Optical Investigation of the Reduction of Unburned Hydrocarbons Using Close-Coupled Post Injections at LTC Conditions in a Heavy-Duty Diesel Engine

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ABSTRACT

Partially premixed low-temperature combustion (LTC) using exhaust-gas recirculation (EGR) has the potential to reduce engine-out NOx and soot emissions, but increased unburned hydrocarbon (UHC) emissions need to be addressed. In this study, we investigate close-coupled post injections for reducing UHC emissions. By injecting small amounts of fuel soon after the end of the main injection, fuel-lean mixtures near the injector that suffer incomplete combustion can be enriched with post-injection fuel and burned to completion. The goal of this work is to understand the in-cylinder mechanisms affecting the post-injection efficacy and to quantify its sensitivity to operational parameters including post-injection duration, injection dwell, load, and ignition delay time of the post-injection mixture. Three optical diagnostics - planar laser induced fluorescence of OH radicals, planar laser induced fluorescence of formaldehyde, and high-speed imaging of natural combustion luminescence - complement measurements of engine-out UHC with parametric variations of main- and post-injection timing and duration. Across all conditions tested, each at 1200 RPM, the optimal post-injection command duration for UHC reduction was approximately 400 microseconds (2.9 °CA). Also, conditions with shorter (3.4 °CA) post-injection ignition delays were over twice as effective on a percentage basis at reducing engine-out UHC as those with longer (5.5 °CA) post-injection ignition delays. Optical data at the post-injection “sweet-spot,” where UHC emissions are minimized, indicate that the post injection promotes transition to second-stage ignition in the near-injector region, most likely by enriching the overly fuel-lean mixtures in the wake of the main injection.

INTRODUCTION

Low temperature combustion (LTC) has been proposed as a strategy for meeting market demands for fuel efficiency while also satisfying regulated limits on NOx and soot emissions from heavy-duty diesel engines. In-cylinder strategies designed to reduce engine-out emissions of these two pollutants are of interest because they could reduce or even eliminate the burden on aftertreatment systems. Compared to conventional diesel combustion, LTC strategies generally can be characterized by high levels of intake charge dilution and increased mixing of fuel with the intake charge prior to combustion.

One method for diluting the intake charge is exhaust gas recirculation (EGR), which reduces the peak temperatures of combustion and hence the thermally produced NOx [1]. The slowing of NOx formation is a result of two effects: an increase in the heat capacity of the intake mixture, which reduces peak temperatures, and reduction in intake oxygen, which slows NOx formation kinetics.

Increased pre-combustion mixing is typically achieved by altering the fuel-injection timing. Conventional diesel operation uses injection timings that occur several crank angle degrees before top-dead-center (TDC), so that the ignition delay is short and combustion occurs near TDC. This combustion phasing is favorable for thermodynamic efficiency, but much of the charge is fuel-rich during combustion, which can also lead to significant soot formation [2]. LTC techniques achieve less soot formation by placing the injections either much earlier or much later than the conventional injection timing.

Early injection schemes - often termed partially-premixed compression ignition (PPCI), premixed-charge compression ignition (PCCI), premixed compression ignition (PCI), or in some cases in the literature, even homogeneous charge compression ignition (HCCI) - operate by providing...
significant time between the injection and the thermodynamic state during compression that induces ignition [3, 4, 5]. Given the long ignition delay of a mixture at early injection timings, these schemes create a positive ignition dwell, which is the time between the end of the injection and the start of combustion. A positive ignition dwell gives all of the injected fuel and air more time to mix before combustion, reducing rich regions where soot could form, while often creating a fast, efficient premixed heat-release profile [6].

Late-injection schemes - such as “modulated kinetics” (MK) combustion [7, 8] - achieve similar ends as the early-injection schemes by injecting fuel very near TDC or even into the expansion stroke. Here, a positive ignition dwell is possible because of high rates of EGR and the cooling of the charge due to expansion. As with early-injection strategies, the positive ignition dwell provides more time for mixing and hence lower soot formation and a more premixed-type combustion event.

While these methods of LTC can lead to substantial reductions in NO\textsubscript{x} and soot emissions, there are still issues remaining. In particular, unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions can increase under these conditions [9, 10]. Going from conventional diesel combustion to LTC operation can be viewed as moving along a trade-off between soot and UHC (and CO); as the ignition delay increases and more premixing is allowed before the start of combustion, fewer regions of the reactants are fuel-rich enough to promote soot production, but UHC emissions increase, especially as the load decreases (for instance see Figure 2). For this reason, we will focus primarily on low-load, LTC conditions where UHC emissions are particularly problematic.

Previous studies have investigated the sources of UHC at LTC conditions. Our own previous work has shown that some overly-lean mixtures in the region of the injector formed after the end of injection do not achieve complete combustion and can be significant sources of hydrocarbons [11, 12]. Other UHC sources, including wall-wetting and fuel in the crevices, can also be important, especially in light-duty engines [13, 14]. The current study focuses on UHC emissions from over-leaning in the bulk charge.

Overly-lean mixtures in the injector region have been measured using a variety of techniques. In our previous work, we used a toluene fluorescence technique in a heavy-duty, single-cylinder, optical research engine as well laser-Rayleigh-scattering in an engine simulation spray facility [12]. For the tracer fluorescence measurements, fuel was doped with a known quantity of toluene and injected into a non-reacting charge to enable quantitative fuel concentration measurements, at least up to the time that combustion would normally commence. Using the fuel concentration data, an equivalence ratio map can be generated corresponding to a given intake oxygen concentration. Equivalence ratio contour maps for an intake-oxygen concentration of 12.7% are shown in Figure 1.

The equivalence ratio contours in Figure 1 show that the mixtures near the injector (left side) become leaner very quickly after the end of the injection, initially at a rate of approximately 4 equivalence ratio units per crank angle degree. By 5 °CA after the end of injection (AEI), the equivalence ratio is 0.5 or lower in the near-injector region. Other optical data showed that first-stage (cool-flame) ignition occurs throughout the jet, but second-stage ignition occurs only in the richer downstream mixtures (right side of images), near 5 °CA AEI [11]. At the conditions examined, the upstream fuel-lean mixtures never achieved second-stage...
ignition in the time available before significant cylinder expansion. Hence, incomplete combustion of those fuel-lean mixtures contributed to UHC emissions.

These results and others like them [15] motivated a follow-up study in the current engine, showing promising results for UHC reduction with the use of post injections [16]. The rationale for using post injections is to enrich the overly-lean mixture near the injector, essentially “kicking” it into second-stage ignition and reducing unburned hydrocarbons from the injector region. Because of limitations in the fuel injection system, only two-injection schedules were tested, one with a short, close-coupled post injection (injection dwell ≈ 1 °CA) and one with a longer post-injection duration and dwell (injection dwell ≈ 3 °CA). The injection schedules for these two tests are in Figure 2a.

![Figure 2a](image)

**Figure 2a.** Injection schedule for a single injection and two post-injection schedules.

![Figure 2b](image)

**Figure 2b.** Normalized UHC measurements for these three conditions. Copyright © SAE International. Reprinted with permission [16].

The engine-out UHC results in Figure 2b illustrate the significant effect that a short, close-coupled post injection can have on UHC reduction. Whereas the longer post injection did not reduce UHC emissions relative to the single-injection baseline, the short, close-coupled post injection reduced the UHC by 27%. Optical investigations of the progression of combustion for these two conditions were consistent with enrichment of the near-injector overly-lean mixture by the post injection, bringing the combustion to completion to reduce UHC emissions.

Despite the obvious gains that were observed by using a short, close-coupled post injection in this previous study, only one short, close-coupled post-injection timing was found to be repeatable due to limitations of the heavy-duty injector. The goal of the current study is to further explore the effect of a post injection on UHC reduction over a much wider range of injection schedules with a fast-responding, light-duty injector.

Fluid mechanical (mixing) and chemical kinetics effects of the post injections are explored in two ways. First, the command duration of injection for close-coupled post injection (DOI2C) is varied from very short (DOI2C=200 microseconds) to relatively long (DOI2C=800 microseconds) for a given main injection duration and timing. This variation in post-injection duration not only changes the amount of fuel delivered in the post injection, but also the penetration and fluid mixing characteristics of the post jet. Short post injections (DOI2C<350 microseconds) do not penetrate to the bowl wall of this engine within the time available for combustion, and have different injection profiles and ignition dwells than long post injections. Additionally, post injections that do not penetrate to the bowl wall do not have fuel/air mixtures that “roll up” along the wall into the large side rollers in the jet-jet interaction regions that characterize low-temperature combustion in diesel engines [17]. These possible differences in penetration, injection profile, and mixing time could significantly change how the post injection enriches the overly-lean mixture left by the main injection.

