

## A comparison of exhaust emissions from vehicles fuelled with petrol, LPG and CNG

**P Bielaczyc<sup>1</sup>, A Szczotka<sup>1</sup> and J Woodburn<sup>1</sup>**

<sup>1</sup> Automotive Research & Development Institute Ltd, BOSMAL, ul. Sarni Stok 93, 43-300 Bielsko-Biala, Poland

E-mail: Andrzej.szczotka@bosmal.com.pl

**Abstract.** This paper presents an analysis of THC, NMHC, CO, NO<sub>x</sub> and CO<sub>2</sub> emissions during testing of two bi-fuel vehicles, fuelled with petrol and gaseous fuels, on a chassis dynamometer in the context of the Euro 6 emissions requirements. The analyses were performed on one Euro 5 bi-fuel vehicle (petrol/LPG) and one Euro 5 bi-fuel vehicle (petrol/CNG), both with SI engines equipped with MPI feeding systems operating in closed-loop control, typical three-way-catalysts and heated oxygen sensors. The vehicles had been adapted by their manufacturers for fuelling with LPG or CNG by using additional special equipment mounted onto the existing petrol fuelling system. The vehicles tested featured multipoint gas injection systems. The aim of this paper was an analysis of the impact of the gaseous fuels on the exhaust emission in comparison to the emission of the vehicles fuelled with petrol.

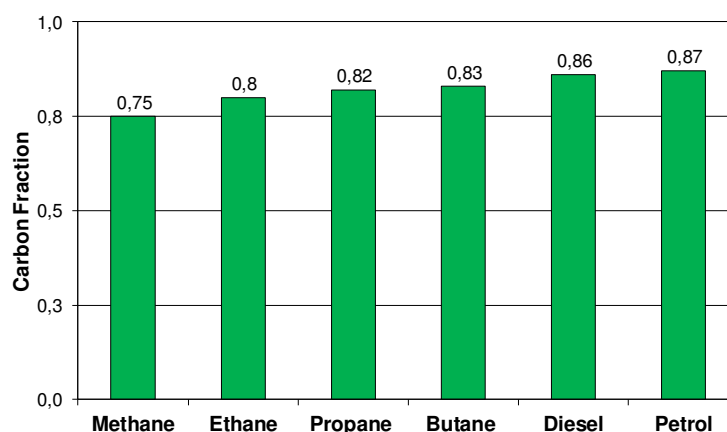
The tests subject to the analyses presented here were performed in the Engine Research Department of BOSMAL Automotive Research and Development Institute Ltd in Bielsko-Biala, Poland, within a research programme investigating the influence of alternative fuels on exhaust emissions from light duty vehicle vehicles with spark-ignition and compression-ignition engines.

### 1. Introduction

Due to necessity of limiting vehicle emissions there is a growing interest in alternative fuels like hydrogen, natural gas – methane (CNG – compressed natural gas), liquefied petroleum gas (LPG), methanol, ethanol, bio-diesel and others. Of particular interest in the above are: natural gas (methane), occurring naturally in the earth [1,2] and LPG which is colourless gas comprised of various hydrocarbons, mainly propane and butane. The driving forces of financial and ecological pressure groups are the main reason for the evaluation studies of alternative fuels (LPG and CNG in particular). Gaseous fuel distribution is well developed in many countries and these fuels are less expensive than petrol due to tax differences and subsidies in some countries.

From the ecological point of view these fuels are interesting due to impact on CO<sub>2</sub> emissions (greenhouse effect) - gaseous fuels contain more hydrogen and less carbon than petrol or diesel fuel (figure1), and higher carbon fractions produce more carbon dioxide CO<sub>2</sub> [3]. There are the additional advantages of the reduction in evaporative and refuelling emissions, particulate and NO<sub>x</sub> emissions benefits and reduction of cancerogenic hydrocarbons emissions. Alternative fuels are suitable for SI stoichiometric or lean-burn engines with MPI or DI fuelling systems and CI engines with indirect (IDI) or direct-injection (DI) fuelling systems. Major advantages and disadvantages of LPG and CNG fuels are shown in table 1 [3-5].





