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What is This?
Effects of exhaust gas recirculation and load on soot in a heavy-duty optical diesel engine with close-coupled post injections for high-efficiency combustion phasing

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Abstract
In-cylinder strategies to reduce soot emissions have demonstrated the potential to lessen the burden on, and likely the size and cost of, exhaust aftertreatment systems for diesel engines. One in-cylinder strategy for soot abatement is the use of close-coupled post injections. These short injections closely following the end of the main injection can alter soot-formation and/or oxidation characteristics enough to significantly reduce engine-out soot. Despite the large body of literature on post injections for soot reduction, a clear consensus has not yet been achieved regarding either the detailed mechanisms that affect the soot reduction, or even the sensitivity of the post-injection efficacy to several important engine operating parameters. We report that post injections reduce soot at a range of close-coupled post-injection durations, intake-oxygen levels, and loads in an optical, heavy-duty diesel research engine. Maximum soot reductions by post injections at the loads and conditions tested range from 40% at 21% intake oxygen (by volume) to 62% at 12.6% intake oxygen. From a more fundamental fluid-mechanical perspective, adding a post injection to a constant main-injection for conditions with low dilution (21% and 18% intake oxygen) decreases soot relative to the original main injection, even though the load is increased by the post injection. High-speed visualization of natural combustion luminosity and laser-induced incandescence of soot suggest that as the post-injection duration increases and the post injection becomes more effective at reducing soot, it interacts more strongly with soot remaining from the main injection.

Keywords
Close-coupled post injection, soot reduction, heavy-duty diesel, exhaust gas recirculation, optical engine

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Introduction
In this work, we investigate the efficacy of post injections for soot reduction over a range of injection schedules and intake-oxygen levels, two engine operational variables that can be adjusted to simultaneously mitigate exhaust soot and NOx, while maintaining high efficiency in direct-injection (DI) diesel engines. This study is motivated by a need for improved understanding of in-cylinder pollutant formation and destruction processes to meet current and future emission standards and efficiency targets.

Over the past two decades, heavy-duty engine emission limits in the United States,1 the European Union,2–4 and much of Asia,5 for particulate matter (PM) and nitrogen oxides (NOx) have been reduced by one or two orders of magnitude. Although modern exhaust aftertreatment technologies are efficient and increasingly robust, they nevertheless impose additional packaging constraints and costs on the overall powertrain system. Recently, in-cylinder emission reduction strategies have been investigated that have the potential to lessen the burden on, and potentially the size and cost of, aftertreatment systems. Concurrent with the reduction in pollutant emission limits, engine efficiency requirements have increased in response to market
forces, carbon dioxide legislation, and fuel-consumption reduction programs.

Engine-out (i.e. prior to exhaust aftertreatment) emissions of NOx from diesel engines can be reduced using exhaust gas recirculation (EGR), which dilutes the intake stream with combustion products, thereby reducing both the intake-oxygen concentration and the flame temperature. EGR strategies can be implemented without a penalty in efficiency if certain engine operating parameters like combustion phasing are simultaneously adjusted with EGR.

While EGR can significantly reduce engine-out NOx, engine-out soot typically increases as the intake-oxygen concentration decreases for conventional diesel operation, at least initially. Engine-out soot is a complicated function of in-cylinder formation and oxidation, both of which are affected by intake-oxygen concentration and temperature. As the intake-oxygen concentration initially decreases from the atmospheric content of about 21% by volume, in-cylinder soot formation becomes increasingly dominant over oxidation, and the engine-out soot increases. After reaching a peak at an intake-oxygen concentration between 9% and 12%, the engine-out soot plummeted, reaching almost immeasurably small quantities below 8% intake oxygen as the oxygen content and flame temperature continue to decrease. However, practical engine operation at intake-oxygen concentrations low enough to eliminate exhaust soot (e.g. 8% O2) presents many problems, including greatly increased unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions due to decreased combustion efficiency, and intake-air management issues, especially for operation with boosted intake at higher loads. Hence, current diesel technology generally uses exhaust aftertreatment with intake-oxygen levels within the range where EGR still has a detrimental effect on soot emissions.

One in-cylinder strategy for mitigating the increased soot emissions with moderate rates of EGR is to add a post-injection after the main injection. Here, a post-injection is a small fuel injection (up to approximately 20% of the total fuel) that follows the main injection and is phased early enough in the cycle to ignite and combust (i.e. very late non-combusting or only partly-combusting post-injections for aftertreatment management are not considered here). One important consideration for post-injection strategies is their impact on fuel economy, which is affected by the combustion phasing of the post injection. Post-injections that can reduce soot while remaining closely coupled to the main injection are preferable from a fuel-efficiency perspective because of their favorable combustion phasing.

**Engine operating parameter effects**

The efficacy of post-injections for soot reduction is dependent on a variety of operational parameters, some of which are addressed in this study: changes in post-injection dwell and duration, intake-oxygen level, and load. For a more detailed review of previous work in the literature investigating these effects and others, refer to O’Connor and Musculus.

**Post-injection dwell and duration**

The majority of post-injection studies have explored the effect of post-injection duration and/or dwell after the main injection on exhaust soot. Almost all of the studies showed a reduction in exhaust soot with the addition of a post injection, although the optimal timing of the post injection varied among studies. For the most part, a shorter dwell between the end of the main injection and the beginning of the post injection resulted in lower exhaust soot, indicating that close-coupled post injections could be an advantageous injection strategy for both reducing emissions and maintaining efficiency. For example, experiments by Hotta et al. analyzed the effect of post-injection dwell on engine-out soot in a single-cylinder, light-duty optical research engine. Experiments at a variety of post-injection timings showed that a post injection with the shortest dwell possible with their injection system, 5 crank angle degrees (CAD), led to the maximum decrease in soot at the same load as a single injection. Later post-injection timings, with post-injection dwells from 7 to 13 CAD after the end of the main injection, had either no effect on exhaust soot or increased exhaust soot. A few studies, however, showed that later post-injection timings provided more substantial soot reduction than earlier timings. The reasons for differences in the optimal post-injection timing in these studies have not been established.

Changes in post-injection duration were also investigated in a number of studies. Many of these studies investigated “split” injections, where the duration of the second injection is prescribed as a fraction of the overall fuel injected each cycle. Here, if the second-injection duration increases, the first-injection duration decreases. With split injections, the second injection can be much larger than the ~20% limit that we use here to define post injections. This method of varying the injection durations is fundamentally different from the constant main-injection approach of the present study, as will be described in section “Experimental overview.” Despite that, several studies showed that post-injection duration could be optimized to minimize exhaust soot. For example, Payri et al. measured exhaust soot for various post-injection timings and post-injection durations at engine operating conditions from the European Steady-State Test Cycle (ESC). For almost all engine operating conditions and a wide range of post-injection timings, post injections reduced engine-out soot. Generally, engine-out soot was minimized at a post-injection quantity of approximately 10%–20% of the total fuel. As will be shown later, this result is similar to the findings of the current work for certain intake-oxygen levels and loads.
**Intake-oxygen level**

Several studies have shown that even with post injections, moderate EGR rates increase the exhaust soot relative to single injection with no EGR.\textsuperscript{18,30,31,34–37} Nevertheless, at a given EGR rate, post injections have been shown to reduce exhaust soot at intake-oxygen levels ranging between 12.6% and 21%. Studies differ, however, in their assessments of whether EGR makes post injections proportionally more or less effective at reducing soot from the level of a single injection at the same load. In this work, we show that post injections can be more effective at reducing soot at higher EGR rates. This conclusion is similar to those in the studies by Shayler et al.\textsuperscript{30} and Pierpont et al.\textsuperscript{36} However, this is not true of all studies,\textsuperscript{31} the reasons for which are not clear.

