

Ethanol Blend Effects On Direct Injection Spark-Ignition Gasoline Vehicle Particulate Matter Emissions

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ABSTRACT

Direct injection spark-ignition (DISI) gasoline engines can offer better fuel economy and higher performance over their port fuel-injected counterparts, and are now appearing increasingly in more U.S. vehicles. Small displacement, turbocharged DISI engines are likely to be used in lieu of large displacement engines, particularly in light-duty trucks and sport utility vehicles, to meet fuel economy standards for 2016. In addition to changes in gasoline engine technology, fuel composition may increase in ethanol content beyond the 10% allowed by current law due to the Renewable Fuels Standard passed as part of the 2007 Energy Independence and Security Act (EISA). In this study, we present the results of an emissions analysis of a U.S.-legal stoichiometric, turbocharged DISI vehicle, operating on ethanol blends, with an emphasis on detailed particulate matter (PM) characterization.

Gaseous species, particle mass, and particle number concentration emissions were measured for the Federal Test Procedure urban driving cycle (FTP 75) and the more aggressive US06 cycle. Particle number-size distributions and organic to elemental carbon ratios (OC/EC) were measured for 30 MPH and 80 MPH steady-state operation. In addition, particle number concentration was measured during wide open throttle accelerations (WOTs) and gradual accelerations representative of the FTP 75. For the gaseous species and particle mass measurements, dilution was carried out using a full flow constant volume sampling system (CVS). For the particle number concentration and size distribution measurements, a micro-tunnel dilution system was employed. The vehicles were fueled by a standard test gasoline and 10% (E10) and 20% (E20) ethanol blends from the same supplier.

The particle mass emissions were approximately 3 and 7 mg/mile for the FTP75 and US06, respectively, with lower emissions for the ethanol blends. During steady-state operation, the geometric mean diameter of the particle-number size distribution remained approximately the same (50 nm) but the particle number concentration decreased with increasing ethanol content in the fuel. In addition, increasing ethanol content significantly reduced the number concentration of 50 and 100 nm particles during gradual and WOT accelerations.

INTRODUCTION

Direct injection spark-ignition (DISI) gasoline engines have been in commercial production since the late 1990's [1, 2] but have only become common in the U.S. light-duty fleet in the past five years. Several passenger car and light-duty truck/SUV models for almost every manufacturer have DISI engines, and it is widely known that smaller displacement, turbocharged DISI engines may likely supplant larger displacement engines as one means for manufacturers to meet the 2016 light-duty vehicle fuel economy regulations. DISI engines can be more fuel efficient, in particular under fuel lean operating conditions, and also offer a performance benefit due to the higher volumetric efficiency at high load. [3]. However, DISI engines tend to make more PM than their port-injected counterparts, with PM mass levels exceeding those of diesels equipped with diesel particulate filters [4].

In 2007, the U.S. Congress passed the Energy Independence and Security Act (EISA 2007) which contained 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 E85 and potentially as a blending component of

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Table 1. Fuel Properties[6,8]

Fuel Property	ASTM Method:	E0	E10	E20
EtOH (vol-%)	D5599	0	9.1	19.8
DVPE (kPa)	D5191	57.9	65.4	63.6
LHV (MJ/kg)	D240	43.11	41.51	39.64
SG (kg/l)	D4052	0.746	0.75	0.755
C (wt-%)	D5291	86.83	82.56	79.66
H (wt-%)	D5291	12.97	12.62	12.84
O (wt-%)	D5599	0	3.36	7.23
T10 (°C)	D86*	51	49	51
T50 (°C)	D86*	104	92	73
T90 (°C)	D86*	159	156	151
Total Aromatics (wt-%)	D5580	45.0	39.9	37.3
Sulfur (ppm)	D5453	29.3	27.7	25.4
Research Octane (RON)	D2699	97.1	100.0	101.2
Motor Octane (MON)	D2700	88.3	89.7	90.2

**These methods were performed on the NREL fuel used in the study as reported in [6,8]. The NREL fuel was obtained from the same supplier using the same feedstocks as this study, but the E10 and E20 content were slightly different, 9.9% and 18.6% respectively.*

gasoline higher than the current 10% level. Thus, there was interest in seeing the effects of the convergence of the two advanced technologies, DISI and ethanol blends, on emission levels. Others have investigated ethanol blend effects on in-use gasoline vehicles and PM emissions [5,6] and 10% ethanol blends with DISI engines [7].

EXPERIMENTAL

A 2007 Pontiac Solstice equipped with a 2.0 L, turbocharged, direct injection engine was operated over several transient and steady state cycles on the 48" roll chassis dynamometer at Oak Ridge National Laboratory's Fuels, Engines, and Emissions Research Center (FEERC). Federal Certification Gasoline (E0), a 10% ethanol blend (E10), and a 20% ethanol blend (E20) were all blended by the fuel supplier (Gage Products) with the same base gasoline. The fuel properties are given in [Table 1](#), and further information for the same fuel

type can be found in a report for a large DOE project on intermediate ethanol blends [6,8]. Test cycles included the Federal Test Procedure 75 (FTP), the US06, the aggressive driving portion of the supplemental FTP, and gradual and wide-open throttle (WOT) accelerations. At least three replicates of each test with each fuel were performed, and criteria emissions, fuel economy, and aldehydes and ketones were measured. In addition, steady state cycles at 30 MPH and 80 MPH were done for particle size distribution measurements.

