International Journal of ENGINE RESEARCH

Standard Article

International J of Engine Research
2021, Vol. 22(1) 152–164
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DOI: 10.1177/1468087419838393
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Influence of fuel injection strategies on efficiency and particulate emissions of gasoline and ethanol blends in a turbocharged multi-cylinder direct injection engine

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Abstract

The effects of a broad range of fuel injection strategies on thermal efficiency and engine-out emissions (CO, total hydrocarbons, NO_x and particulate number) were studied for gasoline and ethanol fuel blends. A state-of-the-art production multi-cylinder turbocharged gasoline direct injection engine equipped with piezoelectric injectors was used to study fuels and fueling strategies not previously considered in the literature. A large parametric space was considered including up to four fuel injection events with variable injection timing and variable fuel mass in each injection event. Fuel blends of E30 (30% by volume ethanol) and E85 (85% by volume ethanol) were compared with baseline E0 (reference grade gasoline). The engine was operated over a range of loads with intake manifold absolute pressure from 800 to 1200 mbar. A combined application of ethanol blends with a multiple injection strategy yielded considerable improvement in engine-out particulate and gaseous emissions while maintaining or slightly improving engine brake thermal efficiency. The weighted injection spread parameter defined in this study, combined with the weighted center of injection timing defined in the previous literature, was found well suited to characterize multiple injection strategies, including the effects of the number of injections, fuel mass in each injection and the dwell time between injections.

Keywords

Injection strategies, gasoline, ethanol, efficiency, particulate emissions, turbocharged direct injection spark ignition, knock

Date received: 26 November 2018; accepted: 26 February 2019

Introduction

The benefits of blending ethanol with gasoline to improve the thermal efficiency of direct injection spark ignition engines have been established in numerous studies.[1–5] Previous work has also shown that gasoline direct injection (GDI) engines tend to have higher particulate mass (PM) and particulate number (PN) emissions compared with port fuel injection (PFI) engines.[6] Stringent particulate emission standards such as EURO 6 with a limit of 6×10^{11} PN/km may be challenging for GDI engines to meet without the use of aftertreatment.[7]

Ethanol provides a means to reduce PN and PM emissions from GDI engines while simultaneously providing efficiency benefits.[8,9] Moreover, advances in fuel injection technologies provide a wider range and more precise control over parameters such as fuel rail pressure, fuel injection timing and injection duration.[10] While many studies have considered the effects of different injection strategies on diesel compression ignition engines,[11–14] there are fewer studies using GDI engine architectures. Prior GDI work includes studies of the effects of split injection, that is, two injection

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events,[1,15,16] but fast piezoelectric injectors allow up to five injections per cycle. The potential of multiple injections remains largely unexplored. Su et al.[17] used a triple injection strategy to demonstrate 80% reduction in particulate emissions with a turbocharged GDI engine. Schmidt et al.[18] showed that multiple injections could be used to improve combustion stability at part load conditions in a GDI engine. The current work fills a gap in the literature on the combined effects of ethanol and multiple injection events on the performance of a production flex-fuel turbocharged direct injection engine. The objective of the study was to identify the efficiency and particulate emission benefits achievable using a broad range of fuel injection strategies of ethanol fuel blends. The results show the sensitivity of different ethanol/gasoline fuel blends to more advanced injection strategies.

Experimental setup

Figure 1 shows the schematic diagram of the experimental facility and the supporting systems. The experimental setup consists of a production Mercedes 2.0 L four-cylinder, in-line turbocharged GDI engine (155 kW Daimler M274), equipped with Bosch piezoelectric fuel injectors. The engine specifications are listed in Table A1 of the Supplemental Appendix. Pressure measurements are made in each of the cylinders using spark-plug pressure transducers (Kistler 6115BFD34Q04) and charge amplifiers (Kistler 5010). The engine can be operated at the manufacturer calibration settings through the Bosch engine control unit (ECU) or using manual control via the ETAS tool INCA, which provides access to override the preprogrammed ECU settings. In addition to the standard measurements recorded from the ECU, intake air pressure, exhaust pressure (both pre- and post-turbo), exhaust temperature, oil and coolant temperatures, engine oil pressure and fuel rail pressure are recorded. The fuel–air equivalence ratio measurement is made using a lambda meter (ETAS LA4) with a broadband lambda sensor (Bosch LSU 4.9). The engine was operated at fixed speed, valve timing, coolant temperature, oil temperature and intake air temperature. The fixed operating conditions and the operating limits in terms of maximum allowable in-cylinder pressure, knock limits and component (turbocharger) protection constraints are listed in Table A2 of the Supplemental Appendix.

The engine is not equipped with any exhaust aftertreatment systems, and engine-out PN emission measurements are made by sampling from the engine exhaust runner using insulated stainless-steel tubing (1.3 cm diameter). Particle number and size distribution in the exhaust are measured with a Cambustion DMS500 system, which uses mobility of nanoparticles in an electric field to produce particle number spectra of nanoparticles between 5 and 1000 nm in size. The time response of the system is 200 ms. Exhaust gas is sampled through a choked orifice and diluted with 150°C dry air in two stages. The first stage has a 6:1 dilution ratio (volume basis) to prevent hydrocarbon, water condensation and particle agglomeration. The second-stage dilution uses a 12:1 ratio. Additional details and working principles of the PN instrument are provided in the study of Hagena et al.[19] For the PN study presented here, the total PN concentration and PN size distribution were recorded for 90 s after the engine reached steady-state at the target operating conditions.

Gaseous emission measurements of CO, CO_2, total hydrocarbons (THC), NO_x and O_2 are made using a fast-response analytical system (HORIBA MEXA-7100 DEGR). The sample is transported to the analyzer using heated lines to avoid condensation. The analyzer settings were changed for each ethanol–gasoline fuel blend using the appropriate O/C and H/C ratios.

Three fuels were considered in this study: E0, E30 and E85. The fuel flow rate was measured using a piston-type flow meter (#213-611-000; Max Machinery). The baseline gasoline (E0) fuel used in the study was a research-grade, un-oxygenated gasoline (Gage Products 40665-55 F). The E0 was splash blended by volume with anhydrous ethanol (E100 anhydrous, purity $\geqslant$ 99.5%, $H_2O \leqslant 0.005\%$; Sigma–Aldrich) to produce the ethanol–gasoline fuel blends: E30 (30% by volume ethanol) and E85 (85% by volume ethanol). The fuel properties are provided in Table A3 of the Supplemental Appendix.

Experimental approach

The fuel injection parameters were varied systematically to determine the effects of different fuels and injection strategies on engine performance. The approach started with single fuel injection events as the baseline operating conditions for each fuel. For the single injection experiments, the start of injection (SOI) timing was varied from 300° to 180° before top dead center (bTDC of the firing cycle) in intervals of 20° and the intake manifold absolute pressures (MAPs) varied from 800 to 1200 mbar.

