A comparison of the exhaust emissions of a vehicle fuelled with petrol and CNG in turn

INTRODUCTION

Continuing pressure to reduce anthropogenic greenhouse gas emissions includes significant moves to reduce such emissions from the road transport sector. While passenger cars’ greenhouse gases (GHG) emissions are relatively modest per vehicle, their sheer number makes them a significant source which has been targeted by legislators for some time. Multiple legal jurisdictions have various legislative packages in place to this end; by 2012 some 75% of all passenger vehicles sold globally were subject to some kind of energy efficiency regulation [20].

The use of alternative fuels (biodiesel, petrol-alcohol blends, CNG (Compressed Natural gas), LPG (Liquid Petroleum Gas)) in vehicular powertrains supports efforts to reduce petroleum use in transportation (what is necessary because of the limited crude oil resources) [12] and helps in reduction of anthropogenic CO₂ emissions. The main drivers that have an influence on future personal transportation are [7,10,15]:

- Climate change as the biggest environmental challenge – strong action dedicated for the contribution of the transport sector to the reduction of greenhouse gas emissions – global CO₂ legislation targets for new passenger cars;
- Emissions regulatory development at European, US (United States) and Asian level – regulation as an incentive for innovation -examples: Euro 5+ and Euro 6, US Tier 2 & 3, CARB (California Air Resources Board) LEV (Low Emission Vehicles) II & III, Japanese Long Term Regulations, new hydrogen vehicles regulations, etc.;
- Automotive growth opportunities in aspects of global energy consumption;
- Powertrain development from a fuel perspective – alternative fuel resources and blending strategies.

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

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New European requirements regarding vehicle emissions for passenger cars (PC) and light commercial vehicles (LCV) were introduced in 2009 for type approval and 2011 for all new types, specified as Euro 5, with further requirements (Euro 6) planned for 2014/2015 (Figure 1).

Natural Gas (NG) is mainly obtained from gas wells or is driven off as a by-product during crude oil production. In Europe NG typically consists of 80%-99% methane and other gases, higher hydrocarbons as ethane, propane, iso- and n-butane and impurities such as helium, nitrogen, hydrogen sulphide, carbon dioxide and water vapour [16]. NG only requires dehydration and some clean-up steps after extraction. NG can be compressed, so it can be stored in special stainless steel bottles and used as compressed NG (CNG). Methane is characterised by soot-free combustion. CO₂ emissions from vehicles fuelled with methane are typically some 25% lower compared with emissions from the combustion of petrol and diesel. The key properties of NG are presented in [3,9]. CNG as a vehicular fuel exhibits significant potential for the reduction of gaseous emissions and particle emissions [1,2,12,13,16-18,21]; such effects have been discussed and confirmed in previous studies [3-6,8]. CNG also has the potential to achieve reductions of greenhouse gas emissions (see [22] for a recent detailed assessment). In fact, the origin of the NG, its methods of extraction, purification and transportation are critical in terms of its overall well-to-wheels energy and GHG balances [11].

1 EXPERIMENTAL PROGRAM

1.1 Test vehicle & fuels / test facility & emissions testing equipment

1.1.1 Test vehicle

Bi-fuel vehicle was used in this study. Bi-fuel vehicle means 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.

Selected key characteristics of the test vehicle are presented in Table 1. The vehicle was powered by an SI engine, with fuel supplied to the engine either via the vehicle’s multipoint injection (MPI) petrol fuel injection system or its MPI natural gas injection system, depending on the fuel type in use.

Tab. 1. Selected key characteristics of the two test vehicles used in this study

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>PC Bi-fuel</th>
</tr>
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<tbody>
<tr>
<td>Engine type</td>
<td>SI, naturally aspirated</td>
</tr>
<tr>
<td>Approx. displacement [dm³]</td>
<td>1.4</td>
</tr>
<tr>
<td>Fuel delivery system type</td>
<td>Port fuel injection (PFI)</td>
</tr>
<tr>
<td>Engine power [kW]</td>
<td>51 (petrol) / 46 (CNG)</td>
</tr>
<tr>
<td>Fuel used</td>
<td>Petrol / CNG</td>
</tr>
<tr>
<td>After-treatment</td>
<td>Close coupled three way catalyst (TWC)</td>
</tr>
<tr>
<td>Emissions standard</td>
<td>Euro 5</td>
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</table>

1.1.2 Test fuels

Standard, commercially available European E5 petrol meeting the requirements of the EN228:2009 standard and commercially available CNG meeting the requirements of the PN-C-04753 standard were used as the base fuel.

1.1.3 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 Photo 1 and Figure 2. The emission tests were carried out using an AVL-Zoellner 48” compact chassis dynamometer. The HORIBA CVS 7400S system with full-flow dilution tunnel and PM sampling system DLS 7100E, a set of HORIBA MEXA 7400 HRTLE and 7500DEGR exhaust analysers, HORIBA VETS7000NT management system were all used to measure exhaust emission levels.
All equipment for the sampling, transfer, conditioning and measurement of gaseous and particulate solid emissions fully complies with [18].

