

Novel Characterization of GDI Engine Exhaust for Gasoline and Mid-Level Gasoline-Alcohol Blends

John M. Storey, Sam Lewis, James Szybist, John Thomas, Teresa Barone, Mary Eibl, Eric Nafziger, and Brian Kaul
Oak Ridge National Laboratory

ABSTRACT

Gasoline direct injection (GDI) engines can offer improved fuel economy and higher performance over their port fuel-injected (PFI) counterparts, and are now appearing in increasingly more U.S. and European vehicles. Small displacement, turbocharged GDI engines are replacing large displacement engines, particularly in light-duty trucks and sport utility vehicles, in order for manufacturers to meet more stringent fuel economy standards. GDI engines typically emit the most particulate matter (PM) during periods of rich operation such as start-up and acceleration, and emissions of air toxics are also more likely during this condition. A 2.0 L GDI engine was operated at lambda of 0.91 at typical loads for acceleration (2600 rpm, 8 bar BMEP) on three different fuels; an 87 anti-knock index (AKI) gasoline (E0), 30% ethanol blended with the 87 AKI fuel (E30), and 48% isobutanol blended with the 87 AKI fuel. E30 was chosen to maximize octane enhancement while minimizing ethanol-blend level and iBu48 was chosen to match the same fuel oxygen level as E30. Particle size and number, organic carbon and elemental carbon (OC/EC), soot HC speciation, and aldehydes and ketones were all analyzed during the experiment. A new method for soot HC speciation is introduced using a direct, thermal desorption/pyrolysis inlet for the gas chromatograph (GC). Results showed high levels of aromatic compounds were present in the PM, including downstream of the catalyst, and the aldehydes were dominated by the alcohol blending.

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INTRODUCTION

Light-duty vehicles with direct injection gasoline (GDI) engines have been in commercial production since the late 1990's [1],[2], but have only become common in the U.S fleet in the past four years. Most manufacturers offer several passenger car and light-duty truck/SUV models with GDI engines, and it is widely accepted that smaller displacement, turbocharged GDI engines will replace larger displacement engines as one means for manufacturers to meet higher light-duty vehicle fuel economy regulations. Turbocharged GDI engines can be more fuel efficient and also offer a performance benefit due to the higher volumetric efficiency at high load [3]. However, GDI engines tend to produce more PM than their port fuel-injected (PFI) counterparts [4],[5],[6],[7],[8],[9], with PM mass levels exceeding those of diesels equipped with diesel particulate filters, as well as conventional port-fuel injected vehicles [10],[4],[11]. Because of the impact of mobile sources on air quality, any large-scale change in engine technology and fuel may have far-reaching effects. As ambient air standards for fine PM decrease, direct emissions of PM from GDI vehicles may affect the air quality attainment status of regions.

With the passage of the Energy Independence and Security Act (EISA 2007), the U.S. Congress set specific goals for the use of renewable fuels (36 billion gallons by 2022). The majority of this goal is expected to be met with ethanol from both corn and "advanced biofuel" sources like cellulosic feedstocks. The mandated volume of ethanol is likely to be utilized as fuel for flex-fuel vehicles (E51-E83) and as other blending components of gasoline higher than the current 10% level. In 2010 and 2011, the U.S. EPA granted a partial waiver for the use of E15, 15% ethanol, in model year 2001 and later gasoline vehicles [12]. Furthermore, E30 has been identified as a potential high octane rating fuel that will enable fuel efficient technologies such as low-speed and high boost without end-gas knock concerns [13]. Beyond ethanol, butanol is also gaining momentum as a renewable fuel. Butanol can be made in similar production facilities to ethanol and its vapor pressure and energy density more closely match gasoline.

Thus, there continues to be interest in seeing the effects of the convergence of two current technologies, GDI and alcohol fuel blends, on emission levels of PM and other pollutants. Our laboratory and others have been investigating ethanol blend effects on in-use gasoline vehicles and PM emissions [5],[8],[7],[14],[6]. In this paper, the emissions of a GDI engine

fuelled with gasoline (E0), 30% ethanol in gasoline (E30) and 48% isobutanol in gasoline (iBu48) are characterized. (The iBu48 is not envisioned as a future fuel, but was selected to match the oxygen content of the E30 blend). A novel method for characterizing soot hydrocarbons (HCs) is presented, and the emissions differences relative to the alcohol blends are illustrated.

EXPERIMENTAL METHODS

Engine Specifications and Operating Conditions

The engine used in this study has been specifically developed for high-efficiency operation with ethanol [15]. The engine is a modified four-cylinder 2.0 L GM direct-injection spark-ignition (DISI) engine with turbocharging, dual independent cam phasing, and a 2-step valve train that enables both early and late intake valve closing for unthrottled operation for most of the load range. This study uses the high lift late intake valve closing strategy. The engine was equipped with a factory three-way catalyst. Engine geometry and specifications are provided in Table 1. A description of the unique engine hardware, control, and data acquisition can be found in Szybist et al. [14].

