



# The Impacts of Mid-Level Biofuel Content in Gasoline on SIDI Engine-Out and Tailpipe Particulate Matter Emissions

## Preprint

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*Presented at the SAE 2010 Powertrains, Fuels and Lubricants Meeting  
San Diego, California  
October 25–27, 2010*

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

**Conference Paper**  
NREL/CP-5400-49311  
February 2011

Contract No. DE-AC36-08GO28308

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# The Impacts of Mid-Level Biofuel Content in Gasoline on SIDI Engine-Out and Tailpipe Particulate Matter Emissions

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## ABSTRACT

In this work, the influences of ethanol and iso-butanol blended with gasoline on engine-out and post three-way catalyst (TWC) particle size distribution and number concentration were studied using a General Motors (GM) 2.0L turbocharged spark ignition direct injection (SIDI) engine. The engine was operated using the production engine control unit (ECU) with a dynamometer controlling the engine speed and the accelerator pedal position controlling the engine load. A TSI Fast Mobility Particle Sizer (FMPS) spectrometer was used to measure the particle size distribution in the range from 5.6 to 560 nm with a sampling rate of 1 Hz. U.S. federal certification gasoline (E0), two ethanol-blended fuels (E10 and E20), and 11.7% iso-butanol blended fuel (BU12) were tested. Measurements were conducted at 10 selected steady-state engine operation conditions.

Bi-modal particle size distributions were observed for all operating conditions with peak values at particle sizes of 10 nm and 70 nm. Idle and low-speed / low-load conditions emitted higher total particle numbers than other operating conditions. At idle, the engine-out particulate matter (PM) emissions were dominated by nucleation mode particles, and the production TWC reduced these nucleation mode particles by more than 50%, while leaving the accumulation mode particle distribution unchanged. At an engine load higher than 6 bar net mean effective pressure (NMEP), accumulation mode particles dominated the engine-out particle emissions, and the TWC had little effect. Compared to the baseline gasoline (E0), E10 does not significantly change PM emissions, while E20 and BU12 both reduce PM emissions under the conditions studied. Iso-butanol was observed to impact PM emissions more than ethanol, with up to 50% reductions at some conditions.

In this paper, issues related to PM measurement using the FMPS are also discussed. While some uncertainties are due to engine variation, the FMPS must be carefully maintained in order to achieve repeatable measurement results.

## INTRODUCTION

Increasing the production and use of biofuels is one of the major approaches to reducing the nation's dependence on foreign oil. Biofuels can also achieve significant reductions in greenhouse gases compared to fossil fuels [1]. In 2010, the U.S. Environmental Protection Agency (EPA) published the Renewable Fuel Standard Program Final Rule. The new renewable fuel standards increase the total volume of renewable fuel required to be blended into transportation fuel to 36 billion gallons by 2022 [2]. Over the next several years, ethanol and biodiesel are expected to make up the majority of this requirement. Numerous studies have been conducted to evaluate the impacts of mid-level ethanol blends (ethanol blends up to 20 vol %) on vehicles and

engines. Sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Biomass Program and the EERE Vehicle Technologies Program, two national laboratories—the National Renewable Energy Laboratory (NREL) and the Oak Ridge National Laboratory—collaborated with industry and other experts to design and execute a test program that assesses the potential impacts of intermediate ethanol blends on typical vehicles as well as other engines using gasoline [3, 4]. The test program focuses specifically on the effects of E15 and E20 on regulated tailpipe emissions, engine durability, drivability, and materials compatibility. In a separate effort, Environment Canada also studied the effects of intermediate ethanol blends on vehicle tailpipe emissions [5-7] and evaporative emissions [8].

Over the past 10 years, there has been increasing evidence that particles generated by the combustion of fossil fuels adversely affect health [9]. Nano-scale particles are of particular concern because they are reported to be small enough to penetrate cell membranes and defenses, yet they are large enough to interfere with normal cell processes, damage DNA, and increase cancer risk [10]. In Europe, a particle number (PN) emission limit of  $6 \times 10^{11} \text{ km}^{-1}$  (Particle Measurement Programme method, New European Driving Cycle test) becomes effective at the Euro 5/6 stage for all categories of diesel vehicles. A PN emission limit for gasoline vehicles is to be defined by September 2014 [11]. The establishment of these limits has led to numerous studies of particle size distribution. With the application of the diesel particle filter (DPF), tailpipe particle emissions from diesel engines have been greatly reduced. Recent studies comparing gasoline direct injection engines and diesel engines showed higher PN emissions from gasoline direct injection engines relative to diesel engines equipped with DPFs [12, 13].

Fuel properties have significant impacts on PM emissions. Researchers have found significant reduction in engine-out PM mass emissions from diesel engines by using biodiesels [14]. Price et al. [15] found higher PM emissions using toluene compared to iso-octane. However, the impacts of biofuels (such as ethanol) on gasoline engine PN counts are rather controversial [16, 17]. Ericsson et al. [13] studied the tailpipe particulate emissions from port and direct-injected vehicles with E5 and E85 fuels. They found lower PNs and total mass by using biofuels. Czerwinski et al. [18] studied nano-particle emissions from two-stroke scooters with ethanol blends. The results show little effects of nano-particle emissions when ethanol was added. Muralidharan et al. [19] studied the characterization of particulates with different blends of ethanol-gasoline in scooters. The average PN concentration did not show any particular trend as the percentage of ethanol in gasoline was increased from 5 to 30 percent. More studies are needed to reveal the impacts of biofuels on PN emissions from gasoline engines.

Although some devices have been developed to measurement PN concentration and size distribution, it has never been easy to get reliable and repeatable results. Previous studies have reported high measurement uncertainty and poor experimental repeatability. Hall and Dickens [20] found that PNs from vehicles and sampling systems are strongly dependent on their pre-history. Mohr et al. [21] found that the sampling method has a high influence on the results of the total number and number size distribution. Li et al. [22] measured the PN using a condensation particle counter and reported poor repeatability of the results. Zervas et al. [23] compared diesel and gasoline particle size distribution using a Scanning Mobility Particle Sizer and an electrical low pressure impactor. They found particle measurements from gasoline engines have a high standard deviation.

Recently, a GM Ecotec "LNF" family 2.0L SIDI turbocharged gasoline engine was installed and instrumented in the Renewable Fuels and Lubricants (ReFUEL) research laboratory at NREL, which provides an opportunity for detailed investigation on the effects of biofuels on engine performance and emissions. As part of larger effort to establish baseline performance of the production engine and control system before conversion to single-cylinder operation [24], this study focused on particulate emissions, both pre- and post-TWC at steady-state conditions.

## EXPERIMENTAL SETUP

### ENGINE

The engine used in this study was a production 2009 GM Ecotec "LNF" 2.0L turbocharged engine, which uses a wall-guided SIDI combustion system. Table 1 lists the engine specifications. Figure 1 shows the schematic of the engine combustion system, including the combustion chamber, piston, valves, spark plug, and fuel injector. In a wall-guided SIDI engine, fuel is injected into the combustion chamber from a side-mounted injector. The fuel-air mixture is then guided towards the spark plug by a special piston recess, assisted by a reverse tumble. Fuel injection typically occurs during the intake stroke to ensure sufficient fuel air mixing before combustion starts. Under most engine operating conditions, the engine burns near stoichiometric conditions so that a TWC can be used to reduce emissions of pollutants. One of the major disadvantages of the wall-guided SIDI engine is high particulate emissions [12, 13].

The study used the production ECU, which utilized the original equipment manufacturer's (OEM's) calibration for the engine and emission control system from a 2009 Chevrolet HHR-SS (a non-flex-fuel vehicle). The engine was connected to a 75-HP AC dynamometer. Although limitations of the engine dynamometer prevented running the engine at its full rated power, it was adequate to cover a majority of federal test procedures and US06 engine operating conditions.