**Load**

A number of studies have investigated the efficacy of post injections at various load conditions.\textsuperscript{32,35,38–43} In these studies, test matrices often followed standard test cycles such as the New European Drive Cycle (NEDC) or the European Stationary Cycle.\textsuperscript{2,3} Load was changed by varying the rail pressure\textsuperscript{32,35,42} and/or the injection duration.\textsuperscript{40,44} Changing load by injection duration can have very different in-cylinder effects than changing load by rail pressure. Changing the rail pressure can significantly affect the reacting-jet structure\textsuperscript{45} and soot formation\textsuperscript{46} in diesel jets. Likewise, soot formation in the jet is not necessarily proportional to increases in injection duration.\textsuperscript{26} As a result, exhaust soot and post-injection efficacy may not be directly functions of load, but instead may be dependent on how the load is changed. Despite these differences, studies using both load-variation techniques have shown that post injections can reduce engine-out soot at a number of loads. For example, Yun and Reitz\textsuperscript{38} changed load by varying injection duration, and found that as load increases, post injections become less effective at reducing soot; post injections at 3 bar gross indicated mean effective pressure (gIMEP) reduced soot by 33%, while post injections at 4.5 bar gIMEP reduced soot by only 16%. Similar trends are described in this study, where we vary load by changing the duration of the main injection.

**Proposed in-cylinder soot-reduction mechanisms**

Within the post-injection literature, there are generally three explanations for how post injections reduce exhaust soot emissions: increased mixing, increased temperature, and injection-duration effects.

**Increased mixing**

Many studies\textsuperscript{19,21–23,36–40,47} conclude that post injections reduce soot by increasing in-cylinder mixing of fresh oxygen with the soot from the main injection, thereby enhancing soot oxidation. Although direct measurements of the mixing effect of post injections have not been established, several authors\textsuperscript{19,35,39} have identified a “sweet spot” in the injection schedule, where the post injection was thought to most effectively mix with the remnants of the main injection. In addition to increasing oxidation of soot, greater mixing could potentially decrease formation of soot. For example, KIVA simulations performed by Yun et al.\textsuperscript{39} predicted that the post injection redistributes the fuel from the main injection within the piston bowl, creating a more uniform mixture with less fuel-rich pockets where soot can form. The simulations also predicted that the mixing mechanism can be particularly important at high-EGR rates, as available oxygen is limited.\textsuperscript{38,39}

**Increased temperature**

A smaller number of studies\textsuperscript{11,18,22,25,32,43} point to the increased temperature from the post-injection combustion as one reason for enhanced oxidation of the main-injection soot. Although direct measurements of cylinder temperature distribution are quite difficult, some studies have shown evidence of the role of increased temperature using alternate methods. For example, Bobba et al.\textsuperscript{22} measured soot temperature in the squish region, where the post injection interacted with the main-injection soot. These measurements, taken with a two-color thermometry method,\textsuperscript{48} showed higher soot temperatures after the post-injection burn; the authors indicated that this increased temperature likely leads to enhanced oxidation of the soot. While temperature effects may contribute to soot oxidation, studies that name increased temperature as a soot-reduction mechanism generally acknowledge the importance of enhanced entrainment and mixing of oxygen as well.

**Injection-duration effects**

Other studies\textsuperscript{17,19,26,27} have identified a separate mechanism that does not explicitly associate reduced exhaust soot with increased mixing or increased temperature, but instead with the effects of splitting the fuel delivery into multiple parts, thereby decreasing the injection duration of each individual part. According to these studies, the post injection can be too short to produce any significant net exhaust soot, and the shorter main injection produces less soot than the original single injection at the same load. This mechanism has often been cited for injection schedules with short, close-coupled post injections. Another mechanism related to injection-duration effects, proposed by Han et al.,\textsuperscript{26} is the concept of “jet replenishment.” Based on computer-model simulations, the authors concluded that soot formation is dependent on injection duration, not just total quantity of fuel delivered to the engine per cycle. This is because as the injection duration increases, the model predicts that the head of the jet, a fuel-rich region where much of the soot
is produced,\textsuperscript{59} is replenished by fresh fuel along the centerline of the jet for as long as the injection is sustained. The longer the injection, the more fuel is delivered to this head region, creating a larger fuel-rich mixture that supports more soot formation. This mechanism also agrees with the idea that splitting a given amount of fuel into shorter injections reduces the overall soot formed as a result of the change in mixture formation due to jet replenishment.

**Overview of current investigation**

Despite a large literature on post injections, consensus on in-cylinder soot-reduction mechanisms achieved through post injections has yet to be established. While the aforementioned studies provide several plausible explanations for soot reduction by post injections, in-cylinder experimental data to support them are limited, so that the merits and ranges of applicability of the various explanations are difficult to judge. In this work, we use a variety of optical techniques to better understand how post injections reduce soot over a variety of engine operating conditions. As is evident from the literature described above, the efficacy of post injections and possibly even the mechanisms by which they reduce engine-out soot may be a function of a great number of engine operating parameters. Hence, we apply the optical diagnostics over ranges of post-injection duration, intake-oxygen level, and load to establish where in the engine operational space close-coupled post injections do or do not reduce exhaust soot in our optical engine. More discussion of remaining research questions and future work is provided at the conclusion of this article.

The remainder of this article is organized as follows: First, we give an overview of the experimental facility and diagnostic techniques. Next, we discuss the effect of post injections on soot emissions at four intake-oxygen levels, three baseline loads, and a range of post-injection durations with data from both exhaust diagnostics; compared to US diesel fuel, it has a slightly higher cetane number\textsuperscript{50} and a slightly lower density, but a much lower boiling point and zero aromatics. The similarity in cetane numbers means that the auto-ignition characteristics of these two fuels are similar, although there may be differences in the liquid-to-vapor transition in the fuel jet as a result of the differences in boiling points. The vaporization differences are not expected to significantly impact the general soot-formation characteristics. The absence of aromatics, however, will almost certainly affect the quantity of soot, but the general in-cylinder mechanisms of soot formation should be similar.\textsuperscript{51} We view these differences in the magnitude soot formation to be an acceptable trade-off in the use of $n$-heptane as the fuel to enable UV laser diagnostics. Although UV laser diagnostics are not used in this study, such diagnostics are anticipated for studies to follow, so $n$-heptane was chosen for consistency with future work. Details of the fuel-injection system are also listed in Table 1.

The engine is designed with a variety of options for optical access (Figure 1). First, an extended Bowditch piston and 45° mirror allow visualization of the combustion chamber through the piston crown-window.

### Experimental overview

**Optical engine experiment**

These experiments were conducted in a single-cylinder, DI, four-stroke heavy-duty diesel engine based on a Cummins N-series production engine. Specifications of this engine are listed in Table 1, and a diagram of the experimental setup is provided in Figure 1.

For these experiments, the engine is outfitted with a Delphi DFI-1.5, light-duty common-rail injector. The Delphi light-duty injector was chosen for its fast-acting response to close-coupled injection commands. The fuel is $n$-heptane, which was selected for its low fluorescence upon illumination by ultraviolet (UV) laser light.

