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Review

Multiple Fuel Injection Strategies for Compression Ignition Engines

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Abstract: Until the early 1990s, the predominant method of fuel delivery for compression ignition engines was the mechanical pump-line-nozzle system. These systems typically consisted of a cam-driven pump that would send pressurized fuel to the fuel injectors where injection timing was fixed according to the pressure needed to overcome the spring pressure of the injector needle. These configurations were robust; however, they were limited to a single fuel injection event per thermodynamic cycle and respectively low injection pressures of 200–300 bar. Due to their limited flexibility, a poorly mixed and highly stratified air fuel mixture would result in and produce elevated levels of both nitrogen oxides and particulate matter. The onset of stringent emissions standards caused the advancement of fuel injection technology and eventually led to the proliferation of high-pressure common rail electronic fuel injection systems. This system brought about two major advantages, the first being operation at fuel pressures up to 2500 bar. This allowed better atomization and fuel spray penetration that improves mixing and the degree of charge homogenization of the air fuel mixture. The second is that the electronic fuel injector allows for flexible and precise injection timing and quantity while allowing for multiple fuel injection events per thermodynamic cycle. To supply guidance in this area, this effort reviews the experimental history of multiple fuel injection strategies involving both diesel and biodiesel fuels through 2019. Summaries are supplied for each fuel highlighting literature consensus on the mechanisms that influence noise, performance, and emissions based on timing, amount, and type of fuel injected during multiple fuel injection strategies.

Keywords: combustion; compression ignition; emissions; fuel injection; nitrogen oxides; particulate matter; injection pressure; multiple injection

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1. Introduction

Compression ignition (CI) internal combustion engines generate power through the auto-ignition of fuel directly injected into the cylinder. The respectively viscous and non-volatile nature of the diesel and biodiesel fuels used for CI engines results in a heterogeneous mixture of fuel and air. Thus, the entire range of fuel-to-air ratios is seen resulting in the generation of hazardous emissions. Early mechanical pump-line-nozzle fuel injection systems for these engines were limited in their ability to reduce the level of stratification as only a single fuel injection event was allowed at fuel pressures between 200 and 300 bar. Advancement of the field to high-pressure common rail electronic fuel injection systems using piezoelectric fuel injectors increased injection pressures up to 2500 bar. This enhanced the homogeneity of the mixture, reducing stratification and emissions. In addition, greater power is generated at a lower fuel consumption while enabling the use of multiple fuel injection events [1].

While enhancing power and improving fuel economy is important, a significant motivation for using multiple fuel injection events is to reduce the pollutant emissions that make up about 1% of the exhaust constituents in CI engines [2]. The primary emission species include carbon monoxide (CO), hydrocarbons (HCs), nitrogen oxides (NO_x), particulate matter (PM), and sulfur oxides (SO_x). Since 2006 and the mandate of the use of ultra low sulfur diesel (ULSD) by the Environmental Protection Agency, SO_x emissions have been largely mitigated since they emanate directly from fuel-bound sulfur. With respect to the other species, understanding their formation helps to explain the methods employed for multiple fuel-injection events as discussed later.

Carbon monoxide and hydrocarbons are products of incomplete combustion, stemming from a rich air-to-fuel mixture, low combustion temperatures, or emitted during a cold start event. Since CI engines run globally lean, HC and CO formation is minimal [3], although there are still circumstances where these species can form. For example, HCs can be a problem during light load operation, due to excessively lean mixtures leading to flame speeds too low for complete combustion [4]. Moreover, CO can form due to poor fuel spray characteristics [5] in addition to a small portion of CO emitted due to chemical kinetics [6]. HCs and CO can be fully oxidized once exhausted from the engine using a diesel oxidation catalyst (DOC) with its effectiveness depending on temperature and the time required for its initial heating under cold-start scenarios. Typically, DOCs need to achieve at least 200 °C for high conversion rates and most efforts endeavor to lower this light-off temperature, with Hoang et al. achieving ~160 °C using simulated diesel exhaust conditions [7].

Nitric oxide (NO) and nitrogen dioxide (NO_2) are the primary constituents of NO_x that form at temperatures in excess of 1700 kelvin in the presence of excess air [8,9]. This is a significant issue for lean operating CI engines where NO_x is predominantly formed during the premixed combustion stage. This is when the piston is close to top dead center (TDC) and in-cylinder pressures and temperatures are the highest. The abatement of NO_x includes in-cylinder means such as exhaust gas recirculation (EGR), where combustion products are introduced to the intake stream to dilute the inducted charge with, mostly inert, gases that lower the overall oxygen concentration and reduce combustion temperatures by raising the average specific heat capacity of the mixture. However, EGR is not the only source of NO_x reduction, as the reduced cylinder temperatures associated with EGR can result in a growth of HC, CO, and PM emissions. In combination, aftertreatment methods of NO_x mitigation including lean NO_x traps (LNTs) and selective catalytic reduction (SCR) are used. LNTs store NO_x on the surface of a catalyst washcoat during lean operation, which is then released and reduced to nitrogen catalytically during a rich regeneration phase [10]. In comparison, SCR is a more straightforward technology, where a urea solution injected into the exhaust stream forms ammonia that reacts with NO_x to form nitrogen and water [10]. SCR systems add complexity since they need on-board tanks for urea storage and require frequent refilling.

Particulate matter, which includes soot along with the inorganic fraction and soluble organic fraction (SOF) of HCs, is the product of incomplete combustion and the agglomeration of small particles of partially combusted fuel and lubricating oil [5,11]. Soot typically makes up more than 50% of PM and is seen as a black smoke in the exhaust [3], while the SOF consists of heavier hydrocarbons condensed or adsorbed on the soot [12]. PM formation is dependent on many aspects, such as the combustion and piston expansion process, sulfur and ash content of the fuel, quality of the lubricating oil including its consumption, combustion temperature, and the EGR level [13]. The primary source of PM involves the diffusion burn phase of CI combustion and the introduction of un-atomized liquid fuel during the combustion process [14]. Exhausted soot is said to be the result of a constant soot formation and oxidation battle, where many factors can affect either the formation or oxidation of soot [14]; namely, a higher local in-cylinder temperature or air-fuel ratio that comes into contact with the diffusing fuel jet will decrease soot formation, and sustained global cylinder temperatures into the expansion stroke will prolong soot oxidation. To note, the terms "PM" and "soot" are used interchangeably in the literature, sometimes being referred to as "smoke", which also falls with the PM spectrum. Although PM can be oxidized during combustion, once it has been exhausted, the only other means of abatement is by using a particulate filter (PF). This filtration device traps PM, but develops a pressure drop when saturated and requires regeneration to oxidize the PM. Not only can this pressure drop decrease performance due to an increased back pressure in the exhaust system, but the frequency of regeneration can also contribute to a reduced fuel economy [15].

Overall, using a high pressure common rail fuel injection system while including a DOC for exhaust abatement can mitigate CO and HC emissions. However, the simultaneous reduction of NO_x and PM is difficult. Lowering combustion temperatures (i.e., minimizing the premixed phase of combustion) to decrease NO_x emissions increases the diffusion burn phase, and effectively grows PM emissions whereas raising the combustion temperature to decrease PM emissions results in higher NO_x emissions. This NO_x-PM tradeoff is a significant hindrance to the implementation of CI engines. While aftertreatment devices can reduce these emissions, their addition comes at an increased cost and complexity. Thus, decreasing these species through in-cylinder technologies is preferred and is a primary focus of the literature involving multiple fuel-injection events.

2. Overview

Before reviewing the implementation of multiple fuel injection strategies, it is necessary to understand the various parameters controlled along with the associated language. This is done through the three phases of combustion involved in single fuel injection events. The first is the premixed burn phase, where a portion of the injected fuel reaches autoignition as the atomized fuel jet mixes with the surrounding air. This is followed by the diffusion burn phase, where fuel burns as it mixes with air in an environment where a flame is already present under respectively high pressures and temperatures. Lastly, there is a third stage where soot will continue to oxidize as the flame is extinguishing [16]. For single fuel injection events, start of injection (SOI) will typically take place during the compression stroke somewhere in the range of 15–5° before top dead center (BTDC) and lasts for a few crank angle degrees. Once SOI has been initiated, there will be short period before the premixed burn phase occurs as the fuel atomizes and mixes with the air. This period is indicated as the ignition delay and involves the duration between SOI, start of vaporization (SOV), and start of combustion (SOC).

Ignition delay can be separated into two stages: physical delay (SOI to SOV), which is the time needed for the break-up of the fuel droplet, entrainment of the air, and fuel vaporization, and the second stage, chemical delay (SOV to SOC), which is dictated by the autoignition kinetics of the fuel. Physical delay is typically longer than chemical delay, and there is often overlap between the two stages [17]. Following the ignition delay, the premixed combustion phase begins, where the propensity for NO_x creation is higher due to the heat release spike. Subsequently, the diffusion burn phase of combustion with a greater PM production tendency takes place shortly before or after the end of injection and lasts until the end of combustion, which contains the late-stage soot oxidation phase.

"Multiple injections" is a general term that describes when more than one fuel injection event per engine cycle is employed. While the terminology used in the literature about multiple injections is diverse, there is generally agreed upon language that will be used throughout this work. Three basic strategies can be employed, with the first choice being a pilot injection approach. Pilot injection schemes break up the main fuel injection event into a respectively small quantity, typically around 5–10% of the total fuel mass that is usually injected during the compression stroke. This is subsequently trailed by a larger main injection event that is injected just before or after TDC. This has two significant effects; the first is a reduction in the peak heat release rate of the main combustion phase through a shortening of the main ignition delay. This dampens the premixed combustion event, which lowers cylinder temperatures and NO_x production. The second effect is a subsequent reduction in the cylinder pressure rise rate, which is widely believed to be a source of combustion noise. Furthermore, pilot injections are not limited to a single pilot. Instead, multiple pilot injections can be used before the main injection event [18–23], and they do not necessarily need to be the same quantity of fuel injected [23].

Some researchers use the term "early injection" to designate an injection event before a pilot injection for combustion strategies employing Homogeneous Charge Compression

Ignition (HCCI) or Premixed Charge Compression Ignition (PCCI) [24,25]. This may be because this "early" injection heat release event does not interact with the main injection energy release. This is where terminology inconsistencies start to appear, as some researchers use "pilot" and "early" injection terms interchangeably. In addition, researchers have used the terms "pre-injection" [26–29] or "boot injection" [30] to describe a pilot injection event. Furthermore, a parameter often discussed involving pilot injections is the "dwell". This designates the time, or crank angle degrees, between the pilot and main injection events. In general, "dwell" can be used to describe phasing between any two injections.

The next type of multiple injection approach is the "split" injection strategy, which designates that the fuel quantity be broken up into two or more equal parts throughout the injection process [31] (e.g., a 50/50 or a 33/33/33 split). This is often used for further NO_x and noise reduction. Notation consistency involving this term is especially loose, as many researchers will refer to any type of multiple injection scheme as a split (e.g., a pilot injection scheme being referred to as a 10/90 split). While splitting of a main injection event is the most common tactic, a split can be applied to any fuel quantity delivered within the cycle. For example, there are examples of pilot splits [18–22], as well as dividing the post injection event [32]. This post injection event, or "after" injection for some researchers, provides a small portion of the total fuel quantity injected later during the expansion stroke. Post injections have been shown to be useful in reducing soot emissions through improved mixing and enhancing the late soot oxidation phase [14]. In addition, post injections can be used to introduce excess hydrocarbons into the exhaust for catalyst warmup or PF regeneration [32,33].