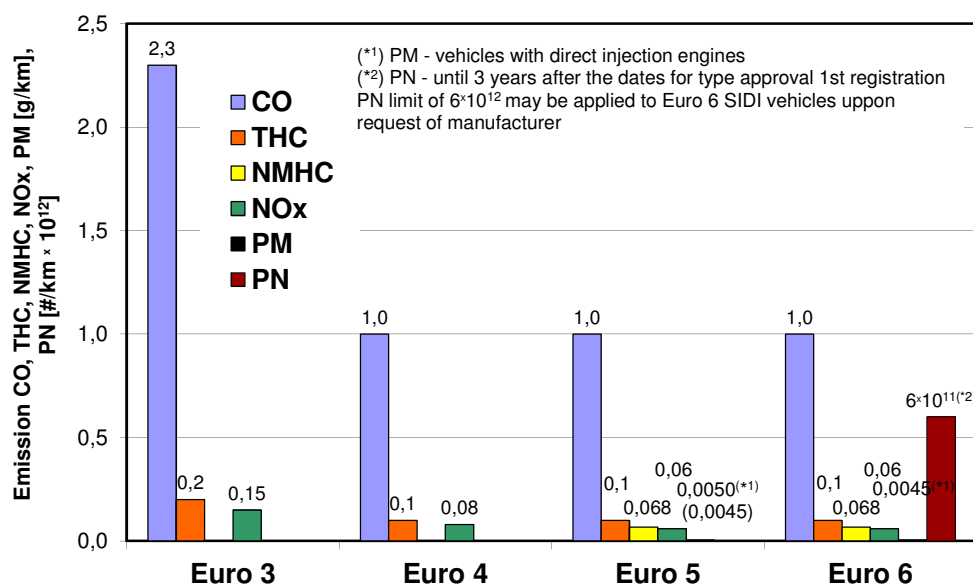
**Figure 1.** Carbon fractions for different fuels.

**Table 1.** Major advantages and disadvantages of gaseous alternative fuels

Fuel	Advantages	Disadvantages
Methane (Natural Gas)	<ul style="list-style-type: none"> <li>• can be produced from a variety of feedstocks, including renewable,</li> <li>• very low emissions of ozone-forming hydrocarbons, particulate matters and toxic compounds,</li> <li>• higher calorific value than petrol on a mass basis,</li> <li>• potentially more complete combustion and lower cold start emissions than petrol (due to its gaseous state),</li> <li>• negligible sulphate and evaporative emissions.</li> </ul>	<ul style="list-style-type: none"> <li>• higher vehicle purchase cost,</li> <li>• lower vehicle range,</li> <li>• exhaust emissions of methane (a potent greenhouse gas) are relatively high,</li> <li>• limited refuelling infrastructure – CNG requires special refuelling stations.</li> </ul>
Propane-Butane (LPG)	<ul style="list-style-type: none"> <li>• cheaper than petrol today,</li> <li>• lower emissions of ozone-forming hydrocarbons and toxic compounds, lower particulate matter emissions,</li> <li>• most widely available clean fuel today,</li> <li>• excellent fuel, especially for fleet vehicles.</li> </ul>	<ul style="list-style-type: none"> <li>• cost will rise with demand,</li> <li>• limited supply,</li> <li>• its composition varies widely between countries and regions.</li> </ul>

As a vehicular fuel, CNG exhibits significant potential for the reduction of gaseous emissions and particle emissions and improvements in energy security [6-22]; such effects have been discussed and confirmed in previous studies, in the context of both passenger cars (e.g. [13], [17]) and other vehicle types (e.g. [2]).

The aim of this study was to assess and compare the emissions performance of Euro 5 vehicles, representative of the European market, operating on petrol and CNG or LPG, for comparison to the Euro 6 limits introduced in September 2014 (figure 2). Some unregulated exhaust emissions ( $\text{CO}_2$  and  $\text{CH}_4$ ) were also measured and analysed.



