

Emissions and Combustion Behavior of a Bi-Fuel Gasoline and Natural Gas Spark Ignition Engine

2011-24-0212

Published
09/11/2011

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doi:[10.4271/2011-24-0212](https://doi.org/10.4271/2011-24-0212)

ABSTRACT

In the last ten years, the number of natural gas vehicles worldwide has grown rapidly with the biggest contribution coming from the Asia-Pacific and Latin America regions. As natural gas is the cleanest fossil fuel, the exhaust emissions from natural gas spark ignition vehicles are lower than those of gasoline powered vehicles. Moreover, natural gas is less affected by price fluctuations and its resources are more evenly widespread over the globe than to oil. However, as natural gas vehicles are usually bi-fuel gasoline and natural gas, the excellent knock resistant characteristics of natural gas cannot be completely exploited.

This paper shows the results of an experimental activity performed on a passenger car fuelled alternatively by gasoline and compressed natural gas (CNG). The vehicle has been tested on a chassis dynamometer over standard (NEDC) and real driving cycles (Artemis CADC), allowing to investigate a wide range of operating conditions. Cylinder pressure has been measured by means of a spark plug with an

integrated pressure transducer. By processing the acquired signal, a combustion analysis has been performed allowing the evaluation of the burning rate affected by fuels properties. Furthermore, regulated and unregulated exhaust emissions have been measured and fuel consumption has been calculated by means of carbon balance method to evaluate engine average efficiency over driving cycles.

CO and HC emissions were higher for CNG respect to gasoline over the type approval driving cycle, mainly because of cold start contribution. Over the much dynamic real-world driving cycles, gasoline showed always higher CO emissions due to the rich combustion operated by engine control during transients. NOx emissions were always higher with gasoline fuelled vehicle. Using the gaseous fuel, a consistent increase in engine efficiency was noticed, particularly evident over Artemis driving cycles. Particulate mass emissions were generally very low and close to background levels. Total particle number relative to gasoline is higher than that of natural gas, exceeding the Euro 5b standard limit currently prescribed only for diesel passenger cars. The slower

combustion rate of natural gas respect to gasoline has not been compensated by appropriate ignition timing. A different ignition timing setup for the natural gas operation could give appreciable engine performance improvement.

INTRODUCTION

The use of natural gas vehicles (NGVs) was first introduced in Italy in the mid-1930s as an alternative to gasoline-powered vehicles. Since the 1970s energy crisis, governments started to promote Natural Gas as a clean alternative to gasoline and diesel fuels to reduce oil dependence and exhaust emissions. Methane, the principal constituent of natural gas, is the cleanest fossil fuel due to its highest hydrogen to carbon ratio. However, since the composition of natural gas varies with its origin, the change in fuel properties affects the engine performance and exhaust emissions [1]. Besides methane, which is a greenhouse gas, is the major hydrocarbon gas component in the exhausts of CNG vehicles [2] and is also one of the most difficult hydrocarbons to catalytically oxidize, with a sensible reduction of CH₄ oxidation efficiency with the catalyst aging [3].

Gaseous fuels form homogeneous mixtures with air more easily, without the need for turbulence or heating, allowing an easier start of engines in cold conditions and a more complete burning. On the other hand, the amount of gas required for combustion occupies a larger volume than if the fuel was liquid causing a reduction of amount of incoming air, which can lead to a loss of horsepower [4]. The lower stoichiometric fuel/air ratio of natural gas compared to gasoline also contributes to reduce the engine power. However, the use of the direct injection has the advantage to eliminate the loss in volumetric efficiency since CNG is directly injected into the cylinder. Also the Liquefied NG provides the horsepower needed for the engine's regular performance. Compared with conventional gasoline engines, SI engines using natural gas can run at higher compression ratios, thus producing higher thermal efficiencies but also increased nitrogen oxide (NO_x) emissions, while producing lower emissions of carbon dioxide (CO₂), non-methane unburned hydrocarbons (NMHC) and carbon monoxide (CO). NO_x emissions can be reduced diluting the intake charge with excess of air or with exhaust gas recirculation (EGR) at stoichiometric condition. Both the lean limit of combustion and the maximum amount of EGR, above which combustion becomes unstable, can be significantly extended by hydrogen addition [5, 6].