### Table 1. Engine and fuel system specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine base type</td>
<td>Cummins N-14, DI diesel</td>
</tr>
<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\textsuperscript{b}</td>
</tr>
<tr>
<td>Intake valve closing</td>
<td>195° ATDC exhaust\textsuperscript{b}</td>
</tr>
<tr>
<td>Exhaust valve opening</td>
<td>235° BTDC exhaust\textsuperscript{b}</td>
</tr>
<tr>
<td>Exhaust valve closing</td>
<td>27° ATDC exhaust\textsuperscript{b}</td>
</tr>
<tr>
<td>Combustion chamber</td>
<td>Quiescent, DI</td>
</tr>
<tr>
<td>Swirl ratio</td>
<td>0.5 (approximately)</td>
</tr>
<tr>
<td>Bore</td>
<td>139.7 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>152.4 mm</td>
</tr>
<tr>
<td>Bowl width</td>
<td>97.8 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>2.34 L</td>
</tr>
<tr>
<td>Connecting rod length</td>
<td>304.8 mm</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 type</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 and arrangement</td>
<td>8, equally spaced</td>
</tr>
<tr>
<td>Spray pattern included angle</td>
<td>156°</td>
</tr>
<tr>
<td>Nominal orifice diameter</td>
<td>0.131 mm</td>
</tr>
</tbody>
</table>

DI: direct injection; BTDC: before top dead center; ATDC: after top dead center.
\textsuperscript{a}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 Figure 1).
\textsuperscript{b}All valve timings correspond to the crank angle of the first detectable movement from fully closed.
Figure 1. Experimental setup of the single-cylinder engine, laser configuration, and dual-camera optical system. The camera field of view is shown in the upper right. ICCD: intensified charge-coupled device.

Windows in the cylinder wall and piston bowl-rim provide laser-sheet access to the spray region. In the current configuration, the laser sheet is oriented parallel to the nominal axis of one of the sprays (12° from horizontal), at an elevation approximately 1 mm below the injector orifice for one of the fuel sprays. At this elevation, the laser sheet is close to the nominal symmetry axis of the jet as possible without striking and potentially damaging (e.g. ablating) the injector tip. The sheet passes through two windows, one in the cylinder wall and another in the bowl-rim, before striking the cylinder head. The bowl-rim window provides a realistic boundary condition for the fuel spray and soot development during operation. Further description of this engine and its optical measurement capability can be found in the studies by O'Connor and Musculus and Musculus et al.

Optical engine diagnostics

These tests used a variety of optical and other measurement techniques. Cylinder pressure was measured with an AVL QC34D pressure transducer with a one-quarter CAD resolution. The apparent heat release rate (AHRR) was calculated from the measured cylinder pressure using standard techniques described in Heywood. These tests used a variety of optical and other measurement techniques. Cylinder pressure was measured with an AVL QC34D pressure transducer with a one-quarter CAD resolution. The apparent heat release rate (AHRR) was calculated from the measured cylinder pressure using standard techniques described in Heywood.53

Engine-out smoke was measured using an AVL 415S smoke meter. This device draws a known sample volume of engine exhaust through a filter and measures the change in reflectance (blackening) of the white filter due to accumulated smoke. For conventional diesel conditions with low adsorbed hydrocarbons, the change in reflectance of the white filter is caused mostly by carbonaceous soot particles in the smoke, which visually appear gray to black, depending on soot loading. For some low-temperature combustion (LTC) conditions that have high adsorbed hydrocarbons, the filter can become tinted with color, which could conceivably bias the reflectivity measurement. Despite the reasonable expectation that adsorbed hydrocarbons could affect the reflectivity, experimental data show that the reflectivity is quite insensitive to adsorbed hydrocarbons and is mostly indicative of carbonaceous soot. Comparisons with other techniques that measure carbonaceous soot mass show that even with adsorbed hydrocarbons, the reflectivity strongly correlates with the carbonaceous soot mass under both conventional diesel and LTC conditions and with both conventional diesel fuel and bio-derived fuels. Furthermore, no color tinting by adsorbed hydrocarbons is discernible from visual inspection of the loaded filter paper from the current study. Hence, we expect that the smoke measurements in the current study are indicative of carbonaceous soot, and we use the terms interchangeably.

The change in reflectance for a given volume of sample gas can be quantified as a filter smoke number (FSN). FSN varies monotonically, although weakly nonlinearly, with soot mass. In each test, sampling commenced before the first fired cycle and continued well after the last fired cycle so that all the exhaust soot for each run was sampled; this amounted to a sampling time of 65 s or approximately 12,000 mL of exhaust gas. Although the engine is skip fired, all FSN data reported in this article have been corrected to the value that would have been measured for continuously fired operation (as if the engine were not skip fired). Repeatability of this measurement was tested at several injection schedules; the standard deviation of the FSN measurements at each of these repeated conditions was approximately 0.004 FSN units for continuously fired operation. Two optical diagnostics were used simultaneously for visualizing in-cylinder soot development. The two techniques share the same perspective, viewing through the piston-crown window as shown in Figure 1. A dichroic beam splitter with a cutoff near 485 nm spectrally separated light emitted from the combustion chamber, with long-wavelength light directed to the soot natural luminosity (soot-NL) imaging system, while the short-wavelength light was directed to the soot planar laser-induced incandescence (soot-PLII) imaging system, both of which are described below.

Soot-NL. A high-speed Phantom 7.1 complementary metal–oxide–semiconductor (CMOS) camera equipped with a Nikon 105-mm focal length, f/2.8 glass lens imaged the soot-NL. The lens aperture was set to f/11. Images with a resolution of 256 × 512 pixels were acquired at half crank-angle intervals (70 μs at
1200 r/min). The exposure time was a function of the intake-oxygen level, with exposure times on the order of 1 ms at 21% O₂ and 10 ms at 12.6% O₂. The high-speed imaging allows for high temporal resolution over a long data set; in this study, the entire combustion event during each fired cycle was imaged using this technique. There are three shortcomings for this technique, however. First, the soot-NL signal increases strongly with soot particle temperature, which introduces a strong bias to hot soot. The bias is important both spatially (within an image) and temporally (one image to the next, such as in the later portions of the cycle when cylinder temperature decreases). As a result, lower signal in the images can mean either there is less soot in that location or that the soot is colder. Second, soot-NL imaging is a line-of-sight technique, such that the three-dimensional soot cloud is projected onto two dimensions. This projection introduces ambiguity when tracking structures that may be at different elevations along the line of sight. This issue is illustrated and discussed in section “Results.” Finally, this technique images luminosity of all sources from inside the combustion chamber, including soot luminosity, chemiluminescence, and other possible sources. For these operating conditions and camera exposure times, the dominant source of light is soot-NL.60

**Soot-PLII.** The fundamental output of a Spectra-Physics Quanta-Ray single-cavity Nd:YAG laser was attenuated to 130 mJ/pulse and formed into a 30-mm wide, approximately 1-mm-thick sheet for soot-PLII within the engine cylinder. As described in section “Optical engine experiment,” the sheet was oriented to probe soot along the approximate symmetry plane of one of the fuel jets. Using the fundamental output at 1064 nm avoids fluorescence of large polycyclic aromatic hydrocarbon (PAH) species, so that only solid soot particles are targeted.61 As described in previous studies,49 the laser-heated soot emits much more strongly at shorter wavelengths than the combustion-heated soot, so the soot-PLII emission was spectrally filtered to shorter wavelengths to improve the signal-to-noise ratio. Soot-PLII data were limited to one frame per cycle, due to repetition-rate constraints of both the laser and camera system.

The two optical techniques, examples of which are shown in Figure 2, complement each other. In these images, the injector tip is indicated by a green dot, and the spray of interest (horizontal from the camera perspective) penetrates from left to right to the bowl wall as indicated by a dashed green line. While these two images were taken at the same instant in time in the same engine cycle and with the same field of view, because of the difference in techniques, there are differences in the images. The soot-NL image Figure 2(a) displays a much broader signal distribution, and significant small-structure variations in the soot-NL intensity are apparent. In the soot-PLII image (Figure 2(b)), smaller pockets of strong signal appear throughout the image, mostly within the roughly conical shape of the horizontal jet. The differences in the signal distribution for the two techniques are largely due to the fact that some soot structures do not intersect the laser sheet, which is aligned along the approximate centerline of the jet. The small-scale structures are also less distinct.