**Figure 2.** Progress in European emission regulations for passenger cars fitted with spark ignition (SI) engines.

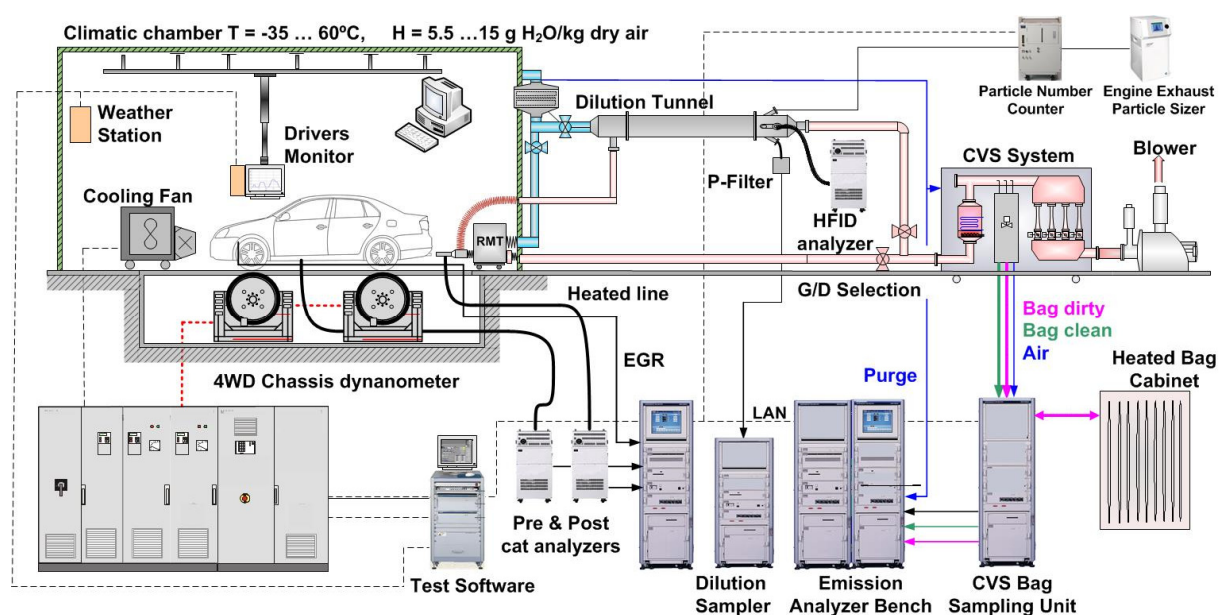
## 2. Research programme

The analysis of exhaust emissions from the bi-fuel vehicles with a spark-ignition engines fuelled with CNG or LPG and, later, with petrol during the NEDC cycle was carried out on a chassis dynamometer in the Emissions testing laboratory (figures 3 and 4) of BOSMAL Automotive R&D Institute in Bielsko-Biala, Poland. The tests presented in this paper were carried out within a research programme investigating the influence of alternative fuels on exhaust emissions from automotive vehicles with spark ignition and compression ignition engines. The objective of the research presented here was to determine the influence of CNG and LPG fuel usage on exhaust emissions in comparison to the emission of the vehicles fuelled with petrol.

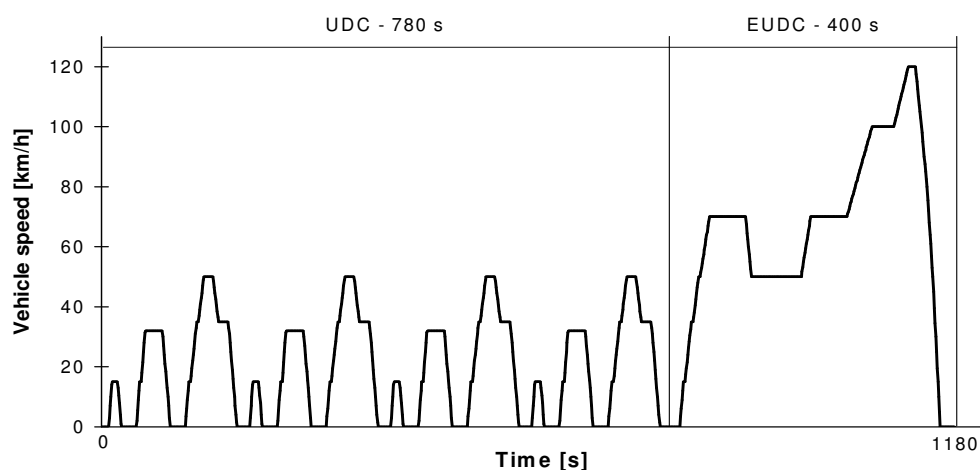
The New European Driving Cycle (NEDC – figure 5), i.e. the current European legislative cycle, described in UNECE Regulation No. 83 [21], was selected as a representative test for this study. The test consists of two phases: the Urban Driving Cycle (UDC), followed by the high-speed Extra Urban Drive Cycle (EUDC).



**Figure 3.** BOSMAL Emission Testing Laboratory – internal view of the climatic chamber.



**Figure 4.** BOSMAL Emission Testing Laboratory – schematic overview, showing the chassis dynamometer, the climatic chamber and the various emissions measurements systems.