Today, more than 11 million NGVs are on the road and 16.5 thousand CNG fuelling stations are operative worldwide [7]. Natural gas has been applied to a wide range of vehicles, including passenger cars, heavy-duty trucks, garbage trucks, three-wheelers (primarily in Asian countries), and buses. Most of the NGVs in use today are converted gasoline- or diesel-fueled vehicles.

In [8] the authors tested a bi-fuel gasoline - natural gas vehicle. The investigations showed that, converting a gasoline vehicle to CNG, there was no statistically significant change in the emission of particles for the vehicle operating on gasoline, before the conversion, compared to the emissions for the vehicle operating on CNG, after the conversion. There was a significant reduction of emissions of total polycyclic aromatic hydrocarbons and formaldehyde when the vehicle was operated on CNG, and a reduction of global warming potential was also observed when the vehicle was run on CNG.

In this paper the results of an experimental activity performed on a passenger car fuelled alternatively by gasoline and natural gas are presented. The vehicle was tested on a chassis dynamometer over standard and real-world driving cycles, in order to investigate a wide range of operating conditions. Cylinder pressure has been measured by means of a spark plug with an integrated pressure transducer and the tested fuels have been compared at the same engine speed and load conditions. By processing the acquired pressure signal, a combustion analysis was performed to evaluate the burning rate affected by fuels properties. The Coefficient of Variation of indicated mean effective pressure (imep) was determined in order to compare the cycle-by-cycle variation for the tested fuels. In addition, regulated and unregulated exhaust emissions were measured and fuel consumption was calculated by means of carbon balance method to evaluate engine average efficiency over driving cycles.

METHODS

EXPERIMENTAL APPARATUS

The experimental activity has been performed on an in use passenger car, whose main characteristics are reported in [Table 1](#).

Table 1. Vehicle characteristics.

Make model	Fiat Panda 1.2 NP
Engine type	L4
Displacement	1242 cm ³
Compression ratio	9.8:1
Rated power	38 kW @ 5000 rpm
Reference mass	1025 kg

Table 2. Characteristics of the driving cycles.

	Average speed	Maximum speed	Mean positive acceleration	Number of accelerations	Idle	Cruising	Acceleration
	km/h	km/h	m/s ²		%	%	%
NEDC	33.6	120	0.53	31	20.4	38.8	23.6
Artemis URBAN	17.7	57.3	0.53	48	20.7	9.6	36.0
Artemis ROAD	57.5	111.1	0.36	48	1.5	21.6	39.7
Artemis MOTORWAY	96.9	131.4	0.27	46	0.7	26.0	40.6

The vehicle was installed on a Schenck Single-Axle Large Roll chassis dynamometer with a 1.59 m diameter. The test bench allows a maximum test speed of 200 km/h and maximum power absorption of 184 kW. The car was driven by a Horiba 7000 Automatic Driving System (ADS) in order to minimize the difference between actual and reference speed reducing tests variability caused by driver inaccuracy.

Exhaust gases were diluted with purified ambient air and drawn through a dilution tunnel. Total diluted flow was held constant by a constant volume sampling positive displacement pump (CVS-PDP).

A Horiba Mexa 7200 H multi-range gas analyzer was employed to measure bags and diluted exhaust concentrations of carbon monoxide (CO), oxygen (O₂), total unburnt hydrocarbons (THC), methane (CH₄) nitrogen oxides (NO_x) and carbon dioxide (CO₂). Nondispersive infrared (NDIR) analyzers have been used for CO and CO₂ measurements, a flame ionization detector (FID) analyzer for hydrocarbons and methane, a chemiluminescence analyzer (CLA) for nitrogen oxides and a paramagnetic detector for oxygen.

Their accuracy is in the range $\pm 0.5\%$ of reading.

