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Cold start and full cycle emissions from a flexible fuel vehicle operating with natural gas, ethanol and gasoline

Amanda Alves Martins [a,1], Rodrigo Anderson Dias Rocha [b,2], José Ricardo Sodré [c,*]

[a] FIAT Chrysler Latin America, Control System Development, Av. do Contorno, 3455, 32669-900 Betim, MG, Brazil
[b] Iveco Latin America, Rodovia MG 238, km 73,5, 35703-106 Sete Lagoas, MG, Brazil
[c] Pontifical Catholic University of Minas Gerais, Department of Mechanical Engineering, Av. Dom José Gaspar, 500, 30535-610 Belo Horizonte, MG, Brazil

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ABSTRACT

This paper describes a comparative study between the pollutant emissions produced by a spark ignition engine operating with three different fuels: commercial gasoline with 22% of ethanol (E22), compressed natural gas (CNG) and hydrous ethanol. The emission levels of oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbons (HC), and methane (CH_4) produced by a flexible fuel engine operating according to the US 1975 Federal Test Procedure (FTP 75) were analyzed. Tests were performed with a mid-size sedan powered by 1.4-L spark ignition engine on a chassis dynamometer. The results for the cold start tests demonstrate that E22 produced the lowest CO and HC emissions, while CNG produced the lowest NO_x emissions. Considering the full test cycle, CNG emitted the lowest CO, NO_x and CO_2 concentrations, and the lowest fuel consumption. Gasoline presented the lowest emission levels of HC and CH_4. Ethanol showed the highest fuel consumption and higher pollutant emission levels than the other fuels, except for CO_2, which was higher than CNG and lower than gasoline.

1. Introduction

An alternative to reduce and control gaseous pollutant emissions is the partial substitution of conventional fossil fuels, such as gasoline, by non-conventional fuels like natural gas (CNG) and ethanol. While the use of ethanol is presently restricted to a few countries, such as Brazil and USA, several countries support the use of CNG as a substitute to gasoline or diesel oil. The world consumption of CNG for automotive application was about 3.5×10^{12} m^3 in 2010 and it is estimated to be around 4.7×10^{12} m^3 by 2020, which will account for a growing of more than 50% in this decade (ANP, 2010). In 2011 the world fleet moved by CNG was about 11.5 million vehicles (ANFAVEA, 2012). The growing use of CNG has been motivated by oil price fluctuations and global warming aspects. India, Iran and Pakistan are world leaders of CNG use in vehicles.

Regarding the use of ethanol, the Brazilian experience shows that vehicles powered by engines with flexible fuel technology has proved to be successful to overcome the difficulties associated to fluctuations of the renewable fuel availability. Since ethanol is produced from sugar cane in Brazil and from corn in the USA, its offer and price on fuel stations depends on crop growth and on market price for food production from those same sources. Flexible fuel engines allow for the use of ethanol and gasoline as fuels, pure or blended at any proportion. It became attractive to consumers as they can always choose from any of those fuels according to price and availability. Flexible fuel vehicles presently accounts for over 90% of the total automobile sales in Brazil. Some flexible fuel vehicles also allow for the use of CNG as fuel, besides gasoline, ethanol and blends of these. The engine brings a CNG kit installed by the vehicle manufacturer, and it is often called as tetra fuel engine.

A flexible fuel engine is designed to operate with two or more different fuels. While this brings some advantages under the customer's viewpoint, some important engine parameters, such as compression ratio, are set to attend all the operational fuels and, thus, they are not optimized for any fuel. Thus, fuel conversion efficiency of a flexible fuel engine is expected to be lower than that of a similar engine dedicated to a specific fuel. That may increase the raw concentration of some pollutant components in the exhaust gas. It has been observed that the carbon monoxide (CO) emission from a flexible fuel engine is higher than that from engines dedicated to gasoline and ethanol. Increased hydrocarbons (HC), oxides of nitrogen (NO_x) and aldehyde emissions have also been observed, in comparison with dedicated engines to those fuels. Regarding

* Corresponding author. Tel.: +55 31 3319 4911; fax: +55 31 3319 4910.
E-mail addresses: amanda.martins@fiat.com.br (A.A. Martins), rodrigo.rocha@br.iveco.com (R.A.D. Rocha), ricardo@pucminas.br, jrsodre@pq.cnpq.br (J.R. Sodré).
[1] Tel.: +55 31 2123 5731; fax: +55 31 2123 5074.
[2] Tel.: +55 31 2107 2621.

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carbon dioxide (CO_2) emission, both decreased concentration and increased concentration have been reported by the use of flexible fuel engines in comparison with dedicated engines (Loiola et al., 2011; Borsari and Assunção, 2012).

The high hydrogen-to-carbon ratio of natural gas may represent an advantage to reduce exhaust pollutant emissions (Hill and D'Agosto, 2011). It has been shown that CO, non-methane hydrocarbons (NMHC), nitrous components, and particulate matter (PM) are lower when CGN is used instead of conventional fossil fuels, such as gasoline and diesel oil (Bosch, 2011). A previous work by Zarante and Sodré (2009) showed that the use of natural gas as a substitute to gasoline substantially reduced CO and CO_2 emissions.