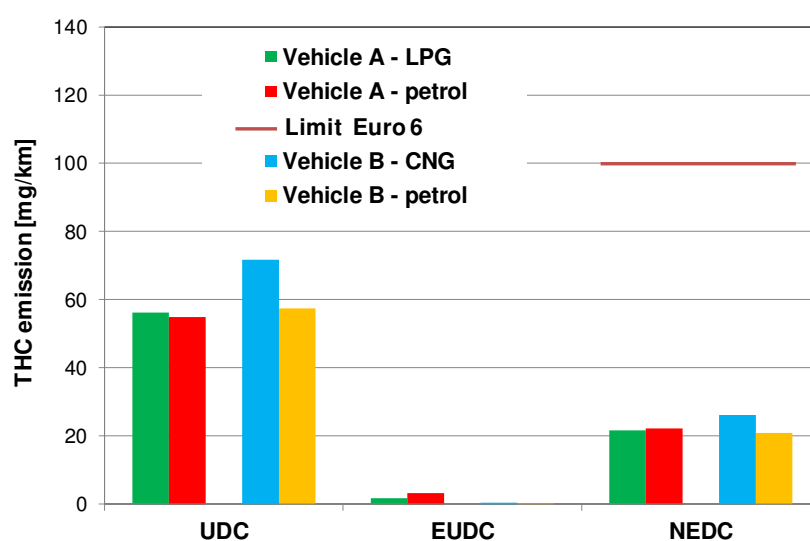
**Figure 5.** The New European Driving Cycle (NEDC)

The tests were conducted on one Euro 5 bi-fuel vehicle (petrol/LPG) and one Euro 5 bi-fuel vehicle (petrol/CNG), both with SI engines equipped with MPI feeding systems operating in closed-loop control, typical three-way-catalysts and heated oxygen sensors. The vehicles had been adapted by their manufacturers for fuelling with LPG or CNG by using additional special equipment mounted onto the existing petrol fuelling system. The vehicles tested featured multipoint gas injection systems. The engines always start up on petrol and are automatically switched over to CNG or LPG operation after a few seconds (if the vehicle is in CNG) or after 1-2 minutes (if the vehicle is in LPG mode). The aftertreatment systems of the cars tested consisted of a three way catalytic converters (TWC) specially adapted for bi-fuel cars (fuelled with petrol and CNG or LPG). The usage of CNG or LPG fuel also caused some changes in the engine constructions of the cars tested. The constructions of the cylinder heads were modified for CNG or LPG operation by changes made to valve and seat materials. The changes to the engines and fuelling systems, together with the installation of a larger TWC cause a slight increase in vehicles mass compared to the standard (petrol only) model.

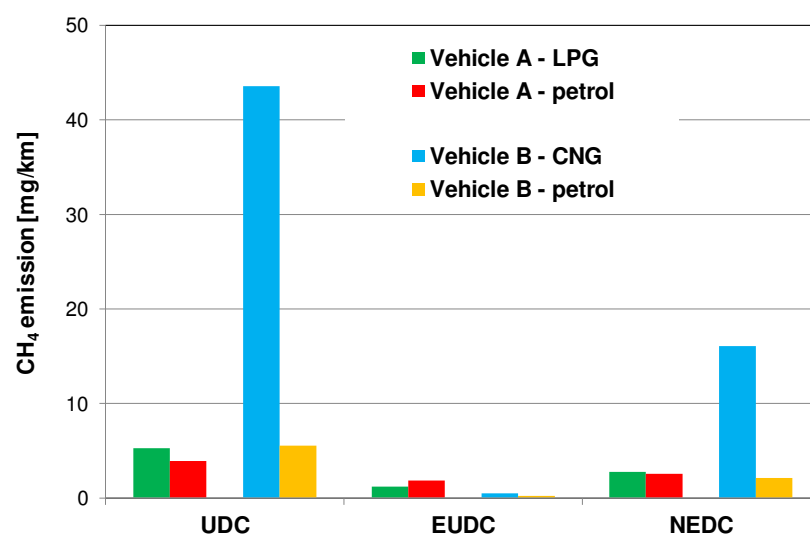
### 3. Test results

A series of tests were performed on a chassis dynamometer facility on the test vehicles, fuelled with petrol and with LPG or CNG (in turn). Tests were undertaken in order to determine the influence of gaseous fuels (LPG and CNG) on emissions in comparison to Euro 6 limits and in comparison to tested petrol. Results obtained using all fuels are presented side-by-side for ease of comparison. Figures 6-11 present the average emissions (in g/km) of THC, CH<sub>4</sub>, NMHC, CO, NO<sub>x</sub>, and CO<sub>2</sub> for both phases, e.g. the UDC and EUDC, as well as for the complete NEDC (UDC+EUDC) from the test vehicles.

Hydrocarbons emissions i.e. THC, CH<sub>4</sub> and NMHC (figures 6-8) of vehicle A fuelled with petrol and LPG in turn were similar for both fuels. For vehicle B fuelled with petrol and CNG in turn, the total emissions of hydrocarbons (figure 6) over the entire NEDC were by 25% higher when running on CNG, which is caused by very high methane emissions (figure 7) over the UDC phase (seven fold higher than for petrol).