Second, the ignition delay of the mixture created with the post injection is varied by changing the combustion phasing of the entire injection schedule. Here, main- and post-injection events are moved as a unit to earlier and later timings relative to a baseline timing. In doing so, the ignition delay of the near-TDC main injection changes only slightly because ambient conditions change minimally near TDC, when the piston velocity is low. The ignition delay of the post injection, however, varies much more because the ambient gases change more significantly at the later injection timing of the post injection when the cylinder contents are starting to expand. In this case, an increase (or decrease) in the ignition delay of the post injection would allow for more (or less) time for mixing between the post-injection fuel and the overly-lean mixture from the main injection. Even though the schedule is shifted, the main- and post-injection durations and dwell between them are held constant, so the fluid mechanics of injection remain largely the same. In this way, the fluid mechanical effects of post-injection penetration and mixing can be separated from kinetics effects, to some degree.
EXPERIMENTAL SETUP

Optical Engine Experiment

Table 1. Engine and fuel system specifications.

<table>
<thead>
<tr>
<th>Engine base type</th>
<th>Cummins N-14, DI diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cylinders</td>
<td>1</td>
</tr>
<tr>
<td>Cycle</td>
<td>4-stroke</td>
</tr>
<tr>
<td>Number of intake valves</td>
<td>2</td>
</tr>
<tr>
<td>Number of exhaust valves</td>
<td>1</td>
</tr>
<tr>
<td>Intake valve opening</td>
<td>17° BTDC Exhaust†</td>
</tr>
<tr>
<td>Intake valve closing</td>
<td>195° ATDC Exhaust‡</td>
</tr>
<tr>
<td>Exhaust valve opening</td>
<td>235° BTDC Exhaust‡</td>
</tr>
<tr>
<td>Exhaust valve closing</td>
<td>27° ATDC Exhaust‡</td>
</tr>
<tr>
<td>Combustion chamber</td>
<td>Quiescent, direct injection</td>
</tr>
<tr>
<td>Swirl ratio</td>
<td>0.5 (approx.)</td>
</tr>
<tr>
<td>Bore</td>
<td>139.7 mm [5.5 in]</td>
</tr>
<tr>
<td>Stroke</td>
<td>152.4 mm [6.0 in]</td>
</tr>
<tr>
<td>Bowl width</td>
<td>97.8 mm [3.85 in]</td>
</tr>
<tr>
<td>Displacement</td>
<td>2.34 liters [142 in³]</td>
</tr>
<tr>
<td>Connecting rod length</td>
<td>304.8 mm [12.0 in]</td>
</tr>
<tr>
<td>Piston pin offset</td>
<td>None</td>
</tr>
<tr>
<td>Geometric compression ratio</td>
<td>11.2:1</td>
</tr>
<tr>
<td>Replicated compression ratio</td>
<td>16:1</td>
</tr>
<tr>
<td>Fuel Injector</td>
<td>Delphi DFI-1.5 (light duty)</td>
</tr>
<tr>
<td>Fuel injector type</td>
<td>Common-rail, solenoid actuated</td>
</tr>
<tr>
<td>Cup (tip) type</td>
<td>Mini-sac</td>
</tr>
<tr>
<td>Number of holes &amp; arrangement</td>
<td>8, equally-spaced</td>
</tr>
<tr>
<td>Spray pattern incl. angle</td>
<td>156°</td>
</tr>
<tr>
<td>Nominal orifice diameter</td>
<td>0.131 mm</td>
</tr>
</tbody>
</table>

†In this optically accessible diesel engine, one of the two exhaust valves of the production cylinder head was replaced by a window and periscope (see Fig. 1).
‡All valve timings correspond to the crank angle of the first detectable movement from fully closed.

The engine used in this study is an optical, single-cylinder Cummins N-series direct-injection, heavy-duty diesel engine. The engine has a bore of 139.7 mm and a stroke of 152.4 mm, and is equipped with a Bowditch piston with an open, right-cylindrical bowl and a flat fused-silica piston-crown window providing imaging access to the bowl, viewing from below. A flat, round window is also installed in place of one of the exhaust valves for imaging access to a portion of the squish region above the piston (view not used in the current study). A 30-mm wide curved window matching the contour of a portion of the bowl-wall allows laser access into the bowl. Additional laser access is available through flat rectangular windows installed in a ring at the top of the cylinder. Because of thermal load limitations of the windows, the engine was skip-fired, with each fired cycle followed by nine motored cycles. Information about engine geometry is in Table 1 and a schematic of the experiment is in Figure 3. Further details about this engine can be found in Refs. [18, 19].

Figure 3. Experimental setup of the single-cylinder engine, laser configuration, and three-camera optical system. The camera field-of-view is shown in the upper right.

The injector used in this study is a Delphi DFI 1.5 light-duty, common-rail injector. A light-duty solenoid-driven injector with 131 micron orifices was used in place of the previous heavy-duty injector for its fast response time and its ability to deliver consistent, close-coupled, short-duration post injections over a range of injection schedules. Because of the low lubricity and low viscosity of special fuels (such as n-heptane) selected for optical research, the production common-rail fuel pump could not be utilized. Instead, a custom high-pressure diaphragm pump specially designed for low-lubricity fuels pressurizes the fuel rail at up to 2000 bar. The delivery rate of the diaphragm pump is limited, however, and as a result it could only sustainably pressurize the fuel rail to 1200 bar at the static back-leak rate of this light-duty injector.
Engine Operating Conditions

The engine is operated in a high-EGR (12.6% intake O\textsubscript{2}) late-injection LTC mode summarized in Table 2, for which the start of main combustion begins slightly after TDC. The low intake temperature in Table 2 was intentionally selected for several reasons. First, diluting the intake with N\textsubscript{2} rather than real EGR yields a higher specific-heat ratio of the charge, so that lower intake temperatures are required to achieve the same compressed temperatures at TDC as with EGR. Even after accounting for differences in compression-heating effects, a relatively low TDC temperature allows fuel injection close to TDC while still achieving a long enough ignition delay for LTC conditions. Injecting close to TDC is desirable from a fundamental perspective because the in-cylinder density remains nearly constant for a relatively long time compared to injecting during the intake or expansion strokes. As a result, the ignition delay for the main injection remains nearly constant for small shifts of the injection schedule, which facilitates the study on kinetic effects described at the end of the introduction. Furthermore, studying in-cylinder processes at nearly constant density is useful for comparison to analysis and/or experiments in constant volume combustion vessels. The cool conditions with near-TDC conditions also provided combustion phasing favorable for efficiency while still achieving pre-combustion mixing times characteristic of LTC. Finally, as discussed below, for more typical U.S. diesel fuels with cetane numbers near 47 (rather than 56 for n-heptane \cite{20}), such cool intake conditions would not be required to achieve the same ignition delays at the high EGR conditions of this study.

As discussed above, UHC emissions are a particular issue at low-load conditions; the engine load-range in this study is varied between one (1) and about six (6) bar gIMEP. More details about the engine operating conditions are in Table 2.

Table 2. Engine operating conditions.

<table>
<thead>
<tr>
<th>Engine Speed</th>
<th>1200 RPM*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Load Range</td>
<td>1-6 bar gIMEP\textsuperscript{4}</td>
</tr>
<tr>
<td>Intake O\textsubscript{2}</td>
<td>12.6%</td>
</tr>
<tr>
<td>Fuel Pressure</td>
<td>1200 bar</td>
</tr>
<tr>
<td>TDC Motored Density</td>
<td>18 kg/m\textsuperscript{3}</td>
</tr>
<tr>
<td>TDC Motored Temperature</td>
<td>837 K</td>
</tr>
<tr>
<td>BDC Pressure</td>
<td>164 kPa</td>
</tr>
<tr>
<td>BDC Temperature</td>
<td>78 °C</td>
</tr>
<tr>
<td>(16:1 Compression Ratio BDC Pressure)</td>
<td>101 kPa (abs)</td>
</tr>
<tr>
<td>(16:1 Compression Ratio BDC Temperature)</td>
<td>36°C</td>
</tr>
</tbody>
</table>

\textsuperscript{4}At this speed, each crank angle degree (°CA) is 139 microseconds in duration.

