Exhaust emissions and fuel consumption of a triple-fuel spark-ignition engine powered passenger car

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Abstract

This paper examines the influence of three different fuels on the exhaust emissions and the fuel consumption of a spark-ignition engine powered passenger car. Tests were performed utilizing compressed natural gas (CNG), liquefied petroleum gas (LPG) and gasoline fuel. The vehicle was driven according to the ECE and EUDC speed profiles with the warmed-up engine. Cause and effect based analysis of the results reveals potentials of utilizing different fuels to reduce vehicle emission and also deficiencies associated with utilization of particular fuel. The highest tank to wheel (TtW) efficiency and the lowest CO₂ emission were observed with the CNG fuelled vehicle. Moreover, the CNG fuelled vehicle featured the highest THC emissions and high NOₓ emissions due to fast TWC ageing being provoked by the utilization of the CNG. Retrofitted LPG fuel supply system features the largest air-fuel (A/F) ratio variations that result in the lowest TtW efficiency and in the highest NOₓ emissions of the LPG fuelled vehicle.

Keywords: Triple-fuel vehicle; On-road measurement; Exhaust emission; Fuel consumption

1. Introduction

The European road transport energy demand will rise from current 235 Mtoe in 1990 to 360 Mtoe in 2030 according to Capros et al. (2008). The road transport is the largest consumer of crude-oil products that power almost the entire road transportation fleet. To loose the dependency of the road transport on the consumption of crude-oil products, consumption of alternative non crude-oil-based fuels is promoted, namely non crude-oil-based fossil fuels or biofuels. Gaseous fuels such as CNG and LPG can be derived from both sources. Due to the high H/C ratio of both fuels compared to the gasoline, CO₂ footprint of CNG or LPG
powered vehicles can be significantly reduced or almost eliminated if fuels are produced from renewable sources as shown in e.g. Holden and Hoyer (2005).

Measurements of exhaust emission of several diesel, gasoline, LPG and CNG powered vehicles are presented and analyzed by Vebeek (2003), Pielecha et al. (2010) and Cachón et al. (2009), while some of the vehicles were bi-fueled. According to the analyses presented in the addressed references the CNG powered vehicles were favored in terms of harmful exhaust emissions followed by the LPG powered vehicles. Results of similar tests were presented also by Martini et al. (2010) that reports opposite trends. The CNG powered vehicles featured several times higher total hydrocarbon (THC) emissions compared to the gasoline, diesel and LPG powered vehicles, but still well bellow EURO 5/6 limit. High NOx emissions with some CNG and LPG powered vehicles are explained just as a consequence of retrofitted, not-optimally tuned CNG and LPG fuel injection systems that resulted in larger variations of the A/F ratios and thus in higher harmful exhaust emissions.

In addition, Winkler et al. (2008) report and analyze mechanisms leading to faster degradation of the THC conversion efficiency of TWC in the CNG powered bi-fuel vehicle compared to operation of the same vehicle utilizing gasoline. It is stated that after a relatively short ageing period (after 35.000km) THC emission is significantly increased if engine was running on the CNG fuel. On the other hand, the same catalytic converter showed high THC conversion rate when the same bi-fuel vehicle was powered by the gasoline, since a methane share in the overall THC emissions was small.

Furthermore, influence of the hydrocarbon composition of a fuel on the nitric oxide conversion in a TWC is analyzed (Van den Brink and McDonald, 1995). It is reported that methane, and to a lesser extent ethane, are particularly unreactive and could be blamed for lower conversion rate of the nitric oxide in the TWC opposite to aromatic hydro-carbon exhaust components.

The analysis presented in this paper contributes to the literature by:
- comparing influence of three different fuels on exhaust emissions and fuel consumption of a spark-ignition engine powered passenger car for two on-road test cycles,
- providing insight into the interaction of the drive cycle characteristics and the engine controlling - predominantly of the spark advance and the A/F ratio,
- showing issues related to conversion efficiency of gasoline fuel optimized TWC while engine is fueled with alternative fuels and,
- analyzing adequacy of the retrofitted LPG fuel delivery systems in terms of the exhaust emissions,
- interpreting cycle averaged exhaust emissions through their time resolved traces considering characteristics of the drive cycle, the engine, fuels and the TWC.

