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# Ethanol Blends and Engine Operating Strategy Effects on Light-Duty Spark-Ignition Engine Particle Emissions

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**ABSTRACT:** Spark-ignition (SI) engines with direct-injection (DI) fueling can improve fuel economy and vehicle power beyond that of port fuel injection (PFI). Despite this distinct advantage, DI fueling often increases particle number emissions, such that SI exhaust may be subject to future particle emissions regulations. In this study, ethanol blends and engine operating strategy are evaluated for their effectiveness in reducing particle emissions in DI engines. The investigated fuels include a baseline emissions certification gasoline, a blend of 20 vol % ethanol with gasoline (E20), and a blend of 85 vol % ethanol with gasoline (E85). The operating strategies investigated reflect the versatility of emerging cam-based variable valve actuation technology capable of unthrottled operation with either early or late intake valve closing (EIVC or LIVC). Particle emissions are characterized in this study by the particle number size distribution as measured with a scanning mobility particle sizer (SMPS) and by the filter smoke number (FSN). Particle emissions for PFI fueling are very low and comparable for all fuels and breathing conditions. When DI fueling is used for gasoline and E20, the particle number emissions are increased by 1−2 orders of magnitude compared to PFI fueling, depending upon the fuel injection timing. In contrast, when DI fueling is used with E85, the particle number emissions remain low and comparable to PFI fueling. Thus, by using E85, the efficiency and power advantages of DI fueling can be gained without generating the increase in particle emissions observed with gasoline and E20.

## ■ INTRODUCTION

The Energy Independence and Security Act of 2007 (EISA) requires a fuel economy improvement from the 2007 current corporate average fuel economy (CAFE) of 24.1 miles per gallon (mpg) to a CAFE of 35 mpg in the year 2020.[1] In response to a presidential memorandum, the United States Environmental Protection Agency (U.S. EPA) and the National Highway Traffic Safety Administration (NHTSA) have accelerated the timeline by requiring a combined car and light truck fleet average $CO_2$ emissions of 250 g/mile by 2016,[2] which is approximately equivalent to a combined fleet fuel economy 35.5 mpg. With these regulations as the impetus, technologies designed to improve fuel economy have begun to be incorporated into production vehicles. These technologies include hybrid electric technology, cylinder deactivation, variable valve actuation, and gasoline direct-injection (DI) fueling.

DI fueling for gasoline engines is an enabling technology for the development of vehicles with better fuel economy. In combination with turbocharging, gasoline DI fueling significantly improves engine power, which allows the engine displacement volume to be reduced for a given application (downsizing), even while the engine performance improves.[3] When the engine is downsized, the engine friction is reduced and the engine operates at higher engine loads for a larger fraction of the operating map, as quantified by the brake mean effective pressure (BMEP), which results in more efficient operation. In addition, gasoline DI fueling reduces the tendency of a fuel to knock because of enhanced charge cooling, allowing the compression ratio to be increased for higher efficiency. As a result, fuel economy can be increased for vehicles with DI fueling compared to engines with port fuel injection (PFI) technology.

DI gasoline engines are being rapidly incorporated into new vehicles in the United States. PFI technology has been nearly ubiquitous in light-duty vehicles over the past 2 decades, accounting for over 99% of all light-duty vehicles sold in the United States each year between 1996 and 2007.[4] Since that time, gasoline DI fueling has begun to emerge, accounting for 2.3% of light-duty gasoline vehicles in 2008 and rising to 8.5% in 2010.[4] The percentage of vehicles with gasoline DI technology in the United States is expected to continue increasing rapidly, with a projection of 60% of all new vehicles by 2016.[5]

While gasoline DI technology is beneficial for fuel economy, it produces an increase in particulate matter emissions in comparison to PFI engines. Aakko and Nylund[6] reported that the particle mass emissions for a gasoline DI vehicle were an order of magnitude higher than for a PFI vehicle for the European 70/220/EEC drive cycle. Similarly, the particle number emissions reported by Aikawa et al.[7] were roughly a factor of 5 higher for the DI vehicle than for the PFI vehicle, although direct comparison of these is difficult because different vehicle drive cycles were used. A report issued by the California Air Quality Board[5] estimates that, on average, particle mass emissions are increased somewhere between 2 and 20 times for gasoline DI engines compared to PFI.

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Reductions in particle emissions from DI engines are being pursued with a number of different strategies. Moore et al.[8] show that increased charge motion achieved through deactivation of one of the intake valves is effective in reducing soot emissions, as quantified by the filter smoke number (FSN). Hedge et al.[9] show that exhaust gas recirculation (EGR) is effective at reducing particle emissions at part-load operation while simultaneously improving fuel consumption, likely through a reduction in throttling losses. Additionally, Iyer and Yi[10] showed that improvements can be made in the targeting of the fuel spray to reduce soot emissions. With DI fueling strategies being relatively new to production engines, further improvements to fuel injection hardware and engine operating strategies may allow for further reductions in particle emissions.

However, solving the issue of increased particle emissions from gasoline DI engines may be complicated by the fact that the fuel diversity in the marketplace is increasing. The same EISA legislation that requires improved fuel economy also requires that the amount of bio-derived fuels increase more than 7-fold from their 2007 levels by 2020.[1] Although there will be a variety of different fuel types that contribute, ethanol is expected to comprise the overwhelming majority of the bio-derived fuel.

A number of investigations have examined the effect of ethanol content on particle emissions in vehicles. Storey et al.[11] found that blends of 10 and 20% ethanol in gasoline (E10 and E20) decreased particle number emissions during vehicle drive cycles, with the 20% blend decreasing particles by about 40% during the high-load US06 vehicle drive cycle. In comparison to gasoline, He et al.[12] found a 20% reduction in particle emissions with E20 but no change with E10. Khalek and Bougher[13] showed that E10 increased particle emissions compared to two different gasoline formulations, both with higher volatility than the E10. This work showed the importance of the hydrocarbon fraction of the E10 blend and suggests that the heavier hydrocarbons used to control vapor pressure of E10 may also increase particulate emissions. Aakko and Nylund[6] found that the particle mass emissions from 85% ethanol (E85) were comparable to those with gasoline in a PFI vehicle but that DI fueling with gasoline produced particle emissions that were an order of magnitude higher.