ALDEHYDE SAMPLING AND ANALYSIS

Gaseous aldehydes and ketones were collected following CVS dilution of the exhaust for each phase of the FTP using dinitrophenylhydrazine (DNPH)-coated solid phase

extraction cartridges (Waters Corp.). The sample flow rate was 0.8 l/min. The DNPH derivatives were solvent extracted with acetonitrile and subsequently analyzed by a Hewlett-Packard 1100 high performance liquid chromatograph (HPLC) using a Restek Allure C18 column with ultraviolet absorption detection for the determination of aldehyde and ketone concentrations. The eluent of the HPLC unit was transferred directly to a Bruker Daltonics® Esquire mass spectrometer where the hydrazone derivatives were positively identified using electrospray with negative ionization mass spectrometry (ESI-MS).

PM SAMPLING AND ANALYSIS

PM Mass

Filter samples were collected on 70mm Teflon™-coated glass fiber filters (Pallflex TX-40, Pall Corp.) following full-flow dilution by the CVS. The temperature of the dilute exhaust was maintained below 50 °C throughout the test. Filters were conditioned and weighed in a temperature and humidity controlled chamber and a balance with 0.1 µg sensitivity was used (Model UMX-2, Mettler-Toledo, Inc.) Two PM mass filters were collected for the FTP cycle: the first filter over the cycle corresponding to Bags 1 and 2, also known as the cold LA4; and the second filter over the cycle corresponding to FTP Bags 3 and 4, also known as the hot LA4 cycle. This approach allowed greater PM mass to be collected without affecting the weighted calculation of cycle emissions. A single filter was collected for the US06 cycle.

PM Size and Number Concentration

A micro-tunnel dilution system was used to dilute exhaust for particle number concentration and number-size distribution measurements. The system is based on an ejector pump dilution design by Abdul-Khalek et al. [9]. In the ejector pump, HEPA-filtered compressed air passes through a venturi nozzle and expands. The expansion of the air creates negative pressure and draws raw exhaust into the pump. One micro-tunnel diluter was placed after the turbocharger (pre-catalyst position) and another after the under floor catalytic converter (post-catalyst position). Short lengths of heated stainless tubing were used between the exhaust port and the ejector pump to avoid storage and release of material in the sampling line as described by Maricq et al.[10].

Number-size distributions of 5 to 160 nm particles were measured during 30 MPH and 80 MPH runs by a scanning mobility particle sizer (SMPS, Model 3936, TSI Inc.) equipped with the differential mobility analyzer (DMA, Model 3085, TSI, Inc.) The dilution ratio for the exhaust samples was 21. The number of particles < 15 nm was relatively low, indicating that the chosen dilution ratio was most likely high enough to avoid nucleation of semi-volatile components inside the micro-tunnel.

For particle number concentration measurements, an additional micro-tunnel was added to increase the dilution ratio to approximately 1000:1. Even at this very high dilution, the detection limit of condensation particle counter (CPC, Model 3025, TSI, Inc.) was exceeded during some of the transients. Thus, for subsequent runs, the DMA was used at a fixed particle diameter, 50 nm, the peak of the steady-state size distributions, to enable counting of the particles. The dilution ratio was maintained at 1000 for all of the transient experiments. All particle number concentrations presented here are corrected for dilution to the raw exhaust value.

OC and EC sampling

For the analysis of the organic and elemental carbon content of the particles, raw exhaust was sampled through a 47mm heated quartz filter (QAOT2500-UP, Pall Corp.) that had been pre-fired in a muffle furnace. The sampling apparatus was a modified version of the sampling apparatuses used for collecting PM from point sources [11]. The heated, stainless steel lines were kept at 190 °C and the filter oven was kept at 125 °C to avoid water condensation. Flow measurements were made with a dry gas meter (DTM-200, American Meter Corp.). The raw exhaust was sampled rather than the dilute exhaust to avoid OC artifacts on the quartz media due to the release of volatile organic compounds which may be adsorbed in the dilution tunnel. Samples were collected pre-catalyst and post catalyst to examine the nature of the engine out PM. Both the 30 MPH and 80 MPH steady-state conditions were used. The filters were analyzed by Sunset Laboratory (Tigard, OR) using the thermo-optical transmission method [12]. Blank values were less than 1% of the sample values.

RESULTS

At least three repetitions of each measurement of the effects of E0, E10, and E20 were carried out. Sufficient PM was collected for accurate mass measurement over the cold and hot FTP and US06 cycles. The vehicle's performance and fuel economy matched expectations for all three fuels; [Table 2](#) shows the expected decline in fuel economy due to the lower energy density of the ethanol blends. NOx emissions were low and showed a downward trend with ethanol blend, while HC emissions increased with the E20 due to higher values in Bag 1, the cold start portion.