For the multiple injection experiments, a progression of experiments was used to investigate the large parametric space of the number of events, fuel injection timing and fuel mass. First, the effects of multiple injection events were studied by increasing the number of injections per cycle to double, triple and quadruple. For these experiments, the total fuel mass was divided equally between the total number of injection events per cycle. The timing of the first injection event, SOI1, and the pause or dwell time between each injection event were varied. For the second series of multiple injection experiments, the fuel mass was varied between the events of a triple injection strategy with fixed injection timing. For the last series of experiments, a triple

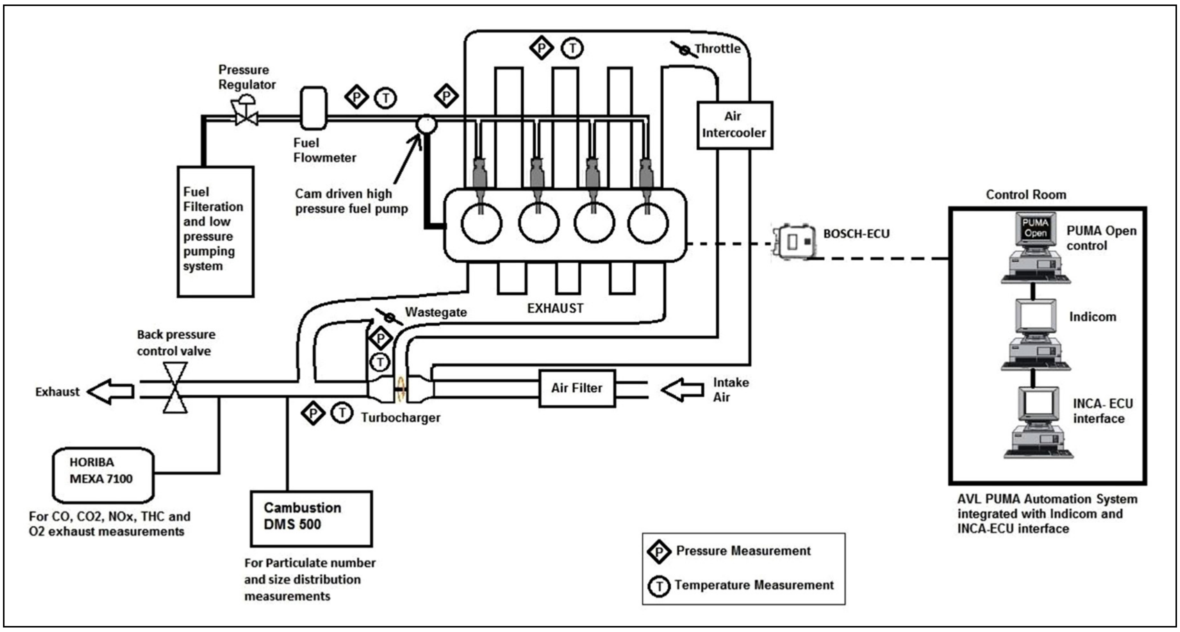

Figure 1. Experimental schematic diagram of the gasoline turbocharged direct injection (GTDI) engine facility and supporting systems.

Table 1. Input parameters and range of values considered in the initial experimental matrix for multiple fuel injection events.

Parameter	Value
Manifold absolute pressure (MAP, mbar)	800, 900, 1000, 1200
Fuels	E0, E30, E85
No. of injection events	1, 2, 3, 4
Fuel mass distribution	Equal fuel mass injected in each event, that is, 100% (1 injection), 50% (2 injections), 33% (3 injections), 25% (4 injections)
Timing of the first injection event, SOI1 (°bTDC)	300, 280, 260, 240, 220, 200, 180
Pause time between each injection event (°)	21, 31.5, 42, 52.5, 63

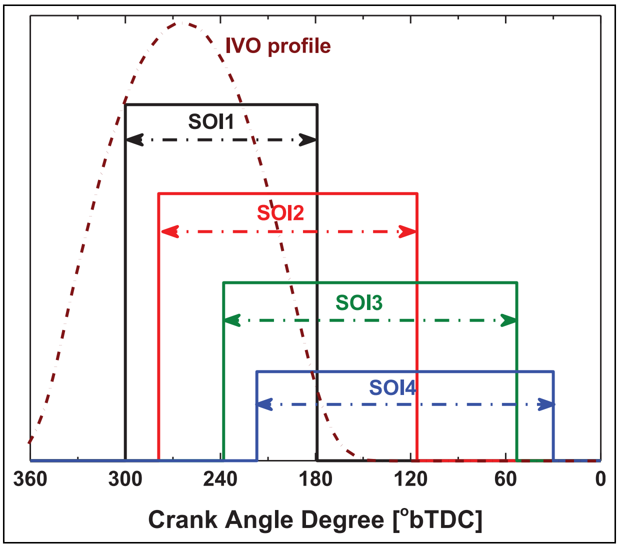

Figure 2. Range of SOI timings (°bTDC) studied for the different injection events. The timing of the intake valve opening (IVO) is provided for reference.

injection strategy was also used where both the fuel mass and the timing of the third injection event were varied, while the timings of the first and second injection events were held constant.

The values considered in the first multiple injection experimental matrix are presented in Table 1, and the range of the SOI timings for each injection is presented in Figure 2. The test matrix for the second and third series of multiple injection experiments was created based on the results from the first series of experiments. The same are presented in the following sections. The final set of results present the effects of triple injection strategies on particulate emissions.

For each injection strategy tested, the spark timing was varied to achieve maximum brake torque (MBT). At boosted intake air conditions, knocking became significant and prevented MBT operation for E0. For the boosted E0 conditions, the spark timing was advanced no further to where the peak in-cylinder pressure oscillations reached the knocking criteria provided in Table A2.

Weighted center of injection timing

In order to facilitate the comparison between the different strategies using multiple injection events, the weighted center of injection (WCOI) timing was used. WCOI was defined in the GDI fuel injection study by Imaoka et al.[20] as the center timing for all fuel injection

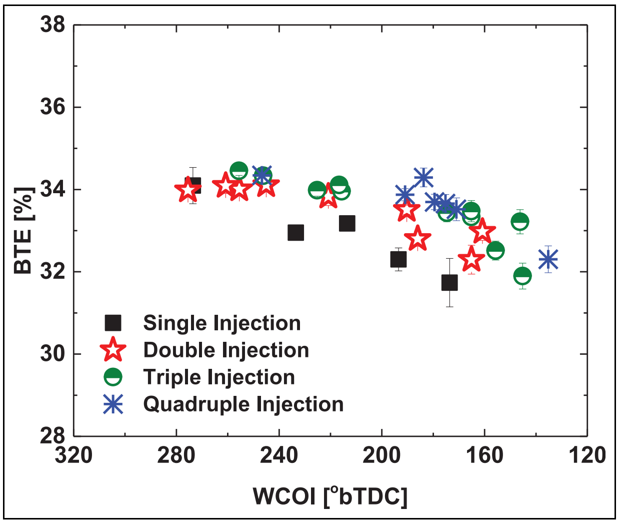

Figure 3. Comparison of BTE for multiple and single fuel injection events for E0 and MAP = 1000 mbar.

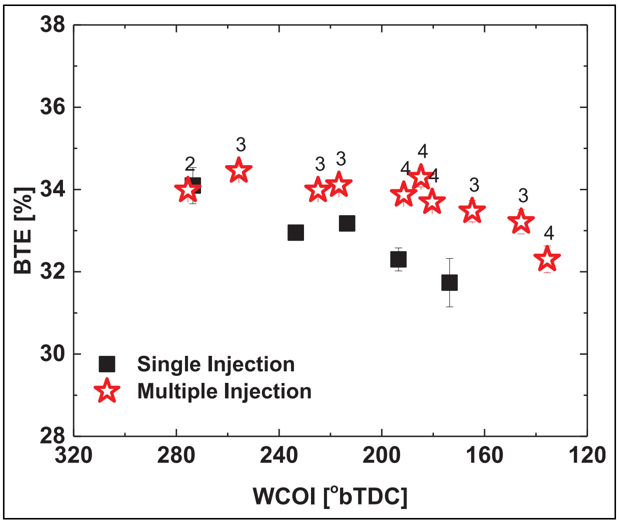

Figure 4. Maximum BTE results from Figure 3 filtered for comparison between single and multiple fuel injection events for E0 and MAP = 1000 mbar. The labels adjacent to the "Multiple Injection" symbols are the number of injections.

durations in a multiple injection event, based on the mass-weighted average for the injection strategy

$$WCOI = \frac{\left(\sum_{i=1}^{N} COI_i * ID_i\right)}{\left(\sum_{i=1}^{N} ID_i\right)}$$

here, COI_i is the center of injection timing of the ith injection event and ID_i is the injection duration of the ith injection. The expression in parentheses is therefore the mass fraction of fuel injected in the ith injection event.