The previous studies investigating the effect of ethanol fuels on particle emissions have operated production engines in their original equipment manufacturer (OEM) configurations and calibrations. There have also been a number of additional recent research efforts to optimize engine efficiency for high concentrations of ethanol to reduce the fuel economy penalty associated with the lower energy density of ethanol.[14−18] In addition to the use of DI fueling, each of these research efforts represents departures from how spark-ignition (SI) engines are conventionally operated, particularly in regard to engine breathing strategies and compression ratio. The purpose of this investigation is to elucidate the effects of fuel type, fueling strategy, and engine breathing strategy on particle emissions in a flexible SI engine that was designed for optimization with ethanol.

## EXPERIMENTAL METHODOLOGIES

**Engine Platform and Experimental Procedure.** The engine used in this study has been developed specifically for high-efficiency operation with ethanol. The base engine is a four-cylinder GM gasoline DI engine with turbocharging and dual independent cam phasing, and the engine has undergone a number of modifications. The detailed description of the unique engine hardware and operating strategy, including cam profiles, have been described in previous publications by Hoyer et al.[19] and Moore et al.[20] and are summarized here. The engine is equipped with custom-designed pistons that increase the compression ratio from 9.2 to 11.85 to leverage the high octane potential of ethanol fuels. The valvetrain has also been modified from its OEM configuration to increase the cam phasing authority to 80 crank angle degrees (CAD) and to accept a two-step VVA system that employs both early and late intake valve closing (EIVC and LIVC) strategies to control the effective displacement and effective compression ratio and to reduce pumping work compared to throttled operation. Pumping work is reduced because intake air flow is controlled through intake valve closing angle rather than throttling, as illustrated in the $P-V$ diagrams in Figure 1. The engine geometry and specifications are given in Table 1. Previous investigations have demonstrated efficiency benefits with both EIVC and LIVC operation.[20−22]

The engine is designed with a DI fueling system, and a PFI system has been added to allow for a direct comparison of fueling strategy. Engine management is performed with a DRIVVEN engine controller, allowing full access to all engine control parameters, including fuel injection timing, fuel injection duration, fuel injection pressure, spark timing, high or low lift cam profile, cam phasing, and throttle position. The engine is equipped with a turbocharger, but all conditions in this study are performed under naturally aspirated conditions by maintaining an open position on the turbocharger waste gate.

**Table 1. Engine Geometry and Specifications**

| | |
|---|---|
| displacement (L) | 2.0 |
| bore (mm) | 86 |
| stroke (mm) | 86 |
| compression ratio | 11.85 |
| fueling | DI and PFI |
| DI pressure (bar) | 100 |