2. Methodology

2.1. Test vehicle

All tests were performed with 2007 VW Touran 2.0 Ecofuel. The odometer showed 152767 km at the beginning of the tests and 154951 km at the end of the tests. The total mass of the vehicle together with testing personnel and testing equipment was 2100 kg, only 80 kg less than maximum allowed total vehicle mass.
Table 1
Power train data

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>swept volume</td>
<td>1984 cm$^3$</td>
</tr>
<tr>
<td>no. of cylinders</td>
<td>4</td>
</tr>
<tr>
<td>compression ratio</td>
<td>13.5:1</td>
</tr>
<tr>
<td>max. power</td>
<td>80 kW@5400 rpm</td>
</tr>
<tr>
<td>max. torque</td>
<td>160 Nm@3500 rpm</td>
</tr>
<tr>
<td>emission standard</td>
<td>EURO4</td>
</tr>
<tr>
<td>gearbox</td>
<td>5-speed, manual</td>
</tr>
<tr>
<td>fuels</td>
<td>originally: CNG, gasoline; retrofitted: LPG</td>
</tr>
<tr>
<td>exhaust gases aftertreatment</td>
<td>three-way catalytic converter</td>
</tr>
<tr>
<td>lambda sensor</td>
<td>2 sensors at TWC inlet and outlet</td>
</tr>
</tbody>
</table>

Basic powertrain data are provided in the Table 1. The vehicle is originally designed by the manufacturer to utilize the CNG and the gasoline. Injection of these two fuels is thus steered by the customized settings of the electronic control unit (ECU). The vehicle was additionally retrofitted with a low-end LPG fuel supply system. Injection of the LPG fuel is thus not steered by customized settings of the electronic control unit (ECU) as is the case for the CNG and the gasoline fuel but the ECU settings corresponding to the gasoline fuel are utilized to inject the LPG fuel. Such approach is generally encountered when retrofitting LPG fuel supply systems.

The engine features a relatively high compression ratio (Table 1) considering external preparation of homogeneous fuel-air mixture, i.e. port injection. This is due to the fact that engine is intended for utilization of the CNG as the primary fuel and thus its higher octane number compared to the gasoline fuel favors a high compression ratio. Consequently spark advance is relatively small when running on the gasoline and the LPG fuel, which is particularly evident at high loads as shown in Section 3.

2.2. Fuels

The following fuels were utilized during the tests:
- CNG with 96.87 %VOL of methane and Wobbe index 50.51 MJ/m$^3$ that is similar to G20 test gas (pure methane),
- regular unleaded type EN228 gasoline fuel (octane number: 95),
- LPG with 35/65 propane/butane mixture complying with EN589.

2.3. Testing equipment

Exhaust emissions were measured with HORIBA OBS-2200 on-board emission testing system that measures standard volume flow of exhaust gasses and emission of CO, CO$_2$, NO$_x$ and THC (Horiba, 2007) as well as ambient conditions.

Race Technology DL2 system (Race Technology Limited, 2009) was used to acquire the data necessary to determine power required for vehicle propulsion. System embodies a 2-axis accelerometer. The measured results are compared and processed together with the data gathered with a 20Hz GPS antenna to obtain better accuracy of the data utilized to determine power/energy required for vehicle propulsion. The procedure considers vehicle air drag and rolling resistance as well as acceleration of the vehicle.

The data of the throttle pedal position and the spark advance were logged by the vehicles On-Board Diagnostics (OBD) with the ScanTool.net ElmScan5 USB data logger.
2.4. Test method

The purpose of the test was to measure the influence of three different fuels on exhaust gas emissions and fuel consumption of the same vehicle, i.e. gasoline, LPG and CNG, while driving the vehicle along equal drive cycles. A New European Driving Cycle (NEDC) was used as a basis for the test. The NEDC consists of four ECE cycles (also known as UDC-Urban Driving Cycle (Fig. 3)) followed by an EUDC (Extra Urban Driving Cycle (Fig. 2)). A 195 s long ECE cycle mimics urban driving. It is characterized by moderate vehicle speeds and accelerations. A 400 s long EUDC mimics extra urban driving and thus includes high velocity segments; however it does not feature severe accelerations requiring maximum engine power output.

Tests were performed on a flat test polygon in a still weather. The test was started after the vehicle warmed-up to the standard working conditions. This is not in line with the official ECE test procedure where vehicle must soak for at least 6 hours at test temperature 20 to 30°C. This inconsistency is justified by the fact that the applied procedure allowed performing the tests for all three fuels consecutively at comparable boundary conditions (weather parameters, road condition,...). Several ECE and EUDC test runs were performed for each fuel type to obtain a sufficient database that allowed analyzing only those test runs with repeatable vehicle velocity traces and thus with repeatable energy consumptions for vehicle propulsion.