The engine was fully instrumented. Cylinder pressure was measured by replacing one production spark plug with a Kistler measuring spark plug with an integral 3-mm cylinder pressure sensor (type 6118BCD25A41). Intake manifold pressure, exhaust manifold pressure, and fuel rail pressure were measured using Kistler pressure transducer types 4005BA5FA2, 4007BA5FA2, and 4065A500A2, respectively. Tektronix current probes (Model A622) were used to measure the spark and fuel injection signals sent from the ECU. Signals from both intake and exhaust camshaft position sensors were also recorded. An AVL IndiMODUL data acquisition system was used to collect high-speed data with resolution of 0.2 crank angle degrees (CAD). K-type thermocouples were used to monitor ambient air temperature, air temperature after compressor, intake manifold air temperature, exhaust gas temperature, gas temperature after turbine, engine coolant temperature, and engine oil temperature. The low-speed data were collected using a Sakor data acquisition system at a sampling rate of 1 Hz. Exhaust emissions were measured using a Sensors SEMTECH portable emissions measurement system (PEMS) capable of recording total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and oxides of nitrogen (NO<sub>x</sub>).

Table 1. Engine Specifications

Displacement	1,998 [cc]
Number of cylinders	4
Bore	86.0 [mm]
Stroke	86.0 [mm]
Connecting Rod Length	145.5 [mm]
Compression Ratio	9.2

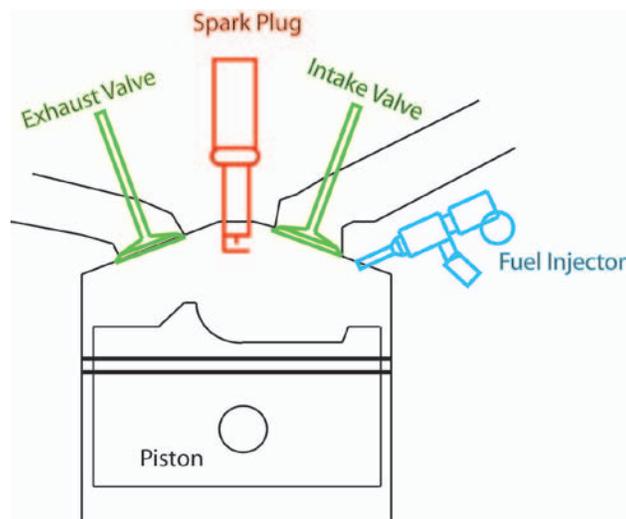


Figure 1. Schematic of the Engine Combustion System

### TSI FAST MOBILITY PARTICLE SIZER (FMPS)

The PN size distribution was measured using a TSI FMPS spectrometer (Model 3091). The FMPS spectrometer performs particle size classification based on differential electrical mobility classification. The charged aerosol enters the analyzer column near on-axis and above the central rod. The particles are deflected radially outward and collected on electrically isolated electrodes that are located at the outer wall. The PN concentration is determined by measuring the electrical current collected on electrodes. An inversion algorithm is used to deconvolute the data and make corrections for the image charges and the time delays in the column, converting currents from the electrometers into 32 channels of output. This process allows the maximum resolution of the instrument to be represented by output channels that are equally spaced on a log scale between 5.6 nm and 560 nm [25]. In this study, the data were collected at a sampling rate of 1 Hz for 3 minutes. The results presented are the averaged PN with the error bar representing the standard deviation.

PN measurement is very sensitive to the sample's relative humidity [26], especially when measuring nucleation mode particles. In order to prevent water condensation and to minimize semi-volatile nucleation in the sampling system, the exhaust samples were diluted using a two-stage dilution system, achieving a total dilution ratio of about 10:1. Figure 2 shows the schematic of the exhaust sampling system. The sample lines in red are heated to 190°C. Engine-out samples were extracted 30 cm downstream of the engine turbine. The post-TWC emissions were extracted 10 cm downstream of the engine TWC. The dilution gas was generated by a Parker Balston purge gas generator (Model 75-45-12VDC), which provided clean, dry, and CO<sub>2</sub>-free air. Two mass flow controllers (MFC) control the dilution gas flow rate. The first stage dilution ratio was about 5:1, and the dilution gas was heated above 100°C by the heated sample line to minimize semi-volatile nucleation. The second stage dilution gas was at ambient temperature to cool the sample gas. Stainless steel tubing was used after the second stage dilution, which further cooled the sample gas to about 45°C before entering the FMPS. The estimated residence time in the sample line is about 3 seconds. During the experiment, only one of the solenoid valves was opened at a time. When solenoid valve 1 was opened, PEMS measured the raw engine exhaust. When solenoid valve 2 was opened, PEMS measured the diluted exhaust sample after the FMPS. Since the dilution gas is a CO<sub>2</sub>-free air, the dilution ratio can be calculated based on the pre- and post-FMPS CO<sub>2</sub> concentration using Equation (1):

$$\alpha = \frac{[CO_{2dry}]_{engine\ out} / (100 + [CO_{2dry}]_{engine\ out} \times (\frac{H}{C}) / 2)}{[CO_{2dry}]_{after\ dilution} / (100 + [CO_{2dry}]_{after\ dilution} \times (\frac{H}{C}) / 2)} \quad (1)$$

in which (H/C) is the fuel hydrogen to carbon ratio.

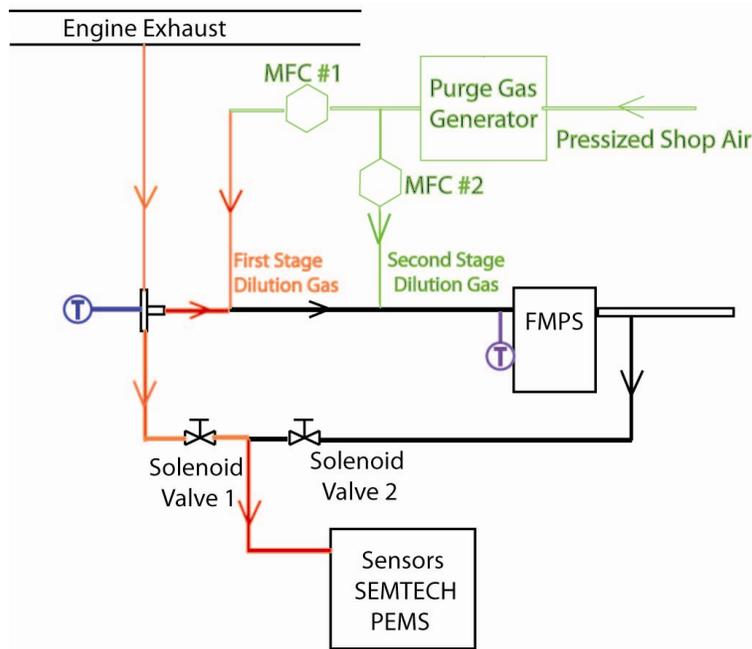


Figure 2. Schematic of Exhaust Sampling System

## FUELS

Ethanol-blended fuels (previously used for a mid-level ethanol blend study at NREL [3, 4]) were used in this study. Three fuels of varying ethanol or iso-butanol blend levels were included in this study to determine the effects of alcohol content and type on exhaust emissions. Certification gasoline (E0) was included in this study for a baseline comparison. Ethanol or iso-butanol blend concentration levels were specified on a volume-percent basis. Fuel-grade ethanol (per ASTM D 4806) supplied by Gage Products Company was used in this study. Iso-butanol was purchased from Industrial Chemicals Corporation. Table 2 summarizes the selected fuel properties. Fuels were splash blends of E0 (certification gasoline, i.e., Indolene). Ethanol-blended fuels were analyzed by the Fuel Analysis Laboratory at the Southwest Research Institute. An 11.7 vol % iso-butanol blend (listed as "BU12" in Table 2) represents the highest oxygen content in gasoline (2.7%) currently allowed by the EPA. The properties of BU12 were calculated based on the properties of the measured E0 and pure iso-butanol.

