INTRODUCTION

Exhaust soot is a heavily regulated emission for diesel engines [1, 2, 3], and while effective aftertreatment systems have been developed for its mitigation, in-cylinder soot reduction techniques remain attractive alternatives to reduce or eliminate exhaust aftertreatment. A sprawling literature on post injections documents the effects of post injections on engine-out soot with variations in many engine operational parameters. Explanations of how post injections lead to engine-out soot reduction vary and are sometimes inconsistent or contradictory, in part because supporting fundamental experimental or modeling data are often not available. In this paper, we review the available data describing the efficacy of post-injections and highlight several candidate in-cylinder mechanisms that may control their efficacy. We first discuss three in-cylinder mechanisms that have been frequently proposed to explain how post injections reduce engine-out soot. Thereafter, to provide a foundation for interpretation of past research, we briefly review basic soot formation and oxidation chemistry, and soot/fluid processes in fuel sprays and engine flows. Next, we provide a comprehensive overview of the literature on the efficacy of post-injections for soot reduction as a function of engine operational parameters including injection duration and dwell, exhaust-gas recirculation, load, boost, speed, swirl, and spray targeting. We conclude by identifying major remaining research questions that need to be addressed to help achieve a design-level understanding of the mechanisms of soot reduction by post injections.

These modern technologies have allowed for more complicated, multiple-injection schedules to be implemented for a variety of purposes, including soot reduction with post injections. Most of the studies discussed in this review used standard common-rail injectors, although other injector technologies can certainly be used with multiple-injection schedules. Further advances in injector technology, such as direct-acting piezoelectric-driven injectors [12] and injection pressure control [14], could potentially lead to better post-injection performance for soot reduction.

There is a large literature on post injections for engine-out soot reduction for both light-duty and heavy-duty engines over a wide range of engine operating conditions. Experimental studies have measured the changes in post-injection efficacy with changes in injection schedule, exhaust-gas recirculation (EGR), load, boost, speed, swirl, and spray targeting, among others. These measurements include both engine-out soot and in-cylinder soot using optical/laser diagnostics. Complementary computer modeling predictions also provide insight into potential in-cylinder processes affecting post-injection performance.

Despite the large number of studies that have investigated how post injections can reduce soot emissions, there is little consensus within the literature about how, or even how well, post injections work. To help frame a detailed discussion on how various engine operational parameters affect engine-out soot reduction by post-injections, we first review three explanations for soot reduction with post injections that have been offered in the literature.

**Enhanced mixing**

Several studies have presented the explanation that post injections reduce engine-out soot by enhancing mixing within the cylinder [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]. Ultimate soot yield depends on a balance between formation and oxidation (discussed in more detail in the following section), and enhanced mixing could conceivably affect formation and/or oxidation. Many authors have hypothesized that enhanced mixing increases oxidation of soot from the main injection [15, 16, 19, 25, 28]. In these explanations, enhanced mixing by the post injection brings fresh oxygen to the soot from the main injection, enhancing oxidation of this soot while simultaneously burning the post-injection fuel.

It is difficult to isolate mixing from other effects of post injections, but one unique study from Konno et al. [30] attempts to do so by using an unconventional post injection. In their experiment, a “combustion chamber for disturbance” (CCD), a small auxiliary combustion chamber located above the firedeck and connected to the main combustion chamber via a small, straight nozzle, provided an additional injection of combustion products into the cylinder. The CCD is akin to a prechamber of older indirect-injection diesel engines, though in this case the main fuel was still delivered by direct injection. The purpose of the CCD was to provide a high-velocity post-jet of combustion products after the main injection. Their results showed that over a large range of CCD injection dwells (varied by changes in injection time), engine speeds (800-1200 RPM), excess air ratios (between 1 and 4), and CCD jet diameters, the CCD injection reduced engine-out soot. Soot reduction was greatest at the highest CCD jet momentums, from which Konno et al. concluded that the increased mixing and/or turbulence introduced by the jet enhanced soot oxidation. This was also supported by the accelerated combustion observed in the apparent heat release rate (AHRR) with the use of the CCD jet. Konno et al. indicated that the combustion products of the CCD jet likely played a smaller role in combustion chemistry than in a conventional post injection, but the enhanced mixing and/or turbulence that resulted from the use of a CCD jet certainly affected the combustion process and oxidation of soot. Even so, a definitive conclusion about post-injection mixing effects on oxidation has not been established.

Whereas many studies have pointed to mixing as a way to enhance oxidation, the computer model predictions of Yun et al. [22] predicted that increased mixing can suppress soot formation from the main injection if the post jet interacts with the burning fuel from the main injection. Three-dimensional Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) simulations using KIVA, examples of which are shown in Figure 1, predicted that the post injection redistributes the fuel from the main injection, creating a more well-mixed fuel/air distribution with smaller and less fuel-rich soot-forming zones. In these tests, the main-injection duration was shortened when a post injection was added to maintain constant load.

The predicted increase in mixing from the post injection is evident in Figure 1, which shows contours of equivalence ratio for a single injection (left) compared to main-plus-post injection (right). In the single-injection case, a large region of high equivalence ratio (maximum near 3.5) resided in the bowl, whereas the maximum equivalence ratio in the main-plus post-injection case was approximately 2.7, and the fuel was more evenly distributed in both the bowl and the squish regions. Additionally, this work showed that this fuel redistribution mechanism could be particularly important at high rates of exhaust gas recirculation (EGR) where oxygen is limited and mixing is crucial to soot reduction. While these modeling results pointed to a post-injection mixing effect on soot formation for this engine and operating condition, experimental data that isolates the post-injection mixing effect on formation is limited and not yet conclusive.
Increased temperature

Other studies have argued that as the post-injection fuel burns, the increased temperature from the additional heat release can enhance the oxidation of soot from the main injection, thereby reducing engine-out soot [15, 27, 31, 32, 33, 34, 35, 36]. This is a difficult explanation to support experimentally, as accurate measurements of in-cylinder temperatures in diesel combustion are challenging, even in optically accessible engines. Two-color soot pyrometry [37] can provide some information about soot temperature, though the uncertainties are considerable. One example is the work by Bobba et al. [15], which measured soot temperature in the squish region where much of the post-injection fuel burned after a relatively long dwell time between the end of the main injection and the start of the post injection. An example of these results is in Figure 2.

Higher soot temperatures were measured in the squish region when the post injection was present, as evidenced by the peaks in temperature during the burn of the post injection in Figure 2. The engine-out soot decreased with the post injection at these conditions, suggesting that temperature may play a role. Similar effects of increased temperature in the squish region were predicted in a computational effort by Hotta et al. [19]. While engine-out soot reduction by post-injections can be correlated to increased in-cylinder temperature, these studies also acknowledged the importance of mixing and/or targeting of the post jet.

Injection duration effects

Finally, a smaller number of studies have noted that soot formation is related to the duration of each injection [28, 38, 39, 40, 41, 42]. Researchers have attributed the engine-out soot reduction to a lack of soot formation in the post injection and/or a non-linear decrease in soot formation with injected fuel mass in the shortened main injection. This mechanism is most often referenced in studies with close-coupled post-injection schedules, where the dwell between the end of the main injection and the beginning of the post injection is very short. An example is work by Desantes and coworkers [39, 40], in which they discussed a “split-flame” concept, pictured in Figure 3. In this concept, it was posited that the fuel from the main injection and the post injection burned separately without any interaction, and the reduction in exhaust soot stemmed from splitting the fuel delivery into multiple injections.

Another common concept related to injection duration effects, proposed by Han et al. [38], is the concept of “jet replenishment.” Based on computer model simulations, these authors concluded that soot formation is dependent on injection duration, not just total quantity of fuel delivered to the engine per cycle. This was because as the injection duration increases, the model predicted that the head of the jet, a fuel-rich region where much of the soot is produced [43], was replenished by fresh fuel along the centerline of the jet for as long as the injection was sustained. The longer the injection, the more fuel was delivered to this head region,
creating a larger fuel-rich mixture that supported more soot formation.

