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Full Length Article

The impact of various ethanol-gasoline blends on particulates and unregulated gaseous emissions characteristics from a spark ignition direct injection (SIDI) passenger vehicle

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ABSTRACT

This study investigated the effects of various ethanol-gasoline blends on the hazardous air pollutants (HAPs) emissions from a wall-guided direct injection passenger vehicle. The fuel economy (FE) as well as regulated and unregulated gaseous emissions was evaluated on a chassis dynamometer using the federal test procedure (FTP-75) mode. Five fuels with varying ethanol contents of E0, E10, E30, E50, and E85 were prepared by blending ethanol into commercial gasoline on a volumetric basis and were analyzed each fuel specification. The engine control schemes of fuel injection quantity for various ethanol blends were adjusted to optimize the engine starting capability, vehicle drivability and emissions performance. The FE of the E85 fueled vehicle decreased by 29% relative to gasoline fuel due to the low energy content of ethanol. Blending ethanol into gasoline produced a dramatic decrease of particulate emission, because pure ethanol has no aromatic compounds and carbon content lower than that of gasoline. As a result, nano-particles were rarely emitted in the vehicle tests of fuels with more than 30% ethanol. Carbonyl compounds emissions, which originate from partial oxidization or incomplete combustion of ethanol, also rose sharply as the ethanol content increased, while volatile organic compound (VOC) emissions were reduced considerably with medium- and high-ethanol formulations due to the lower proportion of aromatic components in these fuels.

1. Introduction

The enforcement of stringent worldwide vehicle emissions regulations, greenhouse gas (GHG) emissions restrictions, and fuel economy (FE) standards has encouraged the utilization of sustainable fuels, energy efficient powertrains, eco-friendly technologies, and vehicle electrification systems in the transportation sector [1,2]. However, the steady growth of vehicle populations in metropolitan areas has resulted in frequent exceedances of established environmental quality standards. Therefore, a substantial reduction of hazardous air pollutants (HAPs) and mobile source air toxic (MSAT) emissions from internal combustion engines (ICEs) is an anticipated feature of advanced vehicle emissions control technologies [3–7].

The development of advanced ICEs technologies has been focused on the maximization of thermal efficiency of approximately 50% with upgrades to combustion concepts, engine hardware, fuel injection pressure, engine control strategy, turbo compound, lean boosting, and other gleaning technologies. In spark ignition (SI) engine, there are significant opportunities for developing a gasoline direct injection (GDI) engines with enhanced power output by increasing the compression ratio and reducing the regulated emissions by adopting of engine control systems that are more sophisticated than the conventional port fuel injection (PFI) engine [8–10]. However, one of the problems found in GDI engines is a strong increase in particulate matter (PM) and particle number (PN) emissions caused primarily by fuel-rich or fuel-pool formation using direct fuel injection in the combustion chamber [11–13].

Most of the PN emissions from GDI engines are emitted in the cold-start phase at low engine coolant temperatures and aggressive transient engine operating conditions because wall wetting on piston heads and cylinder liners is aggravated by fuel-rich control with high injection pressure [14–18]. Excessive wall wetting characteristics in combustion chambers can be prevented by the adoption of split- or multi-injection schemes before the spark ignition stage and by increasing injector holes numbers in conjunction with the use of fuel injection pressures of up to 300–400 bars [19–21]. The PN concentrations from conventional GDI engines have been shown to decrease by 1–2 orders of magnitude when various engine technologies are adopted with the potential to meet the

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Nomenclature

CPC	Condensation Particle Counter
CVS	Constant Volume Sampler
DCVVT	Dual-Continuously Variable Valve Timing
DSI	Double Split Injection
DVPE	Dry Vapor Pressure Equivalent
ECU	Engine Control Unit
EEPS	Engine Exhaust Particle Sizer
EMS	Engine Management System
FBP	Final Boiling Point
FE	Fuel Economy
FFV	Flexible Fuel Vehicle
FTIR	Fourier Transform Infrared
FTP	Federal Test Procedure
GC–MS	Gas Chromatography-Mass Spectroscopy
GDI	Gasoline Direct Injection
GHG	Green House Gas
GPF	Gasoline Particulate Filter
HAPs	Hazardous Air Pollutants
HEPA	High-Efficiency Particulate Air
HPLC	High-Performance Liquid Chromatography
ICE	Internal Combustion Engine
IHCs	Individual HCs
LHV	Low Heating value
MTBE	Methyl Tertiary-Butyl Ether
PAH	Polycyclic Aromatic Hydrocarbon
PFI	Port Fuel Injection
PM	Particulate Matter
PN	Particle Number
PTC	Positive Temperature Coefficient
SIDI	Spark Ignition Direct Injection
TWCs	Three-Way Catalytic converters
VOCs	Volatile Organic Compounds
WLTC	Worldwide-harmonized Light duty Test Cycle

Euro-6 PN regulations of 6.0×10^{11} N/km without GPF systems [14–16,22].

