mass of fuel injected in the late injection pulse, the average in-cylinder temperature is comparable to the baseline case (Figure 3d), while high KI events are also observed. The peak KI values for the pre-ignition events are lower than the baseline case (Figure 3d), which exhibits higher average in-cylinder temperatures than all the late injection cases considered in Figure 16 (designated by the darker red circles, refer to scale in Figure 3c).

Figure 16. Variation of knock intensity with combustion phasing (CA05) on changing DOI of late injection for a fixed SOI of -30 CAD aTDC. The legend shows the DOI of late injection in us, and the fraction of total mass in bracket.

3.4.2 Optimization of start of injection of late injection pulse

The SOI timing of the late injection pulse was next examined at -40, -30 and -15 CAD aTDC with a fixed injection duration (DOI) of 10% of the total fuel mass. The variation in KI as a function of combustion phasing (CA05) is presented in Figure 17. Several pre-ignition events are observed when the SOI timing for the late injection pulse is at -40 CAD aTDC, and these are accompanied by relatively high KI values. The KI of the pre-ignition events which occur at a SOI timing of -30 CAD aTDC are lower, while zero pre-ignition and super-knock events are observed for a SOI timing of -15 CAD aTDC. This again suggests that the charge cooling effect is greater as the late injection pulse is moved closer to TDC, which is suggested by previous work [25].
Figure 17. Variation of knock intensity (KI) as a function of combustion phasing (CA05) for varying SOI of late injection for fixed DOI of 700 μs.

### 3.4.3 Summary of late injection optimization

Figure 18 presents a summary of tests conducted for injection durations (DOIs) ranging from 400 to 800 μs (in steps of 100 μs) and SOI timings of -15, -30 and -40 CAD aTDC for the late injection pulse. The horizontal red dotted line represents a PI count of zero. As the DOI for the late injection pulse increases, the PI count decreases. However, the IMEP also decreases, and the CoV of IMEP increases. These trends are similar to those previously observed. In general, advancing the SOI timing of the late injection event results in a higher PI count, but also a higher IMEP and CoV of IMEP. By contrast, moving the SOI timing for the late injection pulse closer to TDC (SOI -15 CAD aTDC) results in a lower IMEP and higher CoV of IMEP. The closer the SOI timing for the late injection pulse is to TDC, the more effective the charge cooling, and hence the lower the average KI. This suggests that the best overall compromise could be to retard the SOI timing for the late injection pulse, while advancing the spark timing to achieve a comparable IMEP and CoV of IMEP to the baseline case (with a single injection pulse, refer to Figure 3d). Nevertheless, careful optimization is required when the SOI for the late injection pulse occurs close to TDC. Delivering a large amount of fuel in the late injection event reduces the IMEP, and increases the CoV of IMEP beyond acceptable levels, whereas delivering too little fuel can be ineffective at suppressing pre-ignition.
3.5 Effect in injection pressure

3.5.1 Baseline operation for varying injection pressure

Increasing the fuel injection pressure is known to benefit the operation of a gasoline engine due to improved fuel atomization. Initially, the engine was operated at the baseline condition to calibrate the performance at higher injection pressures. Tests were performed while maintaining the SOI timing of the single injection pulse at -300 CAD aTDC, with the DOI corresponding to that for stoichiometric operation. Higher injection pressure should provide better fuel atomization. However, the higher momentum can also increase the likelihood of liquid fuel impinging on the cylinder liner, which is a known cause of pre-ignition [25].

The IMEP, PI count, and CoV of IMEP for three different fuel injection pressures (130, 150 and 170 bar) is presented in Figure 19. The IMEP increases with increasing fuel injection pressure, while the CoV of IMEP can be maintained below the acceptable threshold for all three injection pressures. Additionally, the PI count reduces when moving from an injection pressure of 130 bar to 150 bar, but increases again when moving from 150 bar to 170 bar. As previously discussed, the PI count is affected by both the higher momentum of

Figure 18. Indicated mean effective pressure (IMEP), pre-ignition count (PI count), average knock intensity (KI) and coefficient of variation (CoV) of IMEP for varying SOI and DOI for the third injection pulse at an injection pressure of 130 bar. A horizontal line designating a PI count of zero (red dotted) is provided for reference.
the fuel spray as well as improved fuel atomization, and there may be competing effects between these two factors that influence pre-ignition.