<table>
<thead>
<tr>
<th>Light-duty, 0.47 liter/cyl</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 RPM, 4 bar IMEP</td>
</tr>
<tr>
<td>0% EGR, 150 kPa intake</td>
</tr>
<tr>
<td>Diesel, common rail, 610 bar P_{rail}</td>
</tr>
</tbody>
</table>

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. While injection duration can be correlated to in-cylinder and/or exhaust soot, the importance of this effect relative to other potential mixing and thermal effects has not been established.

Despite the large number of studies on post injections, little consensus exists as to how the three mechanisms above, and perhaps others, act to reduce soot in diesel engines. Before even considering the question of the mechanism(s) of soot reduction by post injections, the degree to which post-injections reduce or even increase soot varies by nearly an order of magnitude in each direction in results presented in the literature. The inconsistency in engine-out soot results is evident in Figure 4, which shows a compilation of data from ten post-injection studies. Here, the ratio of engine-out soot with a post injection to that without a post injection is plotted against the start of post injection. Note that Figure 4 is not from a single controlled study, but rather a compilation of data; operating conditions such as main injection scheduling/duration, post-injection duration, load, speed, and EGR are not held constant across these studies.

The somewhat even distribution of data above and below unity in Figure 4 indicates that post-injection efficacy is not universal, but rather highly sensitive to the engine and/or operating condition. This dependence will be discussed at length, using the studies shown in Figure 4 among many others, in the third section of this paper.

Though each of the soot-reduction mechanisms described above is certainly plausible, insufficient evidence exists to quantify the relative importance among the mechanisms for different operating conditions. As such, this manuscript aims to provide an overview of the state of post-injection research and clearly define what we as a community do and do not know about post injections for soot reduction.

The paper is organized as follows. This introductory section concludes with an overview of some important terminology that will be used in the discussion of post injections for soot reduction. Next, we provide an overview of soot formation and oxidation processes in diesel engines. This begins with an overview of soot chemistry that is pertinent to diesel combustion situations. We use this foundation to build an understanding of soot formation in diesel jets, based on significant research in both computational studies and experimental work in spray facilities and in optical diesel engines. We close the soot formation/oxidation overview by discussing the role of engine flow fields on soot formation and oxidation, and how post injections may interact with these flow features to reduce engine-out soot. The third section presents a review of the effects of various engine operating parameters (injection scheduling, EGR, load, boost, speed, swirl, and spray targeting) on post-injection soot-reduction efficacy as reported in the post-injection literature. Finally, we pose several remaining research questions that remain unanswered.

Terminology

Before we delve into a discussion of the technical aspects of post injections, it is helpful to define terminology that will be used throughout this paper. Though not an exhaustive list, the following definitions explain terms that are found...
Throughout the literature, yet may not be precisely defined among studies.

**Post injection**

A particular multiple-injection schedule where a quantity of fuel is allocated into separate portions such that the second injection duration is much shorter than the first, or main, duration. The specific cutoff for which the second injection is small enough relative to the main injection to constitute a post injection rather than a generic split injection is not well defined, but a maximum of approximately 20% of the total fuel in the post injection is consistent with most existing self-described post-injection studies.

**Split injection**

A general multiple-injection schedule where a quantity of fuel is split into separate portions. The individual split injections are often described by the percentage of the total fuel that each contains. Studies often explore effects of split injections through parameter sweeps with the allocation of fuel shifted between two injections, such as from 10% in the first injection and 90% in the second injection, to 90% in the first and 10% in the second injection. Hence, split-injections are a broad category of multiple injections, of which post-injections are a subset.

**Close-coupled**

An injection scheme where the dwell between the end of one injection and the beginning of the next injection is short, such that combustion phasing for the second injection is still favorable for thermodynamic efficiency. Some studies have shown considerable engine-out soot reduction for post injections that are late in the expansion stroke, but the combustion phasing degrades the thermodynamic efficiency. Such late-injection schemes would not be characterized as close-coupled. The threshold for characterizing a post-injection schedule as close-coupled is not well defined, but dwells of at most a few crank angle degrees are typical.

An alternate definition for “close-coupled,” found in certain literature and common in industry, implies that all post injections intended for in-cylinder soot reductions are considered “close-coupled.” According to this alternative definition, post-injections that are used for exhaust aftertreatment management are not close-coupled. This aftertreatment-based definition is very different than the efficiency-based definition of close-coupled used here.

**SOIC, DOI**

Commanded injection-schedule start of injection (SOIC) and duration of injection (DOI). These descriptions differentiate the commanded injection schedule, i.e., the pulses sent to the drive electronics, from the actual injection schedule, i.e., when fuel is actually emerging from the injector nozzles. Injector dynamics, rail dynamics, and other system issues can lead to significant differences between the commanded injection schedule and the actual injection schedule.

**OVERVIEW OF SOOT PROCESSES IN DIESEL ENGINES**

**Soot Formation and Oxidation Chemistry**

As briefly reviewed above, the post-injection literature proposes three overall mechanisms by which engine-out soot might be reduced by the addition of a carefully selected post injection: enhanced mixing, increased temperature, and injection duration effects. The action of all three mechanisms ultimately involves soot formation and oxidation rates, and depends on in-cylinder fluid-mechanical and chemical kinetic processes. The literature on soot formation and oxidation chemistry is vast and still evolving, and it is beyond the scope of this work to include all of the fundamental details. Instead, in this section, we provide an engineering-level overview of a few important aspects of in-cylinder soot formation and oxidation chemistry. In the sections to follow, the soot formation and oxidation processes will be applied to more practical aspects of in-cylinder processes, with discussion of many example studies from the post-injection literature from which some insight into post-injection effects on soot formation and oxidation may be gained.

The evolution of the in-cylinder soot yield results from a battle between the chemical processes of formation and oxidation. The relative rates of these two processes, each of which is comprised of several complicated steps, are highly sensitive to ambient conditions, particularly temperature and equivalence ratio. These conditions are non-uniform and constantly changing during the highly unsteady event of diesel combustion. The discussion here provides a brief overview of some of the key aspects of basic soot chemistry, followed by a brief discussion of how soot chemistry can be applied to diesel combustion. For a more detailed discussion of soot formation and oxidation, the effects of engine operating conditions, and the process of soot formation and oxidation in diesel engines, see for instance the review by Tree and Svensson [46].

Soot formation can be considered, in general, as a five-step process that starts with fuel and ends with fully formed soot agglomerates [47, 48, 49, 50, 51]. The five general steps are summarized in Figure 5 [46]. The first step, pyrolysis and/or fuel decomposition, involves the splitting of fuel molecules into smaller molecules such as acetylene and resonantly stabilized radicals (e.g., propargyl). These smaller molecules serve as building blocks for soot precursors [49, 52], which include polycyclic aromatic hydrocarbons (PAH).

Nucleation, the transition of gas-phase precursors to particles, creates the starting point for subsequent soot particle growth. Nucleation occurs at flame temperatures above 1300 K [53].
After the nucleation site has been created in a relatively high-temperature zone, the soot particle mass increases through surface growth, coalescence, and agglomeration, all of which may happen simultaneously. These later processes may proceed at lower temperatures than the initial precursor synthesis and nucleation steps, and indeed, they often happen away from high-temperature zones. The progress rates of the soot formation processes, from fuel decomposition and precursor synthesis to nucleation, coalescence, and agglomeration, increase with the concentration of the reactants involved, such that other factors being equal, more fuel-rich mixtures generally form soot more quickly.