Table 2. Test Fuel Properties

Fuel	%-EtOH/iBOH (vol-%)	LHV (MJ/kg)	RON	MON	(R+M)/2	SG	C (wt%)	H (wt%)	O (wt%)	H:C	O:C	T90 (°C)
E0	0	43.03	97.1	88.3	92.7	0.745	86.03	13.18	0	1.826	0	159.1
E10	9.83	41.12	100	89.7	94.85	0.749	82.69	13.16	3.62	1.896	0.0329	156.2
E20	19.43	39.52	101.2	90.2	95.7	0.7532	79.5	13.11	7.112	1.965	0.0672	151.2
BU12	11.70	41.77	NA	NA	NA	NA	83.38	13.23	2.7	1.891	0.0243	NA

## ENGINE OPERATION CONDITIONS

Experiments were conducted at 10 steady-state engine operating conditions, which are listed as engine speed and NMEP in Table 3. The value "800 rpm - 1 bar" represents the engine running at idle. In this paper, "speed-NMEP" will be used to represent an engine operation condition. For example, "1000-3" means the engine was running at 1,000 rpm and 3 bar NMEP. While steady engine oil and coolant temperature (about 88°C) were controlled by engine ECU at most operating conditions, slow increases in engine oil and coolant temperature were observed at "3000-6" and "3000-9" due to the limited cooling capability of the engine radiator in the test cell.

Table 3. Engine Operation Conditions

Engine Speed (rpm)	Engine NMEP (bar)
800	1
1000	3
1500	3 and 6
2000	3, 6, and 9
3000	3, 6, and 9

## RESULTS AND DISCUSSION

### TOTAL PN CONCENTRATION

It is now generally accepted that automotive particle emissions fall into two broad categories: accumulation mode particles and nucleation mode particles [27]. Accumulation mode particles are mainly carbonaceous in nature and greater than 30 nm in particle size [27]. Nucleation mode particles, with particle sizes generally below 30 nm, comprise predominantly condensed volatile material, mainly sulfate and heavy hydrocarbons [27]. Nucleation mode particles are formed during combustion and dilution, usually through homogenous and heterogeneous nucleation mechanisms [28]. Nucleation mode particles are more sensitive to temperature, humidity, dilution, and sampling system factors [26]. For the initial discussion, the FMPS particle size data are collapsed into total particle counts for these two particle size regions. Data presented in this section are pre-TWC emissions.

Figure 3(a) shows the total nucleation mode PN concentration at the conditions studied; Figure 3(b) shows a rescaled subset of conditions where "800-1" and "1000-3" have been removed so that the remaining operational modes are better defined. Figure 4(a) shows the total accumulation mode PN concentration at the conditions studied; Figure 4(b) shows a rescaled subset of conditions for greater clarity. It is quite obvious that at low engine speeds (<1,500 rpm), the total nucleation PN concentration is more than 3 times higher than other conditions. A comparison of "800-1" and "1000-3" reveals that nucleation mode PN and size distribution do not change significantly. The major difference is related to the accumulation mode particles. At 2,000 rpm, the nucleation mode PN distributions are almost the same when load is increased from 3 to 6 bar. Again, the major difference is related to the accumulation mode particles. As the load was further increased to 9 bar, both nucleation mode and accumulation mode particles increased. In summary, a clear trend of an increase in the total accumulation mode PN concentration with engine speed and load was observed at engine speeds higher than 1,500 rpm.

Upon examining the engine calibration, it was discovered that the engine control strategy at low speed and low load is different from other conditions. At "800-1" and "1000-3," fuel rail pressure is low and very unstable.

This may be partially due to the OEM's use of a three-lobe, cam-driven high-pressure fuel pump feeding a common fuel rail for all four cylinders. Fuel pressure oscillation differences across each fuel injector feed likely presented a significant design and control challenge. Another major difference at low engine speeds is the fuel injection timing, which is presented in Figure 5. The black solid line represents the boundary of the two fuel injection control strategy regions. At low speed and low load (lower left corner in Figure 5), fuel injection timing is retarded as engine speed and load increase. In the other regions, fuel injection is advanced with increasing engine speed and load. Fuel injection timing is one of the dominant factors influencing PN emissions. Figure 6 shows the nucleation mode and accumulation mode PN concentration as a function of fuel injection timing at eight operating conditions studied (excluding "800-1" and "1000-3"). Disregarding the results at idle, a clear trend of increasing total accumulation PN emissions with advancing fuel injection timing was observed. Nucleation mode PN emissions also increased with advancing fuel injection timing. The increase in PN emissions is most likely due to the increasing liquid fuel impingement on the piston bowl. This may result in liquid fuel that is not totally vaporized and well mixed with the ambient air at the start of combustion. As a consequence, local fuel-rich combustion or even pool fire could occur near the piston, generating high emissions of PM. It is worth noting that although good correlation was observed between PN emissions with fuel injection timing, other parameters, such as fuel injection pressure, could also influence PN emissions. The best way to reveal the influence of fuel injection timing on PN emissions is to conduct a fuel injection sweep study while maintaining other parameters constant. This will be included in a future study with independent engine control.

Figure 3 and Figure 4 also reveal the effects of biofuels on total PN emissions. Generally speaking, biofuels reduce both nucleation and accumulation PN emissions. At idle, "1000-3", and "3000-6", E10 generates higher nucleation mode particles. At most of the remaining conditions, increasing biofuel content reduces nucleation mode particles. At 6 bar NMEP, E10 generates about 15% higher accumulation mode particles than E0. For all other conditions, increasing biofuel content reduces accumulation mode particles. As will be discussed in the next section, this observation for E10 loses its strength when examining the detailed PN distribution data. Iso-butanol exhibited stronger effects in reducing both nucleation mode and accumulation mode PN emissions.

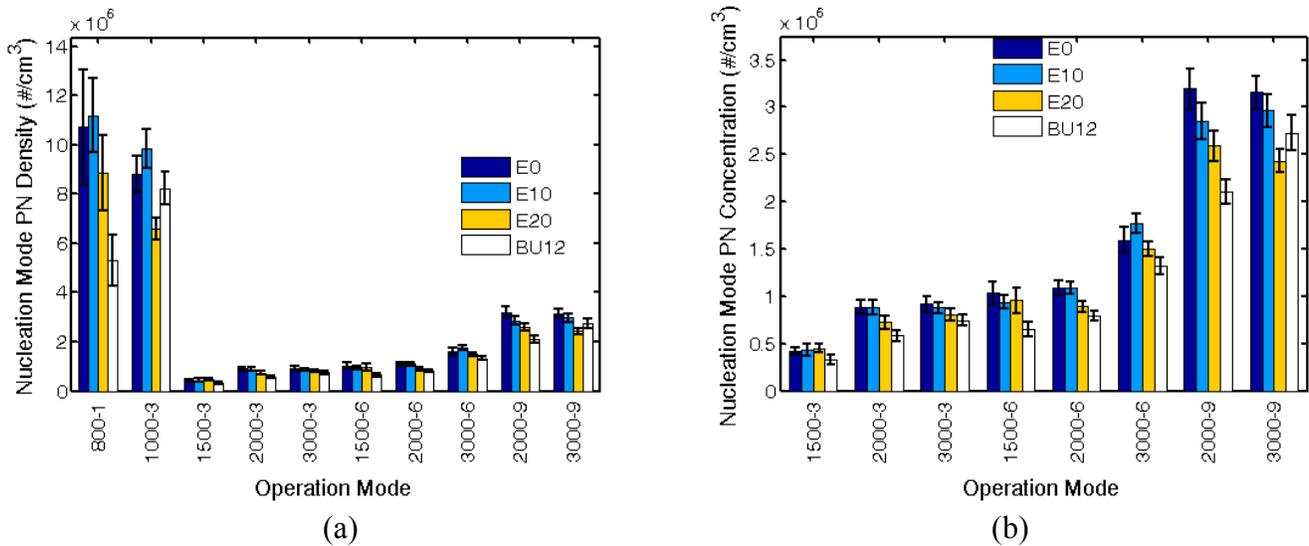
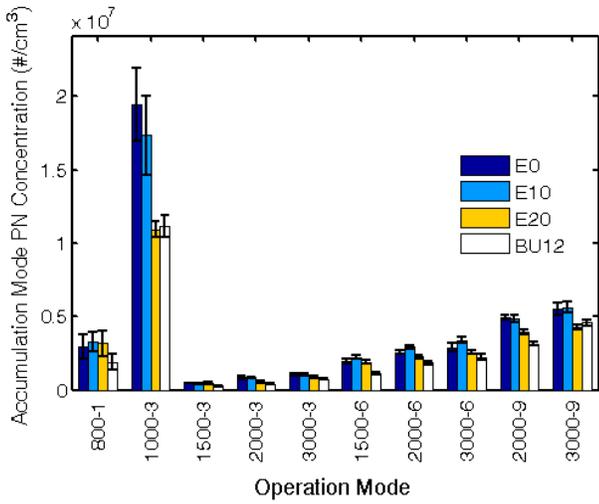
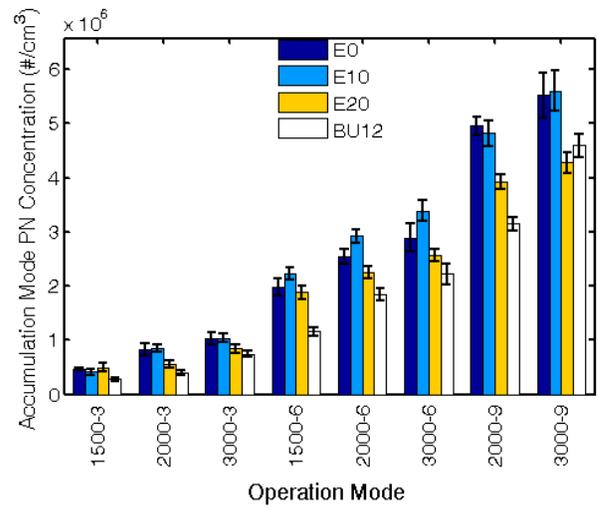