There has been significant research into employing multiple fuel injection events for low temperature combustion (LTC) operation. LTC is a regime for CI engines where an intended homogeneous mixing process is married with low flame temperatures; hence, simultaneously reducing both NO_x and PM [34]. While this work focuses on conventional CI combustion regimes, a succinct summary of LTC options and examples of the use of multiple fuel injection events is provided.

2.1. History of Multiple Fuel Injection Events Using Diesel Fuel

The use of multiple fuel injection events is not a new concept as there are accounts of experimentation with pilot injections as early as 1937 to reduce combustion noise and to combat fuels with low cetane numbers and poor ignition qualities [35]. The first publication that investigates multiple injections in a CI engine dates to 1984 [36]. This study concluded that combustion noise and emissions could be reduced using a split injection approach. To note, this effort did not use common rail or modern high-pressure fuel injection hardware. Instead, they achieved split injections using a "split injection device" installed on the high-pressure side of the injection system. Furthermore, the literature cites efforts involving the use of pilot injections in the timeframe of 1989 to 1991 [26,37–40]. These efforts targeted a reduction in ignition delay and rapid pressure rise for the purpose of NO_x emissions abatement. In addition, Herdin in 1990 [41] experimented both with "modulated" injections (i.e., rate shaping) and pilot injections. They reported advantages in HC, CO, and combustion noise due to the shortened ignition delay, but experienced issues with increased smoke at low load.

The first true record of the promise of a pilot injection occurred in 1992, when Shundoh et al. experimented with different methods of reducing ignition delay [42]. They found that the use of a pilot injection could simultaneously reduce NO_x by 35% and smoke up to 80% under a consistent fuel consumption. Another promising study by Needham et al. followed in 1993 that employed high-pressure common rail electronic injection and "flexible" injection control [43]. They were able to meet Tier 1 medium duty emissions requirements without an oxidation catalyst. Also in that year, Bower and Foster conducted experiments with split injections in a physically simulated CI combustion chamber [44]. They were the first to highlight fuel distribution differences with split injections and the effect it has on mixing and vaporization. This study marks the start of academic research.

Prior, all research had been done by Original Equipment Manufacturers or 3rd party automotive developers.

Overall, 1994 was a significant year. Starting with Nehmer and Reitz [35], a first study was conducted using the lab's heavy-duty single cylinder CI engine. The engine was a modified version of the Caterpillar 3406, having a displacement of 2.44 L and compression ratio of 15:1. It was tested at a constant 80% load and 1600 revolutions per minute (rpm). The effects of injection rate-shaping and pilot injections were investigated. For this work, the injection parameters varied were the pilot quantity, 10–75%, and the pilot-main dwell, 3–8°. They successfully implemented pilot injections that produced lower levels of NO_x without growing soot levels. They postulated that an optimal pilot quantity existed somewhere between 10 and 25%. Moreover, they reported that split injections allow combustion to continue into the expansion stroke without an increase in PM due to the enhanced mixing introduced. This study was also the first to discuss the wave dynamics present when employing multiple injections in a common-rail system due to the injector closing. This phenomenon can either increase or decrease the local rail pressure at a particular injector, causing the delivered fuel mass to vary during subsequent injections.

In parallel within the same laboratory, Tow et al. [45] examined a triple injection event, in addition to expanding test conditions to lower load points. The same engine was used and operated at 1600 rpm; however, this time at 25% and 75% load. The goal of this effort was to study a larger range of dwell times between double injections in addition to the triple injection strategy. They reported that a 50/50 split with a significantly long dwell (10°) could reduce particulates up to three times without an increase in NO_x at 75% load. They also said that a small pilot quantity (13%) was effective in reducing NO_x at both 25% and 75% load. As for the triple injection cases, it was proven that they offer added control and performance if the parameters are calibrated appropriately. The 7/44/49 injection case, with 2° and 10° dwell times between the respective injections produced simultaneous NO_x and soot reductions of 40% and 50%, respectively, at low load. Furthermore, they saw that a long dwell before the last triple injection reduced PM. They attributed this effect to an enhanced fuel air mixing provided by the multiple injections, as well as particulate oxidation late into the expansion stroke. This last observation is significant as it is the first indirect mention of the potential of post injections for PM oxidation. This fact, along with the findings relating to pilot injections by Nehmer and Reitz, results in these two publications being two of the highest cited works within this area.

Concurrently, Ishida et al. [46] performed experiments with pilot injections at the University of Nagasaki. They experimented with a 3.3 L High Speed Direct Injection (HSDI) Mitsubishi 4D31-T four-cylinder CI engine with a compression ratio of 16:1. A mechanical pilot injector system developed by Yoshizu and Nakayama [47] was used, where pilot quantity was varied by changing the seat diameter of the plunger, and pilot/main dwell could be varied by changing the plunger lift. Operating points at a fixed engine speed of 1750 rpm and low and high load points of 3.97 and 8.30 bar, respectively, were tested at a fuel pressure of 18.5 MPa. The main injection was varied from 5° to −5° BTDC while the pilot/main dwell was held at approximately 5°. It was reported that the maximum heat release rate was greatly reduced at low load, whereas high load was not significantly affected. Moreover, pilot and main ignition delays were about half of the single injection cases and were more affected by load than pilot quantity. Significant improvements in the NO_x-fuel consumption trade-off were seen at low load with a delayed main injection timing. Reductions of 12 g/kW-h and 6 g/kW-h were observed at both low and high loads, respectively. This fuel consumption reduction was attributed to a decrease in exhaust energy, as seen via a diminished exhaust gas temperature that resulted from an enhanced thermal efficiency due to earlier combustion with the pilot injection. The second explanation for this improvement was a reduction in cooling losses, as well as an estimated 5% increase in mechanical efficiency. A slight increase in smoke was observed due to the overlap of the main spray and pilot combustion events.

Contributing to the boom of research in 1994, Yamaki et al. [48] experimented with pilot injections using a 6.9 L six-cylinder turbocharged heavy-duty CI engine. Pilot timing and quantity were investigated, allowing for reduced NO_x and HCs at low load, a 50% reduction in PM at low speeds along with increased torque, and an improved cold start ability. Concurrently, Ishiwata et al. [49] investigated pilot injections on their single cylinder CI engine through their Timing and Injection Rate Control System (TICS) that was described as a "two spring" mechanical injector used in conjunction with a high fuel pressure. Overall, there were issues about the accuracy of their fuel timing and quantity; hence, their tests provided inconclusive results.

That same year, Nakakita et al. [50] set out to optimize pilot injection timing on an optical HSDI 0.9 L CI engine fitted with a high pressure electronic fuel injection system. Engine speed was held at 1800 rpm and two different injector nozzle types (0.26 mm four-hole and 0.18 mm five-hole) were tested at low and medium load at fuel pressures of 95 and 40 MPa, respectively. At each operating condition, main injection timing was varied from 0° to 10° after top dead center (ATDC) while using various pilot/main dwell times. They said that a delayed main injection timing was necessary for NO_x reduction. Specifically, this was due to the advancement of main combustion brought on by the pilot injection that cancels the positive effect of a heat release rate reduction. At light load, they reported significantly decreased HC emissions with a small reduction in NO_x levels without any increase in PM at delayed main injection timings. This was only possible with the smaller hole injector nozzle. At medium load, NO_x reduction was respectively smaller and came with an increased level of smoke.

The efforts of 1994 are concluded with Durnholz et al. [27], who investigated "preinjections" and rate shaping as a means for emissions and combustion noise reduction. Results showed it was possible to reduce combustion noise by as much as 10 dB over the entire load range, along with simultaneous reduction of NO_x and HC levels without a significant increase in smoke. These benefits in emissions and combustion noise were realized using a respectively small pilot injection (~6%) and pilot/main dwell of 15°.

Implementation of the TICS system was researched further by Minami et al. [51] in 1995, when they experimented with a turbocharged 12.1 L six-cylinder CI engine. Initial testing at 1000 rpm and low load yielded up to a 70% reduction in the peak heat release rate and a pilot quantity of 12% was found to be optimal. Thus, the remainder of testing conducted at 1200 rpm and various loads employed a 12% pilot injection amount, while the pilot SOI was varied from approximately 15° to $-5°$ BTDC with a pilot/main dwell of about 9°. The effects of pilot injection were clear at low load, where simultaneous reductions in NO_x, HC, and fuel consumption were attained, but with a small growth in the level of smoke while the SOF decreased. This increase in smoke was a function of the entrainment of the pilot burned gas by the atomized main spray that slowed the main combustion event. Emissions effects were less clear at medium load, as pilot injections helped stabilize combustion in regions where low NO_x levels are typically present. No noticeable effect on heat release or emissions were seen at high load with pilot injections, and only a small penalty in fuel consumption occurred that was postulated to be due to an ineffective usage of the pilot injection.

That same year, Pierpont et al. [52] set out to reach simultaneous NO_x and PM reductions using multiple injections at high load including the presence of EGR; an operating condition notorious for PM production. Using the same engine setup as their earlier studies, they tested double and triple injections at 75% load and 1600 rpm. They, again, saw that a smaller injection proceeding the main injection was effective in reducing PM, this time calling it a "secondary" injection. Overall, they were successful in reducing NO_x and PM well within the Tier 1 standard while employing 6% EGR; however, there was a penalty in the brake specific fuel consumption (BSFC) due to a delayed injection timing.

The same laboratory produced another publication in 1996 by Han et al. [53], digging into the exact mechanism behind NO_x and soot reduction with multiple injections. For this effort, they conducted physical experimentation in conjunction with simulations using a

KIVA-II combustion model. Regarding NO_x reduction, they concluded that the mechanism was like that of a delayed single injection event. Specifically, the reduced heat release rate during the first injection diminishes NO_x produced by decreasing the level of pre-mixed combustion, whereas the second injection event does not contribute further to the generation of NO_x. Their findings with respect to soot reduction were more profound as they were able to visualize the soot reduction with multiple injections. This mechanism can be explained as follows: normally, a single injection produces a continuous, high momentum jet with a rich, soot-producing region at the tip of the jet. Conversely, under multiple injections the soot production is discontinued at the termination of the first injection. Then, the injection that follows is introduced into a lean, high temperature environment resulting from the initial pre-mixed combustion event. This enables prompt and fast combustion. The soot produced during the initial injection continues to oxidize, having a favorable effect on the competition between soot formation and oxidation. This confirmed their lab's earlier theory that multiple injections enhance fuel mixing and vaporization.

In 1997, Yokota et al. [54] had developed their Homogeneous charge Intelligent Multiple Injection Combustion System through KIVA-II simulations and set out to verify their findings using a single-cylinder engine. Simulations predicted that improvements in the NO_x-fuel consumption trade-off could be attained by using a pilot injection early in the induction stroke. When tested, the results showed worsened trade-offs in both NO_x-fuel consumption and NO_x-smoke. Moreover, there were difficulties involving early autoignition of the fuel and inadequate homogenization. Improvements in the fuel consumption-smoke tradeoff were seen for delayed pilot injections, albeit with increased HCs and CO emissions.