At any time during this process, soot formation can be stymied by the presence of oxidizing species, typically O, O$_2$, and especially OH. Several investigations of soot oxidation chemistry have been undertaken at atmospheric conditions with a variety of fuels, from methane to heavier hydrocarbons such as ethylene, m-xylene, and n-dodecane [54, 55, 56, 57, 58]. These investigations outline two pathways of soot oxidation. In fuel-lean mixtures, O$_2$ and OH pathways of soot oxidation are important. OH molecules are highly reactive at the surface of soot particles [54, 56]. These surface reactions form CO, a molecule that does not participate in any further soot-formation reactions [46]. Simultaneously, O$_2$ molecules, more plentiful at fuel-lean conditions, are not as reactive at the surface, and instead penetrate into the internal soot structure, causing internal burning and subsequent fracturing of the soot molecules [56, 57, 58]. Simultaneous measurements of soot particle diameter and number density confirm that prior to bulk burnout of soot, the number density increases significantly due to the fracturing of large molecules. Late in the soot burnout process, soot molecules of all sizes are oxidized through OH surface pathways [58]. A schematic of this process is shown in the bottom portion of Figure 6, taken from Ref. [57].

At fuel-rich conditions, results vary regarding the impact of the soot-fracturing by the O$_2$ pathway [57, 58]. Experiments performed with ethylene fuel did not observe the soot fracturing pathway, but instead saw the dominance of the OH oxidation pathway at all particle sizes through the flame [58]. In the same experiment, however, soot produced with heavier hydrocarbon fuels such as m-xylene and n-dodecane, did undergo a fracturing process in addition to the OH burnout [57]. The reasons for these differences are unclear.

Additionally, the extent to which soot burns, termed the “soot burnout” [57], determined the sites of the fracturing in these studies. In low-burnout conditions (less than 15% soot oxidation), fracturing occurred predominantly at the “bridges” connecting primary soot particles, as shown in the upper oxidation path in Figure 6. For high soot-burnout (greater than 15% of soot oxidation), there was further fracturing of primary particles by O$_2$ molecules as well as OH oxidation at the surface, shown in the bottom path in Figure 6.

Many empirical soot models, especially those applied to diesel combustion modeling, do not account for these detailed nuances of soot oxidation chemistry. As described in the review of soot models by Kennedy [59], commonly used soot models use non-physical shortcuts for estimating soot oxidation rates. These include calculating soot oxidation rate as a function of the concentration of only O$_2$, and modulating soot oxidation rate to scale with soot formation rate. As described above, these empiricisms do not account for the multiple pathways for soot oxidation and the different roles of O$_2$ and OH. Several more detailed mechanisms, however, account for oxidation by both O$_2$ and OH at different types of carbon sites [60, 61, 62].

This more detailed understanding of soot formation and oxidation chemistry may help to improve the understanding of post-injection processes in diesel engines.

**Chemical-Kinetic Modeling of Diesel Soot Formation/Oxidation**

The dependence of soot formation and oxidation processes on both mixedness and temperature can be illustrated through chemical kinetic simulations of many of the processes described above. Figure 7 shows the predictions of one such simulation [63], with soot yield as a function of mixture equivalence ratio and temperature. The closed reactor simulations used detailed soot formation and oxidation kinetics at each combination of equivalence ratio and temperature, at a pressure of 60 bar, typical of TDC conditions in diesel engines. The soot yield is the net formation after a simulation time of 2 milliseconds, which is a relevant timescale for diesel engines. Note that not all conditions are practically accessible in diesel combustion,
i.e., both high temperature and high equivalence ratio (top-right portion) generally do not occur simultaneously.

Figure 7 shows that according to detailed soot formation and oxidation modeling, net soot formation is positive within a peninsula, over a range of temperatures and above an equivalence ratio ($\phi$) threshold near $\phi=2$. Moving across the peninsula from left to right, soot formation in fuel-rich mixtures does not begin until the temperature is sufficiently high, and the net soot formation initially increases with increasing temperature. Eventually, increasing temperature reduces soot formation rates while increasing oxidation rates, so that the soot yield peaks and then decreases at higher temperatures [63]. In the equivalence-ratio direction, soot yield increases monotonically moving upward as the mixtures become more fuel rich, owing to the increasing concentration of reactants, as described above.

Soot Formation and Oxidation in Diesel Jets

While the $\phi$-$T$ plot of Figure 7 lends insight into soot formation/oxidation tradeoffs under static conditions, conventional diesel combustion occurs in a dynamic in-cylinder environment with considerable spatial and temporal variation of temperatures and mixing states. Hence, the balance between soot formation and oxidation processes also varies considerably throughout the chamber and during the combustion event. Nevertheless, current understanding of the structure and evolution of diesel spray combustion provides a framework upon which the soot formation and oxidation processes described above may be applied to gain insight into net soot production in diesel jets. The conceptual model of conventional diesel combustion proposed by Dec [43] provides a description of the reacting diesel jet structure and soot formation and oxidation processes. Figure 8 shows an illustration from the model during the “quasi-steady” period of diesel-jet combustion, which occurs between autoignition and the end of fuel injection.

During the quasi-steady period, and in the absence of interactions with in-cylinder surfaces, the characteristic features of the reacting jet remain essentially unchanged, even as the jet continues to penetrate into the combustion chamber during the fuel injection event. As shown in Figure 8, the high-pressure liquid-fuel spray emerges from the injector and entrains hot ambient gases as it penetrates into the combustion chamber. At some downstream location, the entrained gases provide sufficient thermal energy to vaporize all of the fuel. Downstream of this “liquid length,” fuel exists only in the vapor phase.

Diesel spray flames are typically lifted, such that significant exothermic reactions occur only downstream of some flame lift-off length (see annotation in Figure 8). Downstream of the lift-off length, the diesel jet is surrounded by a diffusion flame. A fuel-rich, partially-premixed reaction-zone also resides across the interior of the jet near the lift-off length [64], and the downstream jet interior contains the hot products of the premixed reaction zone, as well as entrained products from the diffusion flame. It is within these hot, fuel-rich mixtures in the jet interior that soot formation occurs for diesel jets, as depicted in Figure 8. One of the key species for soot oxidation, OH, exists primarily in the hot diffusion flame surrounding the jet. Hence, in the conceptual model, once
soot is formed, it is oxidized primarily at the boundary of the diffusion flame and the interior soot, as indicated in Figure 8.

The net soot formation within the jet interior is strongly affected by mixing upstream of the lift-off length, and hence by the magnitude of the lift-off length. A longer lift-off allows more unreacted ambient gases to be entrained prior to combustion, thereby reducing the equivalence ratio of the mixtures as they enter the reaction zone. As described in the previous section, the soot formation processes depend on the reactant concentrations, so that a reduction of the fuel concentration through increased mixing upstream of the lift-off length reduces the overall soot formation rate. Figure 9 provides experimental data that illustrates the dependency of soot within the diesel jet on the degree of mixing upstream of the flame lift-off. The data points show the peak optical density (KL) from laser-extinction measurements of soot in diesel jets over a range of operating conditions, as indicated in the figure inset, plotted versus the mean equivalence ratio at the lift-off length. To help collapse the data, the optical density measurements are scaled according to the ambient density. Figure 9 shows that as the lift-off length increases (moving from left to right), the soot within the jet decreases, eventually reaching zero when the lift-off is long enough such that the mean equivalence ratio is no larger than 2.

Mixing prior to reaction, such as that affected by the flame lift-off, is clearly important for net soot-formation. However, the quasi-steady jet features illustrated in Figure 8, including the lift-off length, are only relevant until the end of the main injection. A conceptual model for conventional diesel combustion after the end of injection has not yet been proposed, but limited in-cylinder optical imaging does provide some guidance. Combined imaging of laser-induced incandescence of soot and OH fluorescence shows that after the end of injection, soot distributions gradually become more disperse and broken into separate pockets [66]. The soot pockets generally remain surrounded by an oxidizing envelope of OH, at least in the early part of the cycle when close-coupled post-injections would be added [66]. If soot after the main injection does reside in fuel-rich pockets surrounded by a diffusion flame with an oxidizing layer of OH, then the post injection cannot affect mixing prior to reaction in the way that flame lift-off does. Nevertheless, one way that a post injection could affect oxidation is by increasing local mixing or the surface area of the diffusion flame that surrounds the remaining main-injection soot, breaking up larger soot pockets and providing fresh oxidizer to these fuel-rich regions. In-cylinder optical imaging shows that residual soot clouds naturally break into smaller pockets as the soot oxidizes late in the cycle [66], and if post-injections accelerate this process, they should aid soot oxidation. Given that diesel combustion after the premixed burn is generally mixing limited, an increase in mixing by the post injection could help increase the mixing rate through an increase in flame area, thereby increasing the rate at which soot is oxidized. Indeed, some studies have shown an acceleration of combustion with the addition of a post injection [30, 40], which would be consistent with increased mixing, and thus increased oxidation of the remaining soot pockets from the main injection.