Figure 19. Baseline data for pre-ignition count IMEP, and coefficient of variation for varying injection pressure. Single pulse injection at -300 CAD aTDC.

3.5.2 Effect of injection pressure for late injection optimization strategy

The optimized late injection strategy for the three injection pressures considered in Section 3.5.1 is now examined in greater detail. Due to the higher injection pressure, the mass of fuel injected for a given DOI also increases. As a result, the fuel fraction corresponding to a fixed DOI will be different at injection pressures of 130, 150 and 170 bar. The fuel fraction corresponding to a given DOI can be inferred from Figure 20.
The effectiveness of the late injection strategy with varying injection pressure is compared at constant DOI for the second injection pulse of 700 μs in Figure 21. A DOI of 700 μs corresponds to 9.2%, 9.9% and 10.1% of the total fuel mass at injection pressures of 130, 150 and 170 bar, respectively. At an injection pressure of 170 bar, there are two pre-ignition events but no super-knock. Lower injection pressures appear to be a better strategy for suppressing pre-ignition. In general, increasing the injection pressure appears to reduce the effectiveness of the late injection pulse delivered close to TDC, leading to a higher PI count. This is also reflected in the average in-cylinder temperature, with higher temperature green symbols observed at higher injection pressure, and cooler temperature blue symbols observed at lower injection pressures (refer to scale in Figure 3c). Nevertheless, the average in-cylinder temperatures are still considerably lower than almost all cases considered in this study, owing to the late SOI timing for the late injection pulse.
3.5.2 Optimization of late injection for an Injection pressure of 150 bar

Tests were conducted for varying SOI timing and DOI for the late injection pulse at an injection pressure of 150 bar, similar to the cases presented in Figure 18. The variation in IMEP, average KI and CoV of IMEP for the three different SOI timings for the second injection pulse (SOI -40 CAD aTDC, -30 CAD aTDC and -15 CAD aTDC) and DOI sweeps from 400 μs to 800 μs (fuel mass fraction in late injection varied from 5.5% to 11.5%) are presented in Figure 22. For a SOI timing of -15 CAD aTDC, the injection duration is limited to 600 μs (8.5%). Beyond injection durations of 600 μs (8.5%), the CoV of IMEP is excessively high due to extreme mixture inhomogeneity at the time of spark discharge. The observed trends are similar to those in Figure 18, where the lower mass of fuel delivered in the late injection pulse becomes ineffective at suppressing pre-ignition, and a higher fuel mass simply decreases the IMEP by a considerable amount. Moreover, moving the SOI timing for the late injection pulse closer to TDC provides improved pre-ignition suppression, while more advanced SOI timing for the late injection pulse results in a higher IMEP.
Figure 2: Summary of variation of IMEP, pre-ignition count, average knock intensity (KI) and coefficient of variation (CoV) for varying SOI and DOI of late injection at an injection pressure of 150 bar. The horizontal zero pre-ignition count line is provided for reference.
3.5.3 Optimization of late injection for an injection pressure of 170 bar

Figure 23 presents equivalent data for an injection pressure of 170 bar, with the DOI for the late injection pulse varied from 400 to 800 μs (corresponding to 5.7% to 12% of the total fuel mass). The IMEP, CoV of IMEP and PI count are similar to those observed at injection pressures of 130 and 150 bar. But the average IMEP values are marginally higher than those observed at injection pressure of 130 and 150 bar. This is expected since the IMEP increases with injection pressure (refer to Figure 19). However, the PI count is also higher for an injection pressure of 170 bar. It should be noted that for same the injection duration, the mass of fuel increases with injection pressure (refer to Figure 20). As a result, a DOI of 700 μs for this case delivers a greater amount of fuel closer to TDC in comparison with the previous cases (10% at 170 bar injection pressure compared to 9% at 130 bar injection pressure). Overall, it appears to be possible to achieve a reduced PI count for a given operating condition by varying the fuel injection pressure, while minimizing the trade-offs associated with the IMEP and CoV of IMEP.