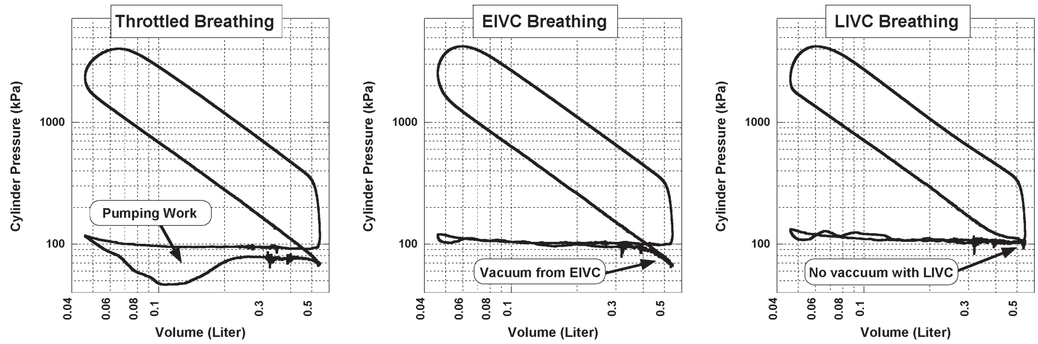


**Figure 1.** $P-V$ diagrams for the three different engine breathing strategies for gasoline.

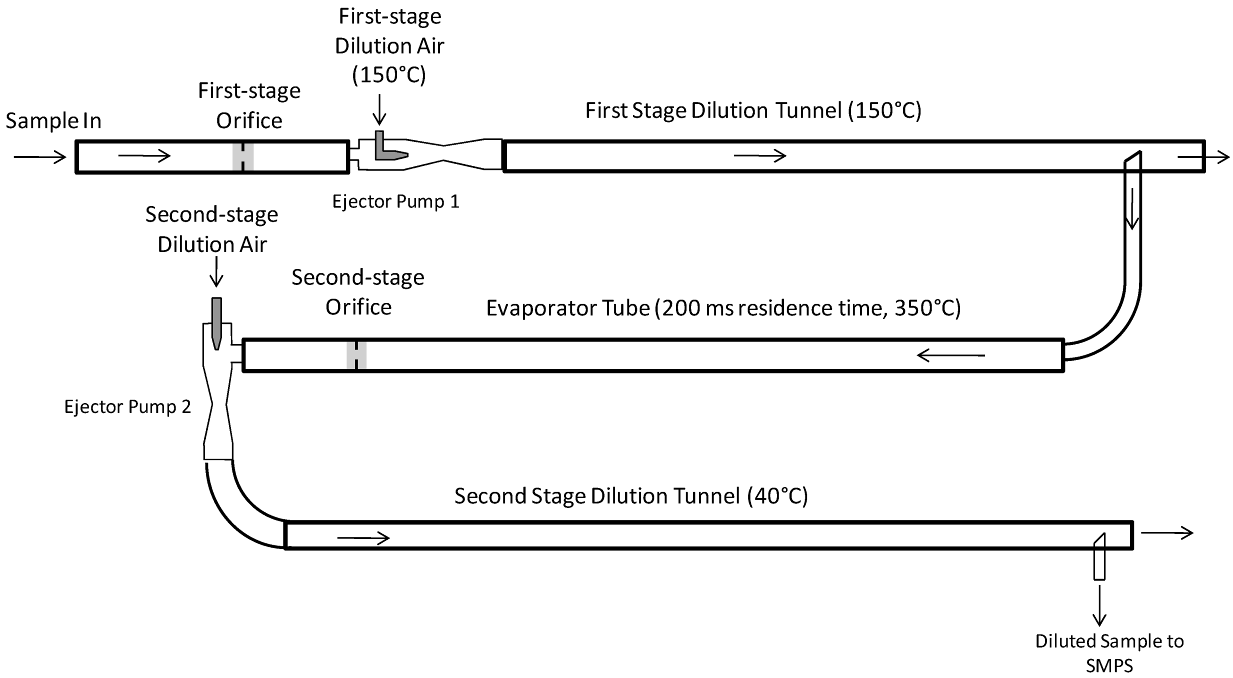


**Figure 2.** Schematic of the two-stage dilution system with an evaporator tube.

Cylinder pressure and fuel injection command signals are acquired at the shaft encoder resolution of 0.2 CAD. The cylinder pressure is recorded from each of the four cylinders using piezoelectric pressure transducers side-mounted in the engine block. The signals are acquired using National Instruments data acquisition hardware and analyzed using the DRIVVEN combustion analysis toolkit (microDCAT).

Gaseous engine emissions are measured using a standard emissions bench. $NO_x$ and hydrocarbon (HC) emissions are measured directly from the hot exhaust using a chemiluminescence analyzer and a flame ionization detector (FID), respectively. Exhaust gas is chilled to condense water in the exhaust prior to measurements of CO and $CO_2$ using infrared analyzers and for oxygen using a paramagnetic analyzer.

Particulate emissions from the engine are measured using an AVL FSN instrument as well as a scanning mobility particle sizer (SMPS). FSN is an industry standard that has long been used to provide rapid and repeatable measurements of smoke emissions for diesel engine research and development. The measurement principle is based on a change in filter paper reflectivity and is intended to be proportional to particulate mass collected on the paper.[23] The sensitivity of the FSN instrument is limited at the lowest particle emission levels with both PFI and DI fueling, but it has proven to be a useful measure at many engine conditions for previous gasoline engine studies with DI fueling in the past.[8,24] FSN is measured from the raw exhaust downstream of the three-way catalyst.

For the particle number size distribution measurements with the SMPS, a two-stage microtunnel dilution system with an evaporator tube is used to condition the exhaust. Number size distributions from 9 to 500 nm diameter particles are measured by a SMPS (model 3936, TSI, Inc.) equipped with the differential mobility analyzer (DMA, model 3085, TSI, Inc.) and condensation particle counter (model 3025, TSI, Inc.). Each SMPS measurement is the average of three SMPS scans, resulting in a total sampling time of about 9 min. The dilution system is based on an ejector pump dilution design by Abdul-Khalek et al.[25] The probe for the SMPS measurements is located in the pre-catalyst position in the exhaust system.

The dilution system is located in close proximity to the engine exhaust, requiring only a short section of insulated stainless-steel tubing (40 cm) to connect the exhaust to the first-stage orifice. The two-stage microdilution system is designed to vaporize the liquid-phase particles, leaving only the solid particles to be measured by the SMPS, as performed previously by the European Particle Measurement Programme (PMP) systems[26] and as in proposed legislation by the California Air Resource Board.[5] In an effort to accomplish this, (1) the air for the first-stage dilution is heated to 150 °C, and the first-stage dilution tunnel is maintained at 150 °C. (2) The second-stage ejector pump draws the sample from the first-stage dilution tunnel, through an evaporator tube, and into the second-stage dilution tunnel. The evaporator tube is maintained at a temperature of 350 °C for a residence time of approximately 200 ms in an effort to vaporize condensed-phase liquid droplets. (3) The air for the second-stage dilution is not heated, and the second-stage dilution tunnel is maintained at a temperature of 40 °C. The lower temperature of the second-stage dilution system is due to the inlet temperature limitation of the SMPS system. The first-stage dilution ratio is 5:1, and the second-stage dilution ratio is 6:1, producing an overall dilution ratio of approximately 30:1. The design of the system is somewhat similar to that of the PMP,[26] but we used a lower dilution ratio to provide a greater number of particles for statistically significant SMPS number size distributions. A schematic of the two-stage dilution system is shown in Figure 2.

**Fuels.** Three fuels differing in ethanol concentration are investigated in this study, including a baseline gasoline, E20, and E85. The full specifications for the fuels are given in Table 2. The baseline gasoline has a high anti-knock index $[(R + M)/2 = 92.9]$, and as a result, it is not necessary to retard spark timing from the maximum brake torque timing for knock mitigation in this investigation. The fuel properties show the expected trends, with specific gravity, research octane number (RON), anti-knock index, and octane sensitivity all increasing with ethanol content. The maximum Reid vapor pressure occurs for the E20 fuel blend because of the well-established azeotrope phenomenon.[27]

**Engine Operating Conditions.** All data for this investigation is collected at an engine speed of 1500 rpm and a load of 8 bar BMEP, with the air/fuel ratio maintained at stoichiometric conditions throughout the investigation to maintain compatibility with three-way catalyst technology.