Another question is the difference in the surface oxidation and interior fracturing mechanisms of soot oxidation by OH and O₂, respectively, as described above. At the boundary of the residual soot pockets from the main injection, OH and O₂ should be plentiful, similar to the conceptual model description of the diffusion flame in Figure 8, such that both pathways could be active. It is unlikely that the highly reactive OH could penetrate into the soot-filled, fuel-rich interior, and indeed, OH is not detected there. The lower-reactivity O₂, however, could conceivably penetrate somewhat into the soot pockets if it can survive passage through the diffusion flame. If so, then the fracturing pathway by O₂ could be active within the soot pockets. O₂ is a difficult species to detect within fuel-rich diesel jets, and no such measurements yet exist. Nevertheless, it is conceivable that post injections could enhance soot oxidation by mixing O₂ deeper into the soot pockets, perhaps by disrupting the diffusion flame so that the O₂ can survive into the soot pockets. Additionally, O₂ may be transported into these pockets of fuel by diffusion through highly-strained flames.
Effect of Engine Flow Fields on Soot Formation and Oxidation

In addition to mixing effects by direct interactions of post-injection jets with main-injection soot pockets, post-injection interactions with in-cylinder bulk flow fields and surfaces can also affect mixing, and hence soot oxidation. Mixing and combustion in diesel engines are dependent on both turbulence at smaller scales and bulk flow motion at larger scales. Hence, post-injection effects on either turbulence or bulk-flow motion can be important for soot oxidation during the mixing-limited period of combustion.

As reviewed by Miles [67], interactions of fuel-spray flows with in-cylinder bulk flows and in-cylinder surfaces can have profound effects on mixing and turbulence. One obvious source of spray-induced turbulence is the strong velocity gradients in the vicinity of the fuel spray, which may interact with or be transported to regions where soot is being oxidized. Perhaps more importantly, however, the spray can interact with in-cylinder flows, especially swirl, to promote large-scale mixing and turbulence production. Spray-swirl interactions can promote mixing and turbulence production by creating bulk flow motions that bring fuel-rich regions together with fresh charge, while also increasing turbulence.

For example, as described by Miles [67], using single injections in light-duty engines with appreciable swirl and a re-entrant bowl geometry, as the spray is deflected downward by the bowl-rim, it displaces high angular-momentum fluid from the outer bowl down into the bottom of the bowl and then toward the center of the chamber. Centrifugal forces from the swirl impede the inward flow, forcing it upward and back outward, thereby creating a large rotating flow structure in the bowl. A complementary counter-rotating structure higher and closer to the center of the chamber forms to accompany the large bowl structure. Together, these two structures bring fuel-rich mixtures out of the bowl and into contact with fresh oxidizer at the interface between the two vortices.

In addition to the bulk mixing provided by these large-scale structures, large deformation rates of the fluid between the structures generate significant turbulence in the same interfacial region between the rich bowl mixtures and the oxidizers in the upper vortex. Hence, the spray/swirl interaction creates bulk flow motion that brings fuel and air together while also generating turbulence at the same fuel/air interface.

The above description of spray/swirl/wall interaction is not guaranteed, however, and depends strongly on the balance between spray momentum, chamber geometry, and swirl ratio. For instance, higher swirl increases the centrifugal forces that resist the inward flow induced by the spray, which leads to a smaller vortical structure in the bowl that may not bring rich mixtures out of the bowl. Conversely, greater spray momentum (e.g., higher injection pressure or longer duration) can push rich bowl-mixtures farther toward the chamber center, thereby creating a single large rotating structure that does not create the turbulence-generating interface of a more optimal swirl/spray combination.

It is also worth noting that in large-bore diesel engines with high swirl, non-solid-body rotation has been observed with higher swirl rates in the center of the chamber [68]. As there is higher angular velocity in the center of the chamber, the mean flow has globally high shear, which increases turbulence production. Also, spray-swirl interactions can affect the local shear rates by targeting the fuel spray into either the bowl or the squish region, where momentum exchange between the ambient crossflow and the fuel spray decelerates the local swirl flow.

In addition to spray/swirl/wall interactions, swirl/squish interactions can also be important. Similar to the effect that the swirl flow has on the spray flow that is redirected inward by the bowl geometry, squish flows can also be deflected by centrifugal forces associated with the swirl. For low levels of flow swirl, the squish flow can penetrate to nearly the cylinder centerline before it turns down into the bowl. At moderate swirl, the inward penetration of the squish flow is reduced and the flow turns down into the bowl farther from the cylinder centerline, where the radial momentum imparted by the squish process is balanced by the centrifugal forces of the swirl flow. For high swirl, the squish flow turns down into the bowl almost immediately after passing the bowl lip. These three general cases create vastly different in-cylinder flow patterns with different rotational directions [67], which can affect the “initial conditions” into which the fuel spray penetrates. Reverse-squish flows during the early expansion stroke could also be important, especially in regard to turbulence production near the bowl lip and subsequent effects on later flow development.

While the above discussion was based on observations with single-injections, the general concept of creating favorable bulk flows and turbulence generation through the interaction of a fuel jet with in-cylinder surfaces and squish/swirl or other flows can apply to post-injections as well. For post injections, the flow-structure interactions might be different than the examples provided above, but some fluid-mechanical mechanism almost certainly contributes to increased soot oxidation with post injections. If so, proper matching of the post-injection event with in-cylinder geometry and flows may be critical for optimizing post-injection performance. Indeed, the disparity in post-injection efficacy among studies in Figure 4 and as reviewed in the next section may be explained to some degree by differences in spray/flow/wall interactions. Furthermore, a large portion of soot oxidation generally occurs after the peak pressure, when isotropic stresses combined with volume expansion decrease the turbulence intensity. One beneficial effect of post injections might be to increase turbulence production during the period of otherwise decreasing turbulence, when soot is also oxidizing.

The concepts outlined in this section provide background information to help interpret experimental observations of post injections for engine-out soot reduction. In the next
section, we transition from fundamentals to applications, and discuss the effect of operational parameters on post-injection efficacy.

**DEPENDENCIES ON ENGINE OPERATING PARAMETERS**

In this section we discuss how the efficacy of post injections for soot reduction changes as engine operational parameters are varied. These parameters include injection scheduling, exhaust gas recirculation, load, boost, speed, swirl, and spray targeting, all of which were commonly varied throughout the literature. While each effect will be discussed separately here, it is important to note that many studies changed several of these parameters simultaneously, and as such, the effect of each of these engine operational parameters on post-injection efficacy may not be separable. For example, several studies [33, 34, 69, 70] measured engine-out soot with post injections at various points on standard drive cycles, such as the New European Drive cycle (NEDC) or the European Stationary Cycle (ESC) [71, 72]. In this type of study, operational parameters like load, speed, and boost are typically varied simultaneously to realize differences between standard operating conditions. In the descriptions below, we have identified these cases and tried to separate the effects as much as possible.

**Injection Scheduling**

The effect of injection scheduling on post-injection efficacy has been studied in several different ways. Broadly speaking, variations in post-injection scheduling can be broken down into two separate aspects. First, the dwell between the end of the main injection and the beginning of the post injection can be varied, thereby changing the combustion phasing of the post injection relative to the main injection, as well as the targeting of the post jet into the combustion chamber and mixture field created by the main injection. Second, the duration of the post injection can be varied, which changes both the fuel quantity and penetration of the post injection and, for a constant main-injection duration, also increases the load. Both of these aspects of post-injection scheduling have been extensively studied within the literature for a variety of engine configurations and operating conditions.