Brake thermal efficiency calculation

For all experiments, the brake thermal efficiency (BTE) was calculated using the following formula

$$BTE = \frac{BP}{(FFR * LHV_{fuel})}$$

here, BP is the brake power (kW), calculated using the torque and speed measurements from the AVL AC induction dynamometer; FFR is the fuel flow rate (kg/s), measured by the piston-type fuel flow meter (#213-611-000; Max Machinery); and LHV_{fuel} is the lower heating value of the fuel blend (kJ/kg) calculated as mass-weighted average of the LHVs of pure gasoline (E0) and pure ethanol (E100).

Experimental results

Multiple fuel injection events—equal fuel mass

The results for BTE for the multiple injection experiments with equal fuel mass in each injection event are presented in Figure 3 for E0 and a MAP of 1000 mbar. The results for the single injection events are provided in the figure for comparison. (Comprehensive results for single injection events are provided in the Supplemental Appendix.) The error bars in all figures are the standard deviations of the recorded combustion cycles unless stated otherwise. Multiple injection events systematically improved BTE above the single injection baseline for all injection timings later than 260 °bTDC; however, there was little sensitivity to the specific number of multiple injection events.

Figures 4 through 7 compare the engine performance for BTE, and the engine-out emissions of CO, THC and NO_x, respectively. The fuel was E0 with a MAP of 1000 mbar. In the figures, the best results for each parameter were plotted, and the multiple injection results were not differentiated by the number of injection events. For example, the data of Figure 4 are down-selected from the results presented in Figure 3. The improvement in BTE achieved via multiple injections is more apparent in Figure 4. Figures 5 and 6 show that multiple injections can lower CO (15%–25%) and THC emissions (~30%). However, NO_x emissions were either unaffected or slightly higher with multiple injections for E0 at 1000 mbar, as shown in Figure 7. Higher combustion efficiencies were observed with multiple injection strategy as seen in Figure 8.

The improvement in BTE, and lower CO and THC emissions for E0 are attributed to improved mixing achieved with multiple injections for the same WCOI. Similarly, Imaoka et al.[20] showed an improvement in the homogeneity index as well as fuel consumption with the use of triple injection compared with single injection.

Results for BTE for E30 and E85 are shown in Figure 9 for MAP of 1000 mbar. Similar to results with E0, multiple injections improve BTE for some more stratified (i.e. later WCOI) conditions. The results for the gaseous emissions for E30 and E85 are presented in

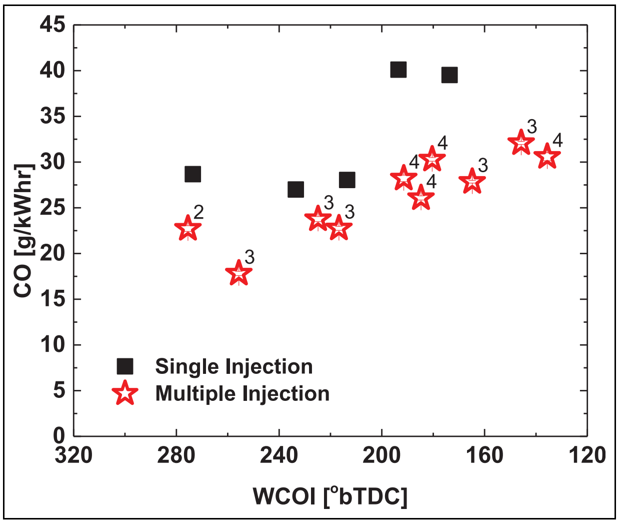

Figure 5. Comparison of CO emissions for single and multiple fuel injection events for E0 and MAP = 1000 mbar. The labels adjacent to the "Multiple Injection" symbols are the number of injections.

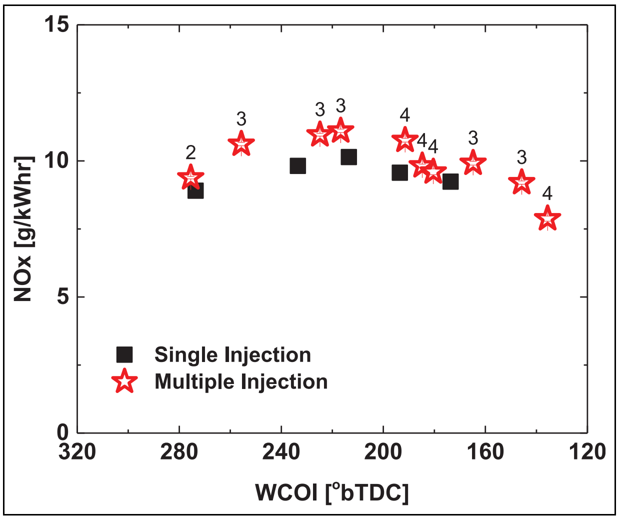

Figure 7. Comparison of NO_x emissions for single and multiple fuel injection events for E0 and MAP = 1000 mbar. The labels adjacent to the "Multiple Injection" symbols are the number of injections.

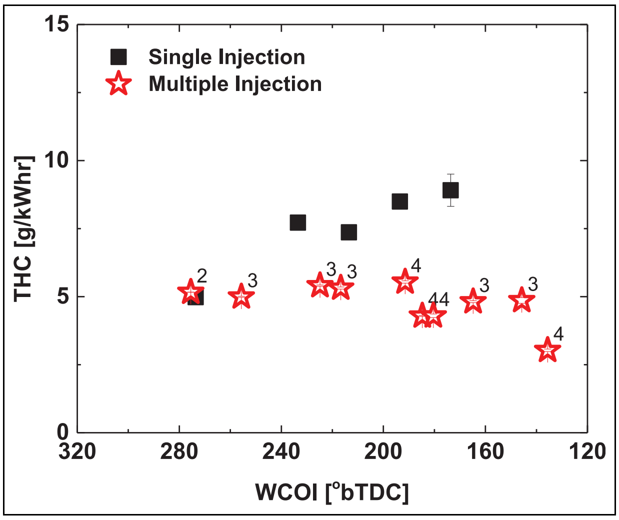

Figure 6. Comparison of THC emissions for single and multiple fuel injection events for E0 and MAP = 1000 mbar. The labels adjacent to the "Multiple Injection" symbols are the number of injections.

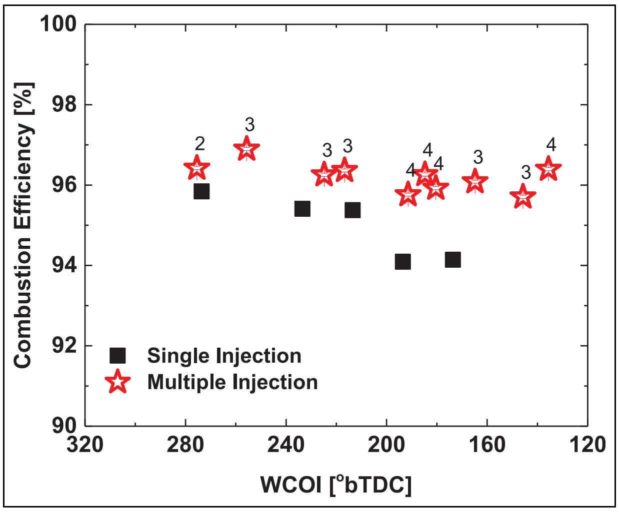

Figure 8. Comparison of combustion efficiency for single and multiple fuel injection events for E0 and MAP = 1000 mbar. The labels adjacent to the "Multiple Injection" symbols are the number of injections.

the Supplemental Appendix. Briefly, only CO emissions were affected significantly for E30 (decreased by 15%).