Table 2. Fuel Properties

| | | gasoline | E20 | E85 |
|---|---|---|---|---|
| specific gravity | ASTM D4052 | 0.7437 | 0.7545 | 0.7865 |
| Reid vapor pressure (psi) | ASTM D5191 | 8.49 | 9.32 | 4.82 |
| net heat of combustion (kJ/kg) | ASTM D240 | 43225 | 39747 | 29168 |
| research octane number | ASTM D2699 | 97.1 | 102 | 106 |
| motor octane number | ASTM D2700 | 88.7 | 90.3 | 88.7 |
| anti-knock index [$(R + M)/2$] | | 92.9 | 96.2 | 97.4 |
| octane sensitivity | | 8.4 | 11.7 | 17.3 |
| aromatics (vol %) | ASTM D1319 | 31.2 | 27.16 | 3.75 |
| olefins (vol %) | ASTM D1319 | 0.7 | 0.48 | 0.25 |
| saturates (vol %) | ASTM D1319 | 68.1 | 53.19 | 8.99 |
| ethanol (vol %) | ASTM D5599 | | 19.17 | 87.01 |
| sulfur (wt %) | ASTM D2622 | 0.0034 | 0.0023 | <0.001 |
| carbon (wt %) | ASTM D5291 | 86.59 | 79.4 | 57.01 |
| hydrogen (wt %) | ASTM D5291 | 13.44 | 13.26 | 13.01 |
| oxygen (by difference)[a] (wt %) | | | 7.34 | 29.98 |
| oxygen (wt %) | ASTM D5599 | | 7 | 30.48 |
| water content (ppm mass) | ASTM D6304 | | 2203 | 3377 |

[a] Oxygen (by difference) = 100 − carbon (wt %) − hydrogen (wt %).

In the past, it has been particularly challenging to achieve low particle emission levels at this engine condition.[8] For each of the three fuels, the engine is operated at the desired engine speed and load using three engine breathing conditions: conventional throttled operation, unthrottled with EIVC, and unthrottled with LIVC. For each fuel and breathing condition, the engine is operated with three different fueling strategies: single injection DI (sDI), multiple injection DI (mDI), and PFI. For the sDI and mDI fueling strategies, a start of injection timing sweep is performed, whereas only a single point is performed for the PFI strategy.

Gaseous emissions, FSN, and engine performance metrics are recorded at each engine operating point. Particle number size distribution measurements with the SMPS are collected at each of the PFI conditions but collected only at three fuel injection timings during the sDI and mDI timing sweeps.

## RESULTS

**Fuel and Operating Strategy Effects on Gaseous Emissions and Efficiency.** Efficiency and gaseous emissions differences between the engine breathing strategies, fueling strategies, and fuel type follow established trends, as illustrated in Figure 3. To summarize, EIVC and LIVC operation result in increased efficiency as well as a reduction of $NO_x$ emissions for a given fuel. The reduction in $NO_x$ emissions is attributed to a reduction in the effective compression ratio and, thus, a lower in-cylinder temperature at the end of compression. Efficiency and emissions are also functions of fuel injection timing with the sDI and mDI fuel injection strategies. When injection timing is retarded from the maximum efficiency point, a decrease in efficiency is accompanied by increases in CO and HC emissions because of a reduction in available mixing time. When injection timing is advanced from the maximum efficiency point, the efficiency decrease is accompanied by an increase in HC emissions, likely because of fuel impingement on combustion chamber surfaces. The trends with injection timing are consistent with the study performed by Moore et al.[8]

Efficiency and gaseous emissions for PFI fueling with gasoline are illustrated by the dashed lines in Figure 3. In all cases, gaseous emissions and efficiency for PFI fueling are comparable to the

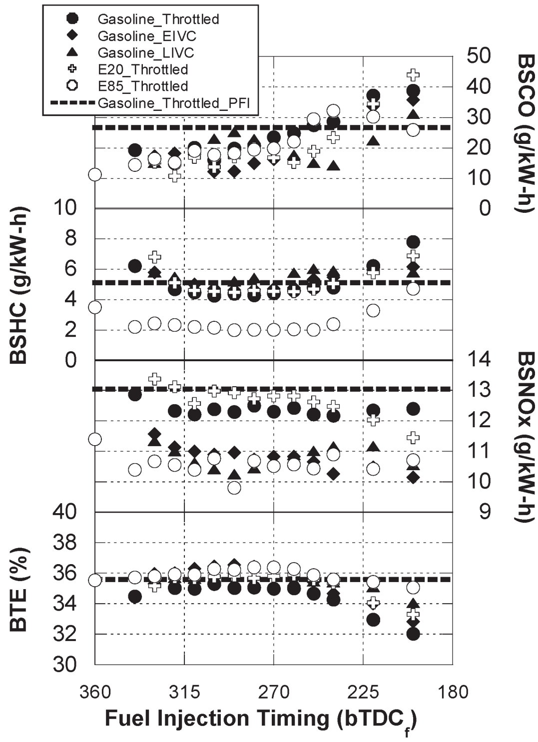


**Figure 3.** Efficiency and gaseous emissions for sDI gasoline operation under the throttled, EIVC and LIVC breathing strategies, throttled sDI operation with E20 and E85, and throttled PFI operation with gasoline.

sDI fueling strategy. This result is expected given that DI fueling strategies allow for higher power, downsizing, and higher compression ratio, but the efficiency remains approximately the same at a specific engine operating point. Gaseous emissions and efficiency from the mDI injection strategy (not shown) do not differ substantially from the sDI fueling strategy.

The effect of ethanol content shown in Figure 3 is consistent with established trends reported previously. HC and $NO_x$ emissions are comparable for gasoline and E20 but are reduced for E85, similar to the findings by Moore et al.[20] Also, brake efficiency is observed to increase with an increasing ethanol content. Higher thermal efficiency with E85 has been reported in previous literature for both engine dynamometer studies[21,28,29] and vehicle studies.[30,31]

Thus, the effects of engine breathing strategy, fueling strategy, and fuel type on engine efficiency and emissions follow trends that have been previously reported in the literature. The EIVC and LIVC breathing strategies both serve to increase engine efficiency and reduce $NO_x$ emissions. For the DI fueling strategies, there is a fuel injection timing for maximum efficiency because of trade-offs between fuel spray impingement and fuel−air mixing time. In comparison to gasoline, E85 reduces $NO_x$ and HC emissions in addition to producing an increase in efficiency.