Most studies showed a reduction in engine-out soot with the addition of a post injection at some dwell and duration, but there was no dwell and duration combination that clearly and universally lead to soot reduction [10, 15, 16, 17, 18, 19, 20, 27, 28, 31, 38, 39, 40, 41, 73, 74]. Researchers reported that often a “sweet spot” could be reached where engine-out soot was minimized [15, 19, 21, 22, 24, 28, 33, 34, 73]. On the whole, studies have shown that shorter-dwell injection schedules reduce engine-out soot more than longer-dwell schedules. For example, Hotta et al. [19] examined 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 schedules showed that a post injection with the shortest dwell possible, 5 °CA, lead to the maximum decrease in soot at the same load as a single injection, as shown in Figure 10. Other later post-injection timings, with post-injection dwells from 7 to 13 °CA after the end of the main injection, had either no effect on engine-out soot or increased engine-out soot.

These authors [19] attributed the reduction in soot from the close-coupled post injection to both enhanced mixing and increased temperature. CFD simulations from the same study predicted that the close-coupled post jet entered the squish region, which contained soot from the main injection and fresh oxygen. As a result, the predicted temperature in the squish region rose due to combustion from the post-injection, shown in Figure 11. Based on the model predictions and experimental trends, the authors argued that the engine-out soot reduction was due to a combination of the enhanced mixing between the main-combustion soot and the oxygen in the squish, and the increased temperature and chemical reaction resulting from the post-injection burn in the squish region. Both the availability of oxygen and higher ambient
temperature in the squish would enhance soot oxidation in this region.

Figure 11. Temperature field comparison between main-injection only (top) and main- plus post-injection operation (bottom), showing increased temperature in the squish region with post-injections. Copyright © SAE International. Reprinted with permission [19].

The timing of the post jet with respect to the piston position and subsequent squish height seems to be an important parameter for the efficacy of this mechanism, although the later timings that resulted in higher engine-out soot were not reported in detail. Though enhanced soot oxidation in the squish was reported in a few papers in the literature, it is by no means universal [15, 19, 22]. Many of the papers do not offer detailed explanations like that provided in Hotta et al. [19].

Certain studies, however, showed that longer post-injection dwells lead to greater engine-out-soot reduction. Results from Chen [20], Shayler et al. [73], and Bobba et al. [15] all showed greater reduction in engine-out soot with post-injection dwells greater than 20 °CA, which may be related to differences in interaction of the post injection with soot and combustion products in the squish region. As described earlier in the overview of soot processes, differences among these studies in spray interaction with in-cylinder surfaces and flows may contribute to differences in the observed post-injection efficacy.

Changes in post-injection duration also affect the performance of post injections. Many of the studies that investigated the effects of post-injection duration included data that fall into the “split injection” category [10, 18, 31, 38, 75, 76]. Wherever possible, only the cases where the split-injection schedule would qualify as post injections (20% or less of the total fuel in the post-injection) are discussed here.

Many studies showed that post-injection duration could be optimized to reduce soot [15, 21, 34]. For example, Payri et al. [34] measured engine-out soot for various engine operating conditions (from the ESC, the European Steady State Test Cycle), post-injection timings (SOI2C), and post-injection durations (DOI2C). For almost all engine operating conditions and a wide range of post-injection schedules, smaller post injections were more effective at reducing soot. Engine-out soot could be minimized at a post-injection quantity of approximately 10-20% of the total fuel.

While post-injection scheduling can be adjusted to reduce engine-out soot, effects on engine efficiency cannot be ignored. Engine efficiency is one of the key concerns for regulators, engine manufacturers, and consumers. Fuel delivery and timing plays a key role in determining engine efficiency through the influence of combustion phasing on thermodynamic efficiency. For instance, later phasing of a portion of combustion, such as might occur with post injections, can decrease efficiency, or by another measure, increase brake-specific fuel consumption (BSFC).

Several authors have addressed the issue of engine efficiency in cases where post injections are used for soot reduction [14, 17, 27, 33, 73, 77]. Many authors measured an increase in BSFC with the addition of a post injection. The extent of this increase could be mitigated, however, by varying both the post-injection duration and the dwell. These trends were shown by several authors[33, 73, 77], but were illustrated simultaneously by Benajas et al.[33]. Figure 12 shows an example of these results at the B50 ESC engine test cycle condition.

Figure 12. BSFC variation from a single injection with post-injection mass (duration) and dwell at the B50 operating condition. Copyright © SAE International. Reprinted with permission [33].

In this study, as in others, increases in BSFC stemmed from increasing dwell and post-injection duration. For example, even at the smallest post-injection fuel mass, 12 mg/cycle, the BSFC at a dwell of 10 °CA was 1.8 g/kWh greater than that at a dwell of 4 °CA. The difference
increased at longer post-injection durations. This trend was observed at several engine test cycle conditions, including high- and low-load conditions, as well as high- and low-speed conditions. The literature also discusses efficiency with respect to the improved mixing and fuel distribution possible with post-injection schedules. For example, the fuel vapor distribution measurements by Mendez and Thirouard [17] not only illustrated the efficacy of post injections for soot reduction by elimination of rich pockets, but they also noted that the post-injection schedule resulted in an 8% reduction in BSFC, presumably due to a better fuel distribution for higher combustion efficiency. This study is discussed further in the Spray Targeting portion of this section.

These results and others like them have an important impact on the manner in which fuel injection schedules can be designed for soot reduction. For example, it is fortuitous that several researchers found that short, close-coupled post injections are best for reducing engine-out soot, since they are also effective at maintaining or even improving BSFC [19, 33, 34]. As discussed above, however, several studies reported that longer dwell times resulted in greater soot reduction [15, 20, 73]. In the cases where there is a competition between BSFC and soot reduction, the optimal post-injection dwells will depend on a balance of both considerations. This type of optimization was discussed in work by Montgomery and Reitz [21]; their work shows that this optimization process is costly but certainly possible.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is a commonly varied intake condition in many post-injection studies. EGR is a process by which gases from the exhaust stream are mixed with the intake stream, effectively diluting the intake mixture - reducing the oxygen content by volume - and decreasing the peak combustion temperatures. Through this temperature effect, EGR can significantly suppress the production of NO\textsubscript{x}, a toxic and highly regulated emission in diesel engines. Despite the positive effects that EGR can have on NO\textsubscript{x} emissions, EGR rates that are practical for normal engine operation can also lead to severe increases in engine-out soot due to the reduction in intake oxygen [46, 64]. Reduction in oxygen content initially increases the soot yield by increasing the overall equivalence ratio and allowing for richer mixtures of fuel and air, both promoting soot formation and limiting soot oxidation.

It can be advantageous to use post injections in conjunction with EGR to simultaneously reduce NO\textsubscript{x} and soot with in-cylinder techniques. Previous studies have shown that post-injection strategies can be implemented without a penalty in NO\textsubscript{x} [27], and as such, many researchers have studied the efficacy of post injections for soot reduction at various levels of EGR [19, 20, 21, 25, 26, 73, 78, 79], all the way down to 12.6% intake O\textsubscript{2} [15, 79]. These studies differ, however, in their assessment of whether EGR renders post injections more or less effective at reducing soot.

For example, results obtained by O'Connor and Musculus [79] showed that post injections became more effective at higher rates of EGR. In this study, a constant main-injection duration was chosen and the post-injection duration was varied to assess the effect of post-injection duration and post-jet penetration. The engine-out soot levels using the post-injection schedules were compared to measurements of single-injection operation at a similar range of loads. This was done for four intake-oxygen levels, 21%, 18%, 15%, and 12.6% by volume, as is shown in Figure 13. At conditions with 21% intake oxygen, post injections were able to reduce engine-out soot as much as 40% versus a single injection at the same load. At 18% intake oxygen, a level typical of current production heavy-duty diesel engines, this reduction increased to 52% at low load. Finally, at 12.6% intake oxygen, the soot reduction at the same low load as a single injection increased to 62%. It should be noted that these results are presented in units of filter smoke number (FSN), which has a monotonic but somewhat nonlinear relationship with soot mass.