Throughout the experiment the engine was operated at an engine speed of 2600 rpm and a load of 8 bar brake mean effective pressure (BMEP) under rich conditions ($\lambda=0.91$). Fuel rail pressure was held at a constant 85 bar with a constant start of injection timing of 323-329 degrees of crank angle before top dead center (CA bTDC). Fuel injection duration was adjusted for each fuel to maintain load. Combustion phasing was also maintained constant by varying the spark timing from 15 to 17 degrees bTDC. Typical of an acceleration condition, this relatively high BMEP operating condition was of interest for soot production, because, as part of this research effort, we are investigating the soot oxidation properties of GDI soot. The soot oxidation studies require the collection of gram quantities of soot on gasoline particulate filter (GPF) substrates, necessitating long periods of operation at a high soot concentration [16].

To determine this particular operating condition, the A/F and soot levels during various load transients on a similar 2.0 L GM LNF engine with a transient-capable OEM controller were measured for several engine speeds. Figure 1 shows results from a transient test at 2600 rpm, in which the throttle position was changed from 30 to 60%. Soot concentration was measured with an AVL Microsoot sensor. The A/F ratio for steady-state testing was selected to be slightly higher than the minimum λ value of 0.89 from these tests due to operational temperature concerns. Note that the temporal response of the Microsoot sensor is 1 s so the signal is considerably broader than the lambda measurement.

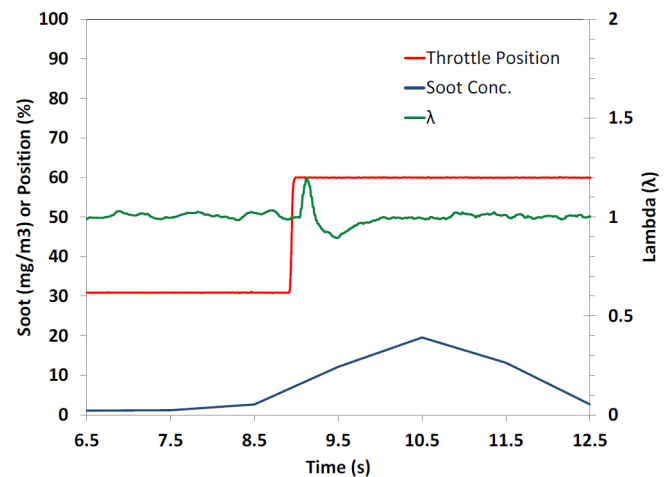


Figure 1. Transient response of A/F to step changes in throttle position. The photoacoustic soot sensor signal is superimposed at the bottom of the graph.

The speed-load combination that produced the highest soot concentration with the lowest temperature was selected for steady-state experiments. Low temperature is important to avoid auto-oxidizing the soot collected in the GPF cores during exposure. Steady-state operation at the selected speed-load point does not produce as high a particle concentration as shown in Figure 1, although the A/F ratio is the same. A steady-state soot concentration level of ~5 mg/m³ was observed in the preliminary experiments, compared to the spike of approximately 20 mg/m³ for the transient case shown.

Figure 2 is a schematic of the entire experimental system used to expose the GPF cores along with analytical techniques.

Table 1. Engine Geometry and Specifications

Displacement (L)	2.0
Bore (mm)	86
Stroke (mm)	86
Compression Ratio	11.85
Fueling	DI
DI Pressure (bar)	100

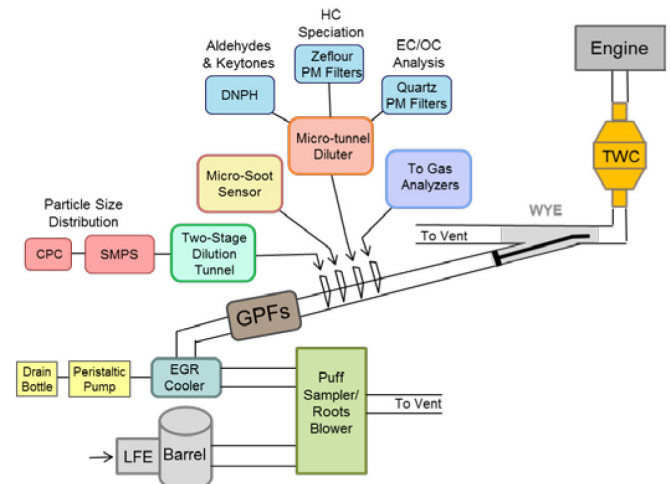


Figure 2. Schematic of experimental setup. Note that all exhaust PM measurements were conducted downstream of the three-way catalyst (TWC).