3. Results

3.1. EUDC cycle

Time traces of measured vehicle speed, exhaust gases standard volume flow, throttle position, spark advance, exhaust gas temperature, CO\textsubscript{2}, CO, NO\textsubscript{x} and THC emission during the EUDC are shown in Fig. 1 for the three analyzed fuels (notation GAS denotes gasoline). Time traces of CO, CO\textsubscript{2}, THC, and NO\textsubscript{x} emission are analyzed for emission concentrations, since this enables better quantification and explanation of their shares, whereas cycle averaged emissions are given later in the paper as mass of particular emission per unit distance to allow comparisons with legislative limits. Concentrations of particular emission can be compared when utilizing different fuels, since corresponding standard volume flows of exhaust gases coincide very well.

3.1.1 Interaction between drive cycle characteristics and engine parameters

It can be observed that desired vehicle speed imposed by the EUDC was successfully followed during test runs with all fuels. Some discrepancies were observed during vehicle deceleration from 120 km/h to stand still. However, during severe decelerations fuelling is cut off and thus the amount of emission emitted during that period is negligible and does therefore not alter the cumulative results.

As expected, throttle position reflects drive cycle characteristics and features the highest values during high speed accelerations and correlates well with standard volume flow of the exhaust gases.

It is evident that throttle position also influences the spark advance. It can be observed that spark advance was larger while using CNG, since it features higher octane number and lower flame speed compared to the gasoline fuel as shown in Mistry (2005), Jahirul et al. (2010) and Demirbas (2002). High octane number of the CNG also results in a relatively low
sensitivity of the spark advance on the operating conditions of the engine. The engine is thus operated near maximum brake torque conditions except during idling and deceleration when spark advance is delayed to ensure smooth engine operation. A different trend in the spark advance is observed for the gasoline and LPG fueled vehicle, since gasoline fuel settings of the ECU are utilized for these two fuels. Differences in the spark advance values are most pronounced at high engine loads, i.e. vehicle accelerations, when compared to the CNG fueled vehicle. During vehicle accelerations spark advance of the gasoline and LPG fueled vehicle is delayed up to 20°CA (degrees crank angle) compared to the CNG fueled vehicle to prevent knocking.

Spark advance is also one of the parameters influencing exhaust gas temperature and furthermore temperature of the catalyst core. The temperature of exhaust gases is the lowest for the CNG fueled vehicle, which can mainly be attributed to the larger spark advance that slightly reduces the temperature of exhaust gases compared to the gasoline fueled vehicle. It is also evident from the Fig. 1 that exhaust gas temperature is higher for the LPG fueled vehicle compared to the gasoline fueled vehicle despite similar spark advance.

3.1.2 Tail pipe emissions

CNG:

Larger spark advance of the CNG fueled vehicle results in higher combustion temperatures and lower exhaust gas temperatures. Lower exhaust gas temperature, very high methane share in the THC emissions of the exhaust gasses and lower efficiency of the THC conversion in the TWC that results from its faster degradation (Van den Brink and McDonald, 1995; Winkler et al., 2008) results in higher THC and NOx emissions during accelerations. CO emissions of the CNG fueled vehicle are low during the whole cycle. CO2 emissions reflects H/C ratio of the fuels, while they drop to zero during severe decelerations due to the fuel cut-off.

Gasoline:

High total mass of the vehicle during testing (addressed in section 2.1.) and consequently higher power demand to follow the EUDC speed trace provoked rich A/F ratios during high speed accelerations (from 100km/h to 120km/h; Fig. 1) for gasoline and LPG fuelled vehicle, since they are controlled by the same ECU maps. In addition, smaller spark advance and composition of the gasoline fuel result in relatively high CO and THC concentrations. NOx concentration is low due to lower combustion temperatures and favorable TWC conversion conditions. During high speed acceleration CO2 emissions are reduced due to rich A/F ratio operation of the engine resulting in higher CO and THC emissions.

LPG:

The LPG was injected utilizing the retrofitted fuel delivery system and the engine was controlled by the gasoline ECU settings while fuelled with the LPG. As a result larger A/F ratio variations compared to fueling with other two fuels are observed when utilizing the LPG: namely rich A/F ratios during accelerations and lean A/F ratios during steady-speed cruising. This results in relatively high NOx emissions during the steady-speed cruising and in high CO emissions during accelerations. THC emissions are low due to their favorable conversion rate in the TWC and composition of the LPG fuel. CO2 emission reflects H/C ratio of LPG, while their decrease during high speed acceleration arises from the rich A/F ratio operation as addressed in the previous section.
Fig. 1. Time traces of vehicle speed, exhaust gases standard volume flow, throttle position, spark advance, exhaust gas temperature, CO₂, CO, NOₓ and THC emission during the EUDC; note: THC emissions are plotted using two THC axes to show the data more clearly.