Figure 23. Summary of variation of IMEP, pre-ignition count, average knock intensity (KI) and coefficient of variation (CoV) for varying SOI and DOI of late injection at an injection pressure of 170 bar. Horizontal zero pre-ignition count line in red-dotted provided for reference.
3.5.4 Comparison of late injection optimization at varying injection pressure

Figure 24 presents a direct comparison between the different injection pressures with the SOI timing for the second injection pulse at -30 CAD aTDC. In general, higher injection pressures lead to a higher PI count. Additionally, the IMEP is higher, and the CoV of IMEP is lower for a higher injection pressure. However, a much higher mass of fuel is required to obtain a PI count of zero as the injection pressure increases. For example, a PI count of zero can be obtained at a DOI of 600 μs using an injection pressure of 130 bar. While for a PI count of zero at injection pressures of 150 and 170 bar, a DOI of 700 and 800 μs, respectively, must be used.

Moreover, for a given DOI, the fuel mass injected increases with the injection pressure, which translates into even more effective pre-ignition suppression at lower injection pressures; albeit at the expense of reduced IMEP. The CoV of IMEP is similar for the three injection pressures, while the average KI is lower for injection pressure of 130 and 150 bar. Overall, increasing the injection pressure at this operating condition introduces more problems (namely a higher PI count) than it can address (reduced IMEP). Using a lower injection pressure would be a better option.
pressure may therefore provide a more optimal solution since it enables more spark advance to increase the IMEP, while maintaining a lower PI count.

3.6 Relationship between IMEP, PI count and average in-cylinder temperature

Figure 25 presents the IMEP, CoV of IMEP, KI and PI count as a function of the average in-cylinder temperature. Each data point incorporates 6000 cycles (average or count), and hence represents one of the operating conditions or injection strategies examined in the study. There is almost a linear correlation between the average IMEP (over 6000 cycles) and the average in-cylinder temperature (Figure 25a). While higher CoVs of IMEP are generally observed for lower in-cylinder temperatures (Figure 25b). Nonetheless, Figure 25c demonstrates the KI values (of the normal cycles in each operating strategy) are highly correlated with the average in-cylinder temperature. The average KI values of normal cycles are limited to 0.5 bar, which is generally considered trace knock.

Figure 25d represents the PI count (per 6000 cycle) as a function of the average in-cylinder temperature. The limits of zero or the maximum PI count correspond with lower and higher in-cylinder temperatures, respectively. There is no one-to-one correlation between the two, but the operating condition with the lower average in-cylinder temperatures does have a PI count of zero. By contrast, the operating conditions with the highest average in-cylinder temperatures always have a non-zero PI count. The data points on the lower right (marked with a yellow circle) correspond to lower PI counts with higher in-cylinder temperatures. These represent the optimized strategies which offer a low PI count, despite the higher average in-cylinder temperatures. These are enabled by injecting a small fraction of fuel late in the cycle, and represent engine operation at higher IMEPs, but with low PI counts.
Figure 25. Indicated mean effective pressure (IMEP), coefficient of variation (CoV) of IMEP, knock intensity (KI) and pre-ignition count (PI count) as a function of the in-cylinder thermocouple temperature for each set of experiments in the current study.