The use of multiple injection events systematically improved BTE in comparison with single injection events for more stratified conditions, that is, later WCOI timing, for all intake air pressures studied. Figure 10 shows the maximum relative improvement achievable in BTE as a function of MAP for the three fuels at WCOI ~173 °bTDC. The improvement in BTE was higher for higher MAPs for all fuels. The higher levels of MAP require longer injection duration to maintain stoichiometric air–fuel ratios, and multiple injection events likely enhanced homogeneity under these conditions. The lower sensitivity of BTE improvement for the E30 blend could be due to the nonlinear behavior of the fuel blend properties such as the vapor pressure and the distillation curve. For ethanol–gasoline blends, some of the parameters critical to fuel–air mixing, such as vapor pressure and the distillation curve, exhibit nonlinear behavior with ethanol content.[2] Blends ranging from E10 to E30 have a vapor pressure that is higher than that of both gasoline and ethanol. This could lead to easier evaporation of fuel, and thus less sensitivity of BTE to multiple injections.

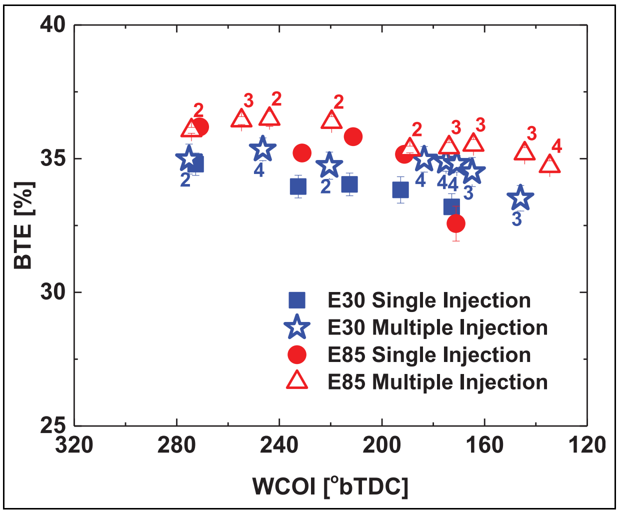

Figure 9. Comparison of maximum BTE for single and multiple fuel injection events for E30 and E85 and MAP = 1000 mbar. The labels adjacent to the "Multiple Injection" symbols are the number of injections.

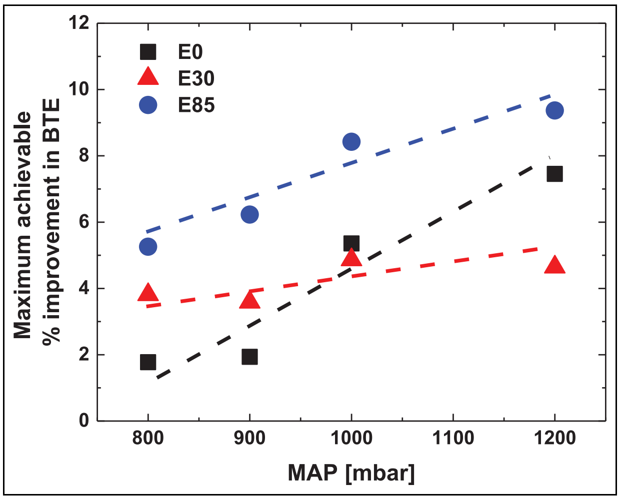

Figure 10. Maximum improvement in BTE achievable using multiple injections relative to the baseline of single injection for WCOI ~173 °bTDC.

Multiple fuel injection events—variable fuel mass

Previous studies with split injection[15,16] have shown that both the amount of fuel injected and the timing of the injections can impact engine performance significantly. In the preceding section, equal fuel mass was injected in each event. In order to explore the effects of varying the fuel mass distribution, a triple injection strategy was used where the injection timings (SOI1, SOI2 and SOI3) were fixed, and the fuel mass in each injection event was varied. Triple injection was selected as the BTE values were slightly better than for double injection and there was little difference between triple and quadruple injection results, as seen in Figure 3. For the first and second injections, fuel mass was varied from 0% to 100% of the total, and for the third injection, the fuel mass was varied from 0% to 50%, based on the combustion stability limit of maximum 5% coefficient of variance (COV) of indicated mean effective pressure (IMEP).

The injection timing was selected based on the results of the previous section. As seen in Figure 3 for multiple injection events, maximum BTE values were similar for WCOI from approximately 220 to 280 °bTDC. So, SOI1 was set at 280 to allow a larger range of timing for SOI2 and SOI3. SOI2 was set at 220 °bTDC because there was a slight decrease in BTE for later WCOI as seen in Figure 3. SOI3 was set at a late timing of 30 °bTDC as previous studies[15,20] suggest that retarded injection timing, closer to firing TDC, has a larger cooling effect which may be able to prevent knock and improve efficiency. All experiments were conducted using E0 (as it was the most sensitive to the use of multiple injections), and no emission measurements were made for this part of the study. The experimental matrix, including the fuel mass distributions considered, the corresponding values of WCOI and resulting BTE, is provided in Table A4 of the Supplemental Appendix.

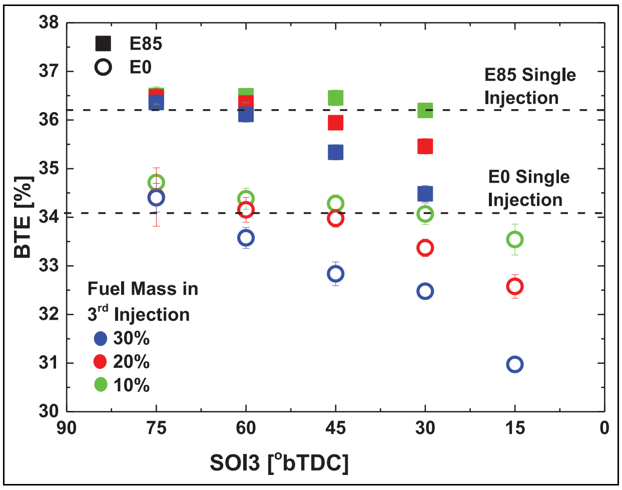

Figure 11. Effects of SOI3 timing and fuel mass on BTE for E0 and E85 and MAP = 1000 mbar. The results for single injection are provided for comparison as the dashed lines.

The maximum BTE for all MAPs was obtained when the fuel was equally split between the first and second injection events and the third injection event was not used. Furthermore, injecting 25% or more of the total fuel mass in the third injection event considerably lowered the BTE. The results emphasize the importance of the injection parameters (injection timing, number of injections and fuel split) on the performance of the engine. In particular, the effects of the third injection event vary significantly based on the timing and fuel mass. In this section, fixed SOI3 of 30 °bTDC and varying fuel mass were used. For the triple injection results shown in Figure 3, the most retarded SOI used was 95 °bTDC. Higher fuel mass in the third injection event, when the SOI3 was as retarded as 30 °bTDC, decreased the BTEs compared with single injection. This trend is clear in Figure 11 (discussed in next section). The decrease in BTE with more retarded SOI3