These operating conditions are designed to parallel those of the previous study by Chartier \textit{et al.} \cite{16} as closely as possible. As described above in the Introduction, this is done purposefully to further investigate the role of short, close-coupled post injections for UHC reduction.

Two important differences between the two studies are the fuel and the fuel injector. In anticipation of fuel concentration and other optical diagnostic measurements to follow, we selected n-heptane as the fuel. While the diesel primary reference fuels of the previous study better reflect the physical characteristics (e.g., boiling point) of typical diesel fuel, as yet, a feasible and quantitative laser-induced fuel-
tracer fluorescence diagnostic has not been developed for such heavy fuels. Techniques for lighter fuels like n-heptane have been developed and successfully employed (see Figure 1 for instance), so it was chosen as the fuel. As will be shown later in the results, the characteristic post-injection UHC behavior observed in Chartier et al. [16] with high boiling-point fuels is retained here using n-heptane.

As shown in Table 3, however, the cetane number for n-heptane is significantly higher than for the diesel primary reference fuel blend used in Chartier et al. Using the same in-cylinder thermodynamic conditions would result in much shorter ignition delays with n-heptane. To match ignition delay, either the temperature or the pressure of the intake stream could be adjusted. The chemical kinetics of ignition and the following combustion processes (including incomplete combustion) depend strongly on temperature, so we were hesitant to decrease the temperature. With the change of injectors, the fluid mechanical processes of fuel penetration and mixing would already be somewhat different, so we chose to reduce the intake pressure (boost) to extend the ignition delay. A lower intake pressure yields a lower in-cylinder density, which would yield richer mixtures at a given downstream position in the jets, but the smaller nozzle size of the light duty injector offsets this effect, so that the mixtures are similar for the two injectors. The TDC conditions required to match temperature and ignition delay are shown in Table 3, and the heat release for the two studies are in Figure 5.

**Table 3. Comparison of operating conditions between current study and Chartier et al. [16].**

<table>
<thead>
<tr>
<th></th>
<th>Current Study</th>
<th>Chartier et al. [16]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake O₂</td>
<td>12.6%</td>
<td>12.7%</td>
</tr>
<tr>
<td>Fuel</td>
<td>n-heptane</td>
<td>32.3% cetane 67.7% heptamethylnonane</td>
</tr>
<tr>
<td>Cetane number</td>
<td>56</td>
<td>42.5</td>
</tr>
<tr>
<td>TDC Motored Density</td>
<td>18 kg/m³</td>
<td>22.1 kg/m³</td>
</tr>
<tr>
<td>TDC Motored Temperature</td>
<td>837 K</td>
<td>837 K</td>
</tr>
<tr>
<td>TDC Motored Pressure</td>
<td>43.2 bar</td>
<td>54.9 bar</td>
</tr>
<tr>
<td>Start of main combustion</td>
<td>360.1 – 366.6 CAD</td>
<td>362.2 CAD</td>
</tr>
<tr>
<td>Ignition delay to main combustion</td>
<td>9.1-9.6 CAD</td>
<td>7.2 CAD</td>
</tr>
</tbody>
</table>

The heat release profiles of the two studies in Figure 5, Ref. [16] and the current study, are qualitatively similar, though the timing is not exactly the same as a result of the 1 °CA difference in SOI1c and slight changes in ignition delay. In the single injection case, a similar first-stage ignition heat release peak appears before the second-stage ignition heat release peak. In the case with a main- plus post-injection schedule (Figure 5b), the post-injection heat release profile is different between the two cases. In the previous study, the post-injection heat release for the sole condition studied was small, so that it appeared on the main injection heat release profile as a small shoulder rather than as a distinct peak. In the current study, the optimal post injection is larger, and the main-injection duration is longer. As a result, the post-injection, while still close coupled, is phased later relative to the main-injection heat release, so that the post-injection heat release peak is later and more distinct.

Engine Diagnostics

Several diagnostics are used to investigate the origin of UHC emissions at LTC conditions: cylinder pressure measurements, exhaust UHC emissions analysis, and three different optical diagnostics.

Cylinder pressure is measured with an AVL QC34D pressure transducer every quarter crank-angle degree. The apparent heat release rate is calculated from the measured...
cylinder pressure using standard techniques described in Ref. [21].

Engine-out UHC emissions are measured with a California Analytical Instruments (CAI) 600 series hydrocarbon analyzer. This analyzer samples the exhaust stream and uses a flame ionization detector to measure total unburned hydrocarbons. The exhaust stream is pulled from the exhaust manifold, within 100 mm of the exhaust valve. The line from the engine to the analyzer is heated to 155 degrees Celsius to prevent condensation of water and hydrocarbons. A pump provides a continuous flow of exhaust gases to the analyzer, and the transit time between the engine and the analyzer is about 4 seconds. All UHC data are averaged over a run-time of 100 fired cycles. To account for the skip-fired operation of the engine, the reported UHC data have been multiplied by 10 to approximate what they would be in a continuously-fired, single-cylinder engine. The standard deviation in UHC measurements between runs is approximately 2 ppm (corresponding to 20 ppm after correcting for a continuously-fired engine).

Three different optical diagnostic techniques are employed to gain insight into the origins of UHC emissions. Two important radical species involved in ignition provide information about the evolution of in-cylinder unburned fuel. Formaldehyde (H₂CO) is produced during first-stage ignition and consumed during second-stage ignition. Detailed chemical kinetics simulations predict that after first-stage ignition, the evolution of formaldehyde mirrors that of the overall pool of unburned hydrocarbons [11]. Hence, formaldehyde serves as a marker of unburned fuel from mixtures that have achieved first-stage ignition but have not yet reached second-stage ignition. Formaldehyde does not serve as a good marker for all unburned fuel, such as that from regions that have not achieved first-stage ignition (e.g., wall wetting and potentially crevices), nor does it mark UHC in rich mixtures after second-stage ignition. However, previous studies [11, 12] have shown that in the near injector region, overly-lean mixtures are a primary source of UHC emissions, so that formaldehyde serves as a good marker for those UHC sources.

The second radical species, the hydroxyl radical (OH), rises in concentration by orders of magnitude at second-stage ignition in fuel-lean to stoichiometric mixtures [21], and hence provides an indication of second-stage ignition and relatively complete combustion and hence low unburned fuel concentration. As described below, two laser-based techniques are used to measure these two radical species, similar to previous studies conducted at LTC conditions in this engine [11, 16].

**Laser induced fluorescence of formaldehyde (H₂CO-PLIF):** The third harmonic output of a Spectra-Physics Quanta-Ray single-cavity Nd:YAG laser at a wavelength of 355 nm is formed into a 30-mm wide sheet with a thickness of 1 mm or less. A pulse energy of 80 mJ at the engine is used laser-induced fluorescence of formaldehyde within the engine cylinder. The sheet is oriented at a 12° angle relative to the firedeck to probe H₂CO along the approximate symmetry plane of one of the fuel jets. LIF emission is collected at wavelengths longer than 310 nm with an intensified Princeton Instruments PI-MAX 3 intensified charge-coupled device (ICCD) camera with a HQi (GEN-III) intensifier and a resolution of 1024×1024, a gate time of 50 ns, and at maximum gain. The camera is fitted with a Nikkor glass f/2.5 lens. Two filters, a 385-nm long-wave-pass and a 40-nm wide bandpass filter centered at 408 nm, reject laser scatter and other interference outside the formaldehyde fluorescence emission band.

**Laser induced fluorescence of OH (OH-PLIF):** A Spectra-Physics Quanta-Ray single-cavity Nd:YAG laser pumps a Spectra-Physics optical parametric oscillator (OPO) to produce the laser excitation for the OH-PLIF technique. The OPO is tuned to near 568 nm and the light is doubled using a BBO crystal to approximately 284 nm to excite the Q1(9), Q2(8), and P1(5) transitions of OH that merge as a result of pressure broadening. The 284-nm laser beam is co-aligned with the 355-nm laser beam for H₂CO-PLIF upstream of the sheet-forming optics. As a result, the laser sheet at 284 nm is approximately the same size as that at 355 nm: 30 mm wide and up to 1 mm thick. The 284-nm laser pulse energy at the engine is 19 mJ per pulse. LIF emission is collected at wavelengths shorter than 385 nm with an intensified Princeton Instruments PI-MAX 3 ICCD camera with a Super-blue, slow-gate intensifier (Gen-II) and a resolution of 1024×1024, a gate time of 410 ns, and at maximum gain. The camera is equipped with an ultraviolet (UV) Nikkor f/4.5 lens. Three filters, a 65-nm wide blocked bandpass filter at 310 nm, a 15-nm wide unblocked bandpass filter at 310 nm, and a color-glass SWG305, reject laser scatter and other interference outside the OH fluorescence band near 308 nm. Detuning the laser off the transition at 284 nm produces almost no signal through the filter pack, indicating that the signal shown in the OH-PLIF images is almost entirely fluorescence of OH.