3.2. ECE cycle

Fig. 2 shows monitored parameters for the ECE. Similar trends to those measured during the EUDC can be observed for the ECE, whereas lower values of the exhaust gases standard volume flow, throttle position, exhaust gas temperature, CO, NOₓ and THC.
emissions arise from the characteristics of the ECE speed trace and thus from lower engine power demand during the ECE.

Similarly as for the EUDC, throttle position and exhaust gases standard volume flow during the ECE reflect drive cycle characteristics. Spark advance of the engine utilizing CNG was slightly increased compared to the values during the EUDC being mainly the consequence of lower engine loads during the ECE. Due to the latter, spark advance of the gasoline and LPG fuelled vehicle approaches spark advance of the CNG fuelled vehicle.

Similarly as for the EUDC, the LPG fuelled vehicle features the highest exhaust gas temperatures but the difference is less pronounced than for the EUDC due to lower engine loads. A more important hint can be extracted from the absolute values of the exhaust gas temperatures, which indicate that TWC is not operated in its high efficiency regime resulting in its lower conversion rates, as shown by Merker et al. (2009) and Hoebink et al. (2000).

Smaller differences in CO emissions between different fuels are the consequence of smaller differences in the spark advance and of lower engine loads. The exceptions are high peaks of the CO emissions that are observed at the beginning of accelerations of the LPG fuelled vehicle, which is caused by the rich A/F ratio. The highest CO emission when using gasoline as a fuel can be mainly attributed to fuel composition.

Similarly to the EUDC, high NO\textsubscript{x} emissions are characteristic for the LPG fuelled vehicle, which is operated with lean A/F mixture during the steady-speed cruising. Unlike, it can be observed that NO\textsubscript{x} emissions are very low when the gasoline and CNG were used as a fuel.

Generally, THC emissions are very low for all three fuels. The highest THC emissions that are characteristic for the engine utilizing CNG might be attributed to lower conversion efficiency of the TWC as explained in section 1 and presented in section 3.1.2. CO\textsubscript{2} emissions again reflect H/C ratio of the fuel and the fuel cut-off during acceleration.
Fig. 2. Time traces of vehicle speed, exhaust gases standard volume flow, throttle position, spark advance, exhaust gas temperature, CO$_2$, CO, NO$_x$ and THC emission during the ECE; note: NO$_x$ and THC emissions are plotted using two axes to show the data more clearly

3.3. Cycle averaged parameters

In the Table 2 cycle averaged emissions over the EUDC are given as emission mass per unit distance. These results will be interpreted in the light of the analyses given with the time traces in sections 3.1. and 3.2..
Cycle averaged CO emissions per km follow the clear trend that is evident from the Fig. 1 and thus explanation in section 3.1 can be used to interpret CO emissions per km in the Table 2. It is furthermore discernable from the Table 2 that the CNG fuelled vehicle emits most THC emission per km. This is due to the fact that higher THC concentration of the CNG fuelled vehicle during the first three acceleration periods contributes more to the cycle averaged THC emission per km than higher THC emissions of the gasoline fuelled vehicle during the last acceleration period despite the highest mass flow of exhaust gasses during that period. The THC emission per km of the LPG fuelled vehicle is significantly lower compared to the THC emission per km while utilizing other two fuels. It is evident from the Fig.1 that the gasoline fuelled vehicle emits the least amount of NOx emissions, whereas it is more interesting to compare NOx emission per km of the CNG and LPG fuelled vehicle. The CNG fuelled vehicle features high NOx emissions during vehicle accelerations, while the LPG fuelled vehicle features high NOx emissions during steady-speed cruising as analyzed in section 3.1. Due to the fact that relatively long periods of steady-speed cruising are characteristic for the EUDC, the LPG fuelled vehicle emits the largest amount of NOx emission per km.

Absolute cycle averaged CO2 emission per km is evaluated out of the measured CO2 concentrations (Fig. 1) and the corresponding mass flows. Subsequently fuel consumption is evaluated using carbon-balance method based on the CO2 emissions and emissions of other species under consideration of the fuel composition. To minimize scattering originating from the repeatability of the velocity traces only those cycles were analyzed that feature simultaneously small differences in the velocity traces and small differences in the energy consumed for the vehicle propulsion over the test cycle. The energy consumed to power the vehicle was calculated out of fuel consumption and lower heating values of the fuels and is inversely proportional to TtW efficiency for a particular fuel.