4. Conclusions

This study examined a variety of fuel injection strategies which can be used to suppress pre-ignition, while minimizing other compromises on the combustion process, e.g., reduced indicated mean effective pressure
or excessive cycle-to-cycle variation. The key findings may assist spark-ignited engines to operate at high specific outputs, without pre-ignition being the limiting factor on efficiency. The conclusions are as follows:

- Splitting the fuel injection event into two pulse generally reduced the PI count, but this was often accompanied by a lower IMEP and higher CoV of IMEP. A lower PI count was generally obtained when the two fuel injection pulses were further apart, and the fuel mass was equally distributed.

- Splitting the fuel injection event into three pulses provided a further reduction in the PI count. When a lesser mass of fuel was delivered in the third injection pulse, with the piston close to TDC, this provided the fewest compromises on the IMEP and CoV of IMEP.

- Least reduction in IMEP was observed by injecting a small fraction of total fuel mass when close to TDC. However, a critical threshold exists for the minimum fuel fraction injected close to TDC, below which the PI count of zero can no longer be maintained.

- A higher fuel injection pressure provided a higher IMEP, while maintaining the CoV of IMEP at comparatively low levels. Coupling the late fuel injection strategy with higher injection pressures provided a lower PI count, without significantly compromising the IMEP or CoV of IMEP. This strategy also partially decoupled the reduction in IMEP with the increase in CoV of IMEP, with a low CoV of IMEP obtained across all test cases.

- Late fuel injection strategies that delivered a small amount of fuel when the piston was close to TDC appeared to benefit to a greater extent from the charge cooling provided by fuel evaporation. This reduced the average in-cylinder temperature, and hence the spark timing could be advanced to offset any reduction in the IMEP. However, the advanced spark timing further increased the cycle-to-cycle variation due to higher heterogeneity in the fuel-air mixture at the time of spark discharge.

- Careful calibration of the fuel injection and spark timing may allow for pre-ignition free operation in high specific output gasoline engines, without compromising the IMEP or CoV of IMEP.

- Future studies may also need to consider any trade-offs that exist between the abovementioned factors and criteria air pollutant emissions.
Acknowledgements

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References


Nomenclature
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<tr>
<td>CAD</td>
<td>Crank Angle Degree</td>
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<td>CA02</td>
<td>Crank angle degree for 2% mass fraction burned</td>
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<td>CA05</td>
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Appendix

A. In-cylinder thermocouple measurement

The thermocouple used in the current study was manufactured by Borg Warner, and was embedded inside a glow plug that was mounted inside the combustion chamber (Figure A1). A K-type thermocouple was used as feedback for closed-loop control of glow plug temperature. A cross-sectional view of the glow plug is presented in Figure A2.

Figure A1. Glowplug used in current study as a thermocouple (courtesy: www.borgwarner.com)

Figure A2. Cross-section of the glowplug showing K-type thermocouple used in current study (courtesy: www.borgwarner.com)
B. Average thermocouple temperature for various injection strategies

The average in-cylinder thermocouple temperature refers to the average of all the cycles (represented in main text by varying color) for a given operating condition and injection strategy. The following figures are listed in the same order as presented in main text. Figure 1*, for example, refers to conditions plotted in Figure 1, with the average KI (for normal cycles) replaced with Thermocouple temperature.

Figure 3b*: Indicated mean effective pressure (IMEP), pre-ignition count (PI count), average thermocouple temperature and coefficient of variation (CoV) of IMEP at 2000 rpm.

Figure 4b*: Average thermocouple temperature, coefficient of variation (CoV) of IMEP, pre-ignition count (PI count) and injection duration as a function of start of injection (SOI) timing at 2000 rpm.
Figure 5b*. Indicated mean effective pressure (IMEP), pre-ignition count (PI count), average thermocouple temperature and coefficient of variation (CoV) of IMEP at 2000 rpm. The SOI for the first pulse was maintained at -300 CAD aTDC, while the SOI for the second pulse was swept from -240 CAD aTDC to -90 CAD aTDC.