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**Figure 2.** Comparison of imaging techniques, simultaneous high-speed imaging of (a) soot-NL with (b) soot-PLII. Both images were acquired at 373 CAD, shortly after ignition of the post jet, with engine operating conditions described above. The green dot indicates the location of the injector, the solid green line indicates the location of the bowl wall, and dashed green lines indicate the jet centerlines of the spray under investigation (horizontal) and the two adjacent to it.

soot-NL: soot natural luminosity; soot-PLII: planar laser-induced incandescence of soot.
in the soot-PLII image, which may be attributed, at least in part, to a lower spatial resolution for the intensified camera.

Although soot-PLII provides a spatially resolved view of the soot, this technique, like many laser techniques, has drawbacks associated with interpreting signal levels. Two issues often arise in this technique: laser attenuation and signal trapping. Visual inspection of the collection of soot-PLII images indicates that laser attenuation is not the dominant problem at these operating conditions. In the PLII image (Figure 2 (b)), several high signal-level regions exist one after the other along the path of laser-light propagation (right to left), indicating that the laser light at 1064 nm is not significantly attenuated by soot clouds of this density.

Signal trapping, however, seems to have an effect on this data set. Signal trapping occurs when particles within the line of sight between the laser sheet and the camera absorb the broadband light produced by the laser-excited soot particles. In this experiment, we measure PLII signal at wavelengths shorter than 450 nm, which are readily absorbed by soot in the line of sight to the camera. The soot-PLII signal from the center of the jet is sometimes unexpectedly low and differs significantly from the traditional view of soot formation in diesel jets; often, almost no signal from the central region will be recorded by the camera. In many images, signal trapping in the post jet is often biased toward the bottom of the image (as in Figure 2(b)) where, as will be discussed later, a large cloud of soot from the main injection often resides. Signal trapping in sooting jets has been noted in previous studies, but the work by Pickett and Siebers showed that the soot distribution in a sooting jet is very similar to that proposed by Dec through both LII and laser-absorption measurements.

**Engine operating conditions**

Engine operating conditions are in Table 2. While the production engine has a compression ratio of approximately 16:1, the compression ratio of the optical engine with a right-cylindrical piston bowl is only 11.22:1. To compensate for the lower compression ratio, the engine is operated to replicate the thermodynamic state at top dead center (TDC) of the piston stroke for a 16:1 compression-ratio engine using a preheated, boosted intake stream. Additionally, this engine is run in skip-fired mode; for every 10 cycles, 9 are motored using a dynamometer and 1 is fired. This is done to reduce thermal loads on the optical components.

The intake stream is pressurized and heated by a compressor and electrical air heater, respectively. EGR is simulated by adding nitrogen (N\textsubscript{2}) to the intake air stream. Diluting the intake stream with nitrogen alone, without water and carbon dioxide, yields a lower heat capacity than real EGR, such that the flame temperatures are somewhat higher than with true EGR for a given intake-oxygen level. At all EGR conditions, the intake charge density, and hence the charge density at TDC, is intentionally held constant to maintain similar spray penetration as EGR is varied. As a result, the global equivalence ratio increases as EGR is increased; the global equivalence ratio is calculated for the replicated 16:1 compression ratio cycle, and ranges are reported in Table 3. For example, the global equivalence ratio of a 1950 μs injection at 21% intake oxygen is 0.28, and at 12.6% intake oxygen, it is 0.47. As will be discussed later, in addition to EGR and other effects, this change in the global equivalence ratio can significantly impact engine-out soot levels. Although the thermodynamic conditions in the 11.22:1 compression-ratio optical engine match those of a 16:1 compression-ratio metal engine, the global equivalence ratio for the optical engine will be lower at all EGR levels. The reduced global equivalence ratio in the optical engine is the result of approximately 50% greater trapped mass.

The choice of intake-oxygen levels was guided by industry practice with regard to EGR levels commonly used to meet emissions regulations. 18% O\textsubscript{2} was chosen as a baseline point because this range of EGR (20%–32%) is commonly used to meet 2010 particulate and NO\textsubscript{x} regulations with the use of both urea-based selective catalytic reduction (SCR) and diesel particulate filter (DPF) aftertreatment systems. The 12.6% intake oxygen is approximately the level that would be required to meet the 2010 particulate and NO\textsubscript{x} regulations without the use of aftertreatment systems. The 15% O\textsubscript{2} is a common intake-oxygen level for LTC conditions. Finally, 21% O\textsubscript{2} was used as a reference for undiluted operation.

This study’s test matrix covers a range of operating conditions, with variations in intake-oxygen content (simulated EGR), load, and post-injection duration. Table 3 shows the range of conditions considered. The test matrix contains two types of injection schedules—a single-injection schedule and a main- plus post-injection schedule. In order to establish consistent terminology, we will refer to injection schedules with only one injection as “single-injection” schedules.
Additionally, we will refer to injection schedules with two injections, a main injection and a post injection, as “main- plus post-injection” schedules. At equivalent loads, a single-injection condition has a longer injection duration than the main injection of a main- plus post-injection condition.

The first set of tests for each EGR condition establishes a baseline soot-versus-load curve for single injections using a sweep in commanded duration of main injection (DOI1C, in μs) from 1350 to as long as 3350 μs, depending on the intake-oxygen concentration tested. For selected main-injection durations, sweeps in the post-injection duration provide data for comparison to the baseline, with the main-injection duration held constant throughout the post-injection duration sweep. For example, at 18% O₂, three selected single-injection conditions have injection durations of 1550, 1950, and 2350 μs. For each selected main-injection duration, the post-injection duration is swept from 300 to 600 μs in 50-μs increments while holding the duration of the main-injection constant.

### Results

In this section, we describe the effect of post-injection duration and EGR on the engine-out soot of this optical engine at a variety of conditions. We begin with an overview of the engine operational data, including injection system characterization and a discussion of the AHRR profiles at all four intake-oxygen conditions. Soot data for the high intake-oxygen conditions (21% and 18% O₂) are presented next, followed by the low intake-oxygen conditions (15% and 12% O₂). In each case, optical data are provided to gain insight into the differences in engine-out soot measurements for different intake-oxygen levels.

#### Injection system characterization

Figure 3 shows mass rate-of-injection profiles derived from spray impingement (momentum) measurements using a Kistler 9215 force transducer connected to a Kistler 5004 charge amplifier. Data were collected at 140 kHz over the span of 200 injections in a collection unit at atmospheric back pressure. The profiles are averaged over 200 injections and low-pass filtered (Gaussian roll-off at 10 kHz) to remove ringing at the natural frequency of the transducer assembly.

In plots a–c of Figure 3, the shape of the main injection was similar across all three main-injection durations. The small fluctuations in the mass rate of injection preceding the start of the main injection are an artifact of the filtering (they disappear at higher roll-off frequencies). The initial rise also has a small “spike” just above 20 mg/s. This spike was determined to be a real component of the data, not a result of the filtering process (the spike remains at higher filter frequencies). Additionally, the main-injection profile remains essentially unchanged even when a post injection is added.

For the DOI1C = 1550 μs and DOI1C = 2350 μs cases in Figure 3(a) and (c), respectively, the shape, duration, and height of the post injection change for each increasing post-injection duration. This is also true for post injections with a duration between 300 and 700 μs in the DOI1C = 1950 μs case. Furthermore, the measured (actual) post-injection duration increases by approximately 1 CAD, or 139 μs, for each step change of the commanded injection duration by 50 μs. For post injections with commanded duration of post injection (DOI2C) greater than 700 μs, the height and characteristic rate-shape stay relatively constant, and the measured (actual) post-injection duration change is approximately the same as the 50 μs change in the commanded duration. These variations in post-injection shape can be seen in the post injections for the DOI1C = 1950 μs case in Figure 4.

