

Regulated and Unregulated Exhaust Emissions from CNG Fueled Vehicles in Light of Euro 6 Regulations and the New WLTP/GTR 15 Test Procedure

Piotr Bielaczyc, Andrzej Szczotka, and Joseph Woodburn
Bosmal Automotive R & D Institute

ABSTRACT

The aim of this paper was to explore the influence of CNG fuel on emissions from light-duty vehicles in the context of the new Euro 6 emissions requirements and to compare exhaust emissions of the vehicles fueled with CNG and with gasoline. Emissions testing was performed on a chassis dynamometer according to the current EU legislative test method, over the New European Driving Cycle (NEDC). Additional tests were also performed on one of the test vehicles over the World Harmonized Light Vehicles Test Cycle (WLTC) according to the Global Technical Regulation No. 15 test procedure. The focus was on regulated exhaust emissions; both legislative (CVS-bag) and modal (continuous) analyses of the following gases were performed: CO (carbon monoxide), THC (total hydrocarbons), CH₄ (methane), NMHC (non-methane hydrocarbons), NO_x (oxides of nitrogen) and CO₂ (carbon dioxide). Furthermore, unregulated exhaust emissions were also examined in certain cases: particle number and mass, as well as emissions of NH₃ (ammonia), NO (nitrogen monoxide) and NO₂ (nitrogen dioxide). The results showed a range of differences in terms of regulated emissions, particulate matter and ammonia emissions, and also in the composition of the NO_x in the exhaust gas (i.e. the NO:NO₂ ratio). Emissions of both CO₂ and particulates were markedly lower when running on CNG. Emissions from the two phases of the NEDC and the four phases of the WLTC were briefly analysed.

CITATION: Bielaczyc, P., Szczotka, A., and Woodburn, J., "Regulated and Unregulated Exhaust Emissions from CNG Fueled Vehicles in Light of Euro 6 Regulations and the New WLTP/GTR 15 Test Procedure," *SAE Int. J. Engines* 8(3):2015, doi:10.4271/2015-01-1061.

INTRODUCTION

The use of alternative fuels (biodiesel, petrol-alcohol blends, CNG (compressed natural gas), LPG (liquefied petroleum gas)) in vehicular powertrains supports efforts to reduce petroleum use in transportation (which is necessary because of limited crude oil resources) [1] and helps in reducing anthropogenic CO₂ emissions.

Natural gas (NG) is considered to be a promising alternative fuel for spark ignition (SI) engines on the basis of advantages such as:

- its abundance - it can be produced from a variety of feedstocks, including renewable;
- substantially lower probability of benzene ring formation, which in turn means a reduction in formation of carcinogenic polycyclic aromatic hydrocarbons (PAHs) and soot [2] during natural gas combustion, since methane does not contain carbon-carbon molecular bonds;
- lower CO₂ emissions (due to its low carbon:hydrogen ratio);
- negligible sulphate emissions (very low sulphur level);
- negligible evaporative emissions;
- potentially more complete combustion and lower cold start emissions than gasoline (due to its gaseous state);
- superior anti-knock properties due to its very high Octane number, thus allowing higher compression ratios and operation under turbocharged conditions;

- extended flammability limits, allowing stable combustion with leaner mixtures;
- lower adiabatic flame temperature (leading to lower NO_x emissions);
- much higher ignition temperature than gasoline or Diesel, making it more difficult to auto-ignite (and thus safer);
- contains non-toxic components;
- much lighter than air (thus safer);
- not a volatile organic compound (VOC);
- higher calorific value than gasoline on a mass basis;
- its summer smog formation potential is very low;
- engines fueled with natural gas in heavy-duty vehicles offer quieter operation than equivalent Diesel engines, making them more attractive for use in urban areas.