**Figure 6.** THC emissions over the NEDC cycle and its UDC and EUDC phases from the vehicles fuelled with petrol and gaseous fuels (LPG or CNG) in turn.

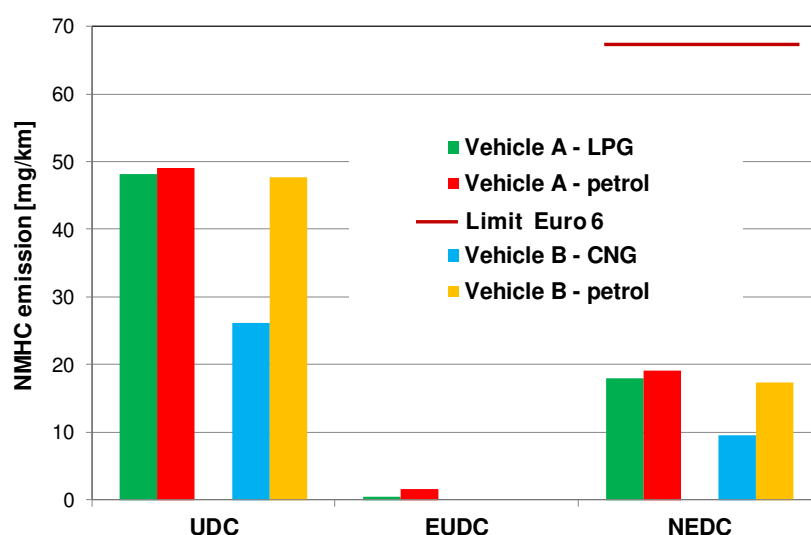


**Figure 7.** CH<sub>4</sub> emissions over the NEDC cycle and its UDC and EUDC phases from the vehicles fuelled with petrol and gaseous fuels (LPG or CNG) in turn.

The high CH<sub>4</sub> emissions from vehicle B fuelled with CNG were due to the fact that the main composition of the fuel was CH<sub>4</sub> (more than 96%), a compound which is very difficult to oxidize in a TWC. Although methane emissions are currently not subject to direct regulation in the EU, they are regulated in the US and are of concern due to methane's role as a greenhouse gas (21 times as absorptive of infrared radiation as CO<sub>2</sub>) [23]. Furthermore, CH<sub>4</sub> can be considered to be indirectly regulated in the EU, since there is a THC limit and a non-methane HC limit – the difference being methane itself.

Methane, as the main (but not sole) hydrocarbon of natural gas vehicle (NGV) exhaust gas is a relatively inert component (no double carbon bonds or longer carbon chains and saturated molecular structure), which leads to it having a higher light-off temperature for conversion than other hydrocarbons (e.g. those which are unsaturated or with longer chains). Petrol does not contain any methane; however, methane is formed in petrol combustion by cracking processes.

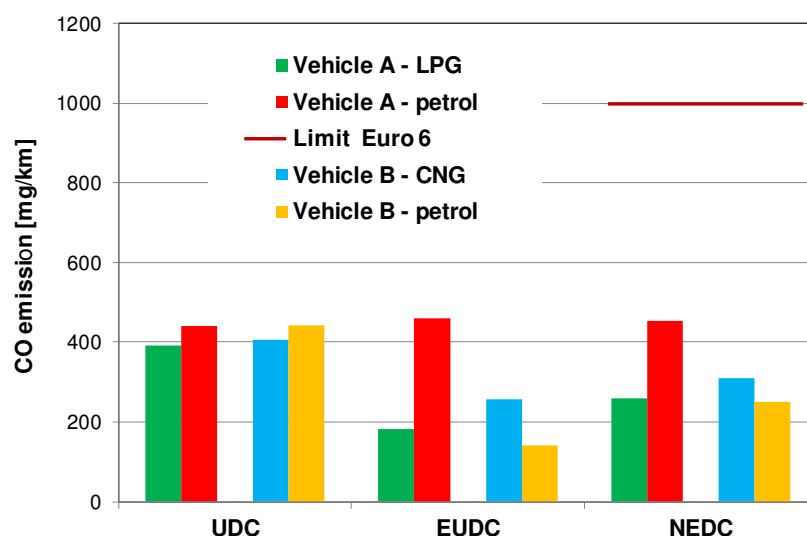
NMHC emissions (figure 8) of both vehicles fuelled with all fuels were lower than 30% of the Euro 6 limit. NMHC emissions over the entire NEDC for vehicle B were 45% lower when running on CNG. The results show that using CNG led to higher THC emissions but lower NMHC emissions [24], relative to petrol, a phenomenon directly related to the composition of the two fuel types.