For DOI2C ranging between 200 and approximately 700 μs, the total fuel mass injected increases linearly at all three load conditions. For a command duration of the post injection longer than 700 μs, the fuel mass per
injection continues to increase linearly, but with a lower slope. The change in the injection-rate behavior at 700 ms command duration, as in Figures 3 and 4, is responsible for the decrease in slope of the fuel mass per injection for the DOI1C = 1950 ms data. The fuel mass per injection results in Figure 5 are the average of 200 injections from the eight-hole nozzle.

Combustion heat release characterization

Representative AHRR profiles are shown in Figure 6 for the four intake-oxygen conditions. Each plot shows the profiles for a single injection with commanded start of main injection (SOI1C) = 347 CAD and DOI1C = 1950 μs, in addition to the profile for a main- plus post-injection schedule with SOI1C = 347 CAD, DOI1C = 1950 μs, commanded start of post injection (SOI2C) = 366 CAD, and DOI2C = 500 μs. Both the AHRR and measured fuel-injection profile are provided on each plot.
The AHRR curves in Figure 6 show similar features among the four intake-oxygen conditions despite the varying levels of EGR. Each curve displays a distinct premixed burn during the injection event, and the ignition dwell between the end of injection and the start of combustion is negative. The premixed burn is followed by a mixing-controlled combustion event, which is less prominent in the heat release analysis because of the relatively low-load conditions. The injection schedules with post injections also include a third peak in the AHRR profile due to combustion of the post-injection fuel.

For all four operating conditions in Figure 6, the clear demarcation between the premixed and mixing-controlled combustion combined with the negative ignition dwell indicates that they are within the envelope of conventional diesel combustion. Despite the significant EGR, these conditions cannot be classified as partially premixed compression ignition (PPCI) because of the

![Graph showing fuel mass per injection for three baseline loads and several post-injection durations. DOI1C: commanded duration of main injection.](image)

![Graphs showing AHRR profiles and injection-rate profiles for different oxygen concentrations.](image)

**Figure 5.** Fuel mass per injection (main plus post) for three baseline loads and several post-injection durations. DOI1C: commanded duration of main injection.

**Figure 6.** AHRR profiles and injection-rate profiles for (a) 21%, (b) 18%, (c) 15%, and (d) 12.6% intake oxygen for both single injection (solid) with SOI1C = 347 CAD and DOI1C = 1950 μs, and main plus post injection (dashed) with SOI1C = 347 CAD, DOI1C = 1950 μs, SOI2C = 366 μs, and DOI2C = 500 μs. The dotted lines denote the measured injection-rate profiles for both injection schedules.

AHRR: apparent heat release rate.
limited mixing that happens before the start of combustion. This is an important differentiation to make because the conditions considered in this study produce significant engine-out soot due to the presence of mixing-controlled combustion, unlike PPCI conditions where engine-out soot is very low. This also means that engine-out UHCs and CO, while not specifically measured in this study, are probably not excessive. As such, the focus of this work is soot reduction for more conventional diesel operation without consideration of issues associated with PPCI operation.

21% and 18% intake O₂

The intake charges with 21% and 18% intake O₂, which correspond to conditions with either no EGR or 20%–32% EGR, respectively, both display similar engine-out soot characteristics as a function of DOI₂ and load, and are therefore discussed together. The variations of engine-out soot with gIMEP for 21% and 18% intake O₂ are shown in Figures 7 and 8, respectively. As described above and in Table 3, the load for the single-injection baselines is increased by lengthening of the main-injection duration. The constant-load perspective is relevant for more fundamental fluid-mechanical considerations, where it is desirable to maintain a constant in-cylinder environment at the start of the post injection (e.g. penetration of the main-injection jet).

In each of these series with post injections, gIMEP was increased by increasing the length of the post injection while keeping the length of the main-injection constant for each (see Figure 3 and Table 3). Figure 7 and 8 show that for the high intake-oxygen conditions, the trend in engine-out soot is non-monotonic with post-injection duration. Initially, as the post-injection duration increases, the engine-out soot decreases. After this initial decrease, the engine-out soot reaches a minimum and begins to rise. After the soot minimum, the slope of the engine-out soot rise with increasing load is steeper than for the baseline single injection. Hence, for very long-duration post injections, the addition of a post injection results in the same or higher engine-out soot as compared to the single-injection baseline; an example of this is found in the DOI₂ = 1950 μs post-injection data in Figure 7. For this series, this “cross-over” point where post injections become detrimental to engine-out soot happens at a load of approximately 720 kPa and a post-injection duration of 800 μs.

Two ways to quantify the efficacy of the post injection with respect to the baseline engine-out soot are by comparing FSN at constant load or at constant main-injection duration. The constant-load perspective is relevant for practical engine operation, where it is desirable to achieve a particular load point. The constant main-injection perspective is relevant for more fundamental fluid-mechanical considerations, where it is desirable to maintain a constant in-cylinder environment at the start of the post injection (e.g. penetration of the main-injection jet).

As an example of the constant-load perspective, consider operation at a load of 500 kPa with 18% intake oxygen (Figure 8). Two ways to achieve this load would be a single injection with a command duration of about 1850 μs or a main injection with a duration of 1550 μs.
plus a post injection with a duration of 500 \( \mu \text{s} \). From this perspective, as shown in Figure 8, the engine-out FSN for the main- plus post-injection operation is 52% lower than that of the single-injection operation. Corresponding differentials occur for all three main-injection durations in Figure 8, where the minimum-soot condition with a main-injection duration of 1950 \( \mu \text{s} \) and post-injection duration of 500 \( \mu \text{s} \) gives a 26% reduction from the single injection, and the minimum-soot condition with a main-injection duration of 2350 \( \mu \text{s} \) and a post-injection duration of 300 \( \mu \text{s} \) gives a 20% reduction from the single injection at the same load.

The alternative perspective is to compare the engine-out soot for a main- plus post-injection schedule to that with only the single injection, but with the same injection duration (at a lower load). For example, in Figure 8 (18% \( \text{O}_2 \)), the FSN for a single injection with a command duration of 1550 \( \mu \text{s} \) is 0.26, while the minimum-soot condition for a main injection of the same duration with the "optimal" post injection (DOI\(_{1C} = 1550 \mu \text{s} \) and DOI\(_{2C} = 500 \mu \text{s} \)) has FSN of 0.19, a reduction of approximately 28%, as annotated in Figure 8. From this perspective, the engine-out soot also initially decreases from an unchanged main injection as the post-injection duration is increased. This trend is important because it clearly shows that the post injection must be interacting in some way with the main-injection soot to reduce the engine-out soot—there is no ambiguity in that respect. This indicates that in this case, the reason for engine-out soot reduction at high intake-oxygen conditions cannot be the injection-duration effect; the reduction in soot must stem from a fluid-mechanical or thermal interaction between the post injection and the main-injection mixture.