From 1998 to 1999, the lab at the University of Wisconsin-Madison published two papers utilizing the two-color imaging method [55] of combustion visualization analysis. The first, by Hampson and Reitz [56], delved further into understanding the soot reducing mechanisms of multiple injections. Using the same engine as a prior study but now modified with an endoscope placed in the cylinder head for imaging, testing was carried out at 75% load and 1600 rpm at 90 MPa of fuel pressure for double and triple injection events. Their conclusions for the soot reduction mechanism of the first two injections confirmed the results of the previous effort by Han et al. [53]. The temperature rise associated with the first injection creates an environment for the second injection to burn rapidly and does not form soot fuel rich zones. Moreover, the increased mixing aids in enhanced oxidation of the already formed soot. There is an added heat release spike connected to the conclusion of the first injection event. This heat release "burst" results from the abrupt growth of the flame towards the tip of the injector once the overly rich fuel region in the jet is discontinued by fresh air and the already developed flame rapidly swallows the newly reactive mixture. As a result, an environment is created for the second injection such that it starts burning as a diffusion flame, and not in a pre-mixed manner. In addition, the slope of the immediate diffusion burn heat release linked to the second injection is steeper than the diffusion burn heat release seen with single injection events; hence, making it plausible that there is an inherent reduction in soot production related to this type of combustion. Results for the triple injections supplied additional insight to soot oxidizing "late" or "secondary" injections. They found that the third injection event was helpful for reducing soot if there was still a short ignition delay connected to the conclusion and resumption between the second and third injections. Furthermore, when the SOI was too far delayed, they reported a "soot catastrophe", where soot output rose by an order of magnitude, highlighting the importance of carefully selecting injection timings. The second study, by Bakenhus and Reitz [57], was similar in analysis by using two-color imaging to visualize both NO_x and soot reducing mechanisms. Their results mirrored those of the lab's earlier studies.

Lastly, in 1999, there was a study by Zhang [58] for Isuzu, another highly cited work. They wanted to understand the effect pilot injections had on NO_x and soot when used for combustion noise reduction. This was done by experimenting with a 0.63 L single-cylinder CI research engine with a compression ratio of 18.5:1 operating at light, medium, and full load at 2200 rpm. Pilot quantities of 12.5%, 25%, and 50% were investigated at identical injection timings and compared to the base single injection case. They were successful in reducing combustion noise and NO_x at light loads but saw slight changes in peak heat release at full load. Often, the rate of heat release plots is used to analyze the NO_x reduction quality of pilot injections, but Zhang demonstrated how cylinder pressure rise rates are an equally valid form of analysis; specifically, explaining that the smallest pilot quantity had the greatest NO_x reduction as a result of having the lowest peak cylinder pressure rise rate as compared to the single injection case. To note, their experiments only showed the NO_x and soot trade-off mechanism, rather than a simultaneous reduction of the two constituents. This is likely due to using a fixed injection timing.

Chen [59] published the first effort motivated by Tier 2 standards in 2000, having the goal of achieving simultaneous reduction of NO_x and particulates using pilot and post injections. They tested a 1.2 L four-cylinder CI engine with a compression ratio of 19.5:1 while employing EGR and a turbocharger. Operating points of 2 and 6 bar brake mean effective pressure (BMEP) at 2000 rpm, and 5 bar BMEP at 1000 rpm were investigated. The pilot injection testing was done by initially fixing a main SOI at TDC and varying the pilot SOI from 10° to 50° BTDC. This resulted in significant NO_x reduction with greater dwells, but this increased HCs along with the BSFC and smoke level. Next, they experimented with fixing the pilot SOI at TDC and varying the main SOI. It was found that a main SOI of 10° ATDC produced simultaneous reductions in NO_x and smoke, and delaying the main injection further continued to reduce NO_x, but at the cost of higher smoke, BSFC, and HCs. Post injections were then explored by holding a 10% pilot quantity at an SOI of 0° ATDC and the main SOI at 8° ATDC. Here, a 10% post injection quantity was injected while varying the SOI between 17° and 31° ATDC. It was seen that post injections delayed up to 27° ATDC were effective in reducing smoke with negligible effect on NO_x and BSFC. After 27° ATDC, a rapid increase in HCs and BSFC was seen. Overall, the triple injection strategy (pilot/post combination) was able to reach a 50% reduction in NO_x and 40% reduction in smoke at medium load, 2000 rpm, and 11% EGR as compared to the baseline single injection case; however, this came with a 6% increase in BSFC. At medium load, 1000 rpm, and 19% EGR, simultaneous NO_x and smoke reduction was also achieved, but with only a 3% increase in BSFC.

In 2001, Lisbona et al. [60] experimented with multiple injections for the purpose of meeting Euro 4 emissions standards. Their setup consisted of a 1.9 L four-cylinder Fiat JTD-F3 CI engine with a compression ratio of 17.5:1 while running with a turbocharger and cooled EGR. Testing was done in-vehicle on a chassis dynamometer and different injection strategies were evaluated at 1500 rpm and 5 bar BMEP. They demonstrated how the Euro 4 emissions standards could be approached without the use of a complex aftertreatment system.

Also in 2001, Montgomery and Reitz [1] explored multiple injections with their heavy-duty single-cylinder CI engine in conjunction with flexible control of EGR and boost while using optimization techniques. Using injection pressure, boost pressure, combustion phasing, dwell, fuel percentage in each injection, and EGR rate as optimization factor, a response surface method [61] was employed to influence calibration points to reach desired emissions and fuel consumption levels. They tested the engine at three operating points used in the US Federal Test Procedure cycle: Mode 3 took place at 993 rpm and 75% load, while Mode 5 was at 1737 rpm and 57% load, and Mode 6 was at 1789 rpm and 20% load. The optimized schedule for Mode 3 was a 60/40 split with a 9° dwell and a SOI of 3° BTDC. This resulted in a 1.4% reduction in BSFC, 56% reduction in NO_x, and 36% reduction in PM as compared to the optimized single injection case. The optimized Mode 5 injection scheme had a 55/45 split, 9.2° dwell, and 2.5° BTDC SOI with simultaneous reductions in BSFC, NO_x, and PM of 7.1%, 54.2%, and 29.7%, respectively. Lastly, Mode 6 ended up with a 70/30 split at 7.7° dwell and 5.5° BTDC SOI along with respective reductions in BSFC, NO_x, and PM of 9.8%, 67.6%, 59.8%, respectively.

Concurrently, Benajes et al. [28] explored pre and post injection events for emissions reductions in preparation of meeting Euro 4 emissions standards. They experimented with a heavy duty 1.75 L single-cylinder CI engine with a compression ratio of 16.3:1. Operating points at four modes of the European Stationary Drive Cycle (ESC) were used while testing the pre and post injection strategies separately. Equating to engine speeds ranging from 1200 to 1800 rpm and loads varying from 50 to 100%, pilot/post injection quantities varying from 5.6 to 20% at main injection timings alternating from 2° to 6° were tested. The pre injection strategy showed improvements in BSFC due to advanced combustion phasing that resulted in more efficient combustion; however, this increased NO_x and soot emissions. They reported that post injections were effective in reducing soot with no change in NO_x and a small penalty in BSFC. A growth in the BSFC observed was exacerbated as the post injection quantity and dwell increased. They attributed the increases in NO_x seen with the pre injection event to the higher maximum cylinder temperatures encountered, while soot reduction was correlated with greater combustion temperatures during the final stages of combustion after 75% of the total fuel mass had been burnt.

Lastly in 2001, Badami et al. [62] explored soot and NO_x formation using pilot injections. They conducted their tests with a 1.9 L four-cylinder CI engine and a compression ratio of 17.2:1. Operating points of 1500 rpm and 5 bar indicated mean effective pressure (IMEP), 2000 rpm, and 2 bar IMEP, and lastly, 2500 rpm and 8 bar IMEP were studied at EGR rates of 14%, 40%, and 16%, respectively. They reported increases in NO_x as pilot quantity rose that was said to be a result of higher cylinder temperatures, although combustion noise decreased. In addition, soot grew due to the reduction in premixed combustion and subsequent growth of the diffusion burn phase. Equivalent results (i.e., NO_x and soot increased) were observed with decreasing dwell.

In 2002, Corcione [29] investigated multiple injections with a 0.44 L single-cylinder CI engine with a compression ratio of 18:1. They experimented with a pilot/main strategy, as well as a pilot/pre/main strategy, both at 1800 rpm. They found for both injection schemes a SOC of 0° BTDC offered the best NO_x and combustion noise characteristics without penalties in engine performance, but the pilot/pre/main injection scheme could achieve a lower peak heat release rate and subsequent rate of heat release.

Concurrently, Yamane and Shimamoto [63] tested both early pilot injection and two stage split injections in an HSDI single-cylinder CI engine and proved that reductions in formaldehyde, NO_x, and smoke were possible with these strategies. An improvement in BSFC was seen with the two-stage split strategy that was attributed to efficiency gains as a result of a growth in constant volume combustion. Conversely, the early pilot injection experiments showed an increase in BSFC but with a reduction in NO_x.

That same year, a lab at the Polytechnic University of Turin in Italy published two papers. Badami et al. [64] produced the first effort while using their 1.9 L four-cylinder CI engine with a compression ratio of 17.2:1. This effort initially tested a pilot/pilot/main injection at 2000 rpm and 2 bar BMEP, with the first two injections having injection quantities of 10% and 7%, respectively. Two variations of this strategy were then explored. Strategy 1 involved fixing the second pilot injection and main injections at an SOI of 7° and 3° BTDC, respectively, while the first pilot injection SOI was varied from 39° to 9° BTDC. Strategy 2 held the first pilot and main injections at SOIs of 35° and 3°, respectively, while the second pilot SOI was varied from 29° to 4° BTDC. Results of both these experiments showed increased NO_x and soot as compared to their earlier tests with only a single pilot injection; however, gains in BSFC and combustion noise were seen. Then, they investigated pilot/main/post schemes using four different tests, with the 1500 rpm experiments having pilot and post injection quantities of 8–15% and 12%, respectively, and the 2500 rpm experiments having pilot and main injection quantities of 3–6% and 4–6%, respectively. The first two strategies focused on short dwell times between the pilot and main injections, while varying the SOI of the post injection. Strategy 3a was carried out at 1500 rpm and 5 bar BMEP and it involved fixed pilot and main SOIs at 5° and 1° BTDC, correspondingly, while varying post SOI from 6° to 17° ATDC. Strategy 3b was then carried out at 2500 rpm and 8 bar BMEP, with pilot and main SOIs fixed at 8° and 3° BTDC, respectively, while post SOI was varied from 10° to 37° ATDC. The last two strategies then focused on post injection in conjunction with a wide pilot/main separation, with Strategy 4a operating at 1500 rpm and 5 bar BMEP and having fixed pilot and main SOIs of 13° and 1° BTDC, respectively, while post SOI was varied from 6° to 17° ATDC. Lastly, Strategy 4b was held at 2500 rpm and 8 bar BMEP, having fixed pilot and main SOIs at 38° and 3° BTDC, respectively, and a variable post SOI from 10° to 37° ATDC. They found that all post injection strategies were effective in reducing soot, but injection parameters had to be carefully selected so the best trade-off between NO_x, soot, and BSFC could be achieved.