Ethanol as an automotive fuel offers various advantages on nanoparticle emissions and HAPs emissions because of the clean combustion characteristics of oxygenated fuels. Additionally, higher octane rating properties relative to commercial gasoline improve engine thermal efficiency by enabling higher compression ratios. However, the main obstacles of ethanol fuels relative to gasoline fuel include FE and cold-start problems under sub-zero temperatures. To overcome these disadvantages, ethanol flexible fuel vehicles (FFVs), which are intended to be used with E0 to E85 fuel mixtures using specially designed engine management system (EMS) controls, were widely propagated several decades ago in the Brazilian, European Union (EU) and United States (US) automotive markets [23–28].

The application of high-ethanol blends over 85–100% (E85-E100) in gasoline for SI engines resulted in negative physical properties, such as higher fuel injection rates of approximately 1.5 times that of gasoline, insufficient fuel evaporation at transient vehicle operation, and higher latent heat of vaporization for stable cold-start performance at low ambient temperatures. The ethanol content in fuel-tank and fuel-line was estimated by an alcohol sensor or oxygen feedback signal for controlling specific stoichiometric air-to-fuel (A/F) ratios for FFVs [29–31]. To address the cold-start problems occurring at sub-zero temperatures, Delphi introduced a heated injector tip using a fast warm-up positive temperature coefficient (PTC) heater which resulted in successful start-ability in 2 s at a −5 °C start condition with E100 [32]. Also, Miyata et al. developed an FFV-EMS package considering the physical properties of ethanol on estimation of ethanol concentration range of E0-E85 and improved fuel transport model in a PFI engine [33]. Stępień et al. [34] investigated on a flex-fuel direct-injection vehicle with ethanol-gasoline blend fuels containing 10% or 85% ethanol of nanoparticle and non-legislated gaseous emissions detergent − dispersant additives in worldwide harmonized light-duty test cycle (WLTC) and steady-state cycle. Nano-particle emissions from ethanol-gasoline blend of E85 showed the lowest PN concentrations. In addition, non-legislated emission components of ammonia (NH_3), nitrogen dioxide (NO_2), nitrous oxide (N_2O), formaldehyde (HCHO), and acetaldehyde (MeCHO), measured with Fourier transform infrared spectroscopy), were only found in negligible amounts. Muñoz et al. [35] compared emissions of a flex-fuel Euro-5 GDI vehicle operated with gasoline, E10, and E85 under WLTC and steady driving conditions, and showed ethanol blending improved the thermal efficiency and suppressed the formation of particle, polycyclic aromatic hydrocarbon (PAH), and nitro-PAH emissions, and lowered genotoxic potential of GDI vehicle emissions. Karavalakis et al. [24,25,36] assessed the impact of ethanol and *iso*-butanol on gaseous and particulate emissions from FFVs. PM mass, PN, and soot mass emissions showed strong reductions with increasing alcohol content in gasoline over the federal test procedure (FTP)-75 and unified cycles. Particulate emissions were found to be clearly influenced by certain fuel parameters, including oxygen content, hydrogen content, and aromatics content. However, HCHO emissions presented strong increments with higher ethanol blends on PFI-FFV and GDI-FFV pickup trucks.

The main purpose of this study was for the determination of PN, regulated, and unregulated emissions behaviors from a spark ignition direct injection (SIDI) vehicle with various ethanol-gasoline blends after precise EMS mapping data under the FTP-75 mode. The target lambda values of ethanol content were calibrated with application engine control unit (ECU) for exactly matching the specific ethanol content from E0 to E85 fuel because the EMS were not for FFVs. Previous researches showed that detailed harmful emissions from ethanol fueled FFV were investigated with different ethanol blends in PFI and SIDI engines. However, ethanol proportion from low to high blending ratio influenced on the engine performance, PN, and gaseous emissions characteristics because of azeotropic properties of ethanol-gasoline ratio that required adequate EMS data calibration. Also, CO_2 and fuel consumption data were provided in view of oxygenated fuels characteristics in SIDI vehicle. The regulated emissions (THC, CO, and NOx), CO_2, PM as well as PN, aldehydes, and VOCs were investigated to assess the vehicle emissions inventory with ethanol as automotive fuels.

2. Experimental apparatus

2.1. Test engine and vehicle emissions analysis

Detailed test engine and vehicle specifications are provided in Table 1. A 2.4L wall-guided GDI engine equipped with a dual-continuously variable valve timing (DCVVT) device and dome-shaped pistons with a compression ratio of 11.3:1 was tested. Fig. 1 shows the geometries of the combustion chamber and the piston of test engine. Two brick under-floor type three-way catalytic converters (TWCs) combined with a double split injection (DSI) strategy were applied to effectively lower vehicle emissions during the cold-start phase of the FTP-75 cycle. The target lambda (λ) values and fuel injection quantity of all ethanol-blended formulations were modified for stable engine operation at cold-start, lambda closed-loop control region, and transient conditions using base gasoline ECU mapping data.

Fig. 2 shows the schematics of the vehicle test equipment, chassis dynamometer, constant volume sampler (CVS) tunnel, and gaseous emissions analyzers for regulated, PM, and unregulated emissions