Figure 6b*. Indicated mean effective pressure (IMEP), pre-ignition count (PI count), average thermocouple temperature and coefficient of variation (CoV) of IMEP at 2000 rpm. The SOI of for the primary and secondary injection pulses are maintained at -300 CAD aTDC and -210 CAD aTDC, respectively, while the ratio of fuel in the two pulses is varied.
Figure 9*: Variation in indicated mean effective pressure (IMEP), pre-ignition count (PI count), average thermocouple temperature and coefficient of variation (CoV) of IMEP for Case 1 (33:33:33).
Figure 11. Variation in indicated mean effective pressure (IMEP), pre-ignition count (PI count), average thermocouple temperature and coefficient of variation (CoV) of IMEP for Case 2 (50:25:25).
Figure 13*: Variation in indicated mean effective pressure (IMEP), pre-ignition count (PI count), average thermocouple temperature and coefficient of variation (CoV) of IMEP for Case 2 (50:40:10).

Figure 14*: Comparison of triple pulsed injection strategies for varying DOIs Case 1 (33:33:33) versus Case 2: (50:25:25) versus Case 3 (50:40:10) for common SOIs (designated in boxed texts).
Figure 15a*: Comparison of triple pulsed injection strategies for varying DOIs Case 1 (33:33:33) versus Case 2: (50:25:25) versus Case 3 (50:40:10) for zero pre-ignition events registered in all cycles. The red dotted rectangles mark the best scenario for each case (maximum IMEP and lowest CoV of IMEP).

Figure 18*: Summary of variation of IMEP, pre-ignition count, average thermocouple temperature and coefficient of variation (CoV) of IMEP for varying SOI and DOI of late injection at an injection pressure of 130 bar. Horizontal zero pre-ignition count line in red-dotted provided for reference.
Figure 2*: Summary of variation of IMEP, pre-ignition count, average thermocouple temperature and coefficient of variation (CoV) of IMEP for varying SOI and DOI of late injection at an injection pressure of 150 bar. The horizontal zero pre-ignition count line is provided for reference.

Figure 3*: Summary of variation of IMEP, pre-ignition count, average thermocouple temperature and coefficient of variation (CoV) of IMEP for varying SOI and DOI of late injection at an injection pressure of 170 bar. Horizontal zero pre-ignition count line in red-dotted provided for reference.
Figure 24*. Comparison of variation of IMEP, pre-ignition count, average thermocouple temperature and coefficient of variation (CoV) of IMEP for varying DOI of late injection at varying injection pressure.
Reviewer 1: Questions & Responses

This paper studies how increasing the number of fuel injections in a boosted, single cylinder research engine might reduce its propensity for preignition and superknock without significantly compromising engine efficiency. The number of fuel injections are increased from one to three, with sweeping of some injection parameters also performed, whilst various, pressure based metrics are presented. These results are also related to a thermocouple that was mounted in the engine.

Overall, this is a well written paper that presents a substantial amount of experimental data. This paper should be accepted for publication pending some editing, as I detail below.

Question/Comment: This paper at times speculates on some of the physical phenomena at play without presenting any evidence. Of particular note are arguments that are based on spray proximity to the liner and the likelihood of oil droplet formation, both of which aren’t measured. Similarly, charge cooling benefits of different injection strategies are argued to be causing different trends, but this isn’t measured.

Please moderate such discussion.

Response: Thank you for this feedback. The discussions relating to spray proximity to the liner, the likelihood of oil droplet formation, and charge cooling have been moderated in the revised manuscript so that we do not make any strong claims which are not well supported by data (this was certainly not our intention).

However, since submitting this paper for review, we have published another paper (Ref [25]) which uses Computation Fluid Dynamics (CFD) to explore many of these phenomena in greater detail. This companion paper certainly supports some of the hypotheses/claims in this paper, and accordingly, we have cited it on several occasions to support our arguments in the revised manuscript. For example, the CFD calculations clearly demonstrated that spray wall impingement played a critical role in pre-ignition tendency for this engine/operating conditions. Nevertheless, the likelihood of droplet formation has not been dealt with experimentally, and remains one of the key missing links in the chain of hypothesis presented.
Question/Comment: The paper would benefit from more information on the thermocouple that is mounted in the engine, including: (a) a sectional view or a scaled schematic showing where the TC is, (b) a discussion of what the TC is measuring, and (c) quantification of its frequency response relative to duration of the preignition events that it is used to examine.