The major disadvantages of CNG as a fuel for motor vehicles are:

- higher vehicle purchase cost;
- lower vehicle range: about 300 km for bi-fuel gasoline conversions and 400-600 km for dedicated CNG vehicles;
- transportation of natural gas onboard a vehicle is complicated: it can be stored as compressed gas at 200 bar, but even in compressed form it still requires 3-4.5 times more volume for storage than gasoline;



- limited refuelling infrastructure - CNG requires special refuelling stations;
- refuelling time is longer than for either gasoline or Diesel;
- refuelling is considered to be the “least safe” moment of its use;
- the extra weight of the fuel tank gives rise to somewhat higher fuel consumption;
- the laminar flame speed of natural gas is lower than that of gasoline and hence it has a lower burning rate;
- injection of natural gas into the intake port at low pressure or directly into the cylinder at high pressure requires special, modified injectors;
- being hydrophilic, it absorbs water vapour, which may later freeze under certain conditions;
- exhaust emissions of methane (a potent greenhouse gas) are relatively high;
- it requires dedicated catalytic converters with high loading of active catalytic components to maximise methane oxidation, at the increase of both weight and cost;
- its composition varies widely between countries and regions, depending on the point of origin of the gas, which affects the stoichiometric air/fuel ratio.

The properties of natural gas are very similar to those of methane (CH_4), which is its main component. NG also contains heavier hydrocarbons such as ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}), and inert diluents such as molecular nitrogen (N_2) and CO_2 . There are also trace levels of sulfur compounds and other hydrocarbon species. The levels of these species vary considerably with geographical source, season and treatments applied during production or transportation [3, 4, 5]. Key properties of natural gas are presented in Table 1.

Table 1. Key properties of natural gas [13]

Property	Value
Hydrogen to carbon ratio	3 - 4
Relative density @ 15°C/ 1 bar	0.72 - 0.81
Boiling temperature @ 15°C/ 1 bar	-162
Autoignition temperature [°C]	540 - 650
Octane number (RON/MON)	120 - 130
Methane number	69 - 99
Stoichiometric air:fuel ratio (by mass)	17.2
Lower heating value [MJ/kg]	38 - 50
Methane concentration [% v/v]	80 - 99
Ethane concentration [% v/v]	2.7 - 4.6
Nitrogen concentration [% v/v]	0.1 - 15
Carbon dioxide concentration [% v/v]	1 - 5
Sulphur concentration [ppm]	< 5
Wobbe Index [MJ/m ³]	41 - 58

The most important differences in the engine out exhaust emissions from NG-powered passenger car vehicles in comparison to those using gasoline are:

- significantly increased CH_4 content in the total hydrocarbon fraction. This results in significantly reduced reactivity of the THC fraction compared to that of gasoline-powered vehicles,

- roughly doubled water content (due to increased hydrogen to carbon ratio of natural gas compared with gasoline), which leads to increased hydrogen formation due to the water gas shift and steam reforming reactions.

As a vehicular fuel, CNG exhibits significant potential for the reduction of gaseous emissions and particle emissions and improvements in energy security [3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37]; such effects have been discussed and confirmed in previous studies, in the context of both passenger cars (e.g. [6], [13], [16], [22]) and other vehicle types (e.g. [3], [14]).

The aim of this study was to assess and compare the emissions performance of Euro 5 vehicles, representative of the European market, operating on gasoline and CNG, for comparison to the Euro 6 limits introduced in September 2014 (Figure 1). CO_2 and some unregulated exhaust emissions were also measured and analyzed. Furthermore, instantaneous concentrations of regulated and unregulated compounds and CO_2 were measured undiluted at the vehicle's tailpipe, in order to gain further insight into emissions phenomena affected by the fuel type in use (i.e. CNG or gasoline).

In addition to regulated pollutants (the definition of which varies somewhat from jurisdiction to jurisdiction), vehicular exhaust gas contains a range of pollutants and substances with deleterious impacts which are not presently regulated. These include particulates (unregulated in the EU for SI engines which do not feature direct injection) and various gases. These gases can be divided into three main groups: hydrocarbons and organic molecules (which are in fact partially regulated); reactive nitrogen compounds (NO_x - which is regulated, but also ammonia (NH_3) and nitrous oxide (N_2O), neither of which are regulated in the EU); and a few others. In terms of unregulated emissions, this study focuses on particulate emissions, as well as the three main reactive nitrogen compounds: NO , NO_2 and NH_3 .