The difference between these two perspectives on comparing post injections to single injection is important and merits some discussion. The constant main-injection duration approach differs from those in many post-injection studies that, while able to show that post injections can reduce engine-out soot, performed the tests with a fundamentally different injection schedule than the method used in this study. Studies like those from Payri et al.,\(^{32}\) Benajes et al.,\(^{42}\) and Mendez and Thirouard\(^{23}\) varied post-injection duration while keeping the total quantity of fuel injected constant by shortening the main injection as the post injection was lengthened. This operational mode is very similar to that of split-injection studies, including those by Pierpont et al.,\(^{36}\) Tow et al.,\(^{40}\) and Bower and Foster.\(^{35}\) In this study, we can confidently conclude that the reduction of soot with post-injection operation below the engine-out soot level of the main injection indicates that the post injection must interact with the residual soot from the main injection because nothing about the main injection itself has changed (see injection-rate profiles in Figure 3 and AHRR profiles in Figure 6 for confirmation). However, when soot reduction is measured for post injections where the main-injection duration has been altered, it is unclear if this soot reduction is truly derived from an interaction between the post jet and the main-injection soot or from changes to the main injection as the duration was altered. This is an important distinction among the many studies within the literature; for studies that have explored both modes of operation, see Bobba et al.,\(^{22}\) Desantes et al.,\(^{17}\) and Hotta et al.\(^{18}\)

To investigate this interaction mechanism further, optical diagnostics are used to observe the evolution of soot within the combustion chamber. In the analysis of these images, it is important to distinguish the evolution of the soot and the evolution of the fluid flow within the combustion chamber. While soot motion can be an indicator of fluid motion,\(^{71}\) it is important to emphasize that the quantity of this "fluid tracer" is evolving as the flow field changes. At high oxygen-content conditions, it can be acceptable to use the leading edge of the soot cloud in the spray from either soot-PLII or soot-NL images as an indication of the head of the jet. This assumption stems from the widely accepted model of soot formation in diesel jets that indicates that much of the soot resides in a region at the head of the spray.\(^{49}\)

Figure 9 shows selected simultaneous soot-NL (left) and soot-PLII (right) images of combustion with a main injection only, where DOI\(_{1C} = 1950 \mu \text{s} \). The end of the main injection is approximately 5 CAD before the first image, and the three timings shown are times at which the post injection would have penetrated to the same distance as the location of the residual soot from the main injection, and ignited, had a post injection been present. The colored outlines in Figure 9, and throughout this article, are subjective boundaries of the large-scale soot structures determined from inspection of dynamic movies, for which the boundaries are much more obvious than in static images. These are not calculated with any thresholding or edge-finding technique, but instead are meant to help the reader visualize certain aspects of the large-scale soot structures and fluid processes in the cylinder.

At this point in the cycle, the main-injection jet has impinged on the wall and rolled into two large-scale recirculation structures on either side of the nominal jet centerline (horizontal dashed line). This is evidenced by the two clouds of soot above and below the jet centerline at 372 CAD. The lower of the two residual main-injection soot structures in Figure 9 is outlined in blue. Additionally, swirl convects these structures around the cylinder axis in a counter-clockwise direction (from the camera perspective), moving the part of the soot cloud outlined in blue in Figure 9 into the path of the post-injection jet, if it were to be injected. Also of note is the similarity between the contours of the soot-NL and soot-PLII images at each crank angle. This indicates that much of the soot exists within the region of the incoming post-jet plane. By contrast, the relatively weak signal on the right side of the soot-NL image at 372 CAD, near the bowl-rim, corresponds to a region in the soot-PLII image that is mostly black, indicating
that the soot-NL in that region is from soot above or below the nominal plane of the jet axis (i.e. the laser sheet).

Figure 10 shows corresponding instantaneous images for a condition with the same main injection but with a post injection added (see table at the top of Figure 10 for operating conditions). This condition is the minimum-soot point for DOI1c = 1950 μs in Figure 8. Additionally, a video of this condition can be found online73.

The images in Figure 10 show the progression of the interaction between the post jet and the main-injection products immediately after the end of the post injection. In these images, the approximate extent of the soot from the post injection is outlined in red, while the approximate extent of the main-injection soot cloud is outlined in blue. Both extents are determined by visual inspection of high-speed movies, in motion, for which the boundaries between main-injection and post-injection soot are more apparent than in individual static images.

Figure 10 shows that at the minimum-soot condition, the post injection clearly penetrates to the bowl wall, evidenced by the impingement of the soot in the head of the post jet with the bowl wall at 374 CAD. It is evident from these images that the interaction with and subsequent rollup along the wall is important to the soot distribution within the engine. Shorter post injections that result in less soot reduction do not reach the bowl wall within the timescales for combustion, which suggests that the penetration of the post injection to the bowl wall may be a critical feature for soot reduction by post injections.

The post jet enters the region of residual soot from the main injection at a time when swirl has pushed one of the soot clouds from the main injection into the path of the post jet, allowing for some interaction between these two structures. This is shown by the overlap in the post (red) and main (blue) soot boundaries in Figure 10. As the jet penetrates toward the bowl wall, it pushes fluid ahead of it “out of the way,” including the...
Figure 10. Simultaneous single-shot images from (left) high-speed soot-NL imaging and (right) soot-PLII at six crank angles for the minimum-soot condition. Images in each pair (left and right) are from the same cycle, but each pair is from different cycles. The annotated outlines show the approximate boundaries of (red) post-injection soot and (blue) main-injection soot. Green dashed lines indicate the jet centerline from the main spray and the two adjacent sprays. A video of this condition can be found online or accompanying multimedia in the digital format.

CAD: crank angle degree; soot-NL: soot natural luminosity; soot-PLII: planar laser-induced incandescence of soot.
constituents of the main-injection products. This displacement mechanism is most apparent in the soot-PLII images from 372 to 374 CAD, wherein soot from the main injection is initially ahead of the post jet, and is progressively pushed forward (right) and to the sides (up and down) of the post jet.

Additionally, as the jet passes through the main-injection products region, it entrains fluid from this region into the jet. This can be seen in many soot-NL videos, where pockets of soot are entrained to the trailing edge of the post jet as it passes the edge of the residual main-injection soot cloud, as can be seen in Cycle 3 in the supplementary video.73 Finally, in the later images when the post jet impinges on the bowl wall, the jet rolls up to either side, similar to that noted earlier for the main injection. This process is shown in the 376 and 377 CAD images in Figure 10. In both the soot-NL and soot-PLII images, impingement and rollup of the post-injection soot cloud are evident at 376 CAD. At the next crank angle, the post and main soot clouds have evolved to the point where it is difficult to differentiate their structures.

The post-jet interaction with the main-injection soot is even more substantial in cases where the post-injection duration is longer. Figure 11 shows soot-NL images for a condition with DOI1C = 1950 μs and DOI2C = 600 μs, which has a gIMEP of 665 kPa. At this condition, the engine-out soot is still less than a single injection at the same load (a reduction of 13%), but with FSN at 0.52, its engine-out soot is greater than both the minimum-soot condition (DOI1C = 1950 μs, DOI2C = 500 μs, FSN of 0.4) and the main-injection-only condition (DOI1C = 1950 μs, FSN of 0.42).

Figure 11 shows high-speed soot-NL images at a range of 371–376 CAD. Note that liquid fuel is still being injected during 371–373 CAD due to the longer post-injection duration at this condition. As a result of the increased fuel quantity of the post injection, more soot is produced in the post jet. This is evidenced by the increased natural-emission signal in these images as compared to the shorter post injection in Figure 10. Although the soot-NL signal is affected by both soot temperature and soot concentration, the soot temperatures should not be significantly greater with longer post injections because the adiabatic flame temperatures are similar for the two combustion phasings. Hence, the increase in soot-NL is likely due to an increase in soot concentration rather than an increase in soot temperature.

More significant interaction between the post jet and the main-injection soot is evident in the videos.74 For

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**Figure 11.** Instantaneous soot-NL images at six crank angles for a long post-injection condition. The annotated outlines (red) show the approximate boundaries of post-injection soot. A video of this condition can be found online74 or accompanying multimedia in the digital format.