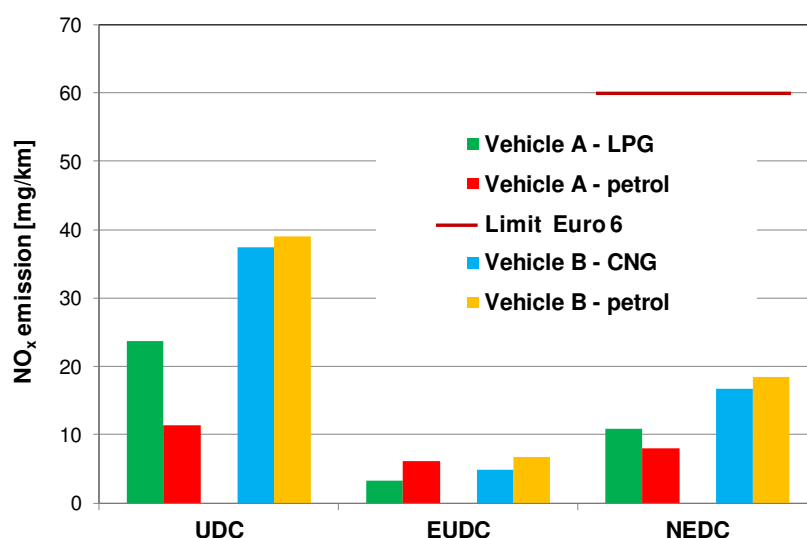
**Figure 8.** NMHC emissions over the NEDC cycle and its UDC and EUDC phases from the vehicles fuelled with petrol and gaseous fuels (LPG or CNG) in turn.

CO emissions of both vehicles fuelled with both fuels were lower than 50% of Euro 6 limit. For vehicle A, emissions of CO were considerably lower when running on LPG (a difference of 43% 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 petrol mode, even if CNG or LPG fuel was chosen as operating fuel and engines are automatically switched over to CNG or LPG operation after a few seconds (if the vehicle is in CNG) or after 1-2 minutes (if the vehicle is in LPG mode). This goes some way towards explaining the small difference in CO emission for both vehicles during the UDC phase (figure 9). During the second phase of the NEDC cycle, i.e. the EUDC phase, these differences were at times much greater, since when in CNG or LPG mode, no petrol is consumed at all by the vehicles.





**Figure 9.** CO emissions over the NEDC cycle and its UDC and EUDC phases from the vehicles fuelled with petrol and gaseous fuels (LPG or CNG) in turn



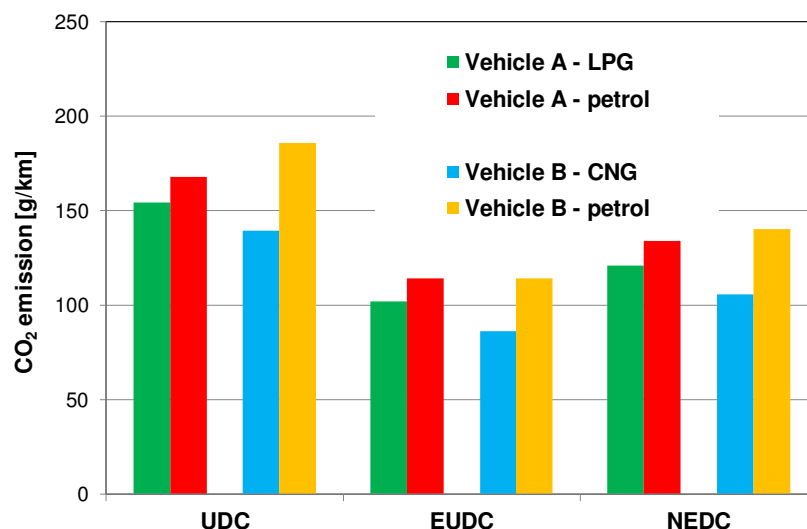
**Figure 10.** NO<sub>x</sub> emissions over the NEDC cycle and its UDC and EUDC phases from the vehicles fuelled with petrol and gaseous fuels (LPG or CNG) in turn.