For both laser-induced fluorescence techniques, the LIF data are limited to one frame per cycle, due to repetition-rate constraints of both the laser and camera systems. The OH-LIF signal is collected 1 microsecond before that of the H₂CO-LIF signal, so that they are virtually simultaneous relative to engine time scales. As shown in Figure 3, the fluorescence emission is collected through the large piston-crown window and directed to the two ICCD and one high-speed complementary metal oxide semiconductor (CMOS) camera using two beamsplitters. A long-wave-pass beamsplitter with a cut-off near 385 nm directs UV light to the OH-PLIF camera. The remaining light is split by a 50% reflectance broadband beamsplitter between the H₂CO-PLIF camera and the high-speed CMOS camera (described below).

These two LIF techniques are used together to simultaneously image intermediate species after first- and second-stage ignition. As described above, H₂CO is a marker
of UHC remaining after first-stage ignition, while OH is a marker of second-stage ignition [11]. It has been shown in previous studies as well as the current work that these two signals generally do not overlap within the plane of the lasers, and that the location where they meet is an indication of the transition from first- to second-stage combustion. An example of this is Figure 6, which is annotated to show each region. The figure shows a partial view from below of the combustion bowl, with the injector on the left (white dot) and the wall of the right-cylindrical bowl on the right (as indicated by a curved white line). The format of this figure will be used throughout this manuscript to show the difference between H\textsubscript{2}CO-PLIF and OH-PLIF signal.

In Figure 6, the two false-colors indicate the two species under consideration: red for H\textsubscript{2}CO and green for OH fluorescence. It is clear that within the plane of the laser, the H\textsubscript{2}CO and OH fluorescence overlap very little, which would appear as yellow in the image. The lack of overlap is consistent with these two species marking the first- and second-stage ignition regions. Later in the cycle, generally after OH fluorescence is first detected, the 355 nm laser can excite not only H\textsubscript{2}CO molecules, but also poly-cyclic aromatic hydrocarbon (PAH) molecules, which are precursors to soot, as well as possible laser-induced incandescence (LII) of soot itself. The emission spectrum and signal intensity of fluorescence from these laser-excited PAH molecules are different from H\textsubscript{2}CO, and hence can be used to discriminate between the two sources.

Our previous studies using OH- and H\textsubscript{2}CO-PLIF imaging used a spectrometer to discriminate between H\textsubscript{2}CO and PAH fluorescence and/or soot LII [16]. The H\textsubscript{2}CO fluorescence spectrum shows a series of characteristic bands within the filter bandpass, while both PAH fluorescence and soot LII spectra are relatively broadband. Additionally, inspection of the images showed that the intensity of the broadband PAH/soot emission was almost universally much brighter than the H\textsubscript{2}CO emission, which remained relatively unchanged until its disappearance at second-stage ignition. The close correlation between the spectral signatures and intensity patterns of H\textsubscript{2}CO and PAH/soot allow discrimination by intensity, without using a spectrometer. For instance, the broad, relatively moderate intensity fluorescence from 355-nm excitation on the left half of Figure 6 (red color in figure) is characteristic of formaldehyde fluorescence, while the smaller, more isolated and intense pockets of emission on the right side of the image are typical of PAH fluorescence and/or soot LII, as labeled in Figure 6. Hence, to allow simultaneous imaging with all three diagnostics, these intensity signatures, rather than fluorescence spectra measured with a spectrometer, were used in the current study to discriminate between formaldehyde and PAH fluorescence.

High-speed natural luminescence imaging: The third technique uses a Phantom 7.1 CMOS camera equipped with a Nikkor 105 mm, f/1.8 lens to record natural luminescence from combustion reactions and combustion-generated products. The camera framing is triggered by the shaft encoder at a resolution of one-half °CA, and the exposure duration is 50 microseconds. Although first-stage ignition reactions yield some weak chemiluminescence that sometimes can be detected with CMOS arrays, in the current study the intensity is too weak after the two beam-splitters for the laser diagnostics. Hence, any ignition chemiluminescence visible in the high-speed images is from second-stage ignition. Natural soot incandescence, when present, is also recorded by the camera. Exposure times were limited to 50 microseconds to avoid over-exposure from the high-intensity soot incandescence. The high-speed natural luminosity images are not presented in the present study, but information gleaned from inspection of the images (e.g., spray/jet penetration and actual injection start/dwell times), is included.

Test Matrix

The test matrix includes engine operating conditions at a variety of commanded injection timings to investigate the effect of post-injection penetration and ignition delay. An overview of the test matrix is in Table 4.

As described in the Introduction, changes in post-injection duration are used to investigate the effect of post-injection mixing and penetration on UHC reduction, while changes in the phasing of fuel-injection timing are used to vary the ignition delay time of the post injection. The baseline main-injection command timing (SOI\textsubscript{1C}) is 352 CAD. During single-injection tests, the command duration of the injection (DOI\textsubscript{1C}) is varied to measure the baseline engine-out UHC emissions in the absence of post injections. The single-
injection DOI1c sweeps are tested at three injection timings, SOI1C=352 CAD, 349 CAD, and 355 CAD. Changes in the injection timing alter the combustion phasing, and as a result, the unburned hydrocarbon emissions (and other emissions, such as NOx and potentially PM, though not measured here).

Table 4. Engine operating test matrix with commanded injection timings and durations.

<table>
<thead>
<tr>
<th>%O2</th>
<th>SOI1C [CAD]</th>
<th>DOI1C [usec] (°CA)</th>
<th>SOI2C [CAD]</th>
<th>DOI2C [usec] (°CA)</th>
<th>Dwell* [°CA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.6</td>
<td>352</td>
<td>600-2400 (4.3-17.3)</td>
<td>362</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
<tr>
<td>12.6</td>
<td>352</td>
<td>800 (5.8)</td>
<td>362</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
<tr>
<td>12.6</td>
<td>352</td>
<td>1000 (7.2)</td>
<td>363.5</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
<tr>
<td>12.6</td>
<td>352</td>
<td>1600 (11.5)</td>
<td>368</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
<tr>
<td>12.6</td>
<td>352</td>
<td>1000 (7.2)</td>
<td>363.25</td>
<td>250-500 (1.8-3.6)</td>
<td>0.5</td>
</tr>
<tr>
<td>12.6</td>
<td>352</td>
<td>1000 (7.2)</td>
<td>365</td>
<td>250-600 (1.8-3.6)</td>
<td>3</td>
</tr>
<tr>
<td>12.6</td>
<td>355</td>
<td>600-2400 (4.3-17.3)</td>
<td>366.5</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
<tr>
<td>12.6</td>
<td>355</td>
<td>1000 (7.2)</td>
<td>366.5</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
<tr>
<td>12.6</td>
<td>349</td>
<td>600-2400 (4.3-17.3)</td>
<td>365</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
<tr>
<td>12.6</td>
<td>349</td>
<td>1000 (7.2)</td>
<td>360.5</td>
<td>200-800 (1.4-5.8)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* Dwell time in each main- plus post-injection schedules is approximated from Mic scattering images of liquid spray in high-speed video with a temporal resolution of 0.5 °CA.

SOI2C is selected to place the post injection close to the main injection while maintaining a clear separation between injections. Engine load variation, previous momentum-based injection rate measurements [16], and optical imaging of the sprays (not shown here) indicate that the separation between the main and post injections becomes unstable when the command pulses are too close. Within a command resolution of 0.25 °CA (~35 microseconds at 1200 RPM), the closest possible SOI2C yields consistently separate injections with a real dwell between injections of about 0.5 °CA. Advancing SOI2C further can lead to unstable injector operation, with some main injection events merging into the post injection and yielding higher load and fuel delivery for those cycles with merged injections. Conversely, if SOI2C is retarded by only 0.25 °CA from the closest consistent timing, the real dwell between injections increases by 1.5 °CA, to about 2 °CA. Thereafter, additional retarding of SOI2C produces equivalent increase in the real dwell between injections (i.e. a further delay of SOI2C by 0.25 °CA also increases the dwell by 0.25 °CA). This initial non-linear relationship between commanded and real injection dwell is attributed to internal injector dynamics that occur when the injection separation is very small.