Response: We apologize for this oversight. The revised manuscript now includes a detailed description of the in-cylinder thermocouple, including the relevant drawings. As the glowplug used in the current study is discontinued, the details are scant. We have managed to get some details on the thermocouple from the OEM.

Question/Comment: Figure 4 is an odd figure. I suggest that it is deleted, and this scale is added to the first figure that uses it, with all later figures just referencing that figure for its scale.

Response: Thanks for this feedback. The original Figure 4 has been removed in the revised manuscript.

Question/Comment: I assume that figure 5 relates only to the single injection event results. If so, I suggest making this clear in the caption and reconsider the split of the discussion and the titles of sections 3.1 and 3.2.

Response: Both reviewers had negative comments relating to this figure, with the second reviewer also noting that it did not add anything new to the paper. Given this feedback, we have removed the original Figure 5 in the revised manuscript.

Question/Comment: Does figure 5 suggest that PI is occurring more often than normal combustion? If so, I don’t understand this. What am I missing? Perhaps this should be explained in the paper to avoid others’ misunderstanding this too.

Response: As per the comment above, the original Figure 5 has been removed from the revised manuscript. However, we felt it was still necessary to address this comment. The original Figure 5 did indeed appear to
be giving misleading information that pre-ignition is occurring more than normal combustion events.

However, what is actually happening here is: all the normal cycle values have a more restricted distribution, and hence they are all overlapping. This gives a false impression that they are less in number.

**Question/Comment:** One minor point on the PI count. I would prefer to see this as a % of all cycles, including normal combustion, as this is more meaningful to the reader.

**Response:** The authors agree that it is more useful to refer to pre-ignition as a percentage rather than count. The current representation was used following other researchers, who often refer to PI per 10,000 or 15,000 cycles. In this regard, we have changed the values to a percent basis in the revised manuscript.

**Question/Comment:** Finally, I note that this paper presents nothing on engine out emissions. Whilst a catalyst might be able to deal with this, it would have been useful to have presented such results, particularly to see whether there are significant trade-offs between preignition avoidance and emissions, which I expect will be the case – that the CoV often increases as PI count reduces suggests this for UHCs, and I would expect some variation of NO and CO too.

**Response:** Unfortunately, engine-out emissions data was not measured in this test campaign due to time and hardware limitations. We certainly agree that there may be some trade-offs in terms of emissions, and we have noted this point in the conclusions of the revised manuscript. As you mention, we would expect that these emissions could be dealt with by the TWC, particularly since all testing was conducted under stoichiometric conditions. We hope that this goes some way to addressing your concerns.

**Reviewer 2: Questions & Responses**

**Question/Comment:** How many segments of 12,000 cycles were used?

**Response:** When the tests were performed, the acquisition system was limited to acquiring 12,000 cycles, and hence the recording was made for one set of such data point. Later, we eliminated this problem, and...
repeated randomly selected operating points to confirm the repeatability. The pre-ignition trends were generally observed to be highly repeatable. Because of the number of conditions dealt with in this study, we could not have repeated all operating conditions/injection strategies again, but the repeatability from the randomly selected point gave us confidence in our data. A further reason for this is the higher-than-usual IMEP and intake pressure that was chosen in this study. To have a higher frequency of pre-ignition events (and more repeatable data) we also ran all experiments at an intake pressure of 2.1 bar, which led to IMEPs of ~25 bar. This increases the pre-ignition tendency, and helps the observations being more repeatable.

Question/Comment: Figure 3 can be removed and associated discussion. The calibration is not clear if the rail dynamics are accounted for, which could increase or decrease injection pressure as a function of injection schedule and frequency. Thus, the mass of injection in secondary or tertiary injections cannot be extrapolated from single injection durations. Please revise.