Fuels

The three fuels investigated in this study were an 87 anti-knock index (AKI) gasoline (E0), a 30% ethanol blend with 87 AKI gasoline (E30), and a 48% isobutanol blend with AKI gasoline (iBu48). E30 was chosen to maximize octane enhancement while minimizing ethanol-blend level and iBu48 was chosen to match the same fuel oxygen level as E30. Fuel properties are given in Table 2. While it is recognized by the authors that iBu48 would likely never be a marketplace fuel, it was felt that the GDI soot oxidation study would benefit from having soot generated with gasoline-alcohol blends having the same fuel oxygen level since that has proved to be an important parameter in past studies of biodiesel blend soot oxidation [16].

Also, it was thought that the enhanced fuel oxygen would amplify effects on the PM chemistry that might be too subtle with lower blends.

Table 2. Fuel Properties.

Fuel Property	ASTM Method:	E0	E30	iBu48
Alcohol (vol-%)		0	30.7	48
DVPE (kPa)	D5191	90.5	91.6	< 85
LHV (MJ/kg)	D240	43.4	38.1	39.7
SG (kg/l)	D4052	.0.729	0.745	0.76
C (wt-%)	D5291	86.0	74.8	75.3
H (wt-%)	D5291	14.0	13.9	13.8
O (wt-%)	D5599	0	11.3	10.9
Total Aromatics (wt-%)	D5580			
Sulfur (ppm)	D5453	6	12	14
Research Octane (RON)	D2699	90.2	100	>100
Motor Octane (MON)	D2700	83.9	88	>88

Sampling and Dilution Systems

Separate systems were used to condition post-three way catalyst exhaust for various particulate matter (PM) measurements:

1. A single-stage micro-tunnel dilution system to provide single dilution exhaust for particulate matter (PM) and DNPH cartridges; and
2. A two-stage dilution system to provide either single or double diluted exhaust to a Scanning Mobility Particle Sizer (SMPS).

The single-stage micro-tunnel dilution system is based on an ejector pump design by Abdul-Khalek et al. [17] in which raw exhaust is drawn into the dilution tunnel as dry, filtered, and

compressed air is passed through an ejector pump. A critical orifice ahead of the ejector pump maintained a constant exhaust sample flow resulting in a dilution of 9-9.2. Following equipment warm up, a volumetric flow meter (DryCal DC-Lite) was used to measure the flow of High Efficiency Particulate Air (HEPA) filtered air. The dilution ratio was calculated as per Equation (1).

$$DR = \frac{\dot{m}_{air} + \dot{m}_{exhaust}}{\dot{m}_{exhaust}} \quad (1)$$

A stainless steel heated line fitted with a sampling probe supplied exhaust to the micro-diluter. The stainless steel line was heated to 190°C to reduce thermophoretic deposition of solid particles and condensation of volatile materials onto the wall of the sampling line. The diluted sample temperature was maintained at 40°C.

The two-stage dilution system is based on an ejector pump design similar to that of the European Particle Measurement Programme (PMP) [18]. This design consists of a micro-tunnel dilution system paired with an evaporator tube. In this system, air heated to 150°C flows in through an ejector pump pulling the exhaust sample through a 150°C first-stage dilution tunnel. The diluted sample is then drawn by a second ejector pump through a 350°C evaporator tube. Following a residence time of approximately 150 ms in the evaporator tube, the exhaust is further diluted with ambient temperature air as the sample enters the second-stage dilution. The second-stage dilution tunnel was maintained at 50°C, as required by the PMP. The dilution ratio for the two-stage dilution system was determined by a CO₂ ratio. The raw exhaust gas CO₂ (wet concentration) was determined and divided by the tunnel CO₂ concentration. The second stage dilution ratio was determined to be about 40. A short (< 0.3 m) length of insulated stainless steel tubing was used to deliver exhaust to the two-stage dilution system from the exhaust pipe.

Two test procedures were performed to validate proper operation of the ORNL two stage dilution system design. First, an aerosolized sodium chloride solution was passed through the dilution system to confirm a zero net loss of solid particulate between first-stage and second-stage dilution. Second, a calibration procedure similar to that of UN-ECE Regulation 83 was performed [19]. For this procedure volatile tetracontane (C₄₀) particles produced by an aerosol generator were sampled through the two stage dilution system. The polydisperse C₄₀ particles were detected by the SMPS after first stage dilution at an approximate concentration of $3.8 \times 10^3/\text{cm}^3$. Near complete vaporization of the volatile particles was observed after second stage dilution. The volatile particle removal efficiency was determined to be >99% for the two stage dilution system.