![Figure 13. Engine-out soot emissions for single injection (filled squares) and main plus post injection (open circles) schedules with SOI\textsubscript{1}=347 CAD, DOI\textsubscript{1}=1950 microseconds, SOI\textsubscript{2}=366 CAD, and varying DOI\textsubscript{2} from 300 to 600 microseconds at four intake-oxygen levels [79]. Note the differences in FSN scale on the ordinate.](image-url)
All these results were at similar loads and injection schedules, although the mechanism by which post-injection efficacy increases with decreasing oxygen content is not yet clear. These findings were similar to those in studies by Shayler et al. [73] and Pierpont et al. [25], but were not universal. For example, post injections in a study by Chen [20] were much less effective at high levels of EGR, resulting in similar engine-out soot levels for single and main- plus post-injection schedules at 40% EGR. The reasons behind these differences are not clear at this time.

Load

Load is another common variable that has been investigated in studies of post-injection efficacy [21, 22, 23, 24, 32, 33, 34]; this is an important quantity to vary as the absolute level of engine-out soot (not normalized by load) generally increases with load as more fuel is delivered during each cycle. In these studies, researchers have often tested a variety of loads according to a standard testing cycle. As discussed above, changing load in a test-cycle format often means that other engine operating parameters, speed in particular, are simultaneously changed. In this discussion of the effect of load on post-injection efficacy, we have tried to separate these effects as much as possible.

In general, load has been changed in two different ways: changes in injection duration [24, 77] and changes in injection pressure [21, 32, 34]. These two methods of changing load have very different effects on in-cylinder processes important to soot production. Changes in injection duration changes not only the amount of fuel injected but also the distribution of fuel within the cylinder, as was mentioned in the discussion of jet replenishment [38] in the introduction. According to the jet-replenishment concept, longer injections can form large regions of fuel-rich mixture at the head of the jet that promote soot formation through the constant delivery of new fuel to the rich region.

Alternatively, changing the injection pressure without changing the injection duration alters not only the distribution of fuel within the cylinder, but also the jet entrainment during injection, resulting in changes in the reacting jet structure [80], fuel/air mixture distribution, and soot formation [65]. As was described at length above, soot formation in diesel jets is highly dependent on initial mixing characteristics in the liftoff length region of the jet. Higher injection pressure results in a longer lift-off length and more mixing within the lift-off region; this can result in suppressed soot formation in the mixing-limited region of the jet. Additionally, higher injection pressure of the post injection itself can change the mixing characteristics of the post jet with the main-injection mixture, altering the efficacy of the post injection.

Despite these differences, measurements have shown that load has an effect on the performance of post injections for soot reduction. In general, post injections are less effective at reducing soot at higher loads over a range of injection schedules and intake conditions.

Measurements by O'Connor and Musculus [79] have shown that post injections are less effective at reducing soot as duration of the main injection (load) increases. For 18% intake oxygen, the optimum post-injection schedule at a gIMEP of 500 kPa reduced engine-out soot by 52%, whereas the optimal post-injection schedule at a gIMEP of 650 kPa only reduced engine-out soot by 19% as compared to a single injection at the same load.

Similar results were measured by Yun et al. [23], who also changed load by increasing injection duration. These results are in Figure 14. At constant engine-out NOx, post injections at 3 bar gIMEP reduced engine-out soot by 33%, while post injections at 4.5 bar gIMEP reduced soot by only 16%, although the absolute reduction in soot in both cases was relatively similar.

![Figure 14. Engine-out soot-NOx trade-off at four loads, comparing single-injection and main- plus post-injection operation [23].](image)

The reduction in post-injection efficacy with increasing load has not been clearly explained in the literature. Based on the experimental results, the reduced efficacy could be due to the nonlinear dependence of soot formation on injection duration, described above as jet replenishment [38]. Load increases with more fuel delivery per injection, resulting from a longer injection duration. This nonlinear growth in soot quantity with fuel mass per injection could mean post injection are less effective at reducing soot on a percentage basis for longer main injections versus shorter main injections. For example, while the absolute reduction in soot was similar at 3.0 bar and 4.5 bar in Figure 14, the post injection was less “effective” on a percentage basis at the higher load. While this explanation is certainly plausible given the experimental results and discussions published in...
the existing literature, it has yet to be shown definitively by experiments or through modeling techniques.

Boost

Increased intake pressure, or boost, in diesel engines both enables higher loads and helps to optimize emissions and efficiency over a range of engine operating conditions. Increasing the pressure and density of the intake charge results in higher peak pressures and temperatures, and can lead to favorable decreases in brake-specific fuel consumption (BSFC) [81]. Boost can also have significant effects on the combustion process. For example, higher boost increases the mass of oxygen in the charge, which can change combustion and soot formation/oxidation characteristics. Additionally, changes in ambient density alter spray and flame characteristics, including liquid length, jet penetration rate, entrainment, and liftoff length [82]. Soot formation and oxidation chemistry are sensitive to many of these spray and flame changes, as well as to ambient pressure [83].

Unfortunately, no post-injection studies available in the literature address the issues of boost independently of other variables. The 50/50 split-injection study of Tanin et al. [77] provides a thorough comparison of boost effects on engine-out particulate matter (PM) for split injections (but not for post injections) relative to single-injection operation. In the absence of post-injection studies focusing on boost, this split-injection study is the best available alternative.

Tanin et al. [77] reported that at a variety of engine operating conditions, engine-out soot could be minimized at a certain boost pressure, as is shown in Figure 15. The engine-out soot for the 50/50 split-injection schedule was consistently lower than for the single-injection schedule, and both injection schedules displayed similar optimal boost levels for minimum soot emissions for this engine and injection system.

No known post-injection studies have varied boost without varying other engine operating parameters as well; most of the studies have followed a standard engine test procedure, varying speed, load, and boost simultaneously [33, 34, 69, 70]. Despite that, an important study that discussed the effect of boost on post-injection performance was performed by Montgomery and Reitz [21]. This study optimized fuel consumption and emissions relative to three baseline conditions using a response-surface method with six variables: injection pressure, boost pressure, combustion phasing, dwell between injections, fuel percentage in each injection of the split injection, and EGR. In this study, the authors compared the effects of EGR versus those of boost pressure, as both variables are means by which to change the quantity of intake oxygen. The optimization process showed that at certain conditions, post injections can reduce engine-out soot with less boost pressure because the post injection enhances the mixing of soot with remaining oxygen.

Speed

Variations in engine speed can result in considerable changes in engine flows and combustion. Engine speed affects several key features of the flows within the combustion chamber, including swirl, squish and reverse squish flows, and tumble. In particular, higher speeds result in higher in-cylinder bulk-flow velocities, which are particularly important in high-swirl, light-duty diesel engines [17, 32, 41, 84]. Experimental data demonstrating speed effects on bulk flows is limited; however, its effect on the fluid velocities in bulk flow structures is minimal when normalized by piston speed [67]. Nevertheless, as discussed in the soot process overview section, higher centrifugal forces associated with increasing swirl at high engine speed, for instance, can affect the development of complementary structures that aid mixing and soot oxidation. Additionally, speed changes the heat transfer throughout the cycle [85]. Faster speeds mean less time for heat rejection during the compression stroke, resulting in higher temperatures and pressures before combustion. Faster speeds also mean that there is less time per cycle for chemical processes to reach completion. While the main combustion events occur on time scales short enough to be completed at a variety of speeds, time available for late-cycle soot burnout is at higher speeds, which may increase the engine-out soot.

Results differ regarding the effect of speed on post-injection efficacy. For example, experiments performed by Badami et al. [32] in a light-duty engine showed that post injections over a range of dwell times could result in greater

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**Figure 15.** Particulate emissions for 50/50 split operation as a function of boost pressure, showing non-monotonic dependency of engine-out soot with boost for constant NOx of 3.3 g/bhp-hr. Percentages in the plot indicate the boost level relative to the baseline boost. Copyright © SAE International. Reprinted with permission [77].
reductions in soot at higher speeds. This was particularly true for close-coupled post injections, where the command dwell time was on the order of 500-1000 microseconds.