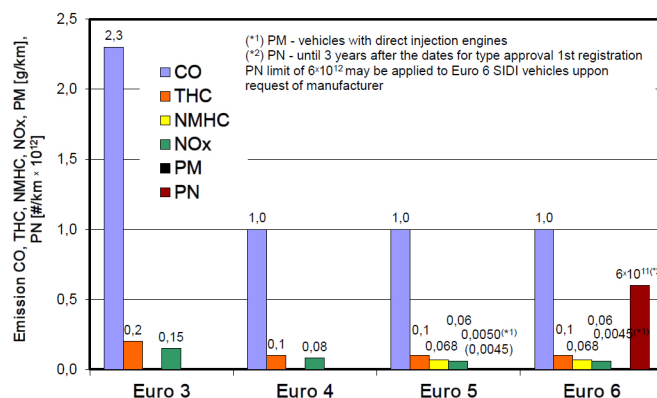


Figure 1. Progress in European emission regulations for passenger cars fitted with spark ignition (SI) engines

The formation of NO_x (and in particular NO) has been studied in great detail; formation and emission of NH_3 has received less attention in the literature, but recent publications have investigated and reviewed this phenomenon (see [38] and references therein). Emission of NH_3 is generally unregulated because NH_3 can play a

significant role in the formation of secondary particulate matter. This particulate matter is mobile and can travel with the wind, and is widely recognized as being able to adversely affect human health, damage plants, corrode building materials and cause the acidification of rain and eutrophication of surface waters [38].

EXPERIMENTAL PROGRAM

Test Vehicles & Fuels / Test Facility & Emissions Testing Equipment

Test Vehicles

Two European bi-fuel (CNG/gasoline) test vehicles were used in this study. According to EU regulations [39], a bi-fuel vehicle is defined as a vehicle with two separate fuel storage systems that can run part-time on two different fuels and is designed to run on only one fuel at a time. Bi-fuel vehicles must fulfill the requirements regarding the limits shown in [Figure 1](#) when operating on either fuel, i.e. CNG and gasoline.

Selected key characteristics of the test vehicles are presented in [Table 2](#). Start-up of the engines of both test vehicles is always performed on gasoline and is automatically switched over to CNG operation after around a dozen seconds (where the vehicle is in CNG mode).

Table 2. Selected key characteristics of the two test vehicles used in this study

Property	Vehicle A	Vehicle B
Vehicle type	LDV (passenger car) Bi-fuel	LDV (passenger car) Bi-fuel
Engine type	SI, naturally aspirated	SI, naturally aspirated
Approx. displacement [dm ³]	<1.5	<1.5
Fuel delivery system type	Port fuel injection (PFI)	PFI
Fuels types supported	Gasoline / CNG	Gasoline / CNG
Aftertreatment system fitted	Close-coupled three-way catalyst (CC TWC)	CC TWC
Test mass (inertia) [kg]	1130	1130
Emissions standard	Euro 5	Euro 5

Test Fuels

Standard, commercially available European E5 gasoline meeting the requirements of the EN228:2009 standard and commercially available CNG meeting the requirements of the PN-C-04753 standard were used. The specifications of both fuels are listed in [Tables 3](#) and [4](#). (Note that by volume the gasoline fuel contained 5% ethanol and that over 96% of the CNG fuel was methane.)

Table 3. Main properties of the gasoline used in this study

Property	Value
RON [-]	95.5
Vapor pressure [kPa]	58.5
Density @ 15°C [kg/m ³]	753.5
Heating value [MJ/kg]	41.99
Ethanol content [% v/v]	5.0
Olefin content [% v/v]	0.9
Aromatic content [% v/v]	33.7
Benzene content [% v/v]	0.79

Table 4. Main properties of the CNG used in this study

Property	Value
Methane content [% v/v]	96.11
Ethane content [% v/v]	2.01
Propane content [% v/v]	0.60
Carbon dioxide content [% v/v]	0.25
Nitrogen content [% v/v]	0.81
Heating value [MJ/m ³]	36.62
Wobbe Index [MJ/m ³]	53.305