To provide a center point for study of the effects of the dwell between injections, we selected the baseline SOI2C timing that yields a real injection dwell of 2 °CA. Post injections are first added to the baseline SOI1C=352 CAD main-injection timing with three different main-injection durations. A sweep of DOI2C at each of these three DOI1C cases is used to observe the variation in UHC emissions with load; longer main-injection durations change the “baseline load” for the DOI2C sweeps. Changes in DOI2C are intended to explore the role of mixing and penetration of the post-jet on UHC reduction. Additionally, SOI2C is varied holding constant SOI1C=352 CAD and DOI1C=1000 microseconds. These tests are used to investigate the effect of post-injection dwell on engine-out UHC levels. Here, three SOI2C timings are used, 363.25 CAD, 363.5 CAD, and 365 CAD. As described above, and according to high-speed video, the dwell times between the end of the main injection and the beginning of the post injection for these commanded times are 0.5 °CA, 2 °CA, and 3.5 °CA, respectively.

Finally, data are obtained for DOI2C sweeps at three different SOI1C timings with the dwell between injections held constant. These cases are used to illustrate the effect of post-injection ignition delay on UHC emissions. As discussed above, these changes in SOI1C do not significantly change the ignition delay of the near-TDC main injection, but the ignition delays of the post injections do change significantly because of the later timings (after TDC) of the post injections. An overview of the injection timings of the various sweeps, along with start of main combustion (SOMC) and start of post-injection combustion (SOPC) is in Table 4. Eight families of timings, all of which are described in the test matrix in Table 4, are included.

Table 5. Start of combustion of both main and post injections for eight injection-timing schemes.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>352</td>
<td>Varies</td>
<td>363.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>352</td>
<td>1000</td>
<td>363.5</td>
<td>Varies</td>
<td>363.1</td>
<td>368.5</td>
</tr>
<tr>
<td>352</td>
<td>1000</td>
<td>363.25</td>
<td>Varies</td>
<td>363.1</td>
<td>367.8</td>
</tr>
<tr>
<td>352</td>
<td>1000</td>
<td>365</td>
<td>Varies</td>
<td>363.1</td>
<td>370.3</td>
</tr>
<tr>
<td>355</td>
<td>Varies</td>
<td>366.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>355</td>
<td>1000</td>
<td>366.5</td>
<td>Varies</td>
<td>366.6</td>
<td>372.3</td>
</tr>
<tr>
<td>349</td>
<td>Varies</td>
<td>360.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>349</td>
<td>1000</td>
<td>360.5</td>
<td>Varies</td>
<td>360.1</td>
<td>365.5</td>
</tr>
</tbody>
</table>

The SOMC is defined as the minimum of the AHRR after the rise in heat release due to first-stage combustion, as indicated in Figure 7. The SOPC is calculated using the difference between the single-injection and main- plus post-injection AHRRs, as shown in Figure 7. To calculate the SOPC, the AHRR of the single-injection schedule is subtracted from the AHRR of the post-injection schedule.
The resulting profile is relatively flat until the start of the post injection, where it dips below zero due to the vaporization of the post-injection fuel. Thereafter, it rises and crosses zero as the net heat release from combustion of the post-injection fuel becomes positive. Here, we take this zero-crossing to be indicative of the beginning of heat release from the post injection.

Ignition delay times for both the main injection (ID_{main}) and post injection (ID_{post}) were estimated using the SOMC/SOPC calculated from the AHRR curves and the actual start of injection, taken from Mie scattering images in the high-speed videos. The results of this calculation are shown in Table 6. These videos have a resolution of 0.5 °CA, and so the uncertainty in the ignition delay estimates is 0.5 °CA.

### Table 6. Ignition delay estimates of both main and post injections for eight injection-timing schemes.

<table>
<thead>
<tr>
<th>SOI_{1C} [CAD]</th>
<th>DOI_{1C} [usec]</th>
<th>SOI_{2C} [CAD]</th>
<th>DOI_{2C} [usec]</th>
<th>ID_{main} [°CA]</th>
<th>ID_{post} [°CA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>352</td>
<td>Varies</td>
<td>363.5</td>
<td>Varies</td>
<td>9.1</td>
<td>3.8</td>
</tr>
<tr>
<td>352</td>
<td>1000</td>
<td>363.25</td>
<td>Varies</td>
<td>9.1</td>
<td>3.4</td>
</tr>
<tr>
<td>352</td>
<td>1000</td>
<td>365</td>
<td>Varies</td>
<td>9.2</td>
<td>3.6</td>
</tr>
<tr>
<td>355</td>
<td>Varies</td>
<td>366.5</td>
<td>Varies</td>
<td>9.6</td>
<td>5.5</td>
</tr>
<tr>
<td>349</td>
<td>Varies</td>
<td>360.5</td>
<td>Varies</td>
<td>9.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>

The ignition delays in Table 6 for both the main and post injection confirm that when the whole injection schedule is shifted by 6 °CA, the ignition delay of the near-TDC main-injection changes only slightly (total change of 0.5 °CA), while the ignition delay of the post-injection changes much more, by over 2 °CA. These differences, as explained above, are used to test the effect of post-injection ignition delay on UHC reduction.

### RESULTS

The results are presented in three sections. First, the single injection results are shown to provide baseline UHC measurements without post injections. Sweeps of DOI_{1C} at three different SOI_{1C} times are used as baselines in the following two sections. Next, we present results from variation in DOI_{2C} with SOI_{1C}, DOI_{1C}, and DOI_{2C} fixed at various values. These data are intended to describe the effect of post-jet mixing and penetration on the efficacy of post injections for reducing UHC emissions. Finally, both single-injection and main- plus post-injection data at multiple SOI_{1C} with a constant dwell between injections and sweeps in DOI_{2C} are presented to illustrate the effect ignition delay on the efficacy of the post injection at reducing UHC. The engine-out UHC emissions data are accompanied by images from the two laser diagnostic techniques to help explain the trends.

### Single-Injection Baseline

UHC emissions data for single-injection duration sweeps at three SOI_{1C} timings of 349 CAD, 352 CAD, and 355 CAD are plotted in Figure 8. These results show a significant variation in UHC emissions with both SOI_{1C} and DOI_{1C}. For each SOI_{1C}, the engine-out UHC level is quite sensitive to injection duration. Very short injections, resulting in loads down to approximately 100 kPa gIMEP, produce high engine-out UHC, up to almost 1400 ppm (C_{1}) after correcting for continuous firing. High-speed luminosity imaging data suggest this is in part due to partial misfires at these very low-load conditions. Injections at mid-length DOI_{1C} produce the least UHC emissions, down to about 300 ppm. After reaching a minimum, the engine-out UHC levels begin to increase with increasing load. Curiously, long injections at all three SOI_{1C} produce very similar levels of engine-out UHC; the three curves in Figure 8 asymptote to nearly the same UHC level for the higher loads.

Also noticeable in Figure 8 is that the later main-injection timing (SOI_{1C}=355 CAD) produces significantly more UHC than the earlier injection timings, particularly at short DOI_{1C}. This trend is likely driven by the phasing of the heat release with respect to TDC. For SOI_{1C}=349 CAD, the start of main combustion is approximately at TDC. As SOI_{1C} is delayed, so is the SOMC. For SOMC that is timed after TDC, the pressure and temperature reduction occurring during the expansion stroke likely leads to more incomplete burning and higher UHC emissions, even though the main ignition delay is similar for all three timings.
The development of the H$_2$CO- and OH-PLIF for a single injection is shown in Figure A1 in the Appendix, which shows LIF measurements from the SOI$_{1C}=352$ CAD, DOI$_{1C}=1000$ microseconds timing. At the first measured crank angle, 363 CAD, the spray (false-colored green) is still visible due to some Mie scattering of the 284-nm laser-light that leaks through the filters. Formaldehyde (false-colored red) is formed within the vapor-fuel/air mixture of the spray, primarily in the downstream region, as the jet penetrates to the bowl wall. After its initial appearance near 363 CAD, the formaldehyde fluorescence signal strength quickly increases, reaching greatest brightness near 365 CAD. Immediately thereafter, at 366 CAD, some mixtures near the bowl rim on either side of the jet axis transition to second-stage ignition, as indicated by the OH-PLIF signal (in green). The OH-PLIF images show that second-stage ignition begins in the roller regions at the wall and grows toward the jet centerline, generally forming an unbroken band along the bowl rim by 369 CAD. During the progression of the OH toward the centerline, the H$_2$CO-PLIF extends farther and farther upstream, eventually reaching the injector by 369 CAD. This temporal upstream progression of H$_2$CO-PLIF is different than the generally uniform initial appearance previously observed in this facility [11], which may be due to the change of injectors for this study. The downstream signal strength of the H$_2$CO-PLIF also decreases somewhat as the OH-PLIF progresses toward it.