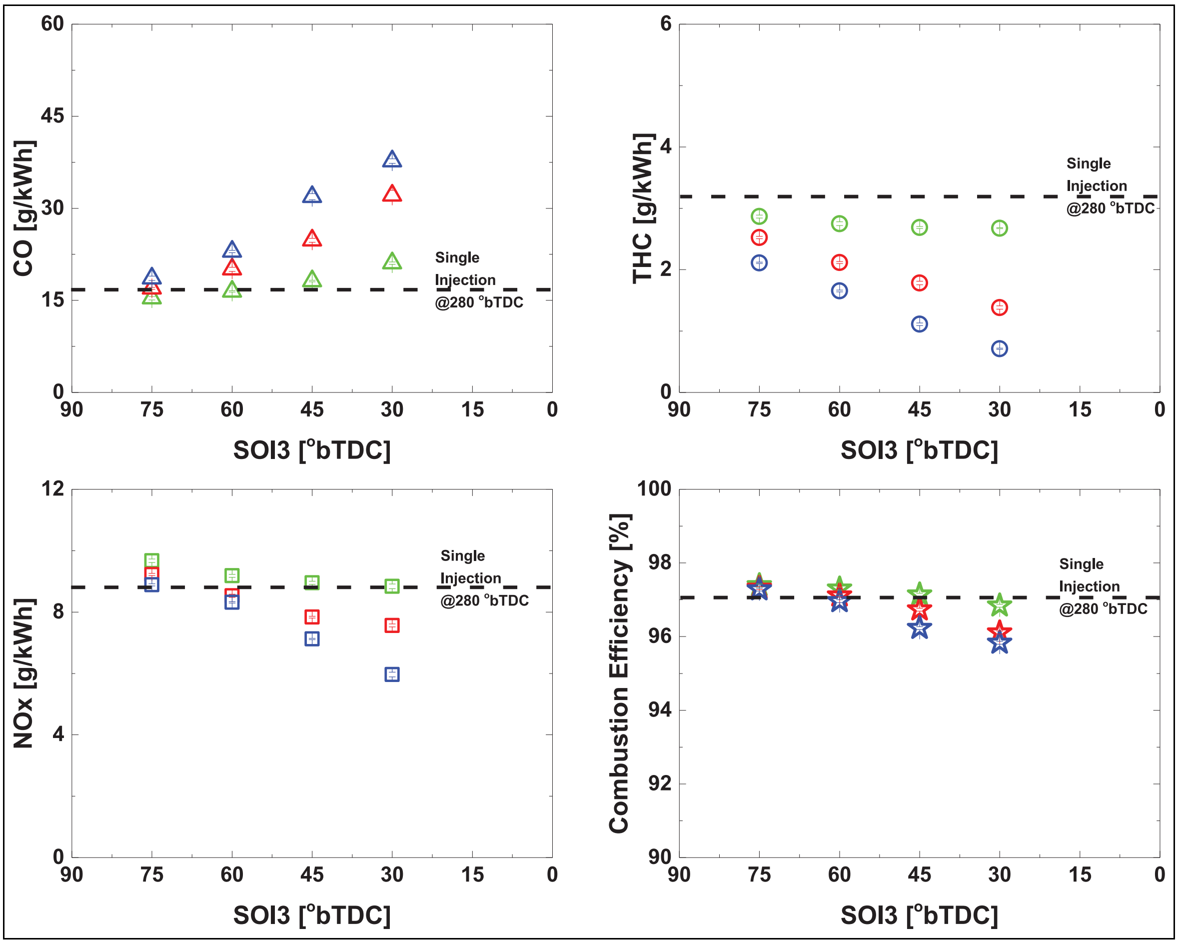

Figure 12. Effects of SOI3 timing and fuel mass on CO, THC, NO_x emissions and combustion efficiency for E85 and MAP = 1000 mbar. The results for single injection are provided for comparison as the dashed line. The color legend is same as for Figure 11.

timing is attributed to higher stratification and poorer mixing resulting from injecting such a large amount of fuel so late in the cycle. The results are consistent with previous studies[15,16] which concluded that with a split injection strategy, the best engine performance was achieved with both injections earlier in the intake stroke.

Multiple fuel injection events—variable fuel mass and injection timing (SOI3)

The previous results showed little benefit to varying the mass in the third injection event based on BTE, but only one set of injection timings was considered. In the next series of multiple injection experiments, a triple injection strategy was explored with fixed total fuel mass, fixed SOI1 and SOI2 timing, but both the fuel mass and the SOI3 timing of the third event were varied. SOI3 ranged from 15 to 75 °bTDC and the fuel in the third injection event was varied from 0% to 30% of the total fuel mass. The fuel mass injected in the first and second events was fixed at equal portions, that is, ranging from 50% to 35% of the total fuel mass. E0, E30 and E85 fuels were used at three MAPs of 800, 1000 and 1200 mbar for the experiments; the BTE and emission measurements were made. Table A5 of the Supplemental Appendix shows the experimental matrix used.

The results for BTE are presented in Figure 11 as a function of SOI3 for E0 and E85. As the SOI3 timing was advanced, the BTE values approached the baseline of the single injection data irrespective of the amount of fuel mass injected in the third event. The performance decreased from the baseline as SOI3 approached TDC firing (15 °bTDC) and as the fuel mass injected in the third event increased. While BTE for some of the triple injection data were slightly higher than the single injection baseline, the improvement was within the standard deviation of the results. Thus, changing the injection timing and fuel mass in the third injection event had small effect on BTE. For clarity, the E30 data are not included in the figure. However, similar trends were observed with E30 fuel as well.

The results for the engine-out CO, THC, NO_x emissions and combustion efficiency are presented in Figure 12 for E85. THC emissions were systematically reduced with

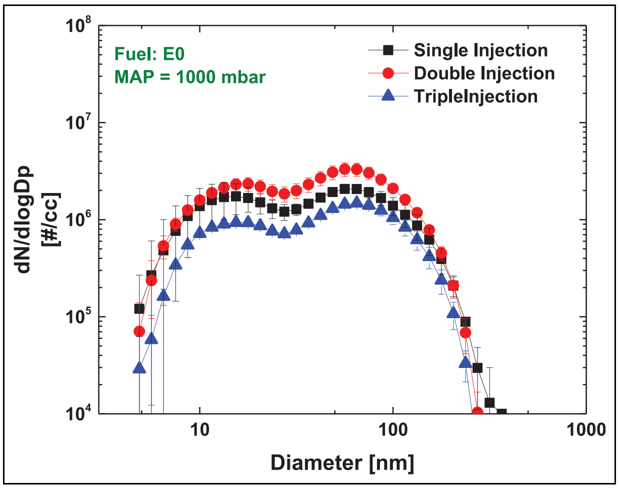

Figure 13. PN size distributions for E0 and MAP = 1000 mbar using the injection strategies presented in Figure 14. The error bars represent the standard deviations of the average recorded PN distribution for 2 days.

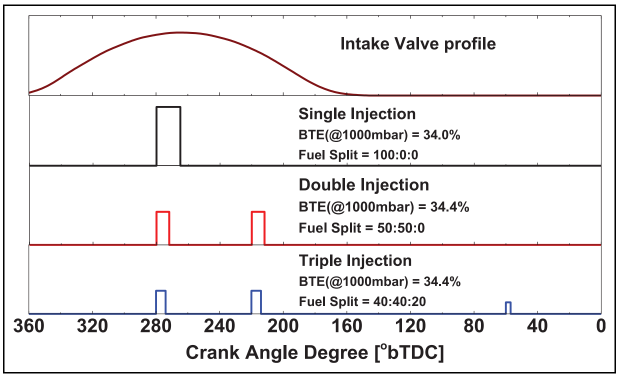

Figure 14. Injection strategies used for comparison of the PN emissions distribution presented in Figure 13. The areas of the bars represent the relative mass in each injection event.

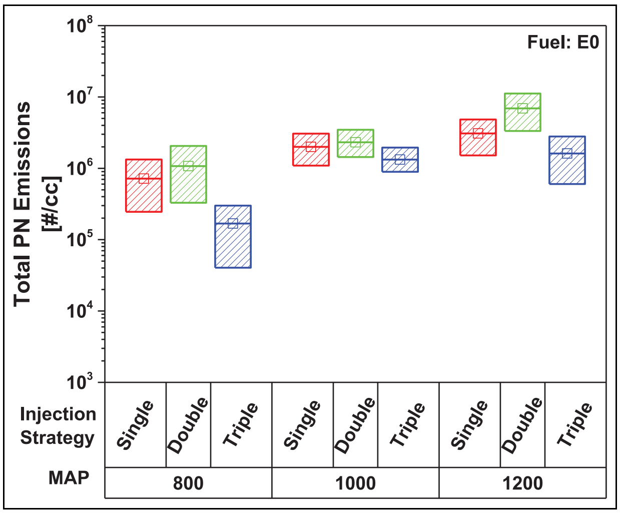

Figure 15. Total PN emissions for E0 as a function of MAP and the injection strategies presented in Figure 14. The limits of each box are the 10th and 90th percentiles, and the square marker is the mean of each condition.

retarded SOI3 injection and increasing fuel mass in the third injection event for all fuel blends. However, CO emissions increased with later injection and increasing fuel mass in the third injection event. The results are consistent with later injection timing leading to increased stratification and less time for mixing and combustion, as indicated by the lower combustion efficiency with later SOI3. Similar sensitivity and trends with respect to SOI3 timing and the distribution of fuel mass were observed for E0 and E30 and for the other MAPs tested. Corresponding results for MAP of 1000 mbar for E0 and E30 are provided in the Supplemental Appendix (Figures A14 and A15).