Figure 3. Nucleation Mode PN Concentration



(a)



(b)

Figure 4. Accumulation Mode PN Concentration

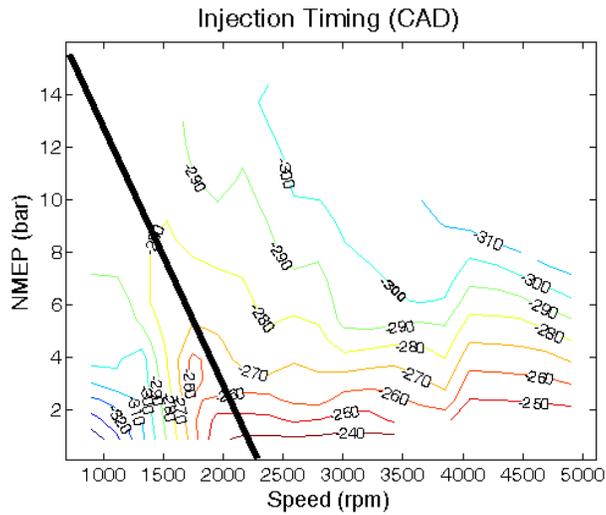
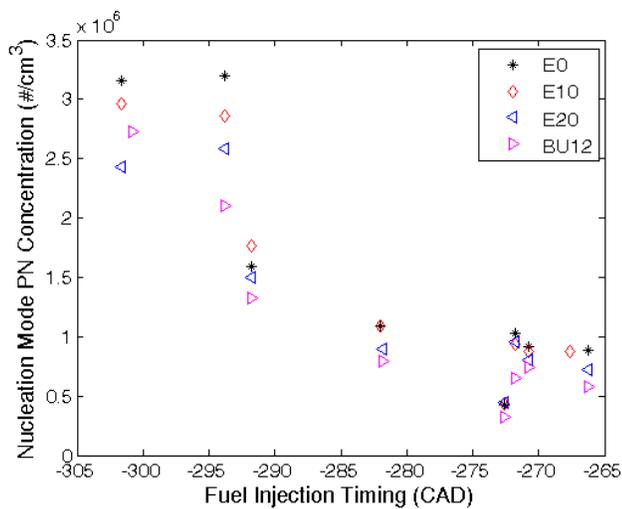
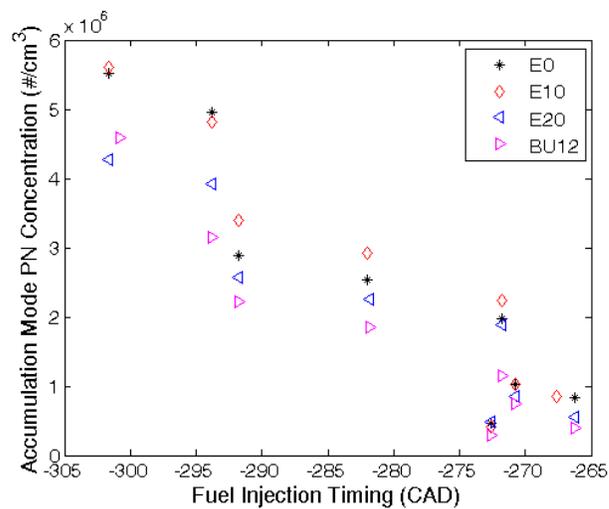


Figure 5. Fuel Injection Timing (-360 CAD is the Beginning of the Intake Stroke; 0 CAD is the Compression TDC.)



(a)



(b)

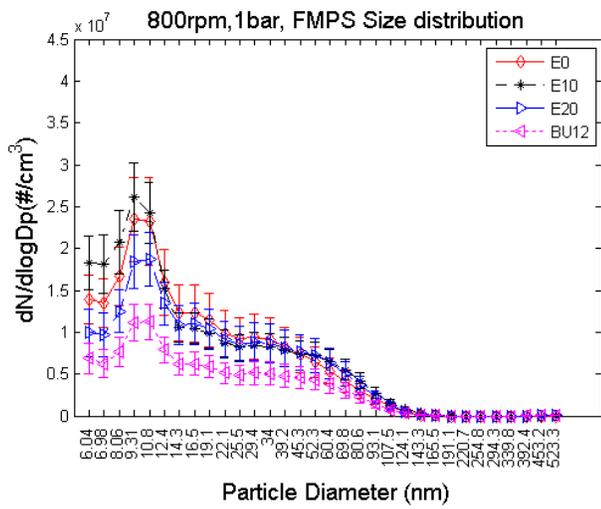
Figure 6. The Influence of Fuel Injection Timing on Nucleation Mode and Accumulation Mode PN Concentration

## PN DISTRIBUTION

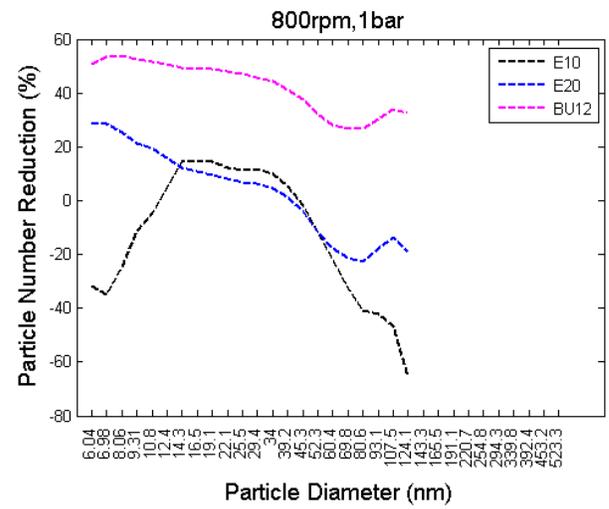
In this section, only pre-TWC particle size distribution at "800-1", "1000-3", "2000-3", "2000-6", and "2000-9" conditions are presented. At speeds higher than 1,500 rpm, although the total PN concentration increases with increasing engine speed, the particle size distribution does not change significantly. It is worth noting that engine calibration parameters such as intake manifold pressure, fuel injection timing, cam phaser position, and spark timing do not change significantly with engine speed, but are strong functions of engine load. Thus, three load points at 2,000 rpm were selected for discussion here.