Response: The original Figure 3 and the associated discussion has been removed from the revised manuscript.

Question/Comment: Figure 5 can be removed, it provides little information to the study. Moreover, the cylinder pressure measurement is highly dubious when shocked by PI, so why attempt to preform analysis on it? This detracts from the manuscript, I recommend removing this.

Response: The authors agree that the figure does not add much to the study and hence has been removed in the revised manuscript.

Question/Comment: The figures with PI count should not have axis that go to negative values, negative is impossible

Response: Thank you for this feedback. All figures in the revised manuscript now only have positive values on the axes.
**Question/Comment:** It would be useful to have one figure with the PI count and other metrics on it with the single injection timing sweep as a “calibration” for the split images. Possibly a shaded region of what the single SOI sweep range of PI, KI, COV were in the figures. This would help to show if the split injection strategies were “better”.

**Response:** Thanks for this feedback. We have added a figure in the revised manuscript which shows the possible ranges of the different parameters for the single injection strategy for varying SOI. This figure can be used by the reader as a “calibration curve” to determine how the multiple injection event strategies compare with the base case, i.e. if they are “better” or “worse”.

**Question/Comment:** Typo line 469 “mass of fuel injected in the third pulse reduces (from Case 1 to Case 3), the also IMEP increases.” Needs to be corrected where “also” appears

**Response:** Thank you for pointing this out. The correction has been made in the revised manuscript.

**Question/Comment:** Label inserts a-e in figure 17 in caption

**Response:** The labels a-e have now been included in the revised manuscript.

**Question/Comment:** Figure 6a should be removed, figure 6b is much more useful

**Response:** Please refer to the final response below.

**Question/Comment:** Figure 8a should be removed, figure 8b is much more useful

**Response:** Please refer to the final response below.

**Question/Comment:** Figure 9a should be removed, figure 9b is much more useful

**Response:** Please refer to the final response below.

**Question/Comment:** Figure 11 should be removed it is almost impossible to determine anything useful
Question/Comment: Figure 13 should be removed it is almost impossible to determine anything useful from the figure as is

Response: Please refer to the final response below.

Question/Comment: Figure 15 should be removed it is almost impossible to determine anything useful from the figure as is

Response: Please refer to the final response below.

Question/Comment: Remove figure 19

Response: Please refer to the final response below.

Question/Comment: Remove figure 20

Response: Please refer to the final response below.

Question/Comment: Remove figure 24

Response: Please refer to the final response below.

Question/Comment: I suggest removing the thermocouple data, it is not necessary, detracts from the story, and the paper is too long as is.

Response: Thank you for this feedback. The authors feel that we did not provide adequate reasoning in the original manuscript as to why the thermocouple data was included in the first place. The reason was because historically, pre-ignition tendency has been associated with normal operating temperature. Operational temperatures changed with the fuels, and it was often observed that fuels that exhibited higher...
average in-cylinder temperatures (for whatever reason) also had a higher pre-ignition tendency. Similarly, changing the lambda, engine speed and other parameters affected the normal engine running temperature. It was found that pre-ignition tendency correlated well with normal engine operating condition. However, these studies were performed in 1950s and there has been no such study in recent times. With the introduction of these thermocouple data, we have made a first attempt to bring out that correlation, or lack thereof. As we observed in the current study, the studies of yesteryear are still valid, and we see a general reduction in pre-ignition tendency for operating conditions where the average in-cylinder temperature is lower. The authors realized that the details on the thermocouple were insufficient, and accordingly we have added them into the appendix of the revised manuscript. In light of these revisions, we believe the inclusion of this data in the manuscript is justified. The fact that pre-ignition tendency in general has some correlation with operational temperature can be better seen via these figures (color-coding is representative of temperature). Having said that, the authors are open to option of removing the figure if the reviewer finds that they do not add much to the main conclusions. If that remains the case, we can remove the figures in the next revision.