Injection strategies to reduce particulate emissions

The effects of the different injection strategies on PN emissions are presented here. While PN emissions were measured for many operating conditions, for conciseness, a summary of the results is presented here. The data are based on the experiments of the previous section, where variable fuel mass distribution and variable timing for SOI3 were investigated.

A comparison of the single, double and triple injection strategies on the PN size distribution as a function of particle size for E0 and MAP of 1000 mbar is presented in Figure 13. For the comparison, the injection timings and fuel mass distributions shown in Figure 14 were used. These injection strategies yielded comparable BTE (see Figure 11) and CO emissions with lower THC emissions (see Figure 12) for the triple injection strategy. The timing and fuel mass distribution used for the triple injection strategy were the conditions that yielded the lowest total PN emissions.

The data in Figure 13 show that the triple injection strategy reduced the PN emissions for E0 for all size particles, yielding a 30% reduction in total PN concentration for the triple injection strategy in comparison with the single injection event. The same trends were observed for E0 for the other intake air pressures studied, as seen in the total PN results presented in Figure 15. The data in Figure 15 also show that increasing MAP from 800 to 1200 mbar increased PN for all injection strategies by almost an order of magnitude (note the decade log scale used in the figure). The increase in PN with increase in MAP or engine load is consistent with the results from previous studies.[21] Increased load requires longer fuel injection duration to maintain stoichiometric combustion. The increase in fuel injection duration leads to higher spray tip penetration and thus higher potential for wall and piston impingement and the formation of fuel films. Fuel films are well-known sources of particulate emissions.[22]

Figure 16 presents the particle size distributions for E0, E30 and E85 at MAP of 1000 mbar for the triple injection strategy presented in Figure 14. Increasing

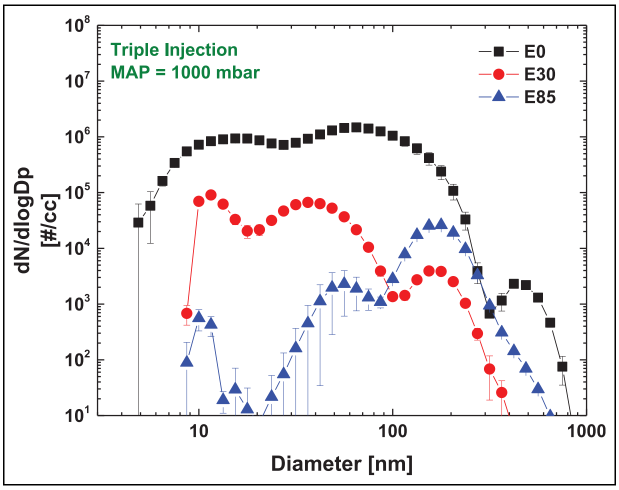

Figure 16. PN size distributions for E0, E30 and E85 at MAP = 1000 mbar using the triple injection strategy shown in Figure 14. The error bars represent the standard deviations of the average recorded PN distribution for 2 days.

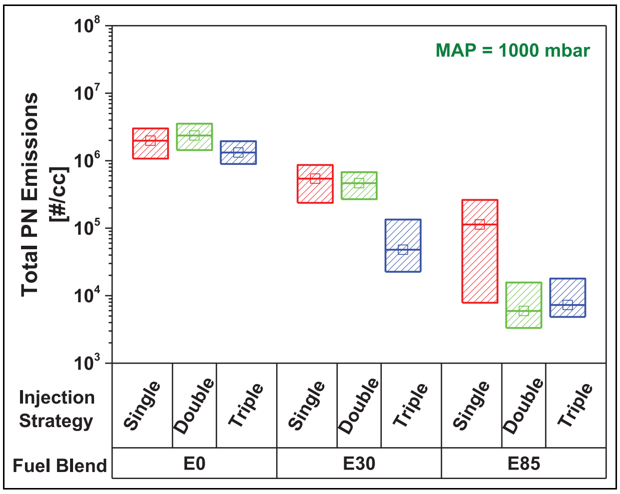

Figure 17. Total PN emissions for E0, E30 and E85 at MAP = 1000 mbar and using the injection strategies of Figure 14. The limits of each box are the 10th and 90th percentiles, and the square marker is the mean of each condition.

ethanol content decreased the PN emissions at all sizes. Figure 17 shows the total PN for each fuel and the effects of the different injection strategies. The multiple injection strategies combined with E85 decreased the total PN emission concentration by over an order of magnitude compared with E0. The triple injection strategy reduced total PN for all fuels, but was more effective at reducing total PN for the ethanol blends.

In this work, the triple injection strategy decreased the fuel mass injected in both the first and the second injection events compared with the double injection strategy. There may have been less wall wetting with the triple strategy due to the shorter injection durations. The triple injection strategy may have also resulted in better fuel–air mixing. Note that the differences in the PN emissions from the single and double injection strategies were small, with considerable overlap between the 10th and 90th percentiles of each distribution.

An additional consideration is fuel injector tip wetting which can lead to particulate emissions. Fischer and Thelliez[23] reported that a split injection increased fuel injector tip sooting compared with a single injection. This could be due to more injector opening and closing events which may lead to higher wetting of the fuel injector tip. The significant decrease in PN emissions with the triple injection strategy observed in the current work indicates that fuel injector tip wetting is not a significant source of PN for the conditions studied.

As seen in Figure 16, the PN emissions in the nuclei mode decrease more with increasing ethanol content than the PN emissions in the accumulation mode. One possible explanation for the larger decrease in the nuclei mode could be that low volatility HCs, from which 10 nm particles originate,[24] may be less prominent in ethanol blends. Alternatively, the chemical pathways for soot nucleation such as the formation of acetylene may be altered by the ethanol. The increase in the accumulation mode with E85 relative to E30 may be an indication of longer residence time for the soot particles that are formed. However, further studies would be required to identify the dominant particulate formation and growth pathways.

Higher PN emissions corresponding to larger diameters for E85 compared with E30 fuel will contribute more to PM emissions. The effects of injection strategy and fuel composition on PM emissions were estimated using the PN data. Assuming the soot particles were spherical and using an effective particle density correlation from Liu et al.,[25] the total PM was calculated. The results are presented in Figure 18, with the caveat that the PN data were collected after removal of particles larger than 1 μm. The removal of the larger particles will significantly affect the total PM; however, the estimates provide information on the trends for the PM in the size range up to 1 μm. The results in Figure 18 show that the ethanol significantly reduced PM for single injection conditions; and both ethanol blends (E30 and E85) yield similar reduction in PM using triple injection strategy.

The reduction in PN emissions observed with triple injection for E0 is consistent with the results of the previous studies[17,26] which attributed the decrease in PN to reduced fuel spray penetration and thus lower piston and wall impingement. Previous literature also reported reduction in PN and PM emissions with an increase in ethanol content in the fuel.[27] Westbrook et al.[28] in their chemical kinetic modeling study found a direct relation between the fraction of oxygen (ethanol) in diesel fuel and reduction in percent of fuel carbon converted to soot precursors, indicating a strong chemical pathway to reducing particulates. Similarly, Chen et al.[29] reported lower PN emissions with E25 compared with gasoline and attributed the low particulate formation

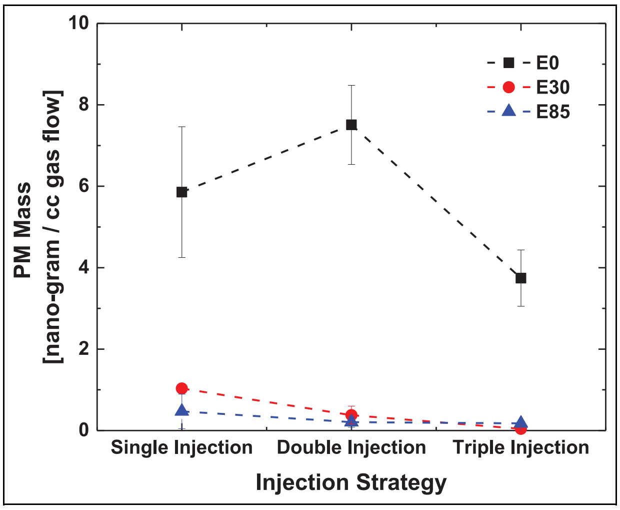

Figure 18. Estimates for particulate mass based on the size-resolved PN data for MAP = 1000 mbar.