The growth of the second-stage ignition region near the bowl rim, as indicated by the OH-PLIF signal, continues through approximately 376 CAD. Small pockets of bright emission appear in some of the H$_2$CO-PLIF images (red) as early as 371 CAD. As discussed in the Engine Diagnostics section, these bright regions can be attributed to PAH fluorescence and/or soot LII as indicated by the annotations on the Figure 6 (also see confirming spectral data in Ref. [22] for similar conditions). During the same time, the intensity of H$_2$CO-PLIF closer to the injector decreases, but does not completely disappear, as it broadens spatially, spreading over the whole near-injector region.

Later in the cycle, the OH-PLIF emission generally remains confined to the outer bowl, rarely appearing within 25 mm from the injector, while the H$_2$CO-PLIF remains in the same region of the residual jet where OH is absent, near the injector. Both the persistence of H$_2$CO and the absence of OH in the near-injector region indicate that the fuel/air mixture near the injector tip never transitions to second-stage ignition. Hence, this region is the origin of at least some, and potentially most [12], of the UHC in the exhaust.

At each of the three SOI$_{1C}$ timings for the single-injection conditions and over the entire range of DOI$_{1C}$, the general character of H$_2$CO- and OH-PLIF distributions (not shown here) is similar to that in Figure A1, indicating that there is room for improvement in the UHC emissions at a variety of engine operating conditions. As discussed above, post injections can help by enriching the fuel-lean mixtures near the injector to provide the additional “kick” needed to push remaining fuel in the center of the bowl into second-stage ignition. In the next two sections, we describe the behavior of these post injections and the mechanism by which they reduce unburned hydrocarbons.

Post-Injection Penetration Sweep

In this portion of the study, the commanded main-injection timing (both SOI$_{1C}$ and DOI$_{1C}$) is held constant and the duration of the post injection is varied to test the effect of post-injection penetration and mixing on UHC emissions reduction. As was discussed in the introduction, we expect that the post injection is helping to enrich the overly-lean fuel/air mixture near the injector. Here, we have chosen three main-injection timings as baselines to which the post-injection effects on UHC emissions may be compared. An example result of this exercise can be seen in Figure 9, where a cubic curve-fit has been added for reference to the single injection engine-out UHC data of the SOI$_{1C}=325$ CAD condition.

As described earlier, SOI$_{2C}$ for the post injection is set to yield a real dwell between injections of 1.5 °CA, as evidenced by optical imaging. The engine-out UHC emissions shown in Figure 9 indicate that a range of post-injection durations, from DOI$_{2C} = 250$ microseconds to DOI$_{2C} = 800$ microseconds, leads to decreases in UHC. The shortest post-injection command duration, 200 microseconds, does very little to reduce UHC, and this is probably because the real injection duration is very short and inconsistent during these tests. High-speed Mie-scatter imaging of the post-injection spray shows that penetration and even the
emergence of fuel from the injector varies significantly from cycle to cycle for the very shortest post injections. Post injections with longer durations, however, are much more consistent and are effective at reducing UHC. The greatest reduction in UHC, 27% from a single injection at the same load, is achieved with DOI$_2C$ = 400 microseconds. This reduction agrees well with the value observed in the previous work [16] at a single post-injection operating condition using a fuel with more typical diesel volatility (Figure 2). The agreement between the results in Figure 9 and Figure 2 indicate that the characteristic behavior of UHC reduction by post injections is not affected by the low volatility of the n-heptane fuel used here.

Figure 9. UHC [ppm C$_1$] emissions as a function of load from single-injection and main- plus post-injection tests at varying DOI$_2C$, where SOI$_1C$=352 CAD, DOI$_1C$=1000 microseconds, and DOI$_2C$=363.5 CAD. UHC emissions have been corrected from skip-fired operation to reflect those of continuous-fired operation.

Figure 10 shows the engine-out UHC levels for three sweeps of DOI$_2C$ starting from three baseline loads of 209, 265, and 438 kPa glMEP, corresponding to DOI$_1C$=800, 1000, and 1600 microseconds, respectively. For each sweep of post-injection duration in Figure 10 (open symbols), the post-injections are added to a main injection with SOI$_1C$ and DOI$_1C$ held constant, with the durations noted above. For each case, the post injections are effective at reducing the UHC levels, and the greatest UHC reduction in all three cases was realized at DOI$_2C$ values of approximately 400 microseconds, which corresponds to a load increase of about 100 kPa glMEP from the addition of the post injection. Hence, DOI$_1C$ (i.e., main-injection load) seems to have little bearing on the optimal DOI$_2C$ for UHC reduction.

One explanation for the similarity in the DOI$_2C$ yielding the minimum UHC emissions at three loads may be the length of post-jet penetration versus the bowl size. High-speed chemiluminescence imaging shows that with a post-injection duration of 400 microseconds, the combusting post-jet penetrates to the wall. However, it does not have sufficient momentum to flatten against the wall and roll up to the sides within the time available before rapid cylinder expansion (before approximately 380 CAD) to the same degree as longer post injections do. Hence, the 400-microsecond post injection may be sized correctly to enrich the overly-lean areas without any additional roll-up along the bowl wall, where it would deposit fuel outside the overly-lean region near the injector. If the bowl diameter was much larger, resulting in a larger overly-lean region in the center, a longer post-injection duration might be optimal, at least with the same injection characteristics. Although this scenario is certainly plausible, there may be other factors that control the optimal post-injection duration, including injection ramp-rate and other injector dynamics issues.

Finally, the dwell between the end of the main injection and the start of the close-coupled post injection has little effect on the ability of the post injection to reduce engine-out UHC. Figure 11 illustrates this by showing a range of post-injection durations at three post-injection injection timings, DOI$_2C$=362, 363.5, and 365 CAD, respectively. The reduction in engine-out UHC is nominally the same, regardless of DOI$_2C$. Nearly all the points lie along the same curve, the exception being the shorter DOI$_2C$ post-injections at the longest dwell between injections.
H$_2$CO- and OH-PLIF data provide insight into the effect of the post injection on the combustion process at the condition with SOI$_1$=352 CAD, DOI$_1$=1000 microseconds, SOI$_2$=363.5 CAD, and DOI$_2$=400 microseconds; this is the minimum UHC post-injection condition for this baseline load and timing (see Figure 9).

A sequence of simultaneous H$_2$CO and OH-PLIF images in Figure A2 in the Appendix shows the effect of the post injection on residual UHC from the main injection. Similar to the single-injection case, first-stage ignition begins before the end of the main injection, as is evidenced by the Mie scattering of the 284-nm laser by the liquid fuel and the formaldehyde signal present at the head of the jet at 363 CAD. Again, the formaldehyde signal increases in strength as the jet penetrates against the bowl wall and the mixture flows along the wall. The beginning of the post injection can be seen at 366 CAD via the Mie scattering of the 284-nm laser light that leaks through the filter pack.

Second-stage ignition of the main-injection mixture begins shortly after the start of the post injection, evidenced by the appearance of OH-PLIF along the bowl wall at 367 CAD, similar to the single-injection condition. The region of second-stage ignition grows in the outer bowl and then at 370 CAD, the upstream fuel jet itself shows signs of second-stage ignition along the outer periphery of the jet. The inner regions of the fuel jet are still dominated by H$_2$CO-PLIF signal, indicating that the inner jet has not yet transitioned to second-stage ignition. By 374 CAD, second-stage ignition progresses to the center of the downstream fuel jet, and the reaction starts to “race back” along the fuel jet, causing second-stage ignition to occur closer to the injector than in the single-injection case (cf. Figure A1). Similar “racing back” has been seen in other studies of UHC [16] and soot [17] in LTC.