In contrast, extensive tests by Payri et al. [34] indicate that post injections are less effective at higher speeds in a heavy-duty engine. They tested several conditions from the ESC, two of which were A50 and B50, which are both 50% load conditions but with different speeds. Several parameters, such as injection pressure, fuel mass per cycle, injection scheduling and EGR, stayed relatively constant between these two test conditions, but the speed changed by 300 RPM. Figure 16 shows the engine-out soot measurements for the single-injection case (labeled nominal) and three post-injection cases with dwells of 4 °CA, 8 °CA, and 12 °CA.

While overall the FSN levels were lower at the higher engine speeds, the post injections were more effective at low speeds. At the lower speed (A50), the post injection resulted in an engine-out FSN reduction of 62%, while at the higher speed (B50), the post injection only reduced the engine-out FSN by 47%. In this case, the post injections are particularly effective at the later timing, 12 CAD. The efficacy of the post injections are even lower, 45% reduction, for the highest speed case, C100 at 1800 RPM (not shown here). However, the operating condition is too different from A50 and B50 for direct comparison.

Variation in post-injection efficacy with dwell times must be given special consideration when varying speed. Studies have reported dwell times both in terms of °CA (as in Payri et al. [34]) and actual times (as in Badami et al. [32]), but the actual time of a crank angle degree is a function of the speed of the engine. How a post-injection dwell time is defined in an engine controller as speed is changed may result in very different post-injection behavior at various speeds. If the post-injection duration and dwell are defined in terms of crank angle degrees, the targeting of the post injection into the main-injection mixture will be similar across engine speeds. If these definitions are in terms of absolute times, however, the targeting of the post jet could be very different, changing its burning and mixing characteristics, and as a result, its effectiveness at reducing soot.

Swirl

Swirl is an important flow feature with respect to the targeting of the post jet into the products of the main injection. Reviewed by Miles [67, 86] for light-duty engines, swirl effects on combustion include increased mixing, enhanced evaporation rates near engine surfaces, and spray/swirl/squish interactions. Each of these flow effects can change the soot formation and oxidation characteristics of the fuel jet, and alter the performance of the post injection for soot reduction.

Various authors have identified swirl as an important parameter for post-injection efficacy as it relates to dwell between the end of the main injection and the beginning of the post injection [22, 28, 41]. The strength of the swirl and the duration of this dwell determine the targeting of the post jet into the residual main-injection mixture, changing how the post injection interacts with the main-injection soot. This relationship was measured by Barro et al. [28] in their recent work on post-jet targeting. Figure 17 shows the measured effect of swirl and dwell on relative net oxidation-rate of soot. Here, the “net oxidation-rate” was defined as the rate of change in the in-cylinder soot as determined from optical two-color pyrometry data.

In this case, the sensitivity of the soot net oxidation rate to swirl strength reversed between short and long dwell periods. At short dwell times, the oxidation rate was greater for cases with higher swirl, presumably indicating that the combination of higher turbulence levels from swirl and close-coupled fuel delivery enhanced the soot oxidation process. The benefit of high swirl dropped off significantly, however, as the post-injection dwell increased.

This change in post-injection efficacy with dwell time may also indicate that post-jet targeting was important. The authors indicated that post injections are most effective if the post injection occurs before the optically-measured in-
cylinder soot peak from the main injection occurs. In this case, the optimal targeting of the post jet depends on the spacio-temporally evolving process of soot formation in the main-injection mixture. In this study [28], the post-injection efficacy was much less sensitive to timing in the low-swirl case. This may indicate that post-injection efficacy is a coupled function of both turbulence and timing, and that the post injection is less effective at low swirl ratios. Their engine-out soot measurements indicated that a post injection can reduce engine-out soot by up to 45% at high swirl ratios, but only 30% for low swirl ratios.

This example also speaks to the issue of dwell times measured in units of time versus units of °CA, as was discussed in the Speed portion of this section. It was important in the Barro et al. study that the dwell was measured in units of time, as the swirl ratio is normalized by the motion of the piston, which determines the length of a °CA. The results of this study further emphasize this difference.

Spray Targeting

Several studies have reported that the combination of spray targeting and engine geometry can play an important role in the efficacy of post injections for soot reduction. In both light-duty and heavy-duty engines, which can have quite different geometries, the targeting of the post jet with respect to the different regions in the combustion chamber seems to be important. In this section, we highlight three studies that have varied the targeting of the post injection, either through changes in injector spray angle or through changes in injection scheduling.

A study by Pierpont et al. [25] investigated the role of spray angle in post-injection efficacy over a variety of split-injection schedules. The authors expected that the injector with a wider included angle, 140°, would have less interaction with the piston for the specified injection schedule than that with the smaller angle, 125°. Figure 18 shows the results of their comparison, and clearly indicates that the smaller included angle performs better for both NO\(_x\) and soot. These results indicate that targeting of the sprays of the main and/or the post injection can be an important mechanism soot reduction with post injections.

Some of the light-duty literature includes discussion of the role of engine geometry in post-injection efficacy, which is to be expected given the highly contoured geometry of most light-duty engines. In some of these cases, interaction of the spray and the engine surfaces has been used to enhance the efficacy of the post injections for soot reduction. As described earlier, the work by Hotta et al. [19] nicely illustrated the role of post-jet targeting in the bowl versus squish, and mirrored the results found in Bobba et al. [15]. Simulations of post-injection and multiple-injection schedules by Liu and Reitz [84] also showed the importance of post-jet targeting between the bowl and squish region for optimal soot reduction.

Researchers have found that the behavior of the post injection changes as the geometry of the engine changes throughout the cycle. For example, spray targeting relative to the squish region has been shown to change soot oxidation characteristics. The study by Bobba et al. [15] emphasized the importance of the spray targeting at the bowl versus the squish region. If the main injection was timed such that it targeted the bowl, soot formed predominantly low in the bowl. The late post jet, targeted into the squish region, did...
little to reduce the soot from the main injection in this case. However, when the main injection was timed later and allowed to penetrate into the squish region, the post jet, also targeted into the squish, was able to enhance the net oxidation of the soot from the main injection that remained in the squish region. An overview of this explanation is shown in Figure 19.

Finally, in studies where combustion is not initiated until after both the main- and post-injection events (or is not initiated at all), interaction of the spray with engine surfaces has been shown to change the fuel/air distribution before soot formation starts, decreasing the incidence of rich pockets that would promote soot formation. Interaction of the fuel spray with the wall is common in small-bore engines, and often this feature is exploited for better mixing of the fuel and air [87]. Even without wall interactions, however, variation in jet development and mixing characteristics of main- plus-post-injection schedules have been measured. Two such examples are the unconfined diesel sprays (i.e., free jets) studied at engine conditions by Bruneaux and Maligne [88] and Parrish et al. [74]. Under certain close-coupled operating conditions in both these studies, the jet structure of the first injection was altered by the second injection, changing mixing characteristics even without the interaction of the jet with engine surfaces.

An example of the importance of the spray/wall interaction for fuel/air mixture preparation with post injections is a non-reacting study by Zhang and Nishida [18]. In this study, the authors varied the fuel percentage in each portion of the split injection. A dual-excitation source laser absorption scattering technique [89] was used to measure the optical thickness of the liquid fuel and vapor fuel separately. The geometry mimicked that of a light-duty engine, with a re-entrant contour to the bowl. The results of this non-reacting study highlighted the role of mixing of the post jet with the main-injection mixture for soot reduction. The authors found that not only did a short, properly-timed post injection enhance mixing of the main-injection mixture, but also that the impingement of the jets onto the bowl wall could be important. As the post jet impinged on the bowl wall, it flowed around the contour, pushing the main-injection mixture away from the wall and enhancing the mixing of the main-injection products with air from the center of the combustion chamber. The authors indicated that this post-jet mixing process could help to reduce fuel-rich zones that promote soot formation.