Ethanol produces higher fuel conversion efficiency than gasoline and CNG (Leite, 2012). On the other hand, the use of hydrous ethanol (6.8% wt./wt. of water content) in a flexible fuel engine in place of gasoline increases specific fuel consumption (Costa and Sodré, 2009; Borsari and Assunção, 2012). The substitution of gasoline with 22% of ethanol by hydrous ethanol reduced CO and HC emissions, but increased CO_2 and oxides of nitrogen (NO_x) emissions (Costa and Sodré, 2009). A correlation between CO and CO_2 emissions has been noticed for engines operating with gasoline (Fernandes, 2009). As CO_2 concentration is increased, the concentration of CO is decreased. However, for operation with CNG, no correlation between CO and CO_2 was observed. For all fuels, gasoline, ethanol and CNG, increased CO_2 concentration was followed by reduced HC concentration.

This work investigates the exhaust emissions from a flexible fuel vehicle operating with a blend of gasoline with 22% of anhydrous ethanol (E22), hydrous ethanol and CNG. The vehicle powered was operated under a standard emission test schedule. Unlike the CNG kits that can be adapted by many automotive workshops in vehicles that were not originally intended to operate with gas fuel, in this case the injection control for the different fuels is done by a single electronic control unit. The exhaust components of interest were CO, CO_2, HC and NO_x.

2. Experimental section

A production vehicle powered by a flexible fuel engine operating with gasoline, hydrous ethanol and CNG was tested following the 1975 U.S. Federal Test Procedure (FTP-75) to investigate exhaust CO, CO_2, HC and NO_x emissions. The vehicle tested was a compact sedan equipped with a 1.4-L, 8-valve, four-cylinder flexible fuel engine (Table 1). The engine allows for utilization of gasoline blended with any concentration of ethanol, hydrous ethanol and CNG. The multipoint fuel injection system was constituted by four liquid fuel injectors and four CNG injectors, controlled by a single electronic control unit with the injection and ignition settings optimized by the vehicle manufacturer. In this wok the gasoline used contained 22% of anhydrous ethanol (E22). The typical composition of the natural gas used in the tests is shown by Table 2 (GASMIG, 2012).

Table 1
Engine details.

Parameter	Value
Number of cylinders	4, in line
Compression ratio	12.35:1
Number of valves per cylinder	2
Bore × stroke (mm)	72 × 84
Displaced volume (cm^3)	1368.1
Rated power @ 5750 rev/min (kW)	62.5 (E22) / 64.7 (ethanol) / 57.4 (CNG)
Rated torque @ 3500 rev/min (N.m)	121.6 (E22) / 122.6 (ethanol) / 104.9 (CNG)

Table 2
Natural gas composition.

Component	Concentration (%)
Methane (CH_4)	89
Ethane (C_2H_6)	6.0
Propane (C_3H_8)	1.8
Heavier hydrocarbons (C_{4+})	1.0
Carbon dioxide (CO_2)	1.5
Nitrogen (N_2)	0.7

The vehicle was tested in a chassis dynamometer with double rolls of 502 mm of diameter each and rated power of 75 kW. A constant-volume sampling system was used, in which the exhaust gas is diluted into air and the sample gas is collected in plastic bags before being directed into the analyzers, keeping a constant sample flow rate. The gas analyzers were constituted by a flame ionization detector (FID) for hydrocarbon measurement, non-dispersive infrared (NDIR) detector for CO and CO_2 measurement, and by a chemiluminescent detector (CLD) for NO_x measurement. The sample gas collected in the bags was directed into the analyzers at the end of each test cycle. During the tests several engine parameters were monitored, such as coolant and lubricant temperatures, intake air temperature and pressure, fuel-air mixture equivalence ratio, injection timing, engine speed, throttle valve position and oxygen concentration in the exhaust gas.

The experiments were carried out following the FTP-75 test schedule (ABNT, 2005). The test is divided into three phases: cold start, transient and hot start. The test routine is defined by vehicle speed variation with time, simulating on-road driving conditions. Basic required parameters for an adequate simulation are vehicle mass, aerodynamic drag coefficient, rolling resistance coefficient and air density.

The first part of the test cycle takes 1372 s (22.87 min), corresponding to a travel distance of 12.1 km at an average speed of 31.46 km/h, and is subdivided into two phases. The first 505 s (8.42 min) of the cycle is the cold start phase, corresponding to a travel distance of 5.78 km at an average speed of 41.20 km/h. That is followed by the transition phase, which takes 867 s (14.45 min) to be completed, corresponding to a travel distance of 6.32 km at an average speed of 22.55 km/h. At the end of the first part of the cycle there is a period of 10 ± 1 min in which the vehicle is kept still with the engine turned off and open hood. After that period the hood is closed and the engine is turned on, giving start to the second part of the cycle. The second part of the cycle is constituted by the hot start phase, which test routine is similar to that of the cold start phase. The full test schedule takes 41.28 min, corresponding to a travel distance of 17.88 km (Fig. 1).

Prior to the tests the vehicle was conditioned at an ambient with temperature of 24 °C for a period of 24 h. The fuel system was cleaned up before refueling with E22 or hydrous ethanol. For the tests with CNG the cylinder pressure was always checked and it should be over 80 bar. In order to eliminate any interference of driving style in the results, the same vehicle driver was used for all the tests. The ambient conditions during the tests were temperature of 24 ± 2 °C, pressure of 0.924 ± 0.009 bar and relative humidity of 33 ± 4%. Three tests were performed for each fuel, and the results shown in the following section represent the average of the measured values. The uncertainties of the measurements are shown as error bars in the figures.

3. Results and discussion

Fig. 2 shows the average CO, HC and NO_x concentrations during the cold start phase of the FTP-75 test cycle for E22, hydrous