Mallamo et al. [65] then published a second paper based on experiments employing their 0.95 L non-road two-cylinder CI engine with a compression ratio of 19:1. They tested similar injection parameters as the earlier effort by Badami et al., this time adding a pilot/pilot/main/post schedule to the mix. Their best results were attained at 3600 rpm and 100% load, where NO_x and PM reductions of 10% and 15% were seen, simultaneously, with no penalty in BSFC.

That same year, Payri et al. [66] studied the effects of post injection on the emissions and performance of a 1.85 L heavy-duty single-cylinder CI engine with a compression ratio of 16.3:1. Five operating points were selected from the ESC to employ post injection quantities ranging from 5–20% while varying the main/post dwell. Here, the main injection timing and EGR rates were identical to respective cases employing single injections at the same operating points. Post injections were reported to be an effective means for soot reduction without an increase in NO_x; e.g., soot reductions of 40–45% at low loads with post injection quantities of 15–20% and a decrease of 25–45% at full load with quantities ranging from 7 to 10%.

Beatrice et al. [67] then published another paper in 2003, this time experimenting with two different engines and their optical variants to investigate pilot and post injection strategies while also confirming their Computational Fluid Dynamics models. The first engine was the same 1.9 L four-cylinder used previously, and the second was a 1.3 L variant with a higher compression ratio of 18:1. Both had duplicate engines modified for optical access. With the 1.9 L engine, they experimented with both a 10%(20°)90% pilot/main strategy, as well as a pilot/main/post strategy where the 10% pilot was held at an SOI of 1.4° BTDC with a 2° dwell leading to the main injection followed by a 27% post injection with a varied SOI from 5° to 12.5° ATDC. The 1.3 L engine tested two 10%/90% pilot/main strategies where the main injection event was held at an SOI of 4° BTDC and the pilot SOI was tested at 18° and 7° BTDC. They claimed the tests were successful in controlling NO_x and soot emissions, although there were no detailed emission results.

Concurrently, Carlucci et al. [68] investigated the effects of pilot injections on a turbocharged 1.93 L four-cylinder CI engine with a 19.8:1 compression ratio. The engine was operated at 1400 rpm at a range of loads from 23 to 45.5 N-m, as well as at 2000 rpm from 25 to 79 N-m. The main injection timing was held at 3.4° BTDC for the 1400 rpm points, while the pilot SOI was varied from 16° to 32.7° BTDC. At 2000 rpm, the main SOI was held at 4.8° BTDC and the pilot SOI was varied from 22.8° to 46.8° BTDC. They concluded that the timing of the pilot injection has a greater effect on the main injection ignition delay in comparison to pilot quantity; however, the influence of either parameter on main injection ignition delay is dependent on load. NO_x was shaped primarily by pilot quantity with the effect of pilot timing more apparent at low speed and low load. Finally, both pilot quantity and timing affected smoke emissions, particularly at medium to high loads.

Also in 2003, Badami et al. [69] investigated the effects of pilot/pilot/main and pilot/main/post injection schemes and their effects on NO_x, soot, noise, and BSFC as compared to their previous pilot injection effort in 2001. The same operating points were tested, employing pilot/pilot/main strategies for the 2000 rpm (2 bar BMEP) condition, and pilot/main/post strategies for the 1500 rpm (5 bar BMEP) and 2500 rpm (8 bar BMEP) conditions. Injection strategies 1 and 2 involved pilot/pilot/main schemes, with strategy 1 utilizing pilot quantities of 10% and 7% for the first and second pilot quantities, respectively, in addition to varying the first pilot SOI from 37° to 12° BTDC while holding the second pilot SOI at 7° BTDC and main SOI at 2° BTDC. Strategy 2 employed the same injection quantities as strategy 1; however, the first pilot SOI was held at 33° BTDC and the second pilot SOI was varied from 28° to 7° BTDC while the main SOI was fixed at 2° BTDC. For the pilot/main/post strategies, strategy 3 was tested at the 1500 rpm (5 bar BMEP) condition while varying pilot and post injection quantities from 8–15% and 11–12%, correspondingly, along with fixed respective pilot and main SOIs of 5° and 0° BTDC, respectively, with a varied post SOI from 5–16° ATDC. Strategy 4 tested pilot and post injection quantities of 3–6% and 4–8%, respectively, with a set pilot SOI of 7° BTDC, main SOI of 3° BTDC, and the post SOI varied from 10–37°. Strategies 1 and 2 experienced increased NO_x and soot emissions compared to the earlier pilot injection study, although reductions in CO and HC emissions were seen, as well as lowered combustion noise and BSFC. Strategies 3 and 4 were seen to produce the same low NO_x levels, if not slightly less than the earlier study, in addition to soot reductions of up to 40% due to post injection. Finally, the lowest soot levels were reached with the close-coupled post injections; however, if the post injection was too delayed, a substantial increase in soot and CO was seen.

In 2004, Park et al. [70] conducted experiments involving pilot and post injections with varying fuel pressures. They used a single-cylinder optical research engine with a displacement of 0.49 L and an 18.9:1 compression ratio. All injection parameters were tested during an 800 rpm idling condition, with 13% pilot and post injections being individually tested at fuel pressures varying from 30 to 120 MPa. First, the effects of varying fuel pressure were explored for a single injection event while varying the SOI from 17° to −3° BTDC. Results showed a downward trend in HCs, CO, and opacity with increasing fuel pressure; however, this did raise NO_x emissions while lowering the IMEP. This result was explained by a greater mixing effect with the air and smaller fuel droplet size associated with high injection pressures contributing to more pre-mixed combustion and an advanced phasing towards TDC. Another benefit of the higher injection pressure is the mitigation of unburned HC emissions associated with excess fuel left in the injector's sac volume. This fuel eventually makes its way through the nozzle at low speeds during combustion and expansion and exits with the exhaust as emitted HC. Pilot injections were then explored at low and high injection pressures (30 and 120 MPa) by varying the main SOI from 16.4° to −5.6° BTDC while also adjusting the pilot/main dwell from 10° to 60°. The results proved that pilot injection with a low injection pressure was more effective in decreasing the peak heat release rate and subsequent NO_x emissions. In contrast, using a high injection pressure achieved a greater IMEP while maintaining smoke and fuel consumption levels. Furthermore, high injection pressures during early pilot injections could cause lean misfires due to overmixing of the fuel. Post injections were then explored at low and high fuel pressures by varying the main SOI event from 18.6° to −1.7° BTDC, as well as the main/post dwell from 0° to 40°. It was seen that the high fuel pressure injection case was effective in reducing soot, producing almost zero soot emissions for all tests, whereas the lower injection pressure case was still effective for soot reduction with respectively delayed post injections. To conclude the study, pilot and post injections were used simultaneously in a triple injection scheme tested at high and low fuel pressures with respective pilot, main, and post SOIs of 35°, 5°, and −15° BTDC, respectively. The high fuel pressure case produced minimal decreases in NO_x and increased opacity, while the low pressure case achieved simultaneous reduction of NO_x and smoke of 30% and 40%, respectively, with a 4% decrease in IMEP.

The lab at the University of Wisconsin-Madison published another work in 2005 where Liu and Reitz [71] used a HSDI single cylinder engine to test optimized injection parameters produced from their KIVA-3V code. The engine was a single cylinder version of a 2.4 L five-cylinder CI engine with a compression ratio of 18.8:1. They employed EGR and boost while testing it at 2000 rpm and part load for two and five injection events. They were able to achieve the best BSFC and emissions results with widely spaced double split injection schemes employing SOIs of ~50° and −13° BTDC.

Also that year, researchers at Brunel University in the UK investigated multiple injections motivated by the goal of meeting Euro 4 emissions. Gill et al. [18] tested up to four injections per cycle with pilot and post injections, having up to three pilot injections per cycle. Experiments were carried out on a Ricardo Hydra single cylinder CI engine modified with a prototype Ford Puma cylinder head and optical access. This engine had a swept volume of 0.5 L and a compression ratio of 15.9:1. All operating points within the test matrix were held at 1500 rpm, 40% load and tested at 80, 100, and 120 MPa of fuel pressure. The pilot/main strategy was first explored by varying the number of pilot injections from one to three. The main SOI was held at 10° BTDC, and the 18% pilot quantities had SOIs varying from 30° to 70° BTDC. Overall, two pilot injections resulted in a heat release rate reduction for the 80 and 100 MPa fuel pressure cases, although with a decreased IMEP as compared to the single pilot injection case. Conversely, the 120 MPa injection pressure case with two pilot injections caused a large spike in heat release and a greater IMEP; however, both spikes were less than the single pilot injection baseline. Three pilot injections showed comparable results to the 80 and 100 MPa two pilot fuel pressure cases, albeit with slightly lower heat release peaks and IMEP. The 120 MPa fuel pressure case with three pilot injections caused a heat release spike as large as the single injection case, as well as a lower IMEP. These results showed there might not be any additional benefit to using three pilot injections over two; therefore, only up to two pilot injections were implemented in the remaining experiments with post injections. Two injection strategies with post injection were studied, both with main and post SOIs of 10° and 0° BTDC, respectively, while the pilot SOIs were 30° BTDC for the single pilot case, and 50° and 30° BTDC for the double pilot injection case. Pilot fuel quantities remained at 18% and post injection quantities were 41% for the single pilot case and 23% for the double pilot case. The results for one and two pilot injections with the addition of a post injection were like the earlier results at the respective fuel pressures without a post injection. Nevertheless, there were gains in IMEP without an increase in the heat release rate, implying a pilot/pilot/main/post strategy could be effective for both NO_x and soot reduction.

Concurrently, Carlucci et al. [72] investigated the effects of using both early and pilot injection events. The tests that were carried out included early/main, pilot/main, and early/pilot/main schemes. This was done while varying the injection quantities of the early and pilot injections, as well as the injection timing. Simultaneous NO_x and soot reduction was reported at low loads and speeds with early injections, and further reductions in NO_x were reached with the addition of the pilot injection, albeit with increased HC emissions.

The final publication of 2005 was produced by Toyota. Hotta et al. [19] used a 0.5 L single-cylinder research CI engine with a compression ratio of 17:1 to investigate the effects of early pilot, late pilot, and post injections. Testing was carried out at full, medium, and light load conditions at 1200, 2000, and 1380 rpm, respectively. This was done with corresponding fuel pressures of 90, 80, and 55 MPa. At full load, an early pilot injection having an SOI of 55° BTDC was seen to have a 6% increase in IMEP along with a 4 dB decrease in combustion noise and a subsequent NO_x reduction. However, this came with an increase in HCs and a slight increase in smoke, though still within the allowable limit. Interestingly, the equivalence ratio under this condition was nearly 1.0, implying complete utilization of air in the cylinder; hence, improving the smoke limit of the engine. At part load and respectively low speed, the early 32% pilot injection event caused a further increase in HC emissions and fuel consumption. This was remedied by implementing a second pilot injection with an added 19% fuel quantity that also reduced combustion noise. In general, the low load condition presented a challenge for the early injection strategy. The combination of the reduced fuel pressure and turbulence caused cylinder wall impingement issues and a subsequent rise in HC emissions. Thus, the low load condition necessitated a small pilot quantity close to the main injection event (~10% pilot quantity and 4° BTDC SOI) which decreased NO_x, fuel consumption, HCs, and noise as compared to the single injection case with an acceptable increase in smoke as well. In addition, a post injection event was evaluated at the low load condition having a quantity of 17% and SOI shortly after the main injection pulse. This attained reductions in HCs, smoke, and fuel consumption, albeit with an increase in NO_x emissions. Adding EGR was effective in keeping the low NO_x levels achieved by the pilot injection while still benefitting from post injection, concluding with a desirable effect on the NO_x-smoke trade-off.