Particle size distributions and the effects of biofuel in reducing PN at selected conditions are presented in Figures 7 through 11. The x-axis displays the mid-point particle diameters, equally spaced on a log scale between 5.6 nm and 560 nm. The PN concentration is normalized to the bin width and displayed on the y-axis as  $dN/d\log D_p$  (#/cc). In this case, the normalized PN concentration is calculated by multiplying the PN concentration by 16, the number of channels per decade. A bi-modal particle size distribution was observed at all conditions with peaks at 10 nm and 70 nm. We also observed a small peak at 20 nm. However, this small peak may not actually be due to the higher particle concentration in this size range. It may instead be an artifact of the way the FMPS groups the particle sizes, electrometer noise, or a poor FMPS deconvolution algorithm. The following discussion focuses on the most prominent peaks (10 nm and 70 nm).

Figure 7(a) shows the particle size distribution at "800-1". At this operating condition, nucleation mode particles dominate the total particle emissions. However, due to the small size of nucleation mode particles, the mass percentage counts for less than 25% of total mass emitted. The effect of ethanol on PN emission is quite complicated. It is worth noting that the coefficient of variation of engine NMEP is about 10% at this engine operating condition, which is the primary reason for the high measurement uncertainty (the sample standard deviation is represented by the error bars), especially for nucleation mode particles. On average, while E10 generates more nucleation mode particles than E0, the opposite was observed for E20. Although up to 40% differences in PN emission were observed, the uncertainty of the different samples envelop the sample means. BU12 had the lowest PN concentration at all size ranges. On average, BU12 reduced nucleation mode and accumulation mode particles by 50% and 30%, respectively.

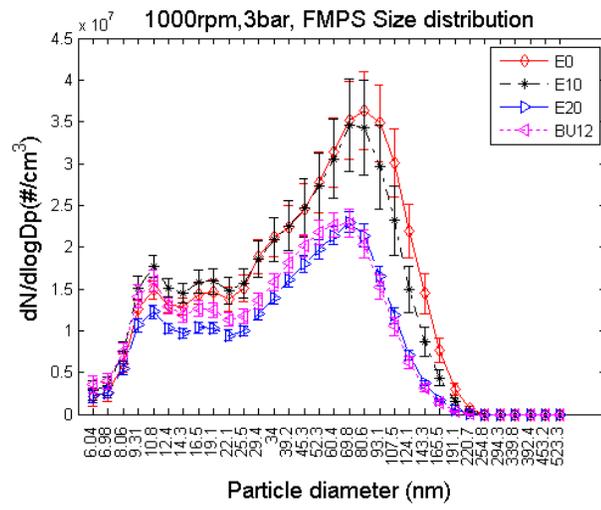


(a)

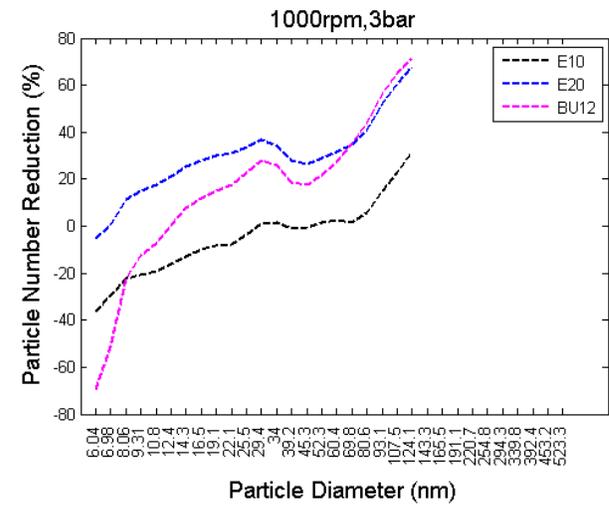


(b)

Figure 7. Particle Size Distribution and the Effects of Biofuels on PN Reduction at 800 rpm–1 bar NMEP

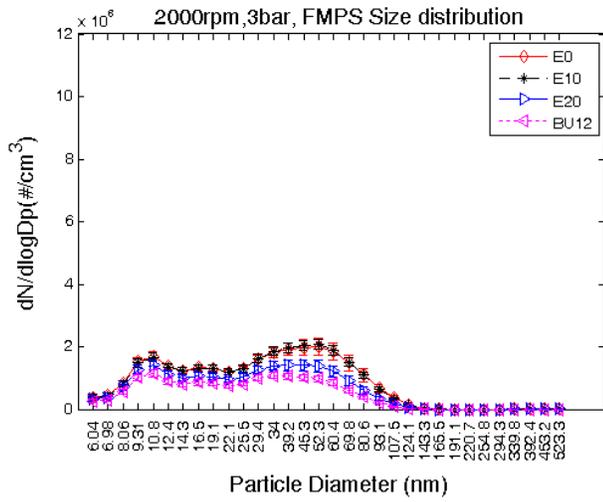


(a)

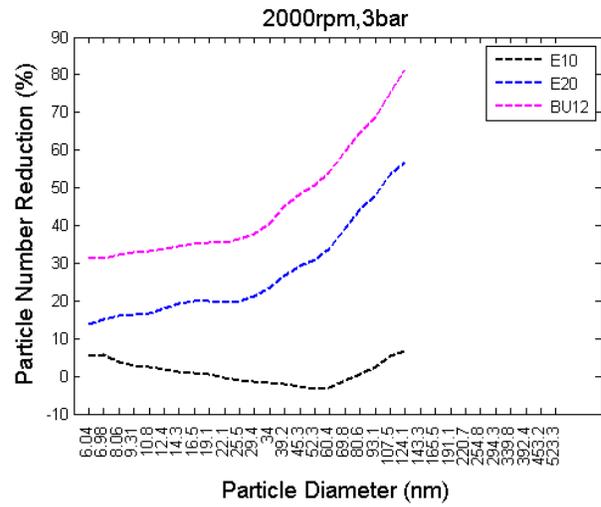


(b)

Figure 8. Particle Size Distribution and the Effect of Biofuels on PN Reduction at 1,000 rpm–3 bar NMEP

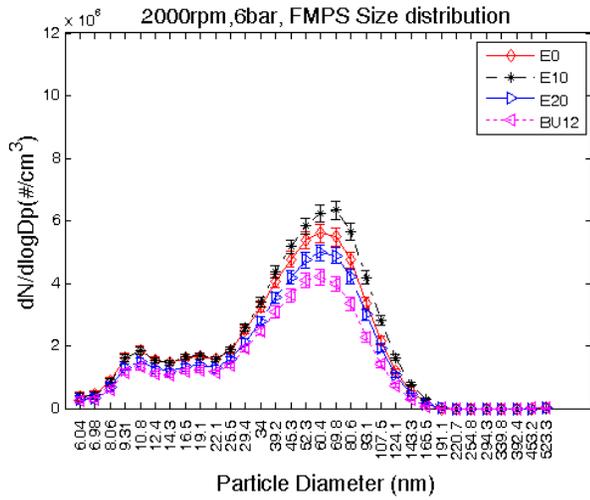


(a)

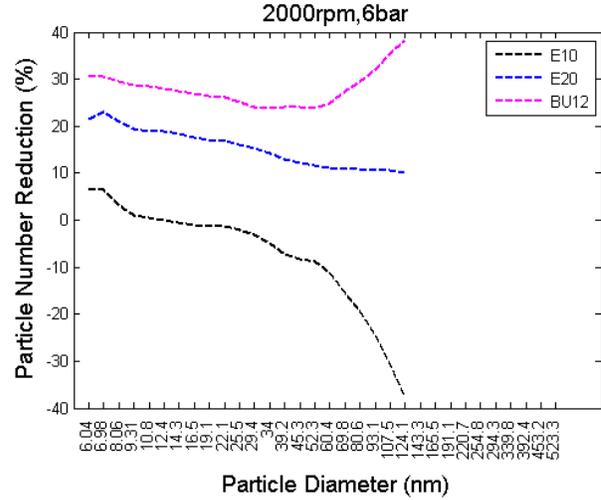


(b)

Figure 9. Particle Size Distribution and the Effect of Biofuels on PN Reduction at 2,000 rpm–3 bar NMEP



(a)



(b)