Particulate Matter (PM) was measured by following the type approval legislation for diesel vehicle collecting diluted exhaust gases on a sampling filter (Pall T60A20). The PM emission is evaluated by gravimetric analysis of the filter (weight difference pre and post test). Moreover, particulate was characterised as total particle number and size distribution. This measurement was carried out by an Electrical Low Pressure Impactor (Dekati ELPI) which is able to count particles with an aerodynamic diameter between 7 nm and 10 μm , sizing them on 12 dimensional stages. ELPI was positioned downstream a dilution system (Dekati Fine Particle Sampler FPS) which dilutes raw exhausts almost 12 times.

The combustion analysis was performed by means of an AVL Indimicro system. The cylinder pressure was measured by means of a spark plug with integrated pressure measurement function, with a resolution of 1 crank angle degree. The piezoelectric sensor is placed into the spark plug shell, allowing the regular engine operations without additional modifications. The measuring range is 0 -200 bar, with a sensitivity of 8 pC/bar. Each channel has a 1 MHz sampling rate and an ADC resolution of 18 bits.

DRIVING CYCLES

Emission factors were measured over the type-approval New European Driving Cycle (NEDC) and on real-world Common Artemis Driving Cycles (CADC) composed by Urban, Road and Motorway phases. The NEDC cycle includes the Urban Driving Cycle (UDC) consisting of four repetitions of the same module, and an Extra-Urban segment (EUDC). It was driven in cold start condition as prescribed by European legislation. The Artemis driving cycles were originally designed by INRETS (Institut National de Recherche sur les Transports et leur Sécurité, France) as real-world cycles representing urban congested traffic [9]. The sequence of the Artemis cycles was driven with hot starting conditions (i.e. hot conditioned engine fluids) after the execution of a NEDC. All the driving cycles were repeated three times. The main kinematic characteristics of the driving cycles are reported in Table 2 [10]; it can be observed in the Artemis Urban cycles more time is spent in accelerations and less in cruising time than the NEDC driving cycle.

Before the test, the vehicle was allowed to soak for at least 8 hours at a temperature of around 24°C. The car was fuelled alternatively with gasoline and natural gas, whose composition, reported in Appendix in Table 4, has been determined using gas chromatography analysis [11].

Fuel consumption has been estimated by means of a carbon balance in the exhaust gases [12]. Emission tests have been repeated 3 times for each fuel. The combustion analysis was carried out averaging the data collected over 500 cycles.

Constant speed tests (15, 30, 50, 70, 100 and 120 km/h) were performed in order to take additional information about emissions and combustion processes.