**Gasoline Particle Emissions.** FSN emissions are given as a function of fuel injection timing and breathing strategy in Figure 4. The dependence of FSN emissions upon fuel injection timing is similar for all three breathing strategies, with advanced timing producing the highest FSN emissions and intermediate timing having little effect. For the most retarded injection timing, a slight rise in FSN emissions is produced for the throttled condition but not for the other breathing strategies.

This response of FSN to fuel injection timing agrees with the well-established trends in published literature. For a similar engine architecture, Worlding et al.[24] reported FSN greater than 1.0 at advanced injection timing of 320 CAD $BTDC_f$ for a wide open throttle condition at 2000 rpm and lower FSN of approximately 0.3 as injection timing is retarded to 300 CAD $BTDC_f$. Similar trends are reported by Moore et al.,[8] where the minimum and maximum FSN measurements as functions of injection timing are highly dependent upon the speed and load condition of the engine.

The particle size distributions for gasoline for the three different breathing strategies are shown at three different fuel injection timings in Figure 5. Note that the ordinate scale for Figure 5a is larger than for panels b and c of Figure 5. The SMPS results qualitatively agree with the FSN results (Figure 4), with the highest particle emissions occurring for the early injection timing and the lowest particle emissions occurring for the later injection timings. It can also be seen that the LIVC breathing strategy produces the highest particle emissions. The higher particle emissions for the LIVC breathing strategy are likely the result of a difference in the fuel and air mixing process compared to the throttled and EIVC cases or possibly fuel spray impingement on the intake valve.

**Multiple Direct Fuel Injections.** In this section, we investigate whether using a multiple injection fueling strategy can be effective in reducing particle emissions. We hypothesize that, by introducing the fuel in two separate injection events, the liquid penetration length can be shortened. This can reduce the amount of fuel that impinges on the piston and ultimately lower particle emissions.

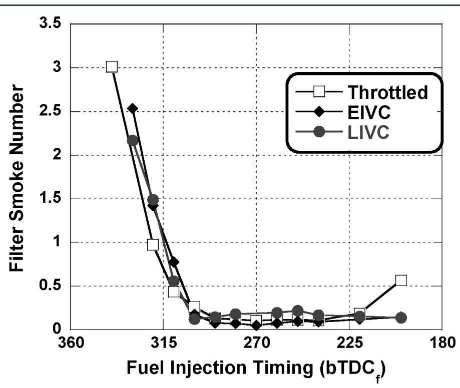


**Figure 4.** FSN as a function of fuel injection timing for gasoline using the sDI fuel injection strategy.

The fuel injection command for the sDI and mDI operating strategies are illustrated in Figure 6 at a commanded injection timing of 280 CAD BTDC for both injection strategies. For the mDI strategy, the two pulses are of equal duration and the time from the end of the first pulse to the start of the second pulse is held constant at 1 ms (9 CAD at 1500 rpm). As a result of the split injection process, the end of injection occurs later for the mDI strategy. Figure 6 shows that the cylinder pressure traces for the two operating strategies are nearly identical with no notable differences in performance. Although the results are not presented here, this mDI strategy does not cause any significant changes in engine emissions or efficiency.

Notable differences in FSN emissions can be seen for the two fueling strategies in Figure 7. At the most advanced fuel injection timing, the mDI strategy produces lower FSN emissions than the sDI strategy, with a FSN reduction of more than 50% at a fuel injection timing of 320 CAD $BTDC_f$. A similar trend is shown for the particle distributions at this injection timing in Figure 8a, where the peak particle concentration is also reduced by approximately 50% for the mDI strategy. This successful reduction in FSN and particle emissions with mDI fueling at advanced injection timing is likely a result of reduced fuel impingement on the piston because of reduced liquid penetration length.

While the mDI strategy enables particle emissions to be reduced at the most advanced timing (Figure 8a), it causes an increase in particle emissions at more retarded fuel injection timing. The increase in particle emissions occurs for injection timing more retarded than 300 CAD $BTDC_f$, as shown in the particle size distributions in panels b and c of Figure 8. This suggests that, while multiple injections reduce fuel spray impingement, it can be detrimental to other aspects of the fuel−air mixing process. As a result, the mDI fueling strategy employed in