CAD: crank angle degree; soot-NL: soot natural luminosity.
example, significant entrainment of the main-injection soot into the tail of the post jet is present during Cycles 1–4 of the video. Furthermore, the post jet penetrates to the bowl wall and a significant amount of soot rolls up on either side, becoming indistinguishable from the main-injection soot. Despite the fact that the engine-out soot level at this post-injection duration is greater than that of the main injection only, the optical data show that there is still significant interaction between the post jet and the main-injection soot and products. Given the evidence of interaction between the post jet and main soot at shorter injection durations, it is only logical that a longer post injection would also have a similar or even greater amount of interaction. However, we posit that the increased engine-out soot at this condition, as compared to the minimum-soot condition, is a result of the increase in soot formed in the longer post jet.

**15% and 12.6% intake O₂**

Trends in engine-out soot are characteristically different at low intake-oxygen levels. In this study, two “low-oxygen” content cases were tested, with 15% and 12.6% intake oxygen, corresponding to 35%–48% and 40%–57% EGR, respectively. At these conditions, engine-out soot continues to increase with decreasing intake oxygen, which is borne out by the significantly higher measured FSN at an equivalent load. As discussed in section “Engine operating conditions,” the global equivalence ratio range increases from 0.2–0.46 at the high-oxygen conditions to 0.34–0.68 for the lowest oxygen condition, which contributes to the increased engine-out soot.

These tests were conducted similarly to those discussed above with reference to Figures 7 and 8. The black squares in Figures 12 and 13 show the baseline engine-out soot measurements, with single injections of increasing duration. At these low-oxygen conditions, the engine-out soot no longer increases linearly with load for the single-injection tests. Instead, it increases more rapidly at higher loads, and the curve-fits shown in Figures 7 and 8 are cubic polynomials.

Similar to the high-oxygen conditions, results from post-injection schedules for the low-oxygen conditions are shown in the blue circles and red triangles, corresponding to different starting baseline loads. The engine-out soot results for the post-injection tests look different than those in the higher intake-oxygen cases. As the duration of the post injection is increased, the engine-out soot initially stays nearly constant; this is in contrast to the unambiguous initial decrease in engine-out soot that was measured at higher intake-oxygen levels. Eventually, as with the higher oxygen-content conditions, the engine-out soot rises rapidly with increasing post-injection duration. Additionally, the “cross-over” point occurs at shorter post-injection durations for the low-oxygen cases compared to the high-oxygen cases.

The maximum soot-reduction efficacy of the post-injection condition as compared to a single-injection condition at the same load is greater for the low-oxygen conditions, as shown in Figures 12 and 13. For example, the maximum engine-out soot reduction with a post injection is 62% at 470 kPa gIMEP for 12.6% O₂ and 32% at 470 kPa gIMEP for 15% O₂. For these cases, however, post injections do not decrease the engine-out soot relative to a constant main injection.

The differences in the features of the post-injection engine-out soot curves between the low-oxygen and high-oxygen conditions may indicate a difference in the in-cylinder interaction of the post injection with the
main-injection soot cloud. One notable dissimilarity between the soot trends at high and low oxygen-content conditions is the initial engine-out soot trend as post injections are added. At high intake-oxygen levels, the engine-out soot decreases with increasing post-injection duration until a minimum engine-out soot level is reached, clearly showing an interaction between the post jet and the residual main-injection products. This interaction was further corroborated by soot-NL and soot-PLII images, which showed interactions between the post jet and the main-injection products such as displacement and subsequent entrainment or colocation of the main-injection products by the post jet. As discussed above, these observations can be made from soot images because at high-oxygen conditions, soot is a fairly good marker of the head of the jet and can be used to discern fluid motion throughout the cycle to some extent.

It is much more difficult to draw any definitive conclusions about soot reduction at the low-oxygen condition for two reasons. First, the shape of the engine-out soot curve with post injections does not indicate an unambiguous interaction between the post jet and the main-injection soot. The initial trend, where engine-out soot does not change with increasing post-injection duration until approximately DOI2C = 400 μs, could be explained by anything from a soot-free post injection that does not interact with or change main-injection soot to a soot-forming post injection that at the same time helps to reduce soot from the main injection by an offsetting amount.

Furthermore, it is difficult to use the soot-NL and soot-PLII images at low intake-oxygen conditions to reveal details of the fluid motion of the post jet because soot may no longer be a good marker of the post-jet boundaries. Figure 14 provides a comparison between the high oxygen-content cases (top) and the low oxygen-content cases (bottom) for the same post-injection timing using both soot-NL and soot-PLII imaging. The high-oxygen case images, like those in Figure 10, clearly show the post-jet structure. However, the post jet in the low-oxygen case images is quite difficult to see as a result of the changes in soot-formation behavior at high-EGR conditions. Due to the longer ignition delay of the mixture at low-oxygen conditions, the soot-formation characteristics have changed, and the post-jet soot (circled in red) can no longer reliably be used as an indicator of the head of the post jet. Fluid mechanically, the two jets should not be appreciably affected by a change in the ambient oxygen concentration, but this expected similarity is not reflected in the soot distributions. As a result, it is very difficult to determine the extent of the interaction between the post jet and main-injection products from soot imaging alone at these conditions.

Experimental Conditions

- SOI1C=347 CAD, DOI1C=1950 μs
- SOI2C=366 CAD, DOI2C=350 μs
- Intake O2 = 18% (top), 12.6% (bottom)
- gIMEP: 540 kPa

Figure 14. Images in each pair (left and right) are from the same cycle, but each pair is from different cycles. A video of this condition can be found online or accompanying multimedia in the digital format.

CAD: crank angle degree; soot-NL: soot natural luminosity; soot-PLII: planar laser-induced incandescence of soot.
The low oxygen-content images in Figure 14 (bottom) also emphasize the almost negligible soot formation in short post injections at high-EGR conditions. Little to no signal from the post jet was measured in most of the soot-PLII images; the soot-PLII image in Figure 14 shows an example of one of the highest levels of signal from the post jet among the many images taken at this condition. In the video, soot from the post injection is only visible in the second cycle. The gain of the high-speed camera capturing soot-NL images was increased by a factor of 4 at the high-EGR conditions. While this saturated the soot-NL signal in the main-injection soot cloud near the bowl wall, it made it possible to see what little signal there is from the post-injection soot, again outlined in red in Figure 14.

Discussion
The focus of this study has been to characterize the dependence of engine-out soot from this optical engine on changes in DOI2C, intake oxygen, and load. Additionally, optical data have provided visualization of the in-cylinder interaction between the post injection and the residual main-injection soot. In this way, both the engine-out soot measurements and in-cylinder soot distributions are compared between high and low intake-oxygen conditions. To summarize these results, Figure 15 shows a conceptual chart of the efficacy of the post injection versus a single injection at the same load over a range of post-injection durations (actual duration of the post injection (DOI2)) and intake-oxygen contents.

The color in Figure 15 indicates the efficacy of the post injection as compared to a single injection at the same load. The deep green regions indicate that the post injection reduces engine-out soot significantly from the single-injection baseline. The yellow regions are where a post-injection schedule does not change the engine-out soot compared to a single injection at the same load. These have previously been termed the “cross-over points” in Figures 7, 8, 12, and 13. And finally, the red region shows where a post-injection schedule can be detrimental to engine-out soot, causing higher engine-out soot than for the single injection at the same load. To help communicate the meaning of the colors, Figure 16 shows the color scheme from Figure 15 mapped onto the FSN versus load results from Figure 8.

Several trends are evident in the conceptual chart of Figure 15. First, there is a central region along the

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**Figure 15.** Conceptual chart of post-injection efficacy as compared to a single injection at the same load (color) and as compared to a constant main injection (solid curves) as a function of DOI2 and intake-oxygen content at a mid-load condition.