Similar results were discussed by Mendez and Thirouard [17], who showed that spray targeting and bowl shape could be designed together to enhance the efficacy of post injections at reducing soot and increasing burning efficiency. In this study, a narrow spray angle coupled with a highly contoured bowl shape guided the spray as it vaporized, depositing vapor in particular regions in the bowl. A planar laser-induced exciplex fluorescence (LIEF) technique [90]
was used with a fuel tracer to measure the density of fuel vapor.

With a single injection, momentum carried much of the fuel out of the bowl and to the upper, outer edge of the piston bowl. A properly-timed, short post-jet deposited more fuel in the bottom of the bowl, as it did not contain the momentum to flow up toward the top of the bowl as the main injection did. In this way, a more even fuel distribution between the bowl bottom and the upper, outer edge of the bowl was produced, eliminating fuel-rich zones that lead to soot formation. This process is illustrated in their visualization, shown in Figure 20.

**REMAINING RESEARCH QUESTIONS**

Despite the large literature on post injections for soot reduction, a clear, design-level understanding remains elusive. There are several remaining research questions that need to be answered before post-injection schemes can be designed by applying understanding of fundamental chemical and fluid-mechanical mechanisms. The following issues are important for the advancement of this topic, but by no means do they constitute an exhaustive list.

First, the general mechanism of late-cycle soot oxidation needs to be clarified. This is an important first step, even without considering post-injection strategies. The diesel conceptual model (Figure 8) proposed by Dec [43] describes diesel combustion, but only up to the end of injection. Other work (e.g., [66]) provides some information about late-cycle soot oxidation, but a comprehensive conceptual-model picture has not been established. To understand how post-injections alter late-cycle oxidation, it is first required to understand late cycle oxidation without post-injections.

- Immediately after the end of injection, does the diffusion flame progress upstream to enclose the entire soot cloud, as postulated in the Soot Processes in Diesel Engines section of this paper?
- Thereafter, how does the large soot cloud break up into smaller pockets? Does a layer of OH remain on the periphery of the soot pockets until they burn out, or is the OH depleted before the soot is fully oxidized? Does soot oxidation occur only at the diffusion flame, or is soot oxidized throughout the pocket cross-section?
- What are the roles of \( \text{O}_2 \) and OH in soot oxidation by fracturing and surface reactions, respectively?
- Does soot formation continue within the pocket even as the soot is being oxidized?
- What specific portion of the soot ultimately survives into the exhaust? Can exhaust soot measurements be correlated to optical observations of features of the burnout process?
- How does EGR, including high rates of EGR relevant to low-temperature combustion, affect the late-cycle soot burnout picture?
- How do other engine operating parameters, in particular speed, affect the extent of both early-cycle and late-cycle soot burnout?

With a clear understanding of late-cycle soot burnout for single-injections, the effects of post-injections can be explored. Given that the post-injection is a fluid-mechanical event, the foremost issue is the fluid mechanical mechanism(s) by which post injections effect a reduction in engine-out soot.

- To what degree does the post injection interact directly with the main-injection soot pockets, i.e., by penetrating into them, and how important is that for net soot reduction?
- How do post injections affect the OH and \( \text{O}_2 \) oxidation pathways, for instance by disrupting the diffusion flame surrounding the residual soot pockets from the main injection?
- Does the post injection increase the flame area of the diffusion flame surrounding the main-injection soot pockets?
- In what way does the post injection displace the main-injection soot, and what sort of displacement is beneficial for
soot reduction (e.g., into/out of bowl, into/out of squish, etc.)?

- What, if any, bulk flows created by the post injection are beneficial for soot reduction?
- Where does the post injection increase turbulence, and by how much, and by what mechanisms?

Additionally, many studies noted the importance of injection duration on soot formation through the jet replenishment concept. The basis for this explanation comes from basic understanding of how liquid jets penetrate through gaseous media, which is a relatively well-understood phenomenon in diesel applications. However, the importance of this mechanism relative to other fluid-mechanic or thermal mechanisms is unclear.

- What is the functional dependence of soot formation on both main- and post-injection duration and how does this change with operating condition?

Beyond the fluid mechanical questions, chemical kinetics issues are also unresolved. Foremost is the question of temperature on soot oxidation, which has been argued to be an important mechanism by some [15, 19, 22] and dismissed by others [28]. Ideally, the influence of temperature on soot reduction by post injections should be isolated from other effects, but it is unclear how this can be done, even with in-cylinder diagnostics. Nevertheless, measurements of the effects of post-injection-induced temperature changes on soot formation and oxidation would be helpful.

- Is the temperature effect happening throughout the bulk of the charge, or only locally, in the vicinity of the post-injection jet?
- How does the main-plus-post injection create a temperature effect that is not otherwise realized by a single injection with the same total fuel mass?
- Does temperature affect the OH and O\(_2\) soot oxidation mechanisms differently?
- How important is the temperature effect relative to fluid-mechanical effects?
- Are there other chemical-kinetic effects of post injections on soot reduction, such as effects on the fracturing and surface reactions of O\(_2\) and OH?

More fundamentally, the balance between formation and oxidation also needs to be explored. The fluid mechanical and chemical-kinetic/thermal effects on soot reduction by post-injections could either reduce soot formation or increase soot oxidation, or both.

- What are the relative magnitudes of changes to formation and oxidation by post injections?

With a better understanding of the fundamental aspects of post-injection soot reduction, more practical issues can be explored. Details of the soot reduction mechanism may change for different operating conditions and engine architectures, and the details of this should be investigated.

- For example, how do the soot reduction mechanisms change between light-duty and heavy-duty engines?
- How should combustion chambers for a given engine size be designed to take advantage of the soot reduction benefits of post injections?
- Where should the post injection be targeted and at what time in the cycle or with what dwell relative to the main injection?
- What aspects of the mechanisms change at high EGR conditions, where both temperature and oxygen content are significantly reduced?

Finally, from an engine operational perspective, previous research has shown that post-injection efficacy is highly dependent on several important engine operating parameters, such as load, speed, and boost. To date, very few studies have isolated the effects of these parameters. With fundamental understanding, answers to these questions should be available, but confirming data for individual parameter variations would be helpful.

It is unlikely that all of these questions can be answered entirely by experiments. Instead, many or most of these questions will likely be answered only by a combination of experiments and computer modeling. A good example of the ways that computer modeling can complement and extend understanding provided by experiments is described in the work on engine fluid mechanics by Miles [67], which was used extensively in the Soot Processes in Diesel Engines section. A similar approach using fluid mechanics with combustion and soot chemistry in computer models, combined with experimental data for validation wherever available, could provide the understanding required to answer the questions posed here.

**REFERENCES**

3. United States Federal Register, 76(179), (2011)
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DEFINITIONS/ABBREVIATIONS

AHRR - Apparent heat release rate
ASOI - After start of injection
ATDC - After top dead center
BSFC - Break-specific fuel consumption
CA°CA - Degrees crank angle (duration)
CAD - Crank angle degree
CCD - Combustion chamber for disturbance
CFD - Computational fluid dynamics
DOI - Actual injection duration
DOI1C - Commanded duration of main injection (in microseconds)
DOI2C - Commanded duration of post injection (in microseconds)
EGR - Exhaust gas recirculation
ESC - European steady-state test cycle
FSN - Filter smoke number
gIMEP - Gross indicated mean effective pressure
IMEP - Indicated mean effective pressure
KIVA - 3-dimensional computational fluid mechanics code for engine simulation
kL - Soot optical density
LIEF - Laser-Induced Exciplex Fluorescence
LTC - Low temperature combustion
NEDC - New European Design Cycle
ΔP - Pressure drop across injector nozzle
PAH - Poly-cyclic aromatic hydrocarbon
PM - Particulate matter
P_{rail} - Rail pressure
RPM - Rotations per minute
SCR - Selective catalytic reduction (exhaust aftertreatment)
SOI - Actual start of injection
SOI_{1C} - Commanded start of main injection (in crank angle degrees)
SOI_{2C} - Commanded start of post injection (in crank angle degrees)
T - Temperature
TDC - Top dead center
ρ_{0} - Ambient density
ϕ - Equivalence ratio