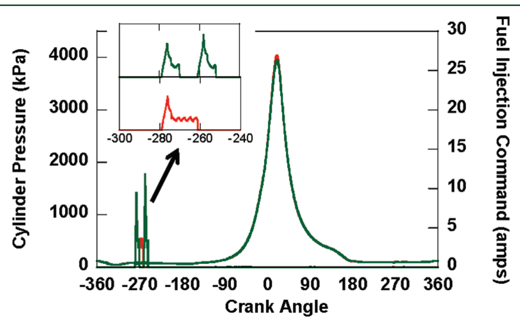


**Figure 6.** Cylinder pressure and fuel injector current for the sDI (red) and mDI (green) fuel injection strategies.

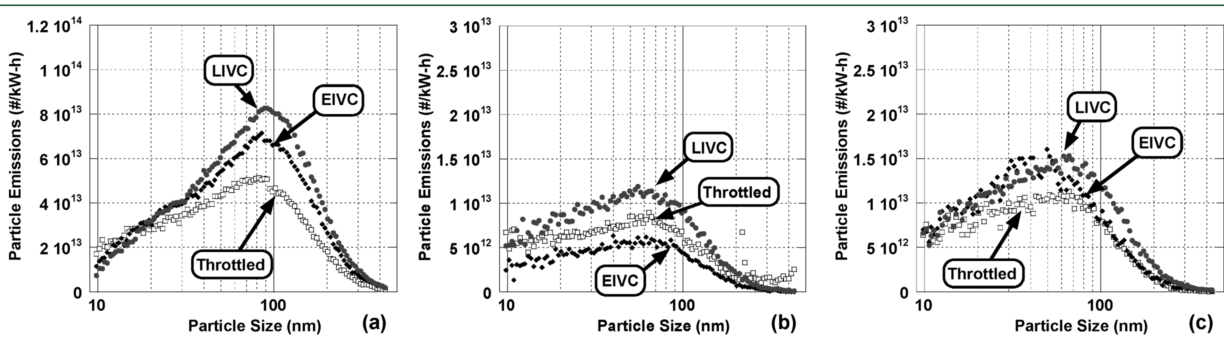


**Figure 5.** Particle emission number size distributions for gasoline at each breathing strategy and sDI fuel injection timing of (a) 320 CAD $BTDC_f$, (b) 280 CAD $BTDC_f$, and (c) 240 CAD $BTDC_f$.

this study is less beneficial than optimized timing with the sDI fueling strategy.

**Ethanol Effects on Particle Emissions.** The FSN measurements for E20 and E85 are shown in Figure 9. The E20 FSN emissions have the same trend as gasoline (Figure 5), with the early injection timing leading to the highest emissions. The most notable difference is that, under the LIVC breathing strategy, E20 produces a higher FSN than is produced for gasoline at injection timing later than 300 CA $BTDC_f$. In contrast, the FSN for E85 remains very low, near the detection limit, at all injection timing conditions. The particle size distributions for E20 and E85 are shown in Figure 10 and agree favorably with FSN results. E20 produces particle emissions that are comparable to gasoline in Figure 5 and in some cases higher. Consistent with gasoline, particle emissions for E20 are highest for the LIVC breathing strategy, indicating that both fuels are being adversely affected by the same mixing or fuel spray impingement process.

The reduction in particle emissions with E85 is seen at all injection timings in Figure 10, but significant concentrations of particle emissions can be formed under certain conditions. Specifically, particle formation is observed for E85 with the LIVC breathing condition at the most advanced injection timing and to a lesser degree at the most retarded timing condition. Particle emissions with E85 have a lower number concentration and a smaller size with a geometric mean diameter of 20−30 nm, instead of 70−100 nm for gasoline and E20. At an injection timing of 280 CAD $BTDC_f$, the injection timing that produces the lowest particle emissions for all fuels, particle emissions of E85 are very low and show no dependence upon the breathing strategy.

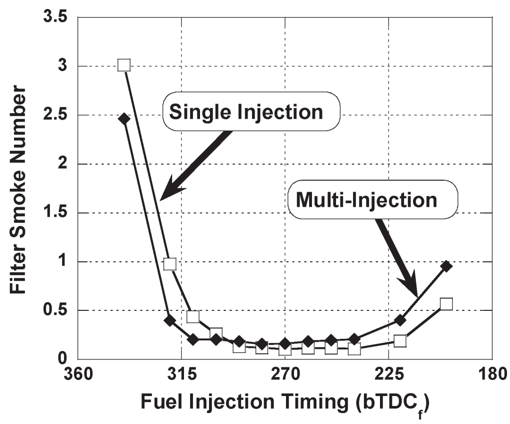


**Figure 7.** FSN as a function of the start of injection timing for the sDI and mDI fueling under throttled conditions.

Thus, the ethanol content can be a very significant factor in influencing particle emissions. The particle emissions produced by gasoline and E20 are similar in magnitude, but E85 is highly effective in reducing particle emissions. Because of the lower total particle number emissions, the particle emissions with E85 are less dependent upon the breathing strategy and fuel injection timing than gasoline and E20.

**PFI Fueling.** We have established that E85 provides a substantial reduction in particle emissions under sDI fueling conditions relative to gasoline. In this section, we compare E85 particle emissions to that for PFI fueling. PFI vehicle particle emissions are relevant because over 99% of light-duty vehicles sold in the United States between 1996 and 2007 are equipped with PFI fueling technology.[4]

PFI fueling has comparable gaseous emissions and efficiency to sDI fueling at this operating condition, as shown in Figure 3. Further, FSN measurements for PFI fueling are found to be low at all breathing conditions for all fuels, with no value exceeding 0.05. The effect of engine breathing on PFI particle emissions is shown in Figure 11. Unlike the sDI and mDI fueling strategies for which the LIVC breathing strategy produces the highest levels of particle emissions, the differences in particle emissions between the breathing strategies is negligible for PFI fueling. It should also be noted that, unlike the previous figures in this study, the ordinate is scaled logarithmically for Figure 11 to compare E20 emissions with the sDI fueling strategy. It can be seen that, relative to PFI fueling, the sDI strategy produces particle emissions that are 1 order of magnitude higher at an injection timing of 280 CAD $BTDC_f$ and 2 orders of magnitude higher at an injection timing of 320 CAD $BTDC_f$.