**Figure 16.** Color map relating the conceptual description in Figure 15 to the measured FSN results in Figure 8. DOI1C: commanded duration of main injection; FSN: filter smoke number; gIMEP: gross indicated mean effective pressure.
DO12 axis where post injections are most effective (green). Very short post injections do little to decrease engine-out soot (yellow, left side), and as post injections become too long, their efficacy decreases (yellow, middle-right) and they can even lead to increases in engine-out soot (red, right side). Additionally, the efficacy of the post injections in the mid-range DO12 region increases as the intake-oxygen content decreases; post injections are proportionally more effective in this engine at lower intake-oxygen levels (darker green, at bottom). Even so, the range of DO12 over which the post injection is effective shrinks with decreasing intake oxygen; the cross-over point is at a shorter DO12 at low intake-oxygen levels than it is at high intake-oxygen levels.

Two special regions in the operational space are shown on the conceptual chart in Figure 15, as delineated by curved black lines. First, at short DO12 and high intake-oxygen (upper left corner), the main-plus-post schedule results in less soot than only the main injection. This is the region in which the engine-out soot remains less than the main-injection soot with increasing post-injection duration, as shown in Figure 7 for 21% O2 and Figure 8 for 18% O2. In the low oxygen-content cases in Figure 12 for 15% O2 and Figure 13 for 12.6% O2, this region does not exist.

Second, a small region at very short DO12 and low oxygen contents (lower left corner) is labeled “no net soot in post.” This region is indicative of the lack of change in engine-out soot with increasing post duration for the low-oxygen cases, such as in Figures 12 and 13. To achieve this, the post injection does not produce any net soot, meaning that either it produces no soot at all, or that any soot that is produced in the post jet is subsequently oxidized or is balanced by enhanced oxidation of the main-injection soot. These two areas have been highlighted to emphasize the differences in engine-out soot trends with post-injection duration between the high and low intake-oxygen cases.

The final parameter that was varied in this study was the starting (main injection) load for the post-injection sweeps. Two important conclusions have been drawn from these results at different baseline-load levels. First, the overall shape of the engine-out soot dependence on DO12 was similar between loads. These results show that engine-out soot behavior is relatively insensitive to load, and that the mechanisms of soot reduction by the post injection may not change at different baseline loads, determined by the duration of the main injection. Second, the DO12 range over which soot reduction is achievable with a post injection decreases as load increases (i.e. the “cross-over” point occurs at shorter DO12).

**Comments on outstanding research questions**

Industrial experience and a large literature of research show that post injections can reduce engine-out soot under moderate-EGR conditions. Close-coupled post injections, in particular, have been shown to not only reduce soot but often maintain fuel efficiency as well. The efficacy of post injections at reducing soot can change significantly with engine operating condition. As was described above, variables such as EGR and injection duration have important effects on post-injection behavior. Previous studies have offered a variety of explanations for why certain post-injection schemes reduce engine-out soot.

To assess the validity and relative importance of the proposed post-injection soot-reduction mechanisms from the literature under different conditions, and to formulate a more rigorous description of the soot-reduction mechanism for post injection in general, several more detailed questions need to be addressed. Some of these are discussed below, although this does not constitute an exhaustive list of remaining questions.

The most fundamental of these issues is the balance between soot-formation and oxidation effects of post injections. Many previous studies, discussed in section “Introduction,” point to enhanced oxidation as the method of soot reduction, either through mixing or through thermal routes. Others point to reduced soot formation by inhibiting jet replenishment. While all of these explanations are certainly plausible, insufficient optical data exist to conclusively describe the interaction. Both exhaust and optical measurements in this study indicate that there is an interaction between the post injection and the main-injection soot, and that fluid mechanic interaction may be important, but the details of this process remain insufficiently described.

Next, the role of targeting of the post jet relative to the main soot cloud has not been established. The soot cloud formed from the main injection creates an “initial condition” into which the post injection penetrates. This initial condition can be altered by changing the dwell between the main and post injections, allowing the main soot cloud to evolve and be transported by in-cylinder flows as dwell time increases. At different dwells, the post jet could interact with a different region of the soot cloud or with different stages of the evolution of the soot clouds. The displacement of, entrainment of, and other interactions with the main-injection soot by the penetrating post jet may be critical features of the soot-reduction mechanism, which may in turn be affected by combustion chamber geometry. By visualizing differences of various interactions and measuring the changes in engine-out soot for different targeting conditions, a better understanding of the sensitivity of the soot-reduction mechanism to post-injection targeting may be gained. Additionally, the post-injection rate profile may play an important role in the efficacy of the post injection at reducing soot. Previous work on the role of injection-rate profiles on fluid mechanic processes in diesel engines has shown the influence of the injection-rate profile on mixing and soot formation.
While fluid mechanic processes associated with the post injection may likely play a role in soot reduction, several authors have also pointed to the importance of the thermal effects of the post injection. Both soot formation and oxidation are highly dependent on temperature, and the addition of fuel through a post injection changes the heat release profile and temperature distribution throughout the cycle.\textsuperscript{29} While the sensitivity of the engine-out soot to bulk-cylinder thermal conditions can certainly be measured, optical data of a thermal mechanism are much harder to measure.

Finally, measurements by Barro et al.\textsuperscript{19} have added additional support to the idea that soot formation may have a nonlinear dependence on injection duration through the “jet replenishment” mechanism. The role of this mechanism relative to the other two discussed here will be difficult to measure directly, but knowledge of this effect will help us further understand the dependence of post-injection efficacy on post-injection duration.

### Conclusion

In the present study, we have taken initial steps toward characterizing the behavior of close-coupled post injections at a variety of intake-oxygen levels, loads, and injection timings. Our salient findings are as follows:

- At high intake-oxygen levels (18% and 21%), close-coupled post injections can reduce engine-out soot over a range of post-injection durations and loads. At these conditions, the engine-out soot level initially decreases with increasing post-injection duration and then subsequently increases, all while the main-injection duration is held constant. This initial decrease in soot clearly indicates an interaction between the post injection and the soot remaining from the main injection.
- At low intake-oxygen levels (12.6% and 15%), close-coupled post injections can also reduce engine-out soot over a range of post-injection durations and loads as compared to a single injection at the same load. Here, the engine-out soot initially stays nearly constant with increasing post-injection duration and then increases sharply, all while the main-injection duration is held constant. This engine-out soot dependency is different from the high oxygen-content cases, and the nature of the interaction between the post jet and the main soot cloud is not clear from the current optical data.
- The characteristic engine-out soot emission trends do not change significantly with “baseline” load (main-injection duration) for a given intake-oxygen condition. However, the range of post-injection durations over which the post injection is effective at reducing engine-out soot is smaller as the load is increased.
- Several types of interactions between the post jet and the main soot were identified from the optical data, mainly fluid mechanic in nature. First, the post jet displaces the main soot as the post jet enters the region occupied by the residual main soot cloud. Next, products of the main injection are entrained into the post jet as the jet passes through the main soot cloud. Finally, in cases where the post jet impinges on the bowl wall, the post jet rolls up on the bowl wall and becomes indistinguishable from the soot remaining from the main injection. In all these interactions, the contents of the post jet can mix with those of the main-injection products; this mixing can change the formation and/or oxidation rates of soot in both the main and post injection.
- Finally, we offer a “conceptual chart” that graphically summarizes the post-injection duration and intake oxygen (EGR) influences on engine-out soot. The chart illustrates the regions by color where post injections reduce engine-out soot at the same load as single-injection operation and also identifies regions where the post injection creates no soot of its own or unambiguously reduces the net soot yield of the main injection.

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### Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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