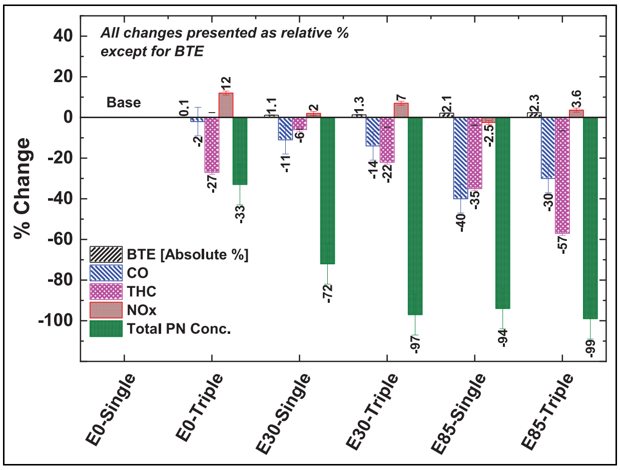

Figure 19. Comparison of single and multiple injection strategies that yielded the highest reduction in PN.

to chemical effects of ethanol. However, Chen et al.[29] also reported that the higher heat of vaporization of ethanol results in high evaporative cooling which enhances formation of residual liquid film mass, which is a source of particulates and thus PN formation also depends on operating conditions.

Figure 19 summarizes the effects of the different fuels and injection strategies on the engine performance metrics for the conditions that yielded the greatest reduction in total PN (SOI1 = 280; SOI2 = 220; SOI3 = 60; fuel distribution = 40:40:20). All ethanol blends yielded improvements in all metrics, except NO_x which was mostly unaffected in comparison with E0. In addition, multiple injection strategies improved the performance further for each fuel blend in comparison with single injection strategies.

Engine sensitivity to different fuel blends

The WCOI enabled comparing single injection data with the results of the multiple injection strategies using the WCOI as a representative injection timing. Some of the engine metrics showed greater sensitivity to WCOI, such as BTE for E0, than other parameters, such as BTE for E30. The timing of the injection strategy is an indication of the homogeneity of the fuel–air mixture; however, WCOI does not completely capture the distribution of the fuel mass in the injection events. Fuel mass distribution also affects stratification and mixing of the fuel and air. To evaluate the role of mass distribution, the results of the study were evaluated using a new parameter defined as the weighted injection spread (WIS). Here, the spread refers to the timing of the different injection events relative to the WCOI. The definition is based on the mass-weighted average relative to the WCOI timing

$$WIS = \frac{2 * \sum_{i=1}^{N} IS_i * ID_i}{\sum_{i=1}^{N} ID_i}$$

where IS_i is the spread of ith injection $= |COI_i - WCOI|$. Note that WIS is zero for a single injection event. The factor of 2 is used to make the WCOI and WIS scales comparable.

Generally, earlier WCOI leads to more homogeneous mixtures and later WCOI leads to more stratified mixtures; however, the spread of injection also affects stratification. For example, higher WIS at later WCOI timing will reduce stratification. For reference, schematic diagrams illustrating different values of WCOI and WIS are provided in the Supplemental Appendix (Figures A1–A3).

Figure 20 presents the BTE, CO, THC and NO_x emission data for E0 as a function of the overall injection characteristics WCOI and WIS. Some clear trends are apparent in the figure. Very retarded WCOIs lead to poor efficiency with moderate emission benefits. The highest BTE values correspond to mid-range WCOIs (~225 °bTDC), not the most advanced injection timing and importantly, for fixed mid-range WCOI, the maximum benefits in terms of efficiency and emissions are found at the maximum values of WIS. The mid-range WCOI timing and higher WIS indicate that favorable performance is achieved by allowing more time for fuel and air mixing and minimizing stratification as much as possible through higher values of WIS. Also, the large range of variability in performance possible for a fixed mid-range WCOI as a function of WIS indicates the value of using WIS to characterize the fueling strategies.

Interestingly, the lowest NO_x and THC emissions occurred at the maximum WIS considered in the study with a WCOI of ~175 °bTDC. These conditions correspond to higher fuel mass injected closer to firing TDC, which may contribute to lower peak in-cylinder temperatures[20] and thus lower NO_x emissions.

Figure 21 presents the results for E85 as a function of WCOI and WIS. Results for E30 are similar and are provided in the Supplemental Appendix (Figure A18).

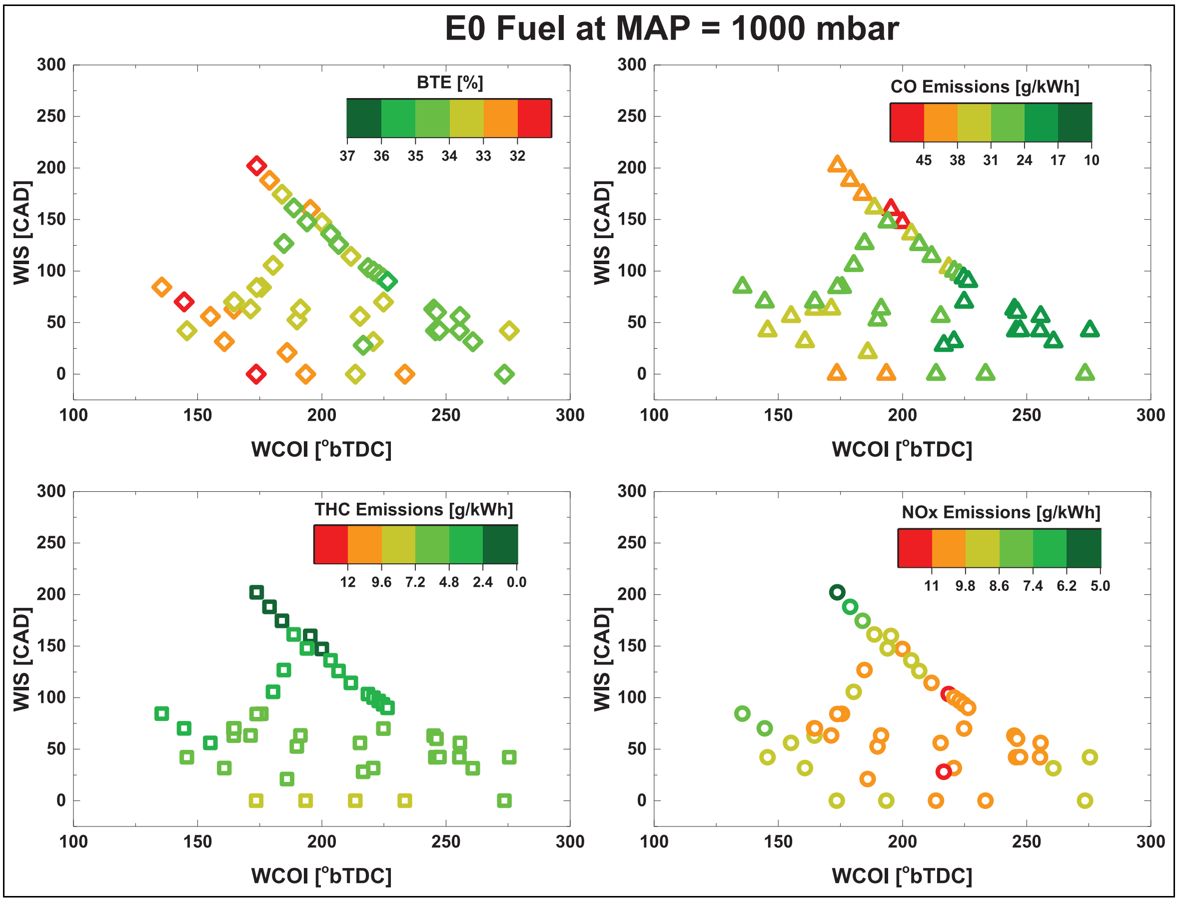

Figure 20. E0 results for MAP = 1000 mbar. (For interpretation of the references to color in the figure legend, the reader is referred to the web version of this article.).