Figure 10. Particle Size Distribution and the Effect of Biofuels on PN Reduction at 2,000 rpm–6 bar NMEP

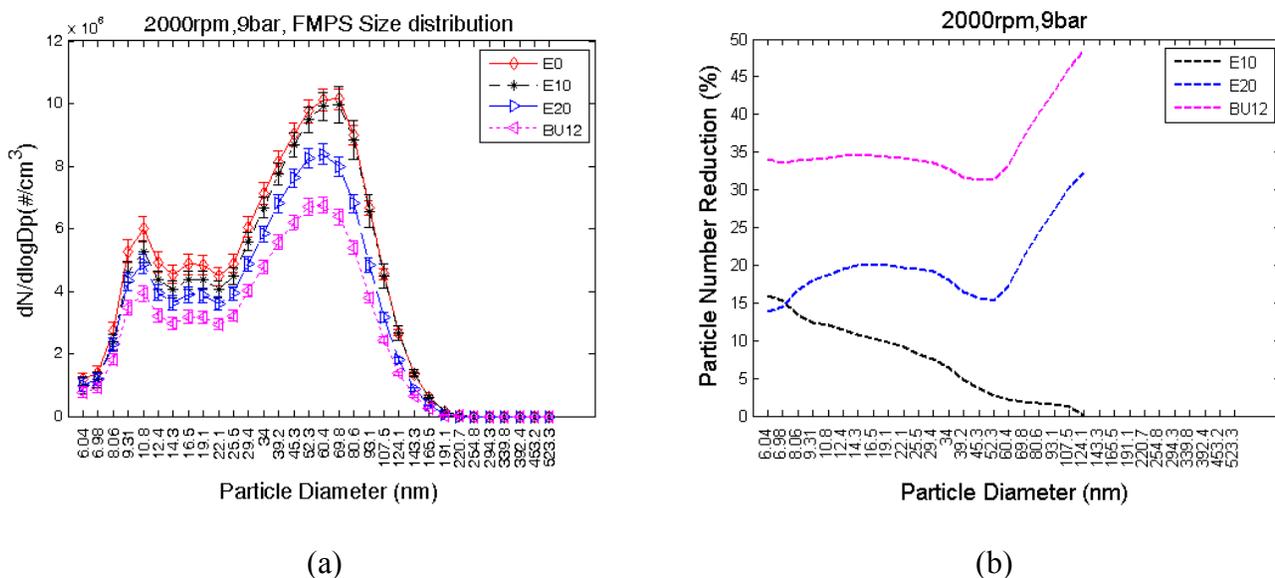


Figure 11. Particle Size Distribution and the Effect of Biofuels on PN Reduction at 2,000 rpm–9 bar NMEP

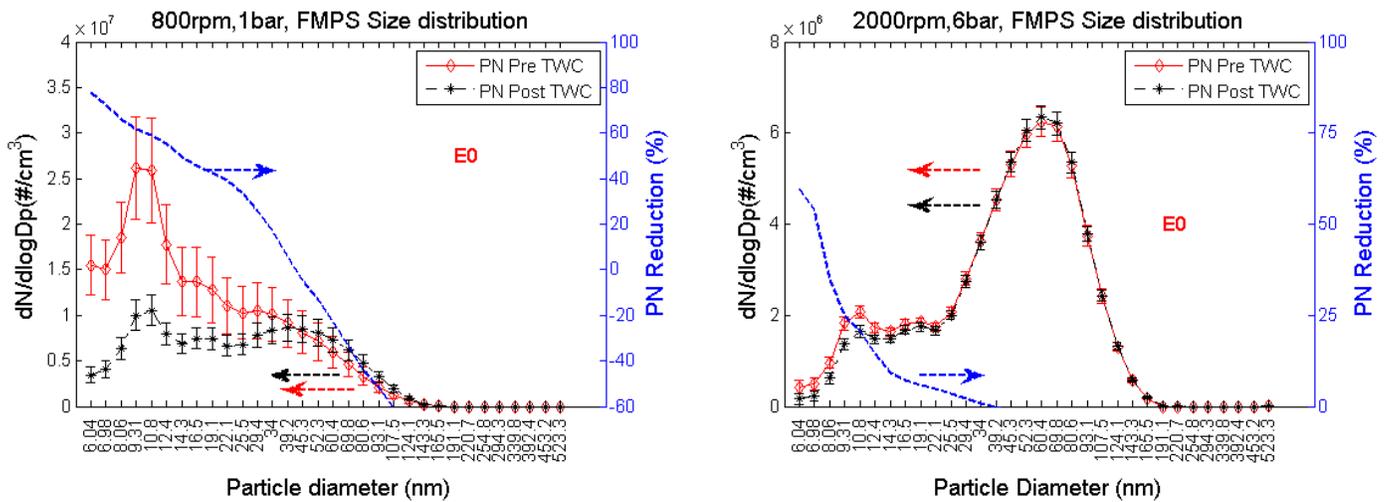
At "1000-3" and engine load higher than 6 bar NMEP, accumulation mode particulates dominate the total PN emissions. The peaks are all observed at about 70 nm. Compared to E0, E10 has very similar total PN and PN size distribution. At most conditions, the differences are within 20%. The only exception is higher accumulation mode particle emissions at "2000-6". Figure 8 shows the particle size distribution and effect of biofuels on PN reduction at "1000-3". Both E20 and BU12 show significant PN reduction at most size ranges. A higher percentage reduction is observed for large size particles. The particle size distribution and effect of biofuels on PN percentage reduction at "2000-3", "2000-6", and "2000-9" are presented in Figures 9 through 11. At these three conditions, both E20 and BU12 show a relatively constant percentage reduction of the nucleation mode particles. E20 reduced nucleation mode PN by about 20%. BU12 reduced nucleation mode PN by about 30%. For accumulation mode particles, PN percentage reduction increased with particle size. BU12 had the lowest particle emissions at all size ranges. The particle size distributions at "1500-6" and "3000-6", while not presented in this paper, exhibited very similar trends to "2000-6". E10 did not exhibit the same behavior. In general, PN from E10 tracked closely with E0, except at 6 bar NMEP where E10 increased accumulation mode PN.

## THE EFFECTS OF TWC ON PARTICLE EMISSIONS

In this study, the TWC was warmed up before measuring the PN by running the engine for 20 minutes at 1,000 rpm at 6 bar NMEP. The measured total hydrocarbons (THCs) and nitrogen oxide (NO<sub>x</sub>) emissions after the TWC were very low at all conditions. Figure 12(a) compares the pre- and post-TWC PN distributions of E0 at idle; the dashed blue lines represent the PN reduction percentage with respect to the particle sizes. The TWC reduced the nucleation mode particles. Up to 50% increases in accumulation mode particles were observed after the catalyst. This could be due to the release of particles that were trapped in the TWC from prior experiments. It should be noted that the apparent increases of accumulation mode particles are all within the measurement uncertainty limits. Figure 12(b) compares the pre- and post-TWC PN distributions of E0 at "2000-6." Again, a reduction of nucleation mode particles was observed, but not as significant as at idle. Similar to idle, the percentage in reduction decreases with increasing particle size. Almost no difference was observed for particles larger than 30 nm. Figure 12(c) compares the pre- and post-TWC PN distributions of E0 at "3000-6". The

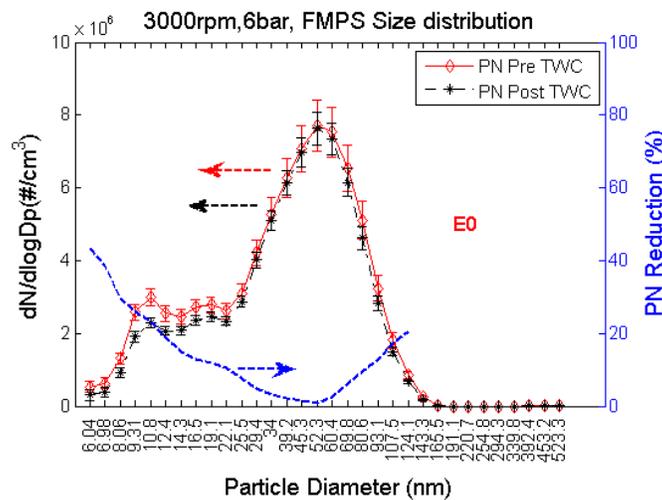
results are very similar to the "2000-6" condition. Clearly, nucleation mode particles are reduced. Although an up to 20% change in PN is also observed for accumulation mode particles, most are within the measurement uncertainty limits.

