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Fuel economy and emissions of light-duty vehicles fueled with ethanol–gasoline blends in a Mexican City

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ABSTRACT

The government of Mexico is mandating increased use of gasoline–ethanol blends as a method for reducing air pollution. However, tests on light-duty vehicles have revealed mixed results in terms of fuel economy and emissions. In addition, little information on the performance of light-duty vehicles fueled by gasoline–ethanol blends exists outside the conditions in Mexico City. Fuel economy and emission factors for commercial Regular (87 octane) and Premium (92 octane) gasoline were compared to corresponding 5% v/v (E05R/E05P) and 15% v/v (E15R/E15P) ethanol blends under the conditions in Monterrey, Mexico, the third largest urban center in the country. Fuel economy was estimated under real-world driving conditions. CO_2, CO, NO_x, and unburned hydrocarbons (HC) emissions were measured for cold- and hot-start tests, as well as for constant-speed (40 km/h) real in-city driving. The highest fuel economy was achieved with pure gasoline, which decreased by as much as 4.4% when an E05R gasoline blend was used and as much as 9.9% when an E15R blend was evaluated. For the Premium blends, the fuel economy decrease was lower: 2.9% and 5.5%, respectively. Even more significantly, the newest vehicles tested experienced the lowest decrease in fuel economy. Overall, the Premium blends, and in particular the E15P blend, resulted in decreased CO, NOx, and HC emissions. However, mixed results for NOx emissions were obtained during the start tests. In addition, HC emissions were higher for the Premium blends compared to the corresponding Regular blends. CO_2 emissions changes were not significant for the constant-speed tests.

1. Introduction

One of the most important arguments in favor of the use of ethanol–gasoline blends in light-duty vehicles is the blends' potential for reducing air pollutant emissions. A significant percentage of this decrease (on a mass basis) is related to the direct and indirect emission of greenhouse gases (mainly CO_2). However, the actual overall life-cycle benefit of using biomass-derived ethanol in fuel blends is still unclear [1–3]. Emission co-benefits include the expected reduction of other air pollutants: unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx = NO + NO_2), and fine particulate matter. However, there is disagreement on this issue [3]. Some, in fact, argue that in countries like Mexico, Tier 1 and Tier 2 regulations should be favored since they provide significantly higher benefits compared to ethanol–gasoline blends [4,5].

Ethanol, an oxygenate additive, has been studied extensively. Ethanol is an additive that increases octane [6,7] and has been proven to increase the Reid vapor pressure, which facilitate cold starts [8,9]. Higher thermal efficiency and pressure inside the cylinders have also been achieved for ethanol-oxygenated fuels [10]. This improved combustion performance counteracts the lower heating value of the fuel blends (provoked by the lower heating value of ethanol), increasing the fuel consumption only marginally and thus the direct CO_2 emissions [11–13]. At the same time, a decrease in CO emissions has been observed while HC and NO_x have had mixed results [10,12,14]. Data in the literature reveals a tendency, albeit inconsistent, for NOx emissions to increase when ethanol content increases [15]. This increase could be explained by the higher temperatures observed in the combustion chambers [10,14]. In addition, the emissions of other unregulated organic compounds are affected. Burning ethanol–gasoline blends tends to increase the concentration of formaldehyde, acetaldehyde, acetone,

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and acetic acid in combustion gases [16–21]. The maximum benefits, in terms of emissions decreases in the most abundant polluting species in exhaust gases (CO_2, CO, HC, NOx), have been attained with 15 vol. % to 30 vol. % ethanol–gasoline blends [7,9,12].

In Mexico, the federal government has made several efforts to reduce emissions from gasoline-powered vehicles. In the 1990s, unleaded gasoline blends with methyl tert-butyl ether (MTBE) as oxygenate and with limits set for benzene, total aromatics, olefin volatility, and sulfur content were introduced [21]. A limited number of studies were performed before, during, and after the new fuel was introduced; therefore, the effects were not precisely quantified [22,23]. Standards to limit the emission of CO, HC, and NO_x for new vehicles were instituted in 2001 and, since then, have been revised. However, air pollution has remained a major environmental problem in the largest cities. The Law for the Promotion and Development of Biofuels is the most recent attempt by the Mexican government to improve air quality. The law requires a reformulation of gasoline using ethanol as oxygenate [5].

Few studies have assessed the direct potential benefits of using ethanol–gasoline blends in Mexican vehicles, and all have been conducted for the prevailing conditions of Mexico City (19° 25′ 10″ N, 99° 8′ 44″ W; average elevation 2240 m above sea level [masl]) [5,24,25]. In this paper, we analyze the results for ethanol-gasoline fuel blends used in Monterrey, Mexico. Monterrey is located in northeastern Mexico (25° 40′ 17″ N, 100° 18′ 31″ W; average elevation 540 masl). It is the third largest metropolitan area of the country (3.93 million inhabitants) and the second largest industrial center in Mexico, with a vehicle fleet of more than 1.7 million units. Currently, Monterrey has some of the worst air quality in the country: The city is in non-attainment status for the 1-h Mexican Air Quality Standard for O_3 and the air quality standards for suspended particulate matter with aerodynamic diameter of less than 10 microns. The possible effects on fuel economy and emissions during cold starts, hot starts, and constant-speed driving conditions in Monterrey were examined for ethanol–gasoline blends.