Another effort motivated by Euro 4 emissions regulations was published in 2007 by Ehleskog et al. [31], where optimal injection scheduling was explored for a main injection split of up to four injections while also using a pilot injection. This effort is significant because the authors bring to light an important distinction between heavy-duty CI and HSDI operation. Unlike heavy-duty CI engines with quiescent conditions, the increased swirl in HSDI engines results in combustion products from the first injection (of a multiple injection event) potentially being carried away by the swirl and not interacting with subsequent injections. This can have important implications regarding soot emissions [73]. Their later testing was done on a 0.48 L Ricardo Hydra single-cylinder research CI engine with a Volvo NED5 cylinder head, bringing the compression ratio to 16.8:1. The test matrix consisted of four 2000 rpm operating points with 8% pilot injections, the first three being at 6.5 bar IMEP and 64 MPa rail pressure, except the third point which was raised to 96 MPa. The first three points also had fixed pilot and main SOIs of 20° and 4° BTDC, respectively, and an EGR rate 16.3%, except for the second point with a rate of 24.5%. The final operating point was at an IMEP of 9.5 bar, rail pressure of 87.3 MPa, 13.8% EGR, and respective pilot and main SOIs of 46° and 3° BTDC. Split main injections varying from one to four injections were tested at each operating point and the dwell times between main injections were chosen by finding the mechanical limit for the shortest dwell possible and adding 1°. Results showed torque increased with the double main injection due to the high heat release for the longest time, subsequently giving the greatest thermal efficiency. As three and four injections were added, combustion duration increased while heat release decreased, overall causing torque to decrease. With respect to emissions, two main injections created the most NO_x while the three and four main injection schemes had lower NO_x, but more PM due to a slower and less efficient combustion process.

An additional study was done in 2007 by Okude et al. [20], this time a single main injection event was studied with up to three pilot injections. Testing was done using a 0.74 L single cylinder CI engine with a compression ratio of 15.7:1 at a constant 1620 rpm and 8.2 bar IMEP. For all tests, the main SOI was fixed at −2.5° BTDC, along with a constant 140 MPa of rail pressure, 24% EGR, and 47 kPa of boost. Additionally, the authors supplied some interesting insight by comparing the case of a normal single pilot (one pilot injection followed by a main injection) to only a single pilot injection (no main injection). Since the pilot injection fuel amount is usually smaller than the main injection event, one might assume that the emissions contributed by the pilot injection are lesser than that of the main injection; however, this is not always the case. It was seen that the more advanced the pilot injection, the less NO_x that is produced by the pilot injection. As for the results of the remaining experiments, the main takeaway was that multiple pilot injections were useful for emissions reduction. This is because smaller quantity injections avoid cylinder wall impingement and a subsequent growth of HC and CO emissions. The double pilot scheme provided the best emissions trade-off and lowest fuel consumption.

In 2008, Ehleskog and Ochoterena [74] set out to further examine the effects of split main injections in hopes of understanding the relationship between main injection split dwell times and soot production. They employed the injection strategies previously investigated [31] that involved a single pilot injection in conjunction with a main injection split. Rather than repeating the same engine tests, these injection strategies were tested in a high temperature, high pressure vessel with optical access to use a planar Laser Induced Incandescence analysis. They were able to repeat the results found previously, seeing that the addition of a pilot injection reduces soot, and splitting the main injection into two equal injection allows for further soot reduction; however, no clear relationship between dwell time and soot production was seen.

The same year, Vanegas et al. [75] experimented with pilot/main and pilot/main/post injection strategies on their 1.9 L four-cylinder CI engine with a compression ratio of 18.3:1. For the pilot/main injection cases, the pilot injection mass was held at 12.5% of the total injected fuel mass and the main SOI was varied from 4° to −5° BTDC, while the pilot-main dwell time was set at 10°, 16°, and 22° for a total of 12 runs. The lowest NO_x emissions with dual injection were seen with a main SOI of −5° BTDC and a dwell of 22°, most likely because of the lengthened combustion duration. HC and CO emission decreased with the dual injection strategy when an advanced SOI and short dwell were used. Regarding smoke emissions, smoke increased compared to the single injection case for all dual injection schemes. For the pilot/main/post injection strategies, the pilot and post injections were again held at 12.5% of the total injected fuel mass and main SOI was varied from 4° to −5° BTDC, but this time with dwells of 13°, 19°, and 25° between pilot and main injections. The post injection timing was varied from 9° to 18° ATDC with a main/post dwell of 13° for the first set, 15° to 24° ATDC with a main/post dwell of 19° for the second set, and 21° to 30° ATDC with a main/post dwell of 25° for the last set. All 12 triple injection cases were able to achieve slightly lower NO_x levels than the dual injection cases, while CO and HC remained constant close to the nominal level seen for all the tests. The lowest soot emissions with triple injections were seen with a main SOI of 4° BTDC and a post SOI of 9° or 15° ATDC.

Concurrently, Mendez and Thirouard [76] implemented up to four fuel injections per cycle to explore HCCI/Highly Premixed Combustion operation in the LTC regime. While LTC operation is not of interest here, they also produced results within the medium to high load range that were representative of conventional CI combustion. They used low compression ratio engines along with the help of EGR for their tests, which is necessary to increase the ignition delay. This greater ignition delay provides more time for charge homogeneity, and coupled with lower temperatures, can reduce soot and NO_x. They tested five small bore light-duty CI engines, three of which were single-cylinders, and two were four-cylinders. At mid load (IMEP of 7 bar) and 2000 rpm it was possible to lower fuel consumption by 8% using a dual injection strategy (SOIs of 7.4° and −5° BTDC) while achieving the same noise and soot levels as a single injection strategy. This was believed to be a result of better fuel distribution and, thus, optimized air usage, in addition to the cooling effect brought on by the second injection event that improved premixing. At high load (IMEP of 13 bar) and 2500 rpm, the NO_x versus soot trade-off was evident with two injections (SOIs of 32° and 19° BTDC). Here, the addition of a third injection (SOI of 4° BTDC) achieved a favorable effect on the trade-off by lowering soot without increasing NO_x emissions or fuel consumption.

In 2009, Lee et al. [21] carried out an investigation of single and double pilot injection strategies employing their 1.82 L single-cylinder CI engine with a compression ratio of 17:1. Experiments included testing at medium load and 1200 rpm with injection parameters as follows: the single pilot injection timing was varied from 10° to 80° before the start of the main injection event while the pilot quantity was adjusted from 10% to 50%. Furthermore, the timing of both pilot injections for the double pilot case were modified in the same range as the single pilot, though pilot quantities of either 15% or 25% were used. Main injection timing was varied from 28° to −4° BTDC for both single and double pilot injections, as well as using two different fuel pressures of 30 and 140 MPa. When the single pilot SOI was more than 40° before the main injection, a drastic decrease in NO_x was seen, PCCI; however, this could also be due to cylinder fuel impingement causing less fuel to participate in combustion. Regarding smoke, a pilot/main dwell greater than 40° caused smoke emissions to increase due to the fuel impinging on the wall of the cylinder. The most advanced single pilot injection of 80° before the main SOI had a medium sized premixed burn phase according to the heat release profile, but it also had the lowest NO_x emissions. This was said to be because the advanced pilot injection resulted in a low ambient cylinder temperature due to PCCI combustion causing delayed combustion phasing. The double pilot injection resulted in a greater NO_x reduction because of a more homogenous mixture formed by the improved turbulent effects from the added injection split. Smoke emissions were also further reduced with the double pilot injection due to the same principle of the rich fuel spray tip region not being replenished and shortened. For both single and double pilot injection cases, the indicated specific fuel consumption and HC emissions increased as pilot/main dwell and pilot fuel quantity grew. With a pilot double split of 15/15/70, an HC reduction of 50% was seen due to the decreased spray penetration and less fuel hitting the cylinder walls. Timing of the second pilot injection did not have a significant effect on the heat release rate, but the heat release of the main injection event was affected. Results showed that a double pilot injection strategy is more advantageous than a single pilot injection due to a greater simultaneous reduction of NO_x and smoke.

Concurrently, Mingfa et al. [22] explored pilot/main, pilot/pilot/main, and main/post injection strategies in a heavy-duty CI engine. Their testing used a 6.5 L six-cylinder engine with a compression ratio of 17.5:1. Overall, 25%, 50%, and 100% load conditions were tested at 1849 rpm and 120, 140, and 160 MPa of rail pressure, respectively. Pilot and post injection quantities were varied for the single pilot and post injection cases, though the relative quantity was not reported. For all injection schedules, the main SOI was held as 0° BTDC, while the pilot dwell was varied from 8° to 40° for both the single and double pilot cases, and the main/post dwell was varied from 6° to 24°. It was seen that single pilot injections were not effective in reducing NO_x or PM at high load but saw reductions in NO_x, CO, and BSFC at low load. The double pilot injections were able to reduce PM due to increased cylinder air utilization but came with a growth of NO_x emissions. Post injections offered benefits in both smoke and CO emissions. The addition of EGR was also studied, allowing for mitigated NO_x creation during the double pilot injection, and thus, having a favorable effect on the NO_x -PM trade-off. The addition of a post injection was stated to offset the added smoke emitted due to EGR use.

In 2013, Yang and Chung [77] experimented with up to four injections per cycle to explore the feasibility of simultaneous NO_x and PM reduction with their HSDI single cylinder CI engine. An AVL 5402 engine was used that had a displacement of 0.51 L and a 17:1 compression ratio and was operated at 2000 rpm and 5 bar IMEP. Initial tests were performed with two injection pilot/main strategies while varying the injection pressure from 30 to 180 MPa. The respectively high increase in injection pressure led to almost zero smoke emissions and attributed to the increased atomization leading to the rapid formation of a lean pre-mixture that reduces ignition delay. However, in this case, the reduction in ignition delay did not contribute to lower NO_x emissions. Instead, the rapid premixed burn of the pilot injection caused an increase in NO_x. The best case occurred with an injection pressure less than 100 MPa where a 50% smoke reduction was seen with slightly higher NO_x emissions. A four-injection pilot/pilot/main/post scheme was then tested at 58 MPa involving a 13% pilot with an SOI of 25° BTDC, followed by a second pilot with a 11% quantity and 16° BTDC SOI, the main injection had an SOI of 4° BTDC, and the 13% post injection was injected at 45° ATDC. The four-injection strategy produced a 55% reduction in particulates and no penalty in NO_x as compared to a single main injection event.

Concurrently, Barman et al. [78] used a design of experiment (DOE) approach to optimize the multiple injection strategy for their light-duty CI engine. The engine speed was varied from 700 to 2600 rpm over a range of loads and employed up to four injections. At low to medium loads, a significant pilot quantity and large pilot/main dwell provided benefits in BSFC, as well as reductions in NO_x and soot. At full load, multiple injections were less effective in NO_x and soot reduction, though a reduction in BSFC was seen. Post injections were found to be an effective method for soot oxidation with a small penalty in BSFC. However, they discussed that a small improvement in BSFC could be achieved with high post injection separation and low injection quantities.