NO<sub>x</sub> emissions (figure 10) from both vehicles fuelled with all fuels were lower than 30% of the Euro 6 limit. For vehicle A, emissions of NO<sub>x</sub> were considerably higher when running on LPG (a difference of 35% over the entire NEDC), but for vehicle B they were 10% lower when running on CNG. The engine calibration and the precise chemistry of the TWC have a great impact on NO<sub>x</sub> emissions and it is possible that for other vehicles fuelled with petrol and with LPG or CNG in turn these trends could be contrary. Because of this, the observed change may not be directly attributable in full to the fuels chemistry itself, but to the interaction of the fuel chemistry with engine operation variables (spark timing, etc.) and also TWC chemistry.

Although they are presently not subject to direct limits in automotive emissions legislation, CO<sub>2</sub> emissions are important with respect to global warming [23] and because CO<sub>2</sub> emissions and fuel economy are intimately related.

As LPG and CNG have lower carbon/hydrogen ratio (figure 1) than petrol, they produce lower CO<sub>2</sub> emissions per unit energy released during combustion. CO<sub>2</sub> emission results are shown in figure 11. It

can be noted that for vehicle A for LPG these emissions were about 10% lower and for vehicle B about 25% lower for CNG fuel than for petrol in both phases, as well as in the complete NEDC cycle.



**Figure 11.** CO<sub>2</sub> emissions over the NEDC cycle and its UDC and EUDC phases from the vehicles fuelled with petrol and gaseous fuels (LPG or CNG) in turn

#### 4. Summary/ Conclusions

The main aim of this paper was to determine the influence of CNG and LPG fuels on emissions in the context of the Euro 6 emissions requirements and in comparison to the emission of the vehicles fuelled with petrol. The analysis were performed on two Euro 5 bi-fuel light duty vehicles (one bi-fuel vehicle petrol/CNG and one bi-fuel vehicle petrol/LPG) .

On the basis of the analyses of results obtained during the NEDC emissions test, it has been found that both vehicle tested with a CNG or LPG multipoint gas injection and an integrated petrol/CNG or petrol/LPG ECU (Electronic Control Unit) already meets the Euro 6 emissions limits, without any further modifications, in particular:

- THC, NMHC, CO and NO<sub>x</sub> emissions meet Euro 6 limits for the Light-Duty Vehicle (LDV) category.
- Observed THC emissions for both vehicles and all fuels (CNG, LPG, petrol) were even lower than the NMHC limit stipulated by these regulations, so emissions limits in this area were comfortably met. NMHC emissions were almost 7 times lower than the Euro 6 limit when running on CNG.
- THC emissions during the NEDC cycle increased when vehicle B was fuelled with CNG, in comparison to petrol, but this increase was far too small to cause problems with the Euro 6 emissions limit. THC emissions for vehicle A fuelled with LPG and petrol were similar for both fuels.
- CO emission during the NEDC cycle increased by 24% when vehicle B was fuelled with CNG, although CO emission from both fuel types was well below the limit. For vehicle A, emissions of CO were considerably lower (by 43%) when running on LPG.
- NO<sub>x</sub> emissions from vehicle A when fuelled with LPG were about 35% higher, but from vehicle B when fuelled with CNG were about 10% lower in comparison to petrol.
- CO<sub>2</sub> emissions were decreased by 10% when vehicle A was fuelled with LPG and by 25% when vehicle B was fuelled with CNG

Gaseous fuels (LPG and CNG) are commonly used in SI engines because their powertrains are relatively easy to convert from liquid to gaseous fuels. These fuels are very attractive as they are cheaper than petrol or diesel. This paper has shown that even certain pre-Euro 6 technologies can meet Euro 6



emissions standards when LPG or CNG is used as a fuel. Additionally, the CO<sub>2</sub> emissions from vehicles operation on gaseous fuels (LPG or CNG) are low. For both these reasons, interest in producing and marketing bi-fuel passenger cars for the European market (among others) is sure to remain high, notwithstanding the current inequalities in NG distribution infrastructure and local availability.

The good performance of LPG and CNG in terms of low emissions of particulates and CO<sub>2</sub> confirm that LPG and CNG have significant environmental potential, even if certain emissions are sometimes higher than when running on petrol.

The emissions and performance of bi-fuel vehicles changes when operating on fuel other than gasoline (e.g. LPG or CNG). The engine and aftertreatment technology, the individual engine calibration strategy, fuel and lubricant oil properties, ambient temperatures and driving conditions are the main factors influencing tailpipe emissions.