In comparison with E0, all metrics improve with the E85. An important conclusion of comparing the data for E0 and E85 is the similar sensitivity of the engine performance to the different fuel blends. The consequence of the similar fuel response facilitates translation of the engine control calibrations between different ethanol and gasoline fuel blends.

It is evident in this study that the injection timing and fuel mass in each injection event play important roles in engine performance. The combination of WCOI and WIS factor into consideration fuel injection timing, spread and fuel mass of each event. If the fuel mass in the first injection event is greater than 80%, the engine efficiency is a strong function of the first injection event, but it is not the sole injection event defining engine performance. For example, changing SOI3 with only 10-30% of the total fuel mass changed BTE by 3% (absolute units, see Figure 11). Thus, defining parameters like WCOI and WIS to characterize multiple injections is necessary and a valuable addition to the literature on multiple injection strategies.

It is noted that WCOI and WIS are overall parameters, and some details such as number of injections may be overlooked using these parameters. However, the combination of WCOI and WIS factor into consideration fuel injection timing, spread and fuel mass of each event; and it is very evident through this study that the injection timing and fuel mass injected in each injection event affect engine performance. With no other parameter or method available at present to characterize the multiple injection strategies such as WCOI and WIS, the authors believe defining these parameters is necessary and a valuable addition to the literature on multiple injection strategies.

Conclusion

The key objective of the study was to quantify the effects of multiple fuel injection events and ethanol fuel blends on engine performance in comparison with a single fuel injection event for gasoline. The large parametric space of different multiple injection strategies had not been previously considered for ethanol blends. Key conclusions based on the experimental results are as follows:

- A combined application of ethanol blends with a multiple injection strategy can help achieve considerable improvement in engine emissions while maintaining engine BTE. In the present work, compared to single injection of E0, a multiple fuel injection strategy using E85 fuel resulted in more than 90%

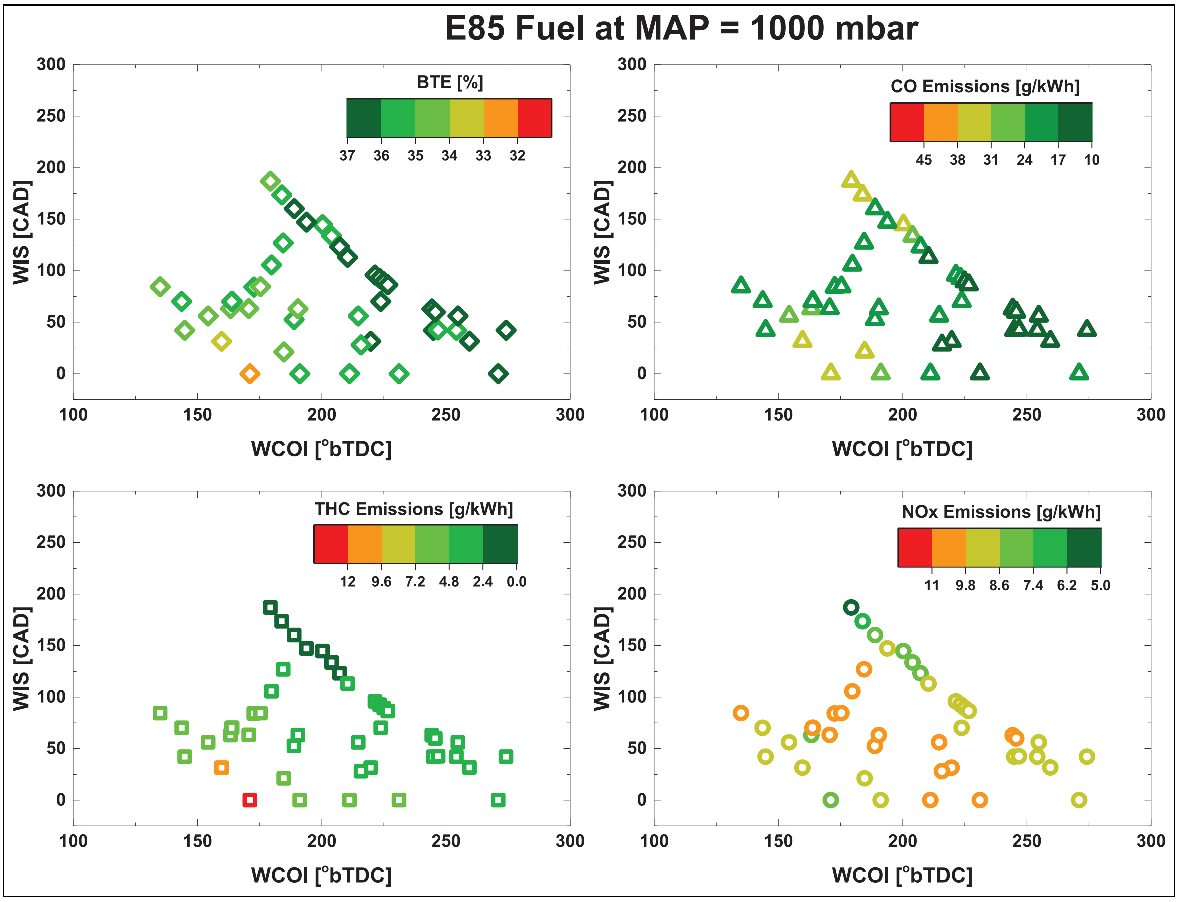

Figure 21. E85 results for MAP = 1000 mbar. (For interpretation of the references to color in the figure legend, the reader is referred to the web version of this article.).

reduction in total PN emission concentration, 50% reduction in THC and 35% reduction in CO on a relative basis, with 2.4% absolute improvement in BTE.

- The ethanol blends outperformed E0 for engine performance metrics considered in this study. For all the ethanol fuel blends tested, the engine performance metrics exhibited similar response and sensitivity to different injection strategies as with E0, thus indicating that injection strategies (e.g. number of injections and injection timing) employed to improve performance in this study (or any other study) can be readily used for different fuel blends.
- Multiple injection strategies are more effective at improving performance at higher MAPs.
- The results of the study showed that engine performance was very sensitive to more than just one characteristic of the injection strategy. For example, the timing and the distribution of fuel mass of the different injection events were all contributors to engine performance. A new parameter, the WIS, was introduced to characterize the different important parameters of multiple fuel injection strategies. The WIS parameter combined with the WCOI timing defined in the previous literature was found well suited to characterize multiple injection strategies, including the effects of the number of injections, fuel mass in each injection and the dwell time between injections. This characterization using WCOI and WIS was useful in making results and trends clearly observable in this work and would also be useful for future multiple fuel injection studies. Favorable engine performance was achieved using a mid-range value of WCOI timing with higher values of WIS.

Acknowledgements

The authors would like to thank Andrew Karpin, Engine Calibration Engineer at Robert Bosch LLC, for technical support.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was supported by the US Department of Energy Vehicle Technologies Office, especially Kevin Stork and Carl Maronde (contract no. DE-EE0006831).

Supplemental material

Supplemental material for this article is available online.

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