The New European Driving Cycle (NEDC - Figure3), i.e. the current European legislative cycle [18] was used as the test cycle. The test consists of two phases: the Urban Driving Cycle (UDC), followed by the high-speed Extra Urban Drive Cycle (EUDC).
2 TEST RESULTS

A series of tests were performed on a chassis dynamometer facility on the test vehicle, fuelled with petrol and with CNG (in turn). 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 petrol. Results obtained using both fuels are presented side-by-side for ease of comparison. Figures 4-7 present the average emissions (in g/km) of CH$_4$, NMHC, THC, NO$_x$, NO, NO$_2$, CO and CO$_2$ for both phases, e.g. the UDC and EUDC, as well as for the complete NEDC (UDC+EUDC) from the test vehicle.

Carbon monoxide (CO) and unburned hydrocarbons (THC) are exhaust gas components which can be effectively removed by a TWC after reaching its light off temperature, when the TWC’s effectiveness is high. However, there is a problem due to CO and THC emissions during cold-start and warm-up conditions (during the first phase of the NEDC i.e. the UDC phase). This means that THC, CH$_4$ and NMHC emissions during the NEDC cycle are effectively determined by emission during the UDC phase (Figures 4 and 5), as the contribution of the second phase (EUDC) is negligible; during the EUDC phase the THC, CH$_4$ and NMHC emissions were at very low levels for the test vehicle for both fuels, confirming the high effectiveness of the TWC at removing hydrocarbons once it had achieved its light off temperature.

For the test vehicle, during the UDC phase, and for the entire NEDC, emissions of total hydrocarbons (Figure 5) were 25% higher and emissions of CH$_4$ (Figure 4) 9 times higher when running on CNG than when running on petrol. However, for NMHC, this situation was reversed.
(Figure 4), and NMHC emission was noticeably lower when running on CNG, the difference being approximately 52%.

The substantial reduction in NO\textsubscript{x} emission (Figure 5) observed for both phases when running on CNG is noteworthy. The lower NO\textsubscript{x} emission results presented here may be at least partially due to greater thermal homogeneity within the cylinder (higher average temperature, but fewer hotspots) when running on CNG than on petrol.

NO\textsubscript{x} formation is influenced by flame temperature effects, fuel chemistry (e.g. the proportion of methane and the content of other, heavier hydrocarbons in the fuel) and fluid dynamics. Additionally, an effect caused by the interaction of the higher specific energy content of methane with the engine control system which was calibrated using petrol as a base fuel has an influence on NO\textsubscript{x} emissions. At higher loads (e.g. the EUDC phase), characterized by flame propagation as a premixed turbulent flame, the flame temperature effect is dominant. Emissions of NO were about 30% and NO\textsubscript{2} about 43% higher from the vehicle when fuelled with petrol than when the vehicle was running on CNG (Figure 6) – a similar reduction that reported in [14].

Regarding CO emissions, the most important part of the NEDC cycle is also engine start-up, with necessary fuel enrichment for proper engine starting and the period during which the TWC has not yet reached light off temperature; emissions during the EUDC phase are much lower (Figure 7).

For the test vehicle, emissions of carbon monoxide were considerably lower when running on petrol (a difference of 27% during the UDC phase, 71% during the EUDC phase and 43% over the entire NEDC).
CO\textsubscript{2} emission results are shown in Figure 7. It can be noted that these emissions were about 25% lower for CNG fuel than for petrol in both phases, as well as in the complete NEDC cycle, due to the lower carbon fraction found in CNG than in petrol.

The main component of NG is methane, which, consisting of one carbon atom and four hydrogen atoms, has a H/C ratio of 4:1. Other combustible trace components are somewhat less hydrogen-rich, but the four next most abundant species typically present in commercial vehicle fuel NG [1] all have H:C ratios $\geq 2.4:1$. Assuming a minimum CH\textsubscript{4} content of ~90 per cent, NG can be assumed to have a minimum H/C ratio of around 3.85:1. In contrast, petrol has a much lower ratio of 1.86:1. Emission of CO\textsubscript{2} is a function of fuel consumption, as well as fuel H:C ratio, and using a fuel with a higher H:C ratio does not always guarantee reduced CO\textsubscript{2} emissions, but for the test vehicle used in this study, the resulting effect was significantly reduced CO\textsubscript{2} emissions.

Fuel consumption (FC) results calculated from carbon balance method are shown in Figure 8. As the units for FC for both fuels are different these figures are not comparable. In terms of energy consumption, multiplying vehicle as consumption of NG and petrol by the volumetric energy density of those fuel types revealed no significant differences in the amount of chemical energy consumed for either phase of the cycle.