## References

- [1] Suga T, Muraishi T, Brachmann T and Yatabe F 2000 *Potential of a Natural Gas Vehicle as EEV (Environmentally Enhanced Vehicle)* CEC/ SAE International Spring Fuels & Lubricants Meeting 2000 Paper No. 2000-01-1863
- [2] Checkel D and Dhaliwal B 2000 *Tailpipe Emissions Comparison Between Propane and Natural Gas Forklifts* CEC/ SAE International Spring Fuels & Lubricants Meeting 2000 Paper No. 2000-01-18654
- [3] Sykes R 1999 *Gas works* Engine Technology International 4/1999
- [4] Watson H and Gowdie D 2000 *A Systematic Evaluation of Twelve LP Gas Mixtures for Emissions and Fuel Consumption* CEC/ SAE International Spring Fuels & Lubricants Meeting 2000 Paper No. 2000-01-1867
- [5] West J F 2000 *All aboard the clean motor* Engine Technology International 4/2000
- [6] McTaggart-Cowan G P, Reynolds C C O and Bushe W K 2006 *Natural gas fuelling for heavy-duty on-road use: current trends and future direction* International Journal of Environmental Studies 2006 63 421-440
- [7] Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport Official Journal of the European Union L 123/42 17.5.2003
- [8] Bhandari K, Bansal A, Shukla A and Khare M 2005 *Performance and emissions of natural gas fueled internal combustion engine: A review* Journal of Scientific & Industrial Research Vol. 64 May 2005 p. 333-338
- [9] Warnecke W, Wilbrand K and Scholey H 2007 *The Drive for Energy Independence in the Next Decades – Fuels for the Future* Proceedings of the 28th International Vienna Motor Symposium (Vienna Austria)
- [10] Suthawaree J, Sikder H A, Jones C E, Kato S et al. 2012 *Influence of extensive compressed natural gas (CNG) usage on air quality* Atmospheric Environment 54 (2012) 296-307
- [11] Semin, R A B 2008 *A Technical Review of Compressed Natural Gas as an Automotive Fuel for Internal Combustion Engines* American J. of Engineering and Applied Sciences 1 (4) 302-311
- [12] Checkel D and Dhaliwal B *Tailpipe Emissions Comparison Between Propane and Natural Gas Forklifts* SAE Paper No. 2000-01-1865 2000 doi:10.4271/2000-01-1865
- [13] Allgeier T, Bischoff C and Foerster J 2004 *Natural Gas as an alternative fuel for motor vehicles* FISITA paper F2004V040 2004 FISITA World Congress
- [14] Karavalakis G, Durbin T, Villela M and Miller W 2012 *Air pollutant emissions of light-duty vehicles operating on various natural gas compositions* Journal of Natural Gas Science and Engineering Vol. 4 January 2012 p. 8-16
- [15] Bielaczyc P, Szczotka A and Wojnarowicz M 2010 *Analysis of the Exhaust Emissions and Performance of a Modern Vehicle Fueled with Petrol and CNG in Turn* FISITA paper F2010-A-133 FISITA 2010 World Automotive Congress Budapest 2010

- [16] Bielaczyc P and Szczotka A 2012 *The potential of current European light-duty CNG-fueled vehicles to meet Euro 6 requirements* Paper 2012-SS4-403 Combustion Engines 4/2012 (151)
- [17] Bielaczyc P, Woodburn J and Szczotka A 2013 *An Assessment of Regulated Emissions and CO<sub>2</sub> Emissions from a European Light-Duty CNG-Fueled Vehicle in the Context of Euro 6 Emissions Regulations* Applied Energy 117 2014 134-141 doi:10.1016/j.apenergy.2013.12.003
- [18] Bielaczyc P, Szczotka A and Woodburn J 2015 *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 SAE 2015 World Congress Detroit
- [19] Verbeek R, Ligterink N, Meulenbrugge J, Koornneef G et al. 2013 *Natural Gas in Transport - An assessment of different routes* Delft report 31.4818.38
- [20] Edwards R, Hass H, Larivé J F, Lonza L et al. 2014 *Well-To-Wheels Analysis Of Future Automotive Fuels And Powertrains In The European Context* JRC85329 Report 2014 doi:10.2790/95533
- [21] UNECE Regulation No. 83 – Annex 8 2011 available online: <http://unece.org>
- [22] Jahirul M I, Masjuki H H, Saidur R, Kalam M A, Jayed M H and Wazed M A 2010 *Comparative engine performance and emissions analysis of CNG and gasoline in a retrofitted car engine* Applied Thermal Engineering 30 2010 2219-2226
- [23] Seinfeld J H and Pandis S N 1998 *Atmospheric Chemistry and Physics: From Air Pollution to Global Climate Change* Wiley Interscience New York
- [24] Howes P and Rideout G 1995 *Evaluation of Current Natural Gas Vehicles Technology Exhaust Emissions at 10 Various Operating Temperatures* SAE Paper 952437