Test Facility and Emissions Measuring Equipment

All experimental work reported in this paper was conducted in the Euro 5/6-compliant vehicle emissions testing laboratory at BOSMAL Automotive Research & Development Institute (Poland). The laboratory is presented in [Figure 2](#) and in [Figure A1](#) in the Appendix. The emission tests were carried out using an AVL-Zöllner 48" compact chassis dynamometer (single roller). A HORIBA CVS 7400S system with a full-flow dilution tunnel and DLS 7100E PM sampling system, a set of HORIBA MEXA HTRLE and 7500 DEGR exhaust analyzers and a HORIBA VETS 7000NT management system were all used to measure exhaust emission levels. A dedicated NH₃ analyzer was used to measure concentrations of that compound. This automotive analyzer measures NH₃/NO_x using a laser-based detection method and features heated sample tubing. The unit measures NH₃ concentrations (0-1000 ppm) at a frequency of 1 Hz.



Figure 2. Interior view of BOSMAL's emissions laboratory

Two types of emission test were performed: continuous pollutant emission measurements and CVS (Constant Volume Sampling) - bag tests measuring the average emission of these pollutants during chassis dynamometer testing.

The NEDC cycle ([Figure 3](#)), i.e. the current European legislative cycle [39] and the WLTC cycle ([Figure 4](#)), i.e. the World Harmonized Light Vehicle Test Cycle were used as the test cycles. The NEDC cycle consists of two phases: the Urban Driving Cycle (UDC), followed by the high-speed Extra Urban Drive Cycle (EUDC). The WLTC cycle consists of four phases: Low, Mid, High and Ex High. The WLTC's trace is more demanding than the NEDC because of the lack of constant speeds, the harsher acceleration, the maximum speed of 131 km/h and the highly dynamic speed trace.

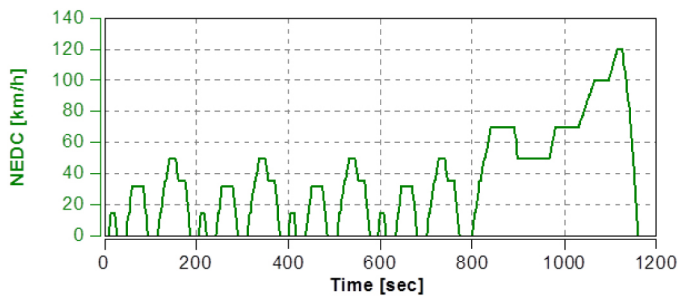


Figure 3. The speed trace for the NEDC test cycle

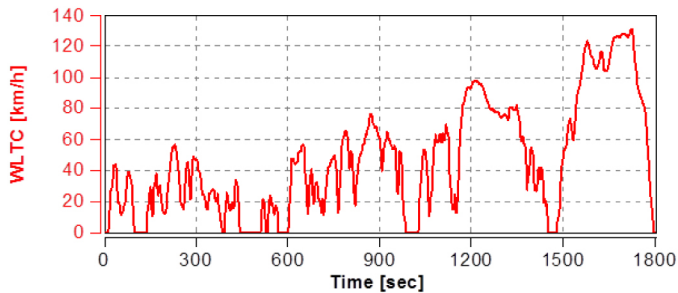


Figure 4. The speed trace for the WLTC test cycle

The chassis dynamometer ('roller') settings for simulating the driving resistance of the vehicles are based on homologation coastdown times of the vehicle models tested. The same settings were used (for each vehicle) for all tests reported here, regardless of the test cycle employed.

RESULTS AND DISCUSSION

For both of the test vehicles/fuels, two or three emission tests were carried out over the NEDC and WLTC cycles (depending on the repeatability of the results). Only one emissions test was performed each day. The vehicles were preconditioned on each fuel prior to beginning the testing on that fuel. The mean values of each measurement series were taken for further analysis. The uncertainties of the emissions measurements (during the NEDC) were around 17% for HC, 12% for CO, 9% for NO_x and 4% for CO₂. Tests were undertaken in order to determine the influence of CNG fuel on emissions in comparison to Euro 5 and 6 limits and in comparison to tested gasoline.