Clearly, the TWC reduces nucleation mode particles. A higher percentage in PN reduction was observed for small particles. This could be due to the following two reasons. First, nucleation mode particles could vaporize and be oxidized by the TWC. At idle, the gas space velocity is very low, which gives more residence time for the particles in the TWC to be oxidized. This would explain the significant nucleation mode particle reduction at idle. Second, some particle nucleation may actually occur in the sampling line. As the TWC reduces hydrocarbon and volatile organic compounds, the effect may virtually eliminate any particle nucleation that might be occurring in the sampling line.



(a) 800 rpm–1 bar, E0

(b) 2,000 rpm–6 bar, E0



(c) 3,000 rpm–6 bar, E0

Figure 12. The Effect of TWC on PN Emissions

## UNCERTAINTIES IN PN MEASUREMENT

Similar to the PN measurement issues reported by other researchers [20–23], measurement repeatability was a primary concern during this study. In this study, the test cell temperature and humidity were not controlled due to the facility limitations. Engine coolant and oil temperature were controlled by the engine itself. No extra cooling capability was supplied. The engine radiator was able to maintain constant coolant and oil temperature at engine speeds up to 2,000 rpm. At "3000-6" and "3000-9" conditions, continuous increases in both coolant and oil temperatures were observed, which change the combustion chamber heat transfer rate. Higher combustion temperatures could increase soot formation. At these different environmental conditions, the ECU could also use a different calibration table to control fuel injection timing and/or spark timing, which also could change PN formation. Figure 13 shows the time histories of the total PN concentrations and engine coolant and oil temperatures during the FMPS sampling period at "3000-6." PN concentrations increase with engine oil and coolant temperatures. It should be noted that the same data acquisition procedure was followed when testing different fuels at "3000-6" and "3000-9" conditions. For example, FMPS sampling started when the engine coolant reached 92°C. Although the "3000-6" and "3000-9" PN data presented in Figure 3 and Figure 4 were not truly taken at steady-state condition, they provide valuable comparison among different fuels.

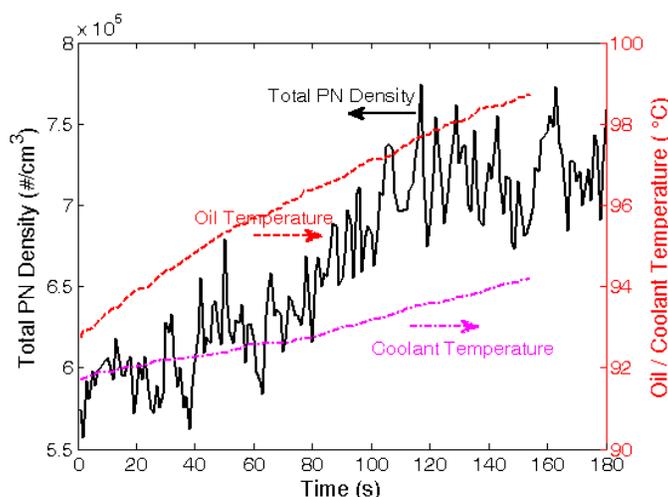


Figure 13. The Effects of Engine Oil and Coolant Temperature on PN Emissions

It is also very crucial to maintain constant engine loads to achieve good measurement repeatability. In this study, the engine load was controlled by the acceleration pedal position. This works very well at most of the selected conditions, except "1000-3". Figure 14 shows the effects of engine load swing on PN emissions at "1000-3". At this condition, although the acceleration pedal position was held constant, the engine load could swing between 2.8 and 3.1 bar. Total PN emissions changed with engine load. About 4 seconds lag of the measured PN concentration to the engine NMEP is due to the measurement delay of the sampling and measurement system. At "1000-3", a 10% change in engine load causes more than a 50% change in total PN emissions. It is worth noting that the data reported in Figure 8 were post-processed by selecting data at 2.8 bar NMEP.

The FMPS is the other major source causing poor measurement repeatability. The first problem is due to potential FMPS baseline shifting during the continuous measurement of moderately high PN densities. Figure 15 shows an example of poor measurement results due to an FMPS baseline shift. The engine was running at 2,000 rpm and 9 bar NMEP. The solid red line represents the measured PN distribution. Right after the emission data were saved, the FMPS baseline data were taken by sending the purge gas into the FMPS, which is

indicated by the black dashed line. An FMPS baseline shift was observed at particle sizes less than 12.4 nm and most prominent at sizes between 70 nm and 255 nm. The blue dashed line shows the post-processed FMPS data by subtracting the baseline PN distribution. However, it does not always achieve consistent measurement results, which means the baseline could change continuously during the measurement. One method to compensate for this problem is to purge the FMPS with clean gas and reset (or re-zero) the background. A long purge time, usually several hours, may be required to eliminate the baseline shift. It should be noted that purging the FMPS may not always remove the baseline shift. In this circumstance, the best solution for removing the baseline shift is to clean the FMPS. As part of this study, the FMPS baseline was checked prior to the start of each data sampling event.

The second problem is due to observed changes in the FMPS sensitivity over time. The authors are not certain of the root cause of this problem, but speculate that it could be due to the non-constant charge of the FMPS charge needle after it is covered with visible soot, or it could be some inherent change in the FMPS electrometer sensitivity over time. Figure 16 compares the measurement results when (for two cases) the FMPS had been used for more than 8 hours to continuously measure moderately high PN concentration values (i.e., a "dirty" FMPS) and (for two cases) after the FMPS was cleaned following the process specified by the FMPS user manual (a "clean" FMPS). A clean FMPS always measured higher PN concentrations than a dirty FMPS. It was also observed that a clean FMPS achieves much better measurement repeatability, as shown in Figure 16. Although the FMPS user manual [25] recommends cleaning the charge needle every 100 hours and cleaning electrometers every 500 hours, the authors established a procedure to clean and zero the FMPS about every 8 hours to achieve good repeatability for the sample exhaust conditions measured for this study.