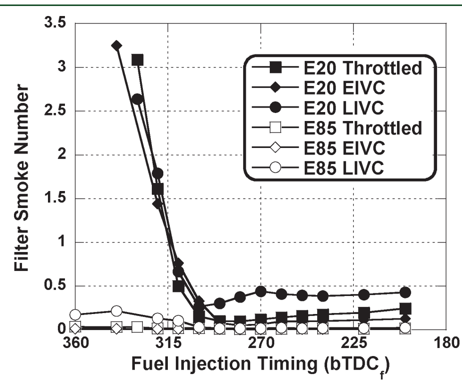


**Figure 9.** FSN as a function of fuel injection timing for E20 and E85 using the sDI fuel injection strategy.

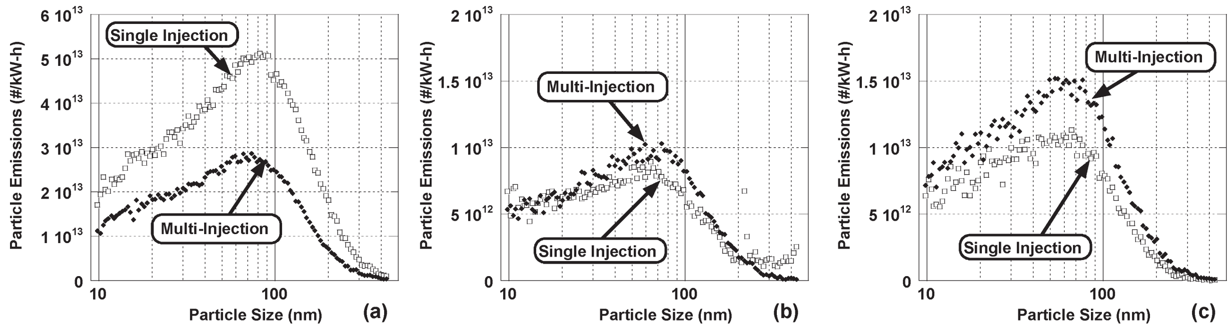


**Figure 8.** Particle number size distributions for fueling with sDI and mDI for gasoline under throttled conditions at an injection timing of (a) 320 CAD $BTDC_f$, (b) 280 CAD $BTDC_f$, and (c) 240 CAD $BTDC_f$.


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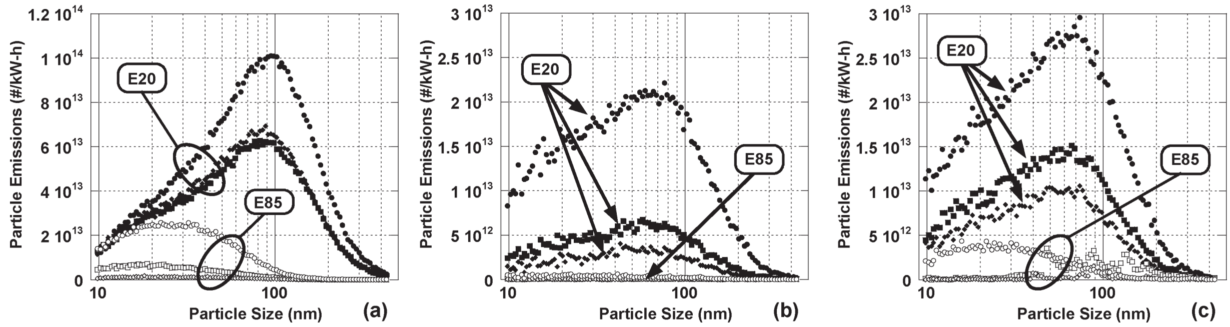


**Figure 10.** Particle size distribution for E20 (closed symbols) and E85 (open symbols) for (■) throttled operation, (◆) EIVC, and (●) LIVC using sDI fuel injection timing of (a) 320 CAD BTDC$_f$, (b) 280 CAD BTDC$_f$, and (c) 240 CAD BTDC$_f$.

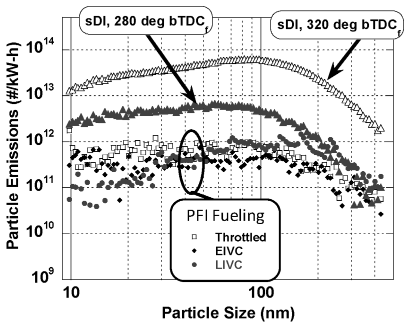


**Figure 11.** Particle emissions for PFI fueling with E20 for the three different breathing strategies in comparison to throttled sDI fueling at two injection timings for E20.

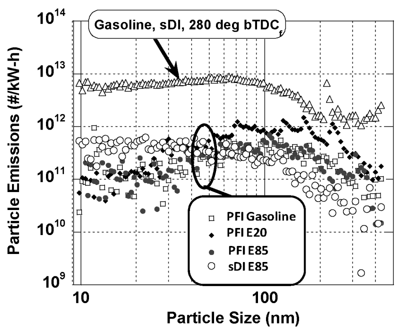


**Figure 12.** Particle size distributions for sDI fueling with gasoline and E85 and for PFI fueling with gasoline, E20, and E85.

The effect of fuel type on particle emissions for PFI fueling is shown in Figure 12. It can be seen that gasoline, E20, and E85 all produce similar particle emissions. This result stands in sharp contrast to the sDI and mDI fueling strategies, where gasoline and E20 produce particle emissions that are higher than E85 at all injection timing conditions. Also shown in Figure 12 are particle emissions from the sDI fueling strategy for gasoline and E85 under the LIVC breathing strategy at an injection timing of 280 CAD BTDC$_f$. While the gasoline sDI particle emissions are an order of magnitude higher than the PFI particles, particles from E85 with the sDI fueling strategy are similar to PFI fueling.

In contrast to fueling with the sDI and mDI injection strategies, neither engine breathing strategy nor fuel type substantially affects particle emissions with PFI fueling. Particle emissions for PFI fueling are low under all conditions, 1−2 orders of magnitude lower than for sDI and mDI with gasoline and E20. We also see that fueling with E85 under sDI does not produce an increase in particle emissions compared to PFI fueling. As a result, DI operation with E85 produces particle emissions that are similar to PFI with all fuels, whereas DI operation with gasoline or E20 leads to a particle emission increase.

## DISCUSSION

**Particle Formation Mechanism.** A number of previous investigators have studied particle formation mechanisms in DI engines through both optical techniques and modeling. Moore et al.[8] show that, at advanced injection timing, liquid fuel spray impinges on the piston and the corresponding computational fluid dynamics (CFD) modeling illustrates that liquid fuel accumulation on the piston remains well after the injection event is completed. Sabathil et al.[32] used an optically instrumented spark plug to spatially resolve the regions of soot luminosity in-cylinder. It was found that the regions of soot luminosity correspond to the bowl feature on the piston, agreeing with the findings of liquid fuel accumulation by Moore et al.[8] Thus, fuel spray impinging on the piston during the intake stroke remains in liquid form through the compression stroke and into the combustion event, where fuel-rich pool fires can form particle emissions.