RESULTS

REGULATED POLLUTANT EMISSION AND FUEL CONSUMPTION

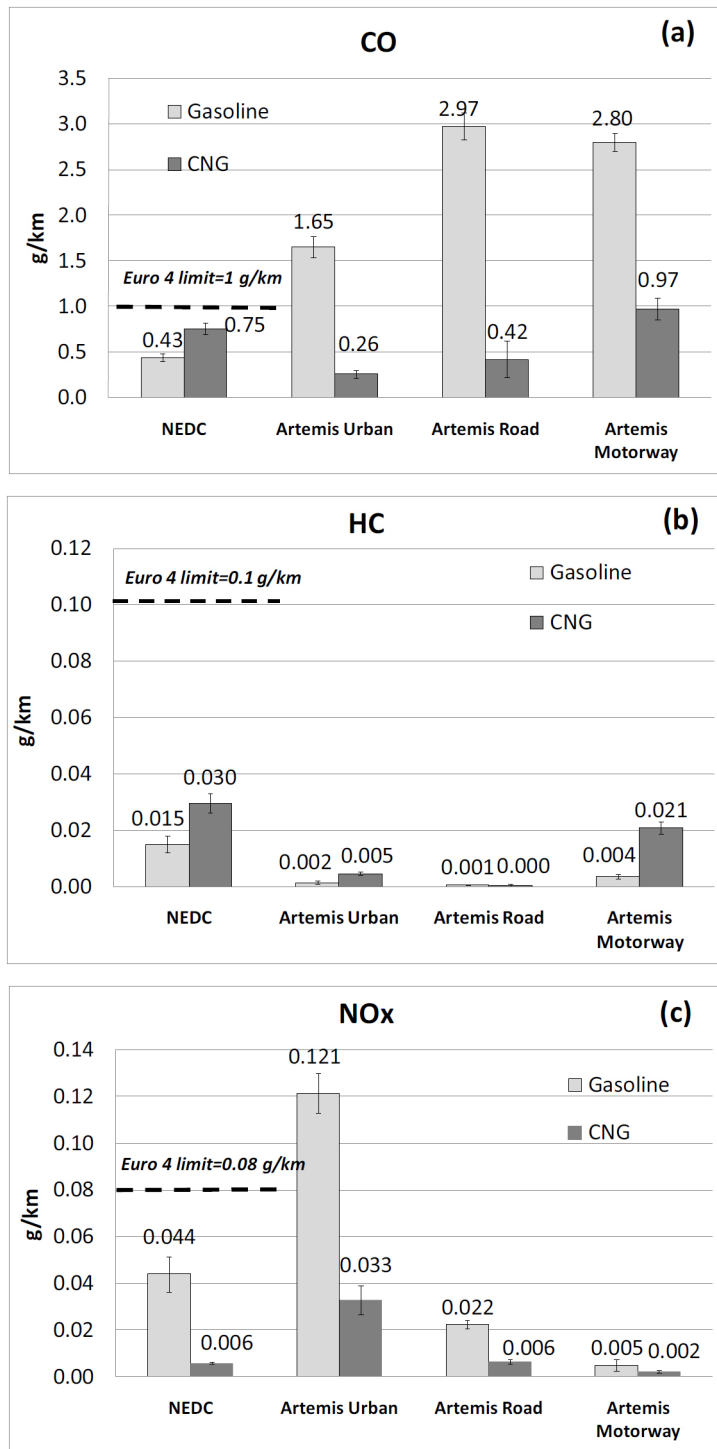


Figure 1. CO (a), HC (b) and NOx (c) emissions over NEDC and Artemis driving cycles.

Figure 1 summarizes CO, HC and NOx emissions measured at the exhaust of the test vehicle fuelled by gasoline and CNG, over both NEDC and Artemis cycles. Data have been averaged over three test repetitions. The figures also report the Euro 4 standard limits for spark-ignition passenger cars that are abundantly complied with both fuels. CNG produces higher CO emissions than gasoline over type approval driving cycle as a possible consequence of a reduced relative air-fuel ratio λ . The largest difference occurs over cold start phase (almost +60% of CNG vs gasoline). The behavior is opposite in real-world driving cycle where gasoline CO emissions are almost 3-7 times higher than CNG ones. The test vehicle fuelled by gasoline has shown a great influence of driving conditions on CO emissions that greatly increase when moving from type approval NEDC, characterized by a long time in steady-state conditions and smooth accelerations, to the Artemis driving cycles, that are highly dynamic. This behavior could be mainly attributed to excessive mixture enrichment during load transients. Figure 2 shows the exhaust raw CO concentrations measured over a portion of Artemis Urban and the instantaneous λ values estimated using the simplified Brettschneider equation [13]. An air fuel ratio lower than stoichiometric during accelerations using gasoline causes high peaks of CO.

As shown in Figure 1 (b), CNG shows higher HC emissions compared to gasoline. Considering the NEDC, this increase is the consequence of the higher light-off temperature for the catalytic oxidation of CH_4 , which represents more than 80% of HC when the vehicle is fuelled by CNG. Over the other driving cycles, it has to be pointed out that measured concentrations become very close to background values, making any comparison much difficult except for Motorway.

NOx emissions, Figure 1 (c), are higher for gasoline over all the test cycles due to air-fuel ratio control not very accurate during transients.

Figure 3 compares CO_2 emissions (a) and fuel consumption (b), in MJ/km, for CNG and gasoline. The reduction of CO_2 emissions for CNG is 21% over the NEDC, while for the Artemis the reduction ranges between 23% and 29% as a consequence of the reduced carbon content of the fuel and lower fuel consumption on mass basis. A 5% reduction of the fuel consumption in MJ/km over the NEDC cycle is observed for the CNG respect to gasoline, while for the Artemis the reduction ranges between 10% and 22%. The higher consumption for gasoline is the consequence of the excessive mixture enrichment during the tests.