On the basis of fuel costs of each km (Figure 9) travelled by the vehicle fuelled with both fuels it has been calculated (taking into account fuels prices of September 2014) that fuel costs of the test vehicle fueled with CNG were about 50% lower than when running on petrol.
Fuel costs of each km travelled over the NEDC cycle and its UDC and EUDC phases for the test vehicle fuelled with petrol and CNG in turn

Full load power measurement results are shown in Figure 10. Engine power and torque of the test vehicle fueled with CNG were about 10% lower than when running on petrol.

SUMMARY/CONCLUSIONS

The main aim of this paper was to determine the influence of CNG fuel on emissions in the context of the new Euro 6 emissions requirements. An analysis was performed on a Euro 5 bi-fuel light duty vehicle in comparison to emissions when the vehicle was fuelled with petrol.

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

1. CO, THC and NMHC emissions meet Euro 5/6 limits for the Light-Duty Vehicle (LDV) category. Observed THC emissions 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.
2. THC emissions during the NEDC cycle increased when the vehicle was fuelled with CNG, in comparison to petrol, but this increase was far too small to cause problems with the Euro 6 emissions limit.
3. CO emission during the NEDC cycle increased by 43% when the vehicle was fuelled with CNG, although CO emission from both fuel types was well below the limit.
4. NOx emissions from the vehicle when fuelled with CNG met limits for both Euro 5 and Euro 6, and were about 30% higher in comparison to petrol.
5. CO2 emissions were decreased by 25% when the vehicle was fuelled with CNG.
6. For the first phase (the UDC), which is critical for determining total emissions during the NEDC, emissions of THC and CO were higher and NMHC and NOx were lower when the vehicle was running on CNG than when it was running on petrol.

CNG is commonly used in SI engines because their powertrains are relatively easy to convert from liquid to gaseous fuels. This fuel is very attractive as it is cheaper than petrol or diesel. This paper has shown that even certain pre-Euro 6 technologies can meet Euro 6 emissions standards when CNG is used as a fuel. Additionally, the CO2 emissions from vehicle operation on 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.

Abstract

Technology for light-duty CNG vehicles is well established, and CNG vehicles have performance comparable to their petrol-fuelled equivalents. CNG is commonly used in spark ignition engines because their powertrains are relatively easy to convert from liquid to gaseous fuels. In addition, the importance of natural gas will increase significantly as fuel for transportation. Apart from its massive availability at attractive current market prices, its particular advantages in terms of CO2 and exhaust emission have led to the increased use of NG as a fuel source. The aim of this paper was to determine the influence of CNG fuel on emissions in the context of the new Euro 6 emissions requirements and to compare exhaust emissions of the vehicle fuelled with CNG and with petrol. To that end, chassis dynamometer tests were performed. An analysis of CO, THC, CH4, NMHC, NOx - NO and NO2 and CO2 emissions during testing, as well as performance, of the vehicle fuelled with CNG and petrol in turn are presented. The results showed differences in terms of regulated emissions, carbon dioxide emissions and the composition of NOx (NO and NO2 share).

Porównanie emisji związków szkodliwych spalin samochodu zasilanego alternatywnie benzyną i CNG

Streszczenie

Technologia lekkich samochodów użytkowych jest dobrze rozwinięta i samochody zasilane CNG mają osiągi porównywalne do ich benzynowych odpowiedników. CNG jest powszechnie stosowane w silnikach spalinowych o zapłonie iskrowym, ponieważ ich układy napędowe są stosunkowo łatwe do przekształcenia z zasilania paliwami ciekłymi na zasilanie paliwami gazowymi, a ponadto znacznie wzrasta znaczenie gazu ziemnego jako paliwa używanego do transportu. Oprócz dostępności w dużej ilości i atrakcyjnej cenie rynkowej, paliwo to daje również istotne korzyści w aspekcie emisji CO2 i związków szkodliwych spalin, co prowadzi do wzrostu wykorzystania gazu ziemnego jako paliwa silnikowego. Celem tego artykułu było określenie wpływu paliwa CNG na emisje spalin w zakresie nowych wymagań Euro 6 i porównanie emisji samochodu zasilanego CNG i benzyną. W tym celu wykonano testy na hamowni podwoziowej. W artykule zaprezentowano analizy wyników emisji CO, THC, CH4, NMHC, NOx – NO i NO2 oraz CO2 podczas testów na hamowni podwoziowej samochodu zasilanego alternatywnie CNG i benzyną. Wyniki pokazały różnice w zakresie emisji limitowanych związków szkodliwych spalin, dwutlenku węgla jak i udziału emisji NO i NO2 w całkowitej emisji NOx.

DEFINITIONS/ABBREVIATIONS

<table>
<thead>
<tr>
<th>CARB</th>
<th>California AirResources Board</th>
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<tbody>
<tr>
<td>CH4</td>
<td>methane</td>
</tr>
<tr>
<td>CNG</td>
<td>compressed natural gas</td>
</tr>
<tr>
<td>NEDC</td>
<td>New European Driving Cycle</td>
</tr>
<tr>
<td>NG</td>
<td>natural gas</td>
</tr>
<tr>
<td>NMHC</td>
<td>non-methane hydrocarbons</td>
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REFERENCES