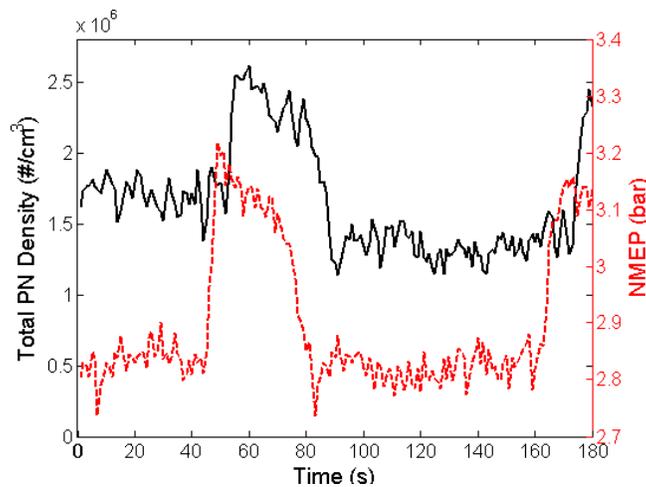


Figure 14. The Effects of Engine Load Swing on PN Emissions

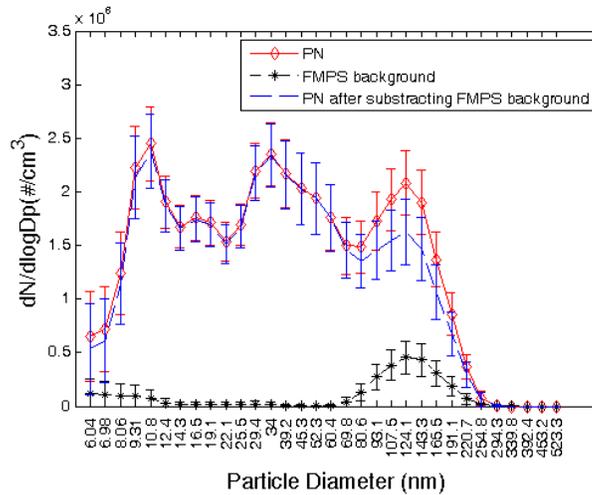


Figure 15. The Effects of FMPS Background Shift on PN Measurements

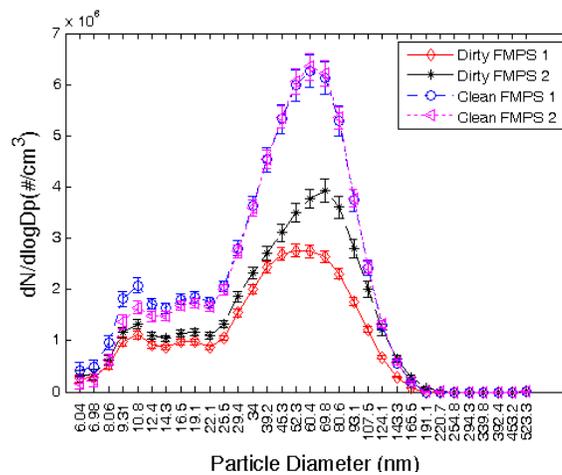


Figure 16. A Comparison of the Measurement Results Between a "Dirty" FMPS and a "Clean" FMPS

## SUMMARY/CONCLUSIONS

The impacts of mid-level biofuel content in gasoline engine PN emissions were studied using a GM 2.0L SIDI turbocharged engine. The particle size distribution both pre- and post-TWC was measured using a TSI FMPS spectrometer. Although this study focused on studying the impacts of biofuel content and type, the results also partially unveil the effects of some key engine operating parameters on PN emissions, which is very valuable for auto manufacturers in designing better SIDI engines with lower pollutant emissions.

The major conclusions from this study are:

- (1) E10 exhibited almost the same particle emissions as E0. E20 and BU12 reduced particle emissions in all conditions studied. Under most operating conditions, BU12 achieved a 30% reduction in nucleation mode particles, while E20 achieved about a 20% reduction. E20 and BU12 achieved a higher percentage of accumulation mode PN reduction than reduction in nucleation mode particles.

(2) A bi-modal PN size distribution was observed at all operating conditions with peaks at 10 nm and 70 nm. At idle, nucleation mode particles dominated the particle emissions. At a load higher than 6 bar NMEP, accumulation mode particles account for more than 60% of total PN emissions.

(3) Fuel injection timing is one of the major factors that influence particle emissions. Accumulation mode particulate emission correlates well with fuel injection timing. For the wall-guided SIDI engine, fuel piston impingement could be one of the key reasons for high PN emissions. Advancing the fuel injection timing increases the possibility of liquid fuel impinging on the piston bowl, which could be the major reason for high PN emissions at low speed / low load conditions.

(4) The TWC reduces PN emissions at idle, where the nucleation mode particulates dominate the total PN emissions. The TWC does not change accumulation mode PN emissions.

(5) The PN emissions are sensitive to engine operating conditions. In this study, a change in total PN emissions with a change of oil and coolant temperature was observed. At some operating conditions, a 10% change in engine load could change total PN emissions by more than 50%.

(6) The FMPS must be carefully maintained to achieve repeatable measurement results.

## **FUTURE WORK**

The study utilized an interim development point of a research engine platform for fundamental fuel combustion studies. Future work will focus on developing this platform into a single-cylinder research engine. First, the production multi-cylinder engine will be converted to a single-cylinder engine with an independent engine control unit providing independent fuel injection, spark timing, fuel rail pressure, and cam phaser position control. As part of this conversion, a dedicated high-pressure fuel handling system will also eliminate unwanted fuel pressure oscillation effects inherent in the OEM system, which would otherwise become worse in a single-cylinder configuration. Second, the current dilution system could only provide reliably consistent data at a dilution ratio of about 10:1. This custom dilution system is designed to have a maximum dilution of around 40:1. If higher particulate levels are expected in future research studies, a dilution system with a higher dilution ratio will be required. Third, it will be very important to develop a FMPS spectrometer calibration procedure for better measurement repeatability; it may be that each PM test scenario in the future must have a unique PN counter calibration procedure. Fourth, future work will also include the study of other un-regulated emissions.

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## **ACKNOWLEDGMENTS**

This work was sponsored by the U.S. DOE Vehicle Technologies Program. The authors gratefully acknowledge the support of DOE Fuels Technologies Program Manager Kevin Stork. The authors also greatly appreciate contributions from the ReFUEL research laboratory staff at NREL including Bob Moore, Scott Walters, Dan Pedersen, and Jonathan Burton.

## **DEFINITIONS/ABBREVIATIONS**

CAD	crank angle degree
CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide

DOE	Department of Energy
DPF	diesel particle filter
ECU	engine control unit
EERE	Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
FMPS	Fast Mobility Particle Sizer
GM	General Motors
LHV	lower heating value
MFC	mass flow controller
MON	motor octane number
NMEP	net mean effective pressure
NO <sub>x</sub>	nitrogen oxide
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PEMS	portable emissions measurement system
PM	particulate matter
PN	particle number
ReFUEL	Renewable Fuels and Lubricants Research Laboratory
RON	research octane number
SG	specific gravity
SIDI	spark ignition direct injection
THC	total hydrocarbons
TWC	three-way catalyst

# REPORT DOCUMENTATION PAGE

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<b>1. REPORT DATE (DD-MM-YYYY)</b> February 2011			<b>2. REPORT TYPE</b> Conference Paper		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> The Impacts of Mid-Level Biofuel Content in Gasoline on SIDI Engine-Out and Tailpipe Particulate Matter Emissions: Preprint				<b>5a. CONTRACT NUMBER</b> DE-AC36-08GO28308		
				<b>5b. GRANT NUMBER</b>		
				<b>5c. PROGRAM ELEMENT NUMBER</b>		
<b>6. AUTHOR(S)</b> X. He, J.C. Ireland, B.T. Zigler, M.A. Ratcliff, K.E. Knoll, T.L. Alleman, and J.T. Tester				<b>5d. PROJECT NUMBER</b> NREL/CP-5400-49311		
				<b>5e. TASK NUMBER</b> FC08.8000		
				<b>5f. WORK UNIT NUMBER</b>		
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> NREL/CP-5400-49311		
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> NREL		
				<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>		
<b>12. DISTRIBUTION AVAILABILITY STATEMENT</b> National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
<b>13. SUPPLEMENTARY NOTES</b>						
<b>14. ABSTRACT (Maximum 200 Words)</b> The influences of ethanol and iso-butanol blended with gasoline on engine-out and post three-way catalyst (TWC) particle size distribution and number concentration were studied using a turbocharged spark-ignition direct-injection engine. Particle size distribution in the range of 5.6 to 560 nm was measured. U.S. federal certification gasoline (E0), two ethanol-blended fuels (E10 and E20), and 11.7% iso-butanol blended fuel (BU12) were tested at 10 selected steady-state engine operation conditions. Bi-modal particle size distributions were observed for all operating conditions with peak values at particle sizes of 10 nm and 70 nm. Idle and low-speed/low-load conditions emitted higher total particle numbers than other operating conditions. At idle, the engine-out particulate matter emissions were dominated by nucleation mode particles. The TWC reduced these nucleation mode particles by more than 50%; the accumulation mode particle distribution was unchanged. At an engine load higher than 6 bar net mean effective pressure, accumulation mode particles dominated the engine-out particle emissions, and the TWC had little effect. Compared to E0, E10 did not significantly change PM emissions, while E20 and BU12 reduced PM emissions. Iso-butanol was observed to impact PM emissions more than ethanol, with up to 50% reductions at some conditions.						
<b>15. SUBJECT TERMS</b> gasoline; ethanol blended; biofuel; iso-butanol; particle size distribution; emissions						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UL	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>	
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (Include area code)</b>	