Suh [79] studied twin pilot injections on a low compression ratio engine the same year as the Tier 3 emissions standards proposal. They tested an HSDI single-cylinder engine modified from a production four-cylinder that was further altered to reduce the compression ratio from 17.8:1 to 15.3:1. Twin pilot injections were compared to both pilot/main and single injection strategies, yielding a 2.1% increase in IMEP over the single injection case for both pilot strategies, as well as NO_x reductions of up to 45.7% without significant penalties in soot.

Also in 2014, O'Connor and Musculus [80] investigated the effects of load variation on the efficacy of soot reduction by close-coupled post injections in an effort to understand the soot oxidation mechanism further. Testing was carried out using an optical 2.34 L single-cylinder CI engine based on a Cummins N-14. The original compression ratio of 16:1 was reduced 11.2:1 to accommodate optical instrumentation; hence, the intake was artificially boosted to bring the effective compression ratio back to 16:1. Main injection timing was held at 13° BTDC while a 13.5–34% post injection quantity was set to an SOI of 6° ATDC under a range of EGR levels. They concluded that post injection usefulness decreases at higher loads, and the range of post injection durations that are effective also shrinks. This was attributed to the varying thermal conditions, dictated by load, that change the structure of the post fuel jet. Specifically, high temperatures and loads cause soot to form further upstream in the post jet, and in greater quantities, swaying the competition between soot oxidation and formation to yield more soot.

In 2015, Warey et al. [81] investigated a combination of physical engine testing, spectral analysis, and zero-dimensional thermodynamic modeling to provide insight into the possible physical mechanisms that contribute to combustion noise reduction with close-coupled pilot injections. The engine used was a 0.48 L single-cylinder CI version of a GM four-cylinder with a 16.7:1 compression ratio and was tested at 1500 rpm and 9 bar IMEP. Pilot quantities of ~6% with the SOI varied from 12° to 1° were used while the main injection SOI was adjusted from 0° to 2° to meet the load requirement. A 3 dB reduction in noise was achieved without a change in exhaust emissions. This was said to be a result of two possible factors. The first involves the relative phase change between pilot and main combustion events that has two potential mechanisms at play. The initial mechanism has to do with the pressure rise and fall associated with heat release and expansion and how this affects pressure oscillations and combustion phasing. It was postulated that if there is not a significant pressure change after TDC or prior to heat release, this impedes pressure oscillations in the critical frequency range (1.3 to 2.6 kHz). The subsequent potential mechanism is that combustion phasing can cause destructive interference in the critical frequency range and does not depend on the cylinder events of compression and expansion. Hence, only the pressure oscillations caused by heat release are important, although this was stated to be less likely. The second factor considered a cause of the close-couple pilot injection noise decrease was the suppression of the pilot heat release due to charge cooling brought on by the main injection. They state this "leads to broadband attenuation of sound pressure levels over a wide frequency range"; thus, decreasing combustion noise for a certain range of dwells. Simulations predicted that this effect was only apparent for a small fraction of the decrease in noise.

In 2016, Biswas et al. [82] investigated multiple injections using a DOE strategy to improve BSFC and torque using a 5.7 L six-cylinder CI engine with a compression ratio of 17.5:1. The focus of the experiments were pilot/main/post and pilot/pilot/main/post strategies at a range of loads and speed of 10–100% and 1200–2400 rpm, respectively. Results showed benefits in BSFC with the pilot/main/post strategy at low loads, though at high loads, the pilot/pilot/main/post scheme provided optimal BSFC. Regarding emissions, the pilot/pilot/main/post strategy achieved lower PM, HCs, and CO, although with marginally higher NO_x levels.

In 2017, Diwakar and Domenech-Llopis [23] performed experiments in conjunction with a computational study to explore the fundamental physics behind combustion noise reduction with multiple injections in CI engines. They experimented with a light-duty 0.49 L single-cylinder engine with a compression ratio of 15.2:1 that operated at a constant speed of 2000 rpm and 5 bar BMEP. A five-pulse injection scheme was used that employed three pilot injections, a main, injection, and a post injection. The goal of testing was to analyze noise reduction when the dwell between the final pilot injection and main injection was varied while all other injection parameters remained constant. The results from varying the delay of injection 3 to 4 from 0° to 4° show a sweet spot at 2° that minimizes combustion noise, increases gross IMEP, and has little effect on NO_x. The optimal dwell time of 2° had the lowest corresponding rate of pressure rise, while still maintaining a relatively high average rise rate. This is said to be due to a localized cooling effect from the 4th injection; thus, delaying premixed ignition to the point that the premixed spike is damped from interaction with the main injection.

Also in 2017, Jorques Moreno et al. [17] explored the influence of pilot injections on the main injection event along with their ability to regulate combustion. The purpose was to increase the feasibility of closed-loop combustion control by decreasing cycle-to-cycle variation and the effects of external disturbances that are a detriment to combustion modes such as HCCI. Closed loop combustion involves the use of an in-cylinder pressure transducer that can be used to estimate heat release and facilitate precise combustion control. Testing was performed on a modified Scania D13 heavy-duty CI engine at an operating point of 1200 rpm with loads ranging from 2.5 to 15 bar IMEP, as well as a constant 10 bar IMEP with engine speed varied from 600 to 1800 rpm. After testing the effects of a small pilot injection along with dissimilar combinations of pilot mass, dwell, fuel rail pressure, and combustion phasing, it was seen that combustion phasing and duration have a greater influence on emissions and performance than pilot injections alone. It was suggested that a greater pilot mass is needed at higher loads to decrease the combustion duration, while at low load, the pilot/main dwell can be used to influence this process.

In 2019, Inaba et al. [83] investigated dual injection strategies with a 0.55 L supercharged single-cylinder CI engine with a compression ratio of 16.3:1 as a means for confirming their numerical simulations. Experiments at 1500 rpm and a range of low operating loads were carried out while varying the pilot SOI from 4° to 6° BTDC and main SOI from 5° to 7° ATDC. They concluded that simultaneous NO_x and soot reduction is possible with delayed dual injections in conjunction with EGR.

2.2. History of Multiple Fuel Injection Events Using Neat Biodiesel

There has been less research about biodiesel fueled CI engines operating with multiple fuel injection events. To the authors' knowledge, the earliest account is from 1999 [84]. Most of the research occurred between 2013 and 2019 and from these limited investigations, only four biodiesel feedstocks (i.e., waste cooking oil (WCO), coconut oil, soybean oil, and karanja oil) have been explored. Moreover, these efforts are divided into neat biodiesel research and those that incorporate biodiesel blends. Biodiesel blends are popular because they are more feasible for large-scale implementation. This is due to the capability to realize emissions reductions without sacrificing fuel economy largely as a result of the lower energy content of biodiesel [85].

Neat biodiesel has been commonly shown to simultaneously reduce CO, PM, and HC emissions, but can increase NO_x emissions due to its greater oxygen content and higher adiabatic flame temperature if combustion phasing is not considered. Conversely, research, such as the efforts by Mangus et al. [86], has shown neat biodiesel can achieve reductions in NO_x emissions by controlling heat release through appropriate injection timing; thus, helping to mitigate the advancement of combustion phasing primarily due to biodiesel's cetane number. With the addition of multiple injections to further control the heat release of biodiesel, it is reasonable to believe there are added gains possible with respect to emissions using neat biodiesel. Initially, studies in this area were conducted exclusively on small single cylinder CI research engines.

In 2008, Stringer et al. [85] began the research on multiple injection strategies with biodiesel using a 0.3 L single cylinder CI engine with a compression ratio of 19.5:1 operating at 4.0 bar IMEP and 1500 rpm. Tests were conducted using pilot injections (~16% total injection quantity for biodiesel and ~14% for conventional diesel) with neat soybean biodiesel at a fuel pressure of 80 MPa. Their results showed that simultaneous reductions in NO_x and PM can be achieved with neat biodiesel using pilot injections when compared to conventional diesel. To note, the biggest reductions were a result of operating in a postulated LTC regime when employing a pilot SOI of 30° BTDC and main SOI of 10° ATDC.

Kim et al. [87] also investigated the use of neat soybean biodiesel with multiple injections in 2008. Using a 0.37 L single cylinder CI engine with a compression ratio of 17.8:1, their effort consisted of comparing a single injection case to a 50/50 split at an injection pressure of 100 MPa and 1500 rpm. The split injections significantly reduced NO_x output compared to the single injection case. Unlike the single injection case, delaying injection for the split injection case resulted in slightly lower soot emissions. However, HC and CO emissions grew due to a longer combustion duration that also caused a reduced thermal efficiency.

The following year, Fang et al. [88] conducted a study with an optical 0.3 L single cylinder research engine with a compression ratio of 19.5:1. The use of the optical setup allowed them to investigate simultaneous NO_x and soot reductions using a pilot injection strategy by measuring engine-out NO_x emissions and analyzing the natural flame luminosity during combustion. They concluded that the natural flame luminosity of the neat soybean biodiesel was always lower than conventional diesel at the same operating conditions, subsequently leading to lower soot emissions. Moreover, a NO_x reduction of up to 30% as compared to conventional diesel at the same operating point was seen using a pilot injection strategy with a respectively delayed main injection event.

In 2010, Yehliu et al. [89] was one of the first to investigate multiple injections with biodiesel utilizing a full-sized CI engine. They experimented with a 2.5 L four-cylinder engine with a compression ratio of 17.5:1. The single injection tests with soybean biodiesel resulted in an increase in NO_x emissions at high load over conventional diesel, along with increased particle concentrations at low load. With the addition of a pilot injection, the neat biodiesel fuel produced decreased NO_x emissions, as well as a lower particle concentration compared to the conventional diesel fuel.

In 2011, Park et al. [90] experimented with neat biodiesel using a similar single cylinder research engine to that used by Stringer et al. in 2008; however, it had a slightly lower compression ratio of 17.8:l. This engine was operated at 1400 rpm and utilized a higher fuel pressure of 120 MPa. Experiments were carried out by comparing a single 10 mg injection to a pilot injection of 3 mg and main injection of 7 mg. The pilot SOI was varied from 30° to 10° BTDC with a fixed main SOI at 0° BTDC. They concluded there was an increase in IMEP when using the pilot injection as compared to the single injection strategy due to a delayed main injection event extending combustion further into the expansion stroke.

Also in 2011, Qi et al. [91] set out to continue the research started by Stringer et al. in 2008 with neat soybean biodiesel; however, this time on a full-sized 2.4 L Ford Lion V6 with a compression ratio of 17.3:1 and with the addition of EGR. Their effort consisted of utilizing a pilot injection strategy at load points of 3 bar and 6 bar at 1500 rpm. The pilot injection timing was held constant at 14° BTDC for the lower load point and 16° BTDC for the higher load point, with both varying the main injection timing from 4° to −4° BTDC. They were able decrease NO_x emissions without any soot penalty, but with a small increase in BSFC by using a respectively delayed main injection timing and EGR.

In 2014, Chen et al. [32] studied the use of double post injections for PF regeneration. It was seen that a mixed feedstock biodiesel (mainly soybean oil) produced lower HC and NO_x emissions along with a small penalty in CO in comparison to diesel. Moreover, biodiesel exhaust temperatures were lower and produced a lower DOC conversion efficiency during the regeneration process.