2. Experimental methods

2.1. Fuel characterization

Fuel economy and emission measurement experiments were performed for six different fuel types. Regular (87 octane, R) and Premium (92 octane, P) base gasoline was blended with reagent-grade anhydrous ethanol to produce the fuel blends tested. The E05R and E05P blends contained 95% vol. Regular or Premium gasoline, respectively, and 5% vol. ethanol, while E15R and E15P were 15% vol. ethanol–gasoline blends. The results for these four blends were compared to commercial gasoline (i.e., commercial Regular and Premium gasoline). The ethanol content was selected based on the future content of Mexican gasoline [5] and an amount that has proven to give good results without the need to modify existing engines [26].

The blends were prepared using a three-necked glass vessel connected to three peristaltic pumps. The pumps fed the appropriate amount of ethanol and gasoline into a container in which the mixture was blended. The outlet of the container was connected to a receptacle in which the reformulated fuel was collected. No additives were required to prevent phase separation [27]. The entire system was hermetically sealed to prevent humidity absorption by the anhydride ethanol.

The physicochemical properties of the ethanol-free gasoline and E15 blends were evaluated. The E05 mixtures were not measured since their physicochemical properties do not vary significantly from the original corresponding commercial gasoline [28]. The following properties of the mixtures were measured: oxygenate content (ASTM D-5599), research and motor octane numbers (ASTM D-2699/ASTM D-2700), Reid vapor pressure (ASTM D-5191), distillation curve (ASTM D-86), oxidation stability (ASTM D 525), and density (ASTM-D-218). Each sample was analyzed in triplicate. All measurements were conducted by the Southwest Research Institute (San Antonio, Texas). Finally, the heating value was determined using an ignition calorimeter (PARR Model 6200) following the ASTM-D240-02(2007) method.

2.2. Fuel economy estimation

To estimate fuel consumption (km/L), the fuel system, including the reservoir, pump, and tubing, was flushed before the tank was filled with a known volume. Real-world driving conditions were simulated using a circuit comprising freeway, arterial, and secondary roads [29]. The complete circuit was 16.8 km long (Fig. 1). After the vehicle was driven in this cycle, the system was evacuated again to measure the amount of fuel left. The difference between the initial and final volumes was taken as the consumption.

2.3. Emissions characterization

A Flexible Gas Analyzer onboard instrument (Snap On®, model AL293-001; Kenosha, WI, USA) was used to sample three light-duty vehicles (Table 1). All vehicles had a fuel supply system consisting of a normally aspirated electronic-controlled sequential multiport fuel injection system. Five species are measured with the instrument: CO_2, CO, HC, O_2, and NO_x (Table 2). Additionally, the analyzer can be connected to the OBD2 port of the on-board computer of the vehicle to record engine speed. The instrument was calibrated using a standard CAM-97 mid-range mixture containing 3200 ppm HC (propane), 8% CO, 12% CO_2, 3000 ppm NO, and nitrogen as the balance. Leak checks were performed before each test. Emission factors were estimated based on the emissions and operational conditions readings, and the duration of each test, as described elsewhere [30]. Briefly, the average emission factor of pollutant i, E_i, in terms of mass emitted per kilometer traveled can be expressed as:

$$E_i = \frac{1}{l}\int_{t_o}^{t_f} Q\left(\frac{y_i P}{RT} M_i\right) \mathrm{d}t \tag{1}$$

where Q is the volumetric flow of the combustion gases in the exhaust, y_i is the molar fraction of pollutant i in the exhaust, P is the pressure, T is the temperature, R is the universal ideal gas constant, M_i is the molecular weight of species i, and l is the distance traveled during the test. Equation (1) was integrated for the duration of the test (t_o–t_f) since the time interval for every measurement registered by the gas analyzer was 1 s. For the cold- and hot-start tests, Equation (1) was modified eliminating the traveled distance term (l) so the units were mass emitted for the total duration of the test (E_i'). When the concentration of any given species was below the analyzer's detection limit, one-half of the detection limit concentration was used for estimation purposes.

Cold-start emissions were measured after the engine was shut down for 12 h; hot-start tests were performed 10 min after the engine was shut down. In each test, the vehicles were first started, and after the pipeline was purged for 15 s, the exhaust was sampled for 180 s. In all cases, the engine speed was left to attain idle levels (approximately 800 rpm). Emissions were estimated for the first 90 s of the test since this represents the time period when most of the emissions in this mode occur [31]. On-road emissions were measured by a single driver at constant speed (40 km/h) under