For liquid fuel to survive on the piston post-injection until combustion, the heat transfer to the liquid fuel, in either droplet or liquid film form, is insufficient to fully vaporize the fuel. The heat-transfer requirement is highly dependent upon the ethanol content of the fuel. In comparison to gasoline, both E20 and E85 require greater injected fuel mass because of the lower energy density of the fuel and higher latent heat requirement per mass of fuel. The average fuel mass injected per cycle is shown in Figure 13a, illustrating an increase in injected fuel from 25 mg/stroke for conventional gasoline to 37 mg/stroke for E85. Figure 13b shows latent heat of vaporization values for the injected fuel based on Heywood.[33] The heat required to vaporize E20 is a factor of 1.5 higher than gasoline and a factor of 4 higher for E85.

As a result, the liquid fuel mass remaining on the piston is expected to increase considerably with the ethanol content. Further, if the sooting tendency of all of the fuels is the same, it is expected that E20 and E85 will produce higher levels of particle emissions based on the increased liquid mass. The results show the opposite trend, a large reduction in particle emissions with E85. This indicates that the sooting tendency of ethanol is considerably lower than that of gasoline. This is consistent with

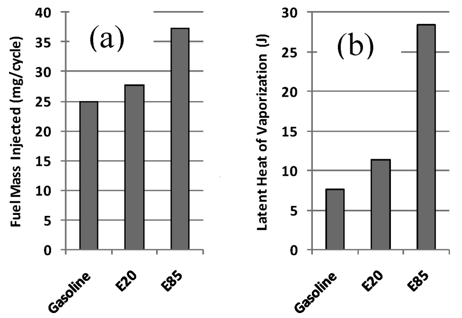


**Figure 13.** (a) Fuel mass injected and (b) latent heat of vaporization.

the a large body of previous work, showing that the combustion of oxygenated fuels produces lower levels of soot and/or particle emissions in diesel engines, for example, see Graboski and McCormick[34] for biodiesel effects on soot emissions and Chapman et al.[35] for dimethyl ether effects on soot formation. Results also show that particle emissions for E20 can increase compared to gasoline, indicating that there may be a trade-off between the reduced sooting tendency of the fuel and the increase in heat of vaporization with ethanol.

**Regulation Compliance with E85.** The findings in this study illustrate that particle emissions for PFI-fueled vehicles have little dependence upon fuel type and DI fueling with gasoline or low-level ethanol blends produces particle emissions up to 2 orders of magnitude greater than PFI. This investigation focuses on a single operating point, 1500 rpm and 8 bar BMEP, a condition for which it is challenging to achieve low particle emissions compared to other selected operating points in the engine map.[8] Over the course of a normal drive cycle, it is expected that DI fueling will increase particle emissions compared to PFI fueling but that the increase will be less substantial than was observed in this investigation.

The current particulate matter emission regulation for light-duty diesel vehicles in the state of California is 0.010 g/mile, and a typical emission rate for a gasoline vehicle with PFI fueling is 0.001 g/mile.[5] Thus, SI engines equipped with DI fueling technology can increase particle mass emissions approximately 1 order of magnitude compared to the PFI baseline and maintain compliance with current regulations. Given the historic trend of increasingly stringent emission regulations, however, it is possible that this emission standard could be subject to future reductions. Currently, light-duty vehicles account for 2% of PM10 emissions and 3% of PM2.5 emissions,[5] and if DI fueling significantly increases the contribution from light-duty vehicles, future reduction in particle emission standards becomes more likely.

In light of this, it is significant that sDI fueling with E85 not only reduces particle emissions relative to gasoline and E20 but also does not increase particle emissions beyond that of PFI with gasoline. In addition, because of advantageous fuel properties, an engine optimized for E85 can have greater efficiency and power than an engine optimized for gasoline.[14−18] Thus, performance advantages, particle emissions reduction benefits, and requirements of increased renewable fuel use given by EISA legislation make an engine optimized for efficiency with E85 an attractive option.

## CONCLUSION

In this study, we examine the effect of fuel type, engine breathing strategy, and fueling strategy on particle emissions from a naturally aspirated SI engine. Three fuels, gasoline, E20, and E85, are used to assess the effect of the ethanol content on particle emissions. The engine breathing strategies include conventional throttled operation, EIVC, and LIVC, and the fueling strategies are sDI, mDI, and conventional PFI.

The main finding of the study is that use of E85 results in 1−2 orders of magnitude reduction in particle emissions relative to sDI fueling with gasoline and E20. Furthermore, sDI particle emissions with E85 are similar to that for PFI fueling with gasoline. Thus, an increase in particle emissions beyond that of PFI engines can be prevented while gaining the efficiency of DI engines using E85.

Additional conclusions are as follows: (1) Fuel injection timing is the engine parameter that has the most influence on particle emissions with DI fueling. Overly advanced fuel injection timing results in very high particle emissions because of fuel spray impingement on the piston, whereas overly retarded injection timing results in insufficient time for the fuel and air to mix. (2) Although it has advantages for engine efficiency, the LIVC breathing strategy used in this study increases particle emissions. This is likely due to the fuel and air mixing process or fuel spray impingement with an intake valve. It is thought that this increase is specific to the experimental system used in this study and not universally applicable to all LIVC breathing strategies. (3) While the mDI fueling strategy employed here is effective in reducing particles at overly advanced injection timing, this strategy results in higher particle emissions than the sDI strategy at more optimal injection timing conditions. (4) The PFI fueling strategy produces very low levels of particle emissions at 1500 rpm and 8 bar BMEP. Particle emissions for PFI fueling are found to be similar for all fuels and breathing strategies investigated.

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