Although we do not have equivalence ratio data for the mixture near the injector after the end of the post injection, certain features of the PLIF images in the post-injection case suggest that the enriching of the fuel/air mixture near in the injector helps to reduce the UHC emissions. It is evident from the images that the formaldehyde signal after the end of the post injection, between 370 and 373 CAD is clearly in the form of a jet and is indicative of the initial first-stage chemistry of the post injection itself. This is in contrast to the same times in the single-injection case, where the formaldehyde signal is much more diffuse as the mixture consists of the overly-lean fuel/air mixture residual from the main injection.

The evidence for the efficacy of the post injection lies in the greater extent to which the OH-PLIF signal appears upstream in the jet; this indicates that more of the mixture is “kicked” into the second-stage ignition when a post injection is present. For example, comparing 375 CAD in the single-injection case (Figure A1) and the same timing in the post-injection case (Figure A2) shows that much more widely distributed second-stage combustion is occurring when a post injection is added than when one is absent. This enhanced second-stage combustion continues throughout the rest of the cycle.

This mechanism for UHC reduction works independently of any obvious bulk-temperature effect. During combustion of the post-injection fuel, shown in the AHRR traces in Figure 4, the cylinder pressure during main- plus post-injection operation is less than that of single-injection operation at the same load, indicating that the bulk cylinder temperature is also less. The UHC reduction by post injections is hence driven by the enrichment and subsequent ignition of the overly-lean fuel/air mixture at the center of the bowl, and not by an increase in the bulk temperature.

These optical results indicate that the post injection has a significant effect on the characteristics of the second-stage combustion and hence the level of UHC at the end of the cycle. Engine-out UHC emissions measurements indicate, though, that not all post-injection durations are as effective at reducing UHC as others. There may be several reasons for this, some of which are discussed here. While these explanations are certainly plausible, we do not have enough experimental evidence at this time to definitively confirm or reject any of them; evaluating these explanations is the focus of future work.

First, post injections of varying length may also have very different injection profiles, a result of injector and rail dynamics. For example, the two post-injection profiles shown in Figure 2a from Chartier et al. [16] are somewhat different, both in their height as well as their shape. Previous analyses of both free diesel jets [23] as well as engine experiments [24, 25] have shown that injection rate profile can change in-cylinder mixing and exhaust emissions. The differences in
injection rate profile between short and long post injections may affect mixing and thereby the equivalence ratio distribution in the residual overly-lean region from the main injection. Consequently, the completeness of combustion, which depends on the local equivalence ratio, may depend on differences in the rate profile with post-injection duration, which will ultimately affect the engine-out UHC levels.

Second, increasing DOI2C reduces the time available for mixing prior to the SOPC (i.e., the ignition dwell for the post-injection). Much like the main injection, the mixture in the near-injector region resulting from the post injection will be increasingly fuel-rich as the ignition dwell decreases (see Figure 1). Hence, increasing DOI2C moves the end of injection closer to SOPC, which may reduce UHC emissions by creating richer mixtures at SOPC. Very long post injections will even have a negative injection dwell, which could significantly reduce UHC emissions by avoiding overly-lean, near-injector mixtures altogether, but likely at the expense of increased soot formation.

Additionally, the source of UHC may vary as a function of injection duration and load. As was noted above with reference to Figure 8, the engine-out UHC levels seem to asymptote to a single line, regardless of injection timing. As will be discussed in the next section, this trend continues with the addition of post injections at each of these timings. This may be indicative of a switch from lean sources of UHC - overly-lean mixtures found near the injector - to rich sources of UHC - fuel-rich pockets that have insufficient time to mix and burn in the late-cycle mixing-controlled combustion.

The trade-off between these effects - UHC dependency on post-injection duration and transition between lean and rich sources of UHC - may explain the existence of an optimal post-injection duration. At this duration, these effects may balance to result in a lower UHC level with post injections.

### Post-Injection Ignition Delay Sweep

In addition to post-injection penetration, another controlling factor in post-injection efficacy is the ignition delay time of the mixture formed by the post injection. Decreasing the ignition delay time provides less time for the mixture in the near-injector region created by the post injection to become overly lean, so that combustion may proceed farther to completion in that region.

As discussed at the end of the previous section, changes in ignition dwell by altering DOI2C may play a role UHC reduction, but the effect is confounded by changes in mixing and penetration with changes in DOI2C. In this section, we attempt to isolate the effects of post-injection ignition delay from spray penetration and mixing by keeping the injection durations and dwells fixed. Here, the entire injection schedule, including the main injection, is advanced or delayed by 3 °CA relative to the baseline point (SOI1C=352 CAD, SOI2C=363.5 CAD). The UHC emission results for just the single injections at the baseline, advanced, and delayed times are discussed with reference to Figure 8.

As shown in Figure 12, the engine-out UHC levels seem to asymptote to a single curve as the absolute reduction (b) in UHC compared to a single injection at the same load. These values are calculated by first fitting a cubic function to the single-injection UHC results (see Figure 8, for instance) and calculating what a single-injection UHC level would be for the same load at each post-injection condition. Then the percentage or absolute reduction from that baseline UHC level is calculated.

Overall, the post-injection trends with DOI2C at the three SOI1C timings are very similar. Very short post injections do not produce significant reduction in UHC, but as the post-injection duration increases, the benefit of the post injection increases until a minimum UHC level is reached. After that minimum level, longer post injections still reduce the UHC emissions relative to a single-injection at the same load, but to a lesser extent. Similar to the single-injection UHC results in Figure 8, the UHC levels for both single and main-plus post-injection schedules seem to asymptote to a single curve at higher loads.

An alternative perspective to Figure 12 is presented in Figure 13, which shows the percentage reduction (a) as well as the absolute reduction (b) in UHC compared to a single injection at the same load. These values are calculated by first fitting a cubic function to the single-injection UHC results (see Figure 8, for instance) and calculating what a single-injection UHC level would be for the same load at each post-injection condition. Then the percentage or absolute reduction from that baseline UHC level is calculated.
reduction in UHC levels was only 14% at a post-injection duration of 350 microseconds.

Figure 13. Percentage reduction (a) and absolute reduction in ppm C<sub>1</sub> (b) in engine-out UHC emissions with the use of a post injection as compared to a single injection at the same load for three injection timings.

Additionally, Figure 13b shows the absolute reduction of UHC (in ppm C<sub>1</sub>) at all three timing schedules. As was noted previously, the very short post injections do little to abate UHC emissions, but post injections with durations greater than 350 microseconds can have a significant impact on engine-out UHC. It is interesting to note that over a range of post-injection durations, from approximately 400 microseconds to 700 microseconds, the post injection reduces engine-out UHC by approximately 80 ppm C<sub>1</sub>, regardless of the main-injection timing (SOI<sub>1c</sub>). While the absolute UHC reductions among the three injection schedule phasings in Figure 13 are quite similar, the results are from a limited set of data, so the 80 ppm UHC reduction should not be generalized as a limit for how much UHC may be addressed with post injections. For these three cases, it may be coincidental that the enhanced-oxidation mechanisms described with reference to Figure A2 result in roughly the same absolute UHC reduction. Other post-injection strategies not examined here (e.g., multiple post injections) could conceivably reduce UHC even further, especially for the higher UHC conditions.

To visualize why one injection schedule was more effective (on a percentage basis) than another, we can look at the effect of the post injection on combustion using the two PLIF techniques. Figure A3 in the Appendix shows the behavior of combustion with the post injection for all three SOI<sub>1c</sub> timings at three points within the cycle. In each of the cases, the post-injection duration is 400 microseconds, which is the approximate minimum in the engine-out UHC for each main-injection timing. The first row is for the advanced injection schedule, the middle row is for the baseline injection schedule, and the bottom row is for the retrograde injection schedule.

The first column depicts the H<sub>2</sub>CO and OH distribution 4 °CA after the end of the main injection, which is close to the beginning of the post injection. At this point in the cycle, the three cases look very similar, most likely because the ignition delay of the main injection is quite similar. In each case, formaldehyde has formed along the jet and second-stage combustion has begun along the wall on either side of the jet axis, as indicated by the green OH signal on either side of the jet. The shape and size of these second-stage combustion regions are similar between the three injection schedules.