Regulated Emissions over the NEDC

Results obtained using both fuels are presented side-by-side for ease of comparison. Figures 5, 7, 9 and 10 present the average bag emissions results (in mg/km) of regulated components, i.e. CO, THC, NMHC, and NO_x for both phases (UDC and EUDC), as well as for the complete NEDC (UDC+EUDC) from both test vehicles. Figure 6 presents modal CO emissions for the initial portion of the UDC phase.

CO emissions of both vehicles fueled with both fuels were lower than 35% of Euro 5/Euro 6 limit. For vehicle A, emissions of CO were considerably lower when running on CNG (a difference of 24% over the entire NEDC). A contrary trend was observed for vehicle B - CO emission over the entire NEDC was by 24% higher when running on

CNG. It is worth pointing out that the vehicles are always started in gasoline mode, even if CNG fuel was chosen as operating fuel. This goes some way towards explaining the small difference in CO emission for both fuels during the UDC phase (Figure 6) and especially at the very beginning of the NEDC (Figure 7). During the second phase of the NEDC cycle, i.e. the EUDC phase, these differences were at times much greater, since when in CNG mode, no gasoline is consumed at all by the vehicle.

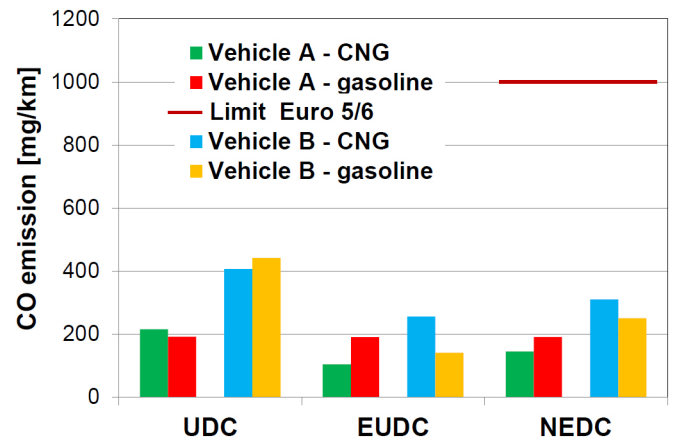


Figure 5. CO emissions over the NEDC cycle and its UDC and EUDC phases from the vehicles fueled with gasoline and CNG in turn

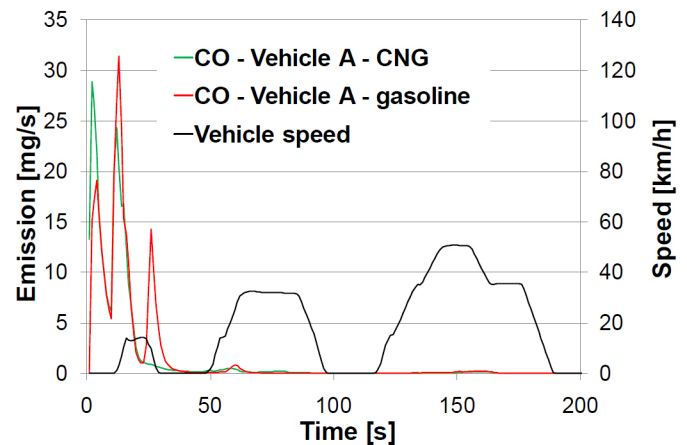


Figure 6. Instantaneous emissions of CO in vehicle A's exhaust over the first 200 seconds of the NEDC from vehicle A fueled with gasoline and CNG in turn

The highest THC emissions were observed for vehicle A fueled with CNG, but these emissions were still lower than 60% of the Euro 5/6 limit. For vehicle A, during the UDC phase, and for the entire NEDC, emissions of total hydrocarbons (Figure 7) twice as high and for vehicle B they were 25% higher when running on CNG than when running on gasoline. This can be attributed to the uncombusted portion of the gaseous fuel that escaped the cylinder, since the catalyst was below its light-off temperature following cold start.

These results show that the most important contribution to the final emission result is given by the cold start and the warmup phase directly following the cold start - i.e. the UDC phase. Emissions are around an order of magnitude lower during the EUDC and thus behavior over the UDC determines performance over the entire cycle.