Additional research was done by Jeon et al. in 2015 [92] using a 0.51 L single cylinder research engine with a compression ratio of 17.1:1. Their study consisted of comparing neat soybean biodiesel to conventional diesel using pilot injections at 4.4 bar and 1500 rpm. They investigated the effects of varying both pilot injection timing from 90° to 20° BTDC and pilot fuel mass from 2 to 6 mg (main injection quantity unknown). They found a reduction in brake specific energy consumption of up to 15.8% is possible for biodiesel when using multiple injections as compared to a single injection. They discussed that multiple injections could allow biodiesel to overcome the inherent disadvantages associated with its higher viscosity during spray development. It was seen that the poor atomization of the biodiesel fuel caused an increased soot concentration in the middle of the combustion process compared to conventional diesel. However, its higher oxygen content and greater temperatures accelerated the soot oxidation process and resulted in lower overall soot emissions.

Concurrently, Mohan et al. [30] studied the effects of injection profile shaping using both injection pressure modulation and a pilot injection. A 2.5 L four-cylinder turbocharged

CI engine with a compression ratio of 18.5:1 was operated with neat WCO biodiesel at various speeds and loads. Results of this study demonstrated that when a smaller pilot injection is used than the main injection, reductions in NO_x and PM as compared to the single injection case can be achieved under a medium engine speed and load scenario.

In 2017, Li et al. [93] explored the effects of post injections using neat soybean biodiesel. Tests were carried out on a 3.8 L four-cylinder turbocharged CI engine with a compression ratio of 17.5:1 at various engine speeds and an IMEP of approximately 10.6 bar. The main-post injection dwell was varied from 8° to 20°, and the post injection quantity was varied from 4% to 20%. They found that when increasing main post dwell and post injection rate, CO and HCs increase while NO_x decreased. Regarding particulates, PM increased with a greater dwell at low injection rates, then a sweet spot of lowered PM was achieved as injection rate was increased. Continuing to raise the injection rate subsequently resulted in the PM again increasing. Particle number grew with increasing dwell at low injection rates, while decreasing to a sweet spot before rising again at higher injection rates. The study concluded that the post injection dwell and rate greatly affect soot reactivity. Most notably, at higher injection rates a decreased activation energy was seen for the soot particles.

Lastly, in 2018 Babu et al. [94] experimented with a 0.55 L single cylinder CI engine with a compression ratio of 16.5:1. They investigated the effect of multiple injections using WCO biodiesel derived from sunflower oil. Timing of the first injection was varied from 19° to 25° BTDC, while the second SOI was varied from −5° to 0° BTDC. Additionally, the injected fuel quantity of the first injection was changed from 75% to 90% of the total injected fuel mass. Simultaneous reduction of HCs, smoke, and NO was achieved without compromising engine performance.

2.3. History of Multiple Fuel Injection Events Using Biodiesel Blends

Research involving conventional diesel blended with biodiesel began in 1999 when Choi et al. [84] set out to understand the effects of using high pressure injection in conjunction with multiple injections and oxygenated fuel blends. Experiments were done using a 2.44 L single cylinder Caterpillar test engine with a compression ratio of 16.1:1. A blend of 20% soybean biodiesel was compared to conventional diesel while testing both single and split injection strategies, all at an injection pressure of 90 MPa. For the high load split injection case, a 50/50 fuel split was employed at 1600 rpm, while the low load case utilized a 61/39 split at 1700 rpm. It was found that the split injection strategy offered an additional reduction in soot emissions at high loads. This was on top of the inherent reduction achieved when using biodiesel. At low loads, biodiesel only offered a small reduction in particulate emissions due to the premixed dominated combustion. However, the split injection case still provided an additional reduction in particulates. Overall, they were able to reduce particulates using biodiesel and multiple injections without any penalty to NO_x emissions.

To follow, there was an absence of blended biodiesel multiple injection research until 2013 when Agarwal [95] investigated the effects of karanja biodiesel blended with conventional diesel. They used a 0.51 L single cylinder CI engine with a compression ratio of 17.5 fueled with B0, B20, and B50 karanja biodiesel blends. Using a 10% pilot injection and advanced injection timing, the B20 blend produced the lowest particle concentration of all the fuels, but at the expense of increased NO_x emissions. Dhar et al. [96] conducted another study in 2015, this time testing a B10 karanja biodiesel blend and saw similar results to the 2013 study.

It was not until 2018 that further research was published when How et al. [97] experimented with a 1.46 L turbocharged four-cylinder engine with a compression ratio of 18.25:1. They tested conventional diesel, as well as B20 and B50 coconut biodiesel blends using single, double, and triple injection strategies at a constant 60 N-m load and 2000 rpm. The multiple injection schedules employed 50/50 and 33/33/33 fuel mass splits with constant dwell angles between injections. By using triple injections with delayed injection timing, they were able to reduce NO_x levels beyond that of conventional diesel with both biodiesel blended fuels. Moreover, they achieved simultaneous reductions in NO_x and PM with the B50 coconut biodiesel blend.

Later in 2018, Teoh et al. [98] continued the work of How et al. on the same test engine and used the same fuel blends, this time focusing on double split injections (50/50) and varying the dwell angle between the two injections. Again, they were able to reach simultaneous reductions in NO_x and PM as compared to conventional diesel. The best results were obtained with a respectively long dwell angel and delayed SOI, where there was a further reduction in NO_x as compared to the triple injection study, but at the cost of an increase in PM.

How et al. [99] conducted an additional study in 2019, using the same hardware and fuels as the previous two studies. Here, the effects of varying the double injection fuel masses were investigated; i.e., 25/75, 50/50, and 75/25 injection splits were applied at a constant dwell angle of 15° and varied SOIs from 12° to −2° BTDC. This time, the B50 blend with a delayed 25/75 split was found to be optimal, achieving reductions in NO_x and PM in comparison to diesel. This attained the lowest PM levels of the three studies along with NO_x emissions equivalent to the best case of the previous double injection study.

In the same year, Plamondon et al. [100] experimented with conventional diesel and a B20 WCO biodiesel blend using pilot injections. Their set up consisted of a Renault 1.5 L turbocharged four-cylinder engine operating at 2 bar BMEP and 2000 rpm. They tested a wide range of pilot SOIs from 64° to 11.5° BTDC at a fixed main SOI of 4° BTDC, in addition to varying the dwell angle from 7.5° to 60°. While they claimed to be using pilot injections, their "pilot" fuel masses ranged from approximately 58–64% (i.e., greater than 50%) of the total injected fuel mass. Their testing was concluded without attaining simultaneous reductions in NO_x and PM compared to diesel. Specifically, they saw a reduction in NO_x while increasing PM. Only the B20 fuel was able to achieve a reduction in both constituents with double injections as compared to the single injection event.

2.4. Low Temperature Combustion

While the focus of this effort is on conventional CI combustion, multiple fuel injection events can be used for LTC operation. LTC can be separated into the different variants of Homogeneous Charge Compression Ignition (HCCI), Partially Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI) combustion. HCCI largely revolves around the use of port fuel injection as the goal is to generate the greatest level of homogeneity at ultra-lean equivalence ratios [101]. Subsequent ignition of the mixture, through autoignition or other means for control (e.g., spark ignited [102]), results in nearly constant-volume combustion and negligible NO_x and PM emissions since combustion temperatures are low, although CO and HC emissions can be higher. Early direct fuel injection in-cylinder is possible to achieve HCCI (e.g., 100 deg BTDC [103]) with highly volatile fuels, such as ethanol, often preferred to help achieve a homogeneous mixture. Use of multiple fuel injections to achieve HCCI with diesel fuel is possible by controlling spray penetration and preventing fuel impingement on the walls while enhancing fuel-air mixing [104].

PCCI operates similarly to the early direct fuel injection in-cylinder HCCI option; however, fuel injection timing is closer to TDC (e.g., 30 deg BTDC [105]). This results in a more heterogeneous mixture and increases NO_x and PM emissions over HCCI operation due to the growth of hot spots and richer fuel-air zones. It does lead to better control of ignition timing which can be an issue for HCCI engines. Like HCCI, multiple fuel injection strategies can be used to achieve PCCI with Mei et al. using two pilot injections [106]. Due to the use of small pilot injections for both direct injection HCCI and PCCI operation, the literature review relevant to pilot injection strategy in the earlier three sections can supply useful insight.

RCCI operation often requires two fuels; a lower reactivity fuel (e.g., gasoline) is added in a port-fuel injected manner and a second, higher reactive fuel (e.g., diesel) is added through direct injection in cylinder [107]. The direct injection process acts as the ignition source helping to ensure reliable combustion timing. The addition of the fuel upstream of the cylinder supplies a significant advantage of RCCI. Namely, the ability to run at higher loads than HCCI and PCCI while maintaining a good level of homogeneity; thus, achieving both low NO_x and PM emissions. Multiple fuel injection events in cylinder can aid in shaping the heat release event leading to less noise and reduced pressure rise rates [108], both endemic to HCCI and PCCI operation. The dual fuel strategy used with RCCI operation deviates from the literature review provided; however, insight into rate shaping and concepts such as dwell could supply guidance.

3. Results

The historical review presented finds a significant volume of work devoted to testing diesel fuel under a multiple fuel injection scenario whereas comparatively less is seen about neat biodiesel and biodiesel blends with diesel. Many mechanisms have been proposed to explain the reduction of exhaust emissions, combustion noise, and fuel consumption possible with multiple fuel injection events. The next two sections will summarize the trends and fundamentals involved based on the fuels tested.

3.1. Summary of Multiple Fuel Injection Strategies Using Diesel Fuels

Starting with pilot injections, a broad range of injection timings and quantities for both the pilot and subsequent main injection events have been explored. This is in addition to a varying number of pilot injections per engine cycle. Pilot injection experimentation began with the goal of combustion noise and NO_x emissions reduction, which has been successful while also being effective in reducing the BSFC. The general thought was that noise could be decreased through lowering peak cylinder pressure rise rates [23,29,58]. The study by Warey et al. in 2015 [81] delved further into the noise reduction mechanism, showing that it only takes a pilot quantity of ~6% to reach significant reductions in combustion noise. This was mainly attributed to two possible mechanisms. First, the pressure rises and falls due to heat release and expansion can influence the relative pilot and main injection combustion phasing that may subsequently impede pressure fluctuations in a critical frequency range. Second, combustion phasing that causes destructive interference may be present only due to pressure fluctuations because of the heat release.

The original notion that NO_x reduction could be attributed to a decrease in peak heat release rate has been confirmed many times [18,46,50,51,53,58]; however, a strong load dependency has also been reported [29,46,50,51,58,68,78]. Every pilot quantity has been explored that can still be considered a "pilot" injection (i.e., quantities less than 50%), and pilot injection timing has been tested as early as 90° BTDC (i.e., the compression stroke) [54]. Significant early injection events often come with piston/cylinder wall impingement issues, especially at low engine speeds and loads with associated low turbulence. This causes oil dilution and spikes in HCs, CO, and PM emissions [19–21,54]. In addition, pilot SOI has been investigated as late as 0° ATDC [59], with a main SOI as delayed as 10° ATDC. At low loads, optimal injection parameters for NO_x abatement appears include a small pilot quantity of 10–15% [45,51,75,77,90].