The next column shows images 7 °CA later, approximately 4 °CA after the end of the post injection. In the baseline injection schedule (center row), there is still some formaldehyde in the jet, but the second-stage combustion, marked by green OH signal, has raced back along the jet axis part way to the injector, converting unburned hydrocarbons to final combustion products. For the retrograde injection schedule (bottom row), the second-stage combustion has raced back along the jet axis somewhat less; here, second-stage combustion stays confined to the outer bowl nearer to the bowl wall. For either the baseline or the retrograde timing, the second-stage combustion never extends into the overly-lean region closer to the injector. Hence, remaining formaldehyde in the vicinity of the injector (red color in images) is still evident. By contrast, for the advanced injection schedule, almost no formaldehyde is detectable, and the second-stage combustion has raced back along the entire jet axis, stretching from the bowl back to the injector. Here, it is quite evident that the post injection helps to combust much of the UHC in the overly-lean region.

Finally, in the late stages of combustion, shown in the right column of Figure A3, the differences in the efficacy of the post injection for each of the shifted injection schedules is also clear. For the advanced injection schedule, almost no formaldehyde fluorescence is visible in the field of view and OH fluorescence is quite strong and extends over a relatively large region of the bowl. For the baseline injection schedule, the OH fluorescence is confined to the outer bowl, and weak formaldehyde fluorescence remains in the near-injector...
region. This is indicative of UHC remaining near the injector. Finally, for the retarded injection schedule, a very strong formaldehyde signal remains in a larger area of the bowl than for the baseline schedule. This correlates well with the engine-out UHC results, showing that the retarded injection schedule result in higher UHC levels.

This marked change in the combustion characteristics for the retarded injection schedule is likely due to the increased post-injection ignition delay. As was discussed above, the advanced injection schedule results in the shortest ignition delay of the post-injection mixture. As the ignition delay increases for the baseline and then for the retarded injection schedule, the mixture formed near the injector has more time to lean-out again after the end of the post injection, resulting in a second occurrence of the over-leaning issues. For conditions with short post-injection ignition delays, the post injection is more able to “kick” the newly enriched mixture into the second-stage chemistry regime quickly due to short ignition delay and favorable thermodynamic conditions.

The long-ignition delay data in Figure A3 (bottom row) also indicate that significant reductions in UHC are still possible if a single or a main-plus-post injection can be tailored to cause second-stage ignition in the near-injector region. Rate-shaping is one potential method to do so, and previous analyses indicate that richer mixtures can be designed by slowing the ramp-down rate [23]. Traditionally, rich mixtures near the injector have been undesirable, especially from a soot-emission standpoint, so most injectors are designed to ramp down rapidly. For partially premixed LTC conditions, however, it may be advantageous to end the injection more slowly to create longer lasting rich mixtures that will achieve second-stage ignition during the ignition dwell before becoming too overly fuel-lean.

Finally, although accurate fuel consumption data are not available for the skip-fired optical engine, and we did not measure any engine-out emissions other than UHC, we can offer our expectations on fuel efficiency and other emissions. Close-coupled post injections should have only minor effects on fuel efficiency and NOx emissions, but could increase soot emissions, depending on operating conditions. The close coupling between the main and post injection keeps the heat release in a portion of the cycle that is beneficial for fuel efficiency, and the post-injection improves combustion efficiency (at least for UHC), so the efficiency should be similar, or even improved with the post injection schemes investigated here. The high rate of EGR used at LTC is the significant controlling factor in NOx emissions, and small changes in the injection schedule, such as those from a single-injection to main- plus post-injection schedule, will not change NOx emissions significantly [26, 27]. But, due to the enrichment effects of the post injections, we expect that soot emissions could increase, especially for the longer post injection durations. Although we did not measure exhaust soot, we did observe that soot luminosity increased markedly for the longer post-injections, so we would expect that exhaust soot might also increase for long post injections.

CONCLUSIONS AND FUTURE WORK

In this work, we have investigated the effect of close-coupled post-injection timing and duration on engine-out UHC emissions compared to single-injection operation at low-load, EGR-diluted LTC conditions in a heavy-duty optical diesel engine. Planar laser-induced fluorescence imaging of formaldehyde (H$_2$CO) and the hydroxyl radical (OH) provided insight into the effects of post-injections on the in-cylinder spatial and temporal progression of first- and second-stage ignition chemistry. Key observations and conclusions are:

1. Over the range of conditions studied, close-coupled post injections reduce UHC emissions by as much as 34% compared to a single injection at the same load.

2. The most important parameter affecting close-coupled post-injection UHC emissions reduction is the duration of the post injection. Across ranges of start of main injection, duration of main injection, and dwell between main and post injections, the minimum UHC emissions always occurred near a post-injection command duration of 400 microseconds, corresponding to a load increase of about 100 kPa gIMEP from the addition of the post injection.

3. The second most important parameter affecting close-coupled post-injection UHC emissions reduction is the ignition delay of the post-injection mixture. At the optimal post-injection durations, conditions with a short (3.4 °CA) post-injection ignition delay achieved over twice the percentage UHC reduction as that for a long (5.5 °CA) post-injection ignition-delay condition.

4. Optical measurements indicate that the optimal post-injection (duration of approximately 400 microseconds) causes second-stage ignition to extend farther upstream than with single injections. As a result, previously measured overly fuel-lean mixtures near the injector achieve more complete combustion, most likely because they are enriched by the post-injection so that the chemical kinetics proceed more rapidly to complete combustion.

5. The optical data also show that with the exception of the conditions with the shortest post-injection ignition delays, UHCs remain within about a 25 mm radius of the injector late in the cycle, even at the optimal post-injection duration. This suggests that much greater UHC reductions may be possible for all of those conditions if the post-injection can be tailored (e.g., by rate shaping) to promote the transition to second-stage ignition in those near-injector regions similar to that achieved for the short post-injection ignition delay condition.

In future work, further analysis of OH and H$_2$CO-PLIF images will elucidate the effects of post injections on the fate of in-cylinder UHCs over a much broader range of injection timing and duration of both the main and post injections. This
work will help to define how in-cylinder mixing and chemical kinetic mechanisms can be altered by adjusting injection schedules. Ultimately, the goal is to define rules for designing injection schedules for low UHC emissions at LTC conditions.

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DEFINITIONS/ABBREVIATIONS

AEI - After end of injection

AHR - Apparent heat release rate

ATDC - After top dead center

BDC - Bottom dead center

BTDC - Before top dead center

CAD - Crank angle degree position (360 CAD is TDC of compression Stroke)

°CA - Degrees crank angle (duration)
DOII\textsubscript{C} - Commanded duration of main injection (in microseconds)
DOI2\textsubscript{C} - Commanded duration of post injection (in microseconds)
EGR - Exhaust gas recirculation
\textit{gIMEP} - Gross indicated mean effective pressure
H\textsubscript{2}CO-PLIF - Formaldehyde planar laser induced fluorescence
LII - Laser induced incandescence
LTC - Low temperature combustion
MK - Mixing kinetics
OH-PLIF - OH planar laser induced fluorescence
OPO - Optical parametric oscillator
PLIF - Planar laser induced fluorescence
PAH - Poly-cyclic aromatic hydrocarbon
PCCI - Premixed charge compression ignition
PCI - Premixed compression ignition
PPCI - Partially-premixed compression ignition
SOII\textsubscript{C} - Commanded start of main injection (in crank angle degrees)
SOI2\textsubscript{C} - Commanded start of post injection (in crank angle degrees)
SOMC - Start of main combustion (in crank angle degrees)
SOPC - Start of post combustion (in crank angle degrees)
TDC - Top dead center
\textit{\Delta t}\textsubscript{ID} - Ignition delay time
UHC - Unburned hydrocarbon
APPENDIX

Figure A1. Evolution of combustion as seen through single-shot simultaneous OH-PLIF (green) and H\textsubscript{2}CO-PLIF (red) imaging for a single-injection case at SOI\textsubscript{2c}=352 CAD, DOI\textsubscript{2c}=1000 microseconds at 265 kPa gIMEP.
Figure A2. Evolution of combustion as seen through simultaneous single-shot OH-PLIF (green) and H₂CO-PLIF (red) imaging for a main plus post-injection case at SOI₁ = 352 CAD, DOI₁ = 1000 microseconds, SOI₂ = 363.5 CAD, and DOI₂ = 400 microseconds at 371 kPa gIMEP.
Figure A3. Comparison of single-shot OH-PLIF (green) and H$_2$CO-PLIF (red) evolution at three timings for three main plus post-injection cases at 4 CAD (left), 11 CAD (middle), and 18 CAD (right) after end of the main injection at 371, 371, and 353 kPa gIMEP.