There are countless reports of pilot/main dwell times that are favorable, but they are relative to the phasing of the injections with respect to piston location, as well as the number of pilot injections. Nevertheless, pilot/main dwells ranging from 2° to 80° have been reported [21,67]. At medium load, it has been reported that pilot influence starts to lessen and requires a larger pilot quantity (around 18–30%) [17,18,21]. At high loads, pilot injections are often reported to have little to no influence on combustion [46,51,58,78]; however, some researchers had success with NO_x and noise reduction at high loads [19,52,65]. This lessened pilot influence as load progresses has been thought to be a function of the decreasing premixed combustion phase, whereas low load is predominately premixed. This necessitates other means of combustion modulation such as main injection splitting. Furthermore, multiple pilot injections have been reported to be effective [18,20,21,77,79,82], even at high loads [82], with even stronger effects at part load. It is generally agreed upon that double pilot injections are optimal [18,20,21,77,79]. An important takeaway from these results is that the use of a pilot injection allows for delayed main injection timing that benefits NO_x emissions, as well as potentially BSFC due to a lengthened combustion event into the expansion stroke [46,50,75,83]. While some researchers found a growth in PM emissions while using pilot injections [19,20,75], many have experienced reductions in PM with little to no penalty in NO_x production [50,77,79,82]. Conversely, researchers have seen NO_x reductions with little to no penalty in PM levels [35] and even simultaneous NO_x and soot reduction [21,42,51,59,65,72,78,83] as compared to a single injection event.

Main injection splits have been successful in reducing NO_x levels and combustion noise [1,31,45,52,53,57,60,76] via the same mechanisms discussed via pilot injections. Moreover, main injection splits in conjunction with pilot injections have compounded benefits in NO_x and combustion noise [31,45,60]. Main injection splitting has been widely shown to increase fuel air mixing to reduce PM production [45,76]. Here, the reports indicate PM reduction with little to no impact on NO_x [45,76], or NO_x emission decreases with little to no impact on PM, as well as simultaneous PM and NO_x reductions [1,45,52,60]. Furthermore, it has been reported than main injection splits can reduce BSFC by maintaining a high heat release rate for a longer amount of time [31]. Main injection splits also brought forth the witness of an additional soot reducing mechanism. This was explained by the discontinuation of the fuel rich soot producing zone at the tip of the fuel jet that is not replenished since the proceeding injection is sent into a high temperature and pressure setting caused by the preceding injection event. This mechanism was first proposed by Han et al. in 1996 and has since been confirmed by multiple studies [56,57]. Main injection splits have been investigated for up to four injections [31,74] with optimal BSFC and PM reports resulting from two injections [31,63,74,76]. A load dependency has also been observed, albeit with a lessened effect of favorable behavior as compared to pilot injections. Overall, it has been reported that main injection splits can be effective at all loads, with generally dampened effects at high load [45,52,78].

The literature has proven post injections to be effective for PM reduction without increasing NO_x emissions while only incurring a potentially small growth of BSFC [14,19,28,60,64–67,70,75,77,78]. Largely, the mechanisms that make post injections effective operate differently than main injection splits or pilot injections. While post injections do share the same quality of discontinuing the soot producing region at the tip an initial fuel jet, that benefit is lessened due to the lower temperatures and pressures occurring during the expansion stroke. Instead, post injection PM reduction is a function of an improved mixing and continued combustion that influences the soot production and oxidation battle. While temperatures are too low to have any BSFC improvements, temperatures are still high enough to contribute to the late-stage soot oxidation phase seen only minimally during the traditional single injection event strategy. The post injection schemes proven to be the most effective deal with post injection quantities of approximately 10–17% [14,19,28,59,64–66,70,77] and SOIs no later than 27° ATDC [59]. Furthermore, post injection effectiveness is highly dependent on load [14,66]. This is similar to pilot injections since the soot producing diffusion phase becomes more predominate as load increases; hence, the soot production and oxidation battle naturally shifts.

While pilot, main, and post injections have been widely studied while employing only one of these respective injection schemes, it is unanimously agreed upon that pilot injection in conjunction with post injection is the most beneficial [19,59,60,64,65,75,77,82], with various methodologies of splitting the pilot, main, and post fuel quantities included [65,77,82]. Furthermore, different injection types benefit from dissimilar fuel pressures. With the reported tests employing fuel pressure ranging from 30–180 MPa [70,77], it has been generally seen that pilot injections are most effective with respectively low fuel pressures [18,28,70,77]. This is to minimize heat release rates from excessive fuel jet penetration, atomization, and mixing; however, this can be combated by splitting the pilot injection. Moreover, high fuel pressures with early pilot injection timing can cause lean misfires due to overmixing [70]. Post injections have been observed to benefit from higher pressures [28,70,77] because of the increased mixing that allows for late-stage soot oxidation, although lower injection pressures still allowed for some post injection benefit. Overall, there has been a wide range of results from the literature with some studies focusing on BSFC improvements, while others concentrate on a single family of emission constituents. Interestingly, favorable literature results with one strategy might incur worse performance for a similar injection scheme in another effort. The overriding agreement is that multiple injection parameter calibration is delicate, and the optimal injection scheme will differ between any two setups. Nevertheless, the literature has illustrated the potential effects and sensitivities of multiple fuel injection events with diesel-fueled CI engines, along with generally agreed upon mechanisms to describe the resultant behaviors. Table 1 provides a more concise visual representation of the generally agreed upon combustion mechanisms that are present with the three main types of multiple fuel injection strategies.

Table 1. Summary of various multiple fuel injection strategy effects using diesel and biodiesel fuels. In this table, use of ↑ and ↓ indicates the respective impact of that injection strategy on the parameter mentioned by either increasing or decreasing the outcome.

Injection Strategy	Combustion	Emissions	Performance
Pilot Injection	Mixing ↑, Main Injection Ignition Delay ↓, Peak Heat Release ↓, Sustained Heat Release ↑	NO_x ↓, PM ↑, Noise ↓	BSFC ↓
Main Injection Split	Mixing ↑, Peak Heat Release ↓, Sustained Heat Release ↑	NO_x ↓, PM ↑, Noise ↓	BSFC ↓
Post Injection	Mixing ↑, Sustained Cylinder Temperatures ↑	PM ↓	BSFC ↑
Pilot + Post Injection	Mixing ↑, Main Injection Ignition Delay ↓, Peak Heat Release ↓, Sustained Heat Release ↑, Sustained Cylinder Temperatures ↑	NO_x ↓, PM ↓, Noise ↓	BSFC ↓

3.2. Summary of Multiple Fuel Injection Strategies Using Biodiesel Fuels

The literature finds similarities with multiple fuel injection operation between conventional diesel and biodiesel fuels with a few differences reported; however, the general behaviors reported in Table 1 are identical between conventional diesel and biodiesel fuels. To begin, the same NO_x reduction mechanism has been observed with the use of pilot injections and delayed main injection timing [85,88,91]. Potential benefits in the IMEP (and effectively BSFC) as a result of pilot injection use was also reported [90] due to the same concept of the combustion process extending further into the expansion stroke. In addition, the same PM reducing tendency of post injections has been reported [93,94]. Conversely, the qualities inherent to biodiesel fuels (i.e., greater cetane number, higher viscosity, and lower energy content compared to petroleum diesel) present deviations in favorable injection parameters compared to conventional diesel. For instance, slightly higher pilot injection quantities (around 15–25%) have been reported with single pilot injections [85,99] when using neat biodiesel to counteract its larger cetane number.

A major difference in biodiesel operation involves the variance in behavior of the soot production and oxidation battle. Due to the higher viscosity of biodiesel fuels, its correspondingly poorer atomization produces an increase in soot concentration in the middle of combustion, but its higher oxygen content and greater adiabatic flame temperature accelerates the soot oxidation process [92]. Furthermore, high post injection quantities (around 20%) have been reported to decrease the activation energy of soot particle oxidation [94]. The beneficial shift in soot production and oxidation inherent to biodiesel use is compounded by the addition of a post injection event, explaining why many researchers have seen lower PM levels with biodiesel compared to diesel when employing multiple injections.

Another difference involves the historical time period when the bulk of efforts have taken place with respect to CI fuel injection technology. While investigations involving conventional diesel-fueled CI engines employing multiple injections have presented a vast number of experiments involving many injection parameters (e.g., timing and quantity to fuel rail pressure), most biodiesel multiple injection research has taken place when many of these injection parameters are generally understood. Hence, a smaller range for a given parameter has been explored with biodiesel; for example, fuel pressure tested involves a respectively reduced span of about 80–120 MPa [85,90]. Another difference has been a stronger focus on PM emissions. Since Tier 3 PM emissions requirements approach zero, PM emissions must be understood in greater depth; thus, the literature has offered more detailed insight into the PM production and abatement qualities when using multiple injections with biodiesel.

Multiple fuel injection events with biodiesel fuels have been proven to be just as effective, if not more so than with conventional diesel. Most studies have reported the same NO_x and PM reduction potentials with biodiesel, and that multiple injections are advantageous as compared to a single injection event. Moreover, a few have attained simultaneous reductions in NO_x and PM levels in comparison to conventional diesel with the same injection scheme; however, these results have been limited to neat soybean biodiesel [85,87,88] and coconut biodiesel blends [97,98]. Here, multiple fuel injection events with biodiesel allow for the inherent benefits of biodiesel (e.g., lower PM, HCs, and CO), while also overcoming disadvantages associated with its lower energy content and higher viscosity through flexible control of injection parameters.

4. Conclusions

Under conventional combustion regimes, compression ignition engines suffer from a NO_x-PM tradeoff where the mitigation of one species results in the growth of the other species. The advent of high-pressure common rail fuel injection systems in combination with multiple fuel injection strategies has shown significant benefits with respect to power and fuel economy while reducing problematic emissions. For both diesel and biodiesel fuels, and their blends, a combination of pilot, main, and post injection strategies is preferred while also potentially splitting the main injection event to help lengthen the combustion event while maintaining the rate of heat release. Interestingly, pilot injections are more effective at lower pressures while post injection strategies prefer higher injection pressures. In addition, optimum operation is found to be fuel, engine, and setup specific with dwell times between the injections based on many factors, such as load and cylinder conditions. Overall, this effort can aid any researcher wishing to explore multiple fuel injection events by supplying starting guidance to operational parameters while describing the pertinent fundamentals underlying the analysis.

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Nomenclature

ATDC	After Top Dead Center
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Center
CI	Compression Ignition
CO	Carbon Monoxide
DOC	Diesel Oxidation Catalyst
DOE	Design of Experiment
EGR	Exhaust Gas Recirculation
ESC	European Stationary Drive Cycle
HC	Hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
HSDI	High Speed Direct Injection
IMEP	Indicated Mean Effective Pressure
LNT	Lean NO_x Trap
LTC	Low Temperature Combustion
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
PF	Particulate Filter
PM	Particulate Matter
PCCI	Premixed Charge Compression Ignition
RCCI	Reactivity Controlled Compression Ignition
rpm	Revolutions per Minute
SCR	Selective Catalytic Reduction
SOC	Start of Combustion
SOF	Soluble Organic Fraction
SOI	Start of Injection
SOV	Start of Vaporization
SO_x	Sulfur Oxides
TDC	Top Dead Center
TICS	Timing and Injection Rate Control System
ULSD	Ultra Low Sulfur Diesel
WCO	Waste Cooking Oil

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