The values of the CO2 emissions per km reflect mainly the H/C ratios of fuels, since differences in the H/C ratios are larger than those in the TtW efficiency. The CNG fuelled vehicle features the highest TtW efficiency, which can mainly be attributed to the large spark advance and thus to the higher effective efficiency of the engine. The lowest TtW efficiency is characteristic for the LPG fuelled vehicle. This is mainly the consequence of larger A/F ratio variations caused by the retrofitted LPG injection system.

Table 2
Emission results for EUDC test cycle

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>CO2</th>
<th>THC</th>
<th>NOx</th>
<th>fuel consumpt.</th>
<th>energy consumpt.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(g/km)</td>
<td>(g/km)</td>
<td>(mg/km)</td>
<td>(mg/km)</td>
<td>(g/km)</td>
<td>(MJ/km)</td>
</tr>
<tr>
<td>EUDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gasoline</td>
<td>6.153</td>
<td>173.9</td>
<td>31.94</td>
<td>59.98</td>
<td>57.90</td>
<td>2.519</td>
</tr>
<tr>
<td>LPG</td>
<td>3.913</td>
<td>170.6</td>
<td>2.48</td>
<td>218.07</td>
<td>58.51</td>
<td>2.686</td>
</tr>
<tr>
<td>CNG</td>
<td>0.625</td>
<td>137.7</td>
<td>61.71</td>
<td>144.24</td>
<td>50.61</td>
<td>2.473</td>
</tr>
</tbody>
</table>

For the ECE (Table 3), similar trends in exhaust emissions per km and fuel consumption for different fuels can be observed as for the EUDC, whereas absolute values of particular emission per km and particular fuel type might differ significantly between the ECE and EUDC.

Analyzing the gasoline fuelled vehicle it can be seen that during the ECE CO emission per kilometer are much lower compared to the EUDC value, since the engine did not enter rich A/F ratio operation for longer periods. In spite this fact it might be noted that CO emission per km of the gasoline fuelled vehicle during the ECE is rather high. Low in-
cylinder temperatures and low exhaust gas temperatures are causing low catalytic core temperatures. Such conditions are characteristic for low engine loads during the ECE and do not favor high CO conversion rate. Higher CO\textsubscript{2} emission per km during the ECE result from lower efficiency of the engine, which is significantly reduced due to long idling periods and additionally due to low engine loads. This explanation is valid also for the fuel consumption and the energy consumption trend. Higher THC emission per km during the EUDC is mainly the consequence of rich A/F operation during the high speed acceleration. Lower NO\textsubscript{x} emissions per km during the ECE result mainly from lower engine loads and thus from lower in-cylinder temperatures reducing the in-cylinder NO\textsubscript{x} formation.

Similar conclusions are also valid for comparisons of the results for the ECE and the EUDC for the LPG fuelled vehicle except for the THC emission per km that are very low for both drive cycles as analyzed previously.

The CNG fuelled vehicle does not enter rich A/F ratio operation during the EUDC and thus CO emission per km is higher during the ECE. This can be explained with lower in – cylinder temperature and lower TWC conversion efficiency. Lower THC emission per km during the ECE can mainly be explained by lower in-cylinder THC formation described by Hallgren (2005), since conversion efficiency of methane in the TWC is low during both drive cycles (Winkler et al., 2008). For other emissions per km, similar conclusions as for the gasoline fuelled vehicle are valid for comparisons of the results for the ECE and the EUDC.

Table 3

<table>
<thead>
<tr>
<th>ECE</th>
<th>CO</th>
<th>CO\textsubscript{2}</th>
<th>THC</th>
<th>NO\textsubscript{x}</th>
<th>fuel consumpt.</th>
<th>energy consumpt.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(g/km)</td>
<td>(g/km)</td>
<td>(mg/km)</td>
<td>(mg/km)</td>
<td>(g/km)</td>
<td>(MJ/km)</td>
</tr>
<tr>
<td>gasol</td>
<td>1.808</td>
<td>235.7</td>
<td>1.36</td>
<td>21.11</td>
<td>75.40</td>
<td>3.280</td>
</tr>
<tr>
<td>LPG</td>
<td>1.352</td>
<td>210.7</td>
<td>1.09</td>
<td>88.33</td>
<td>70.38</td>
<td>3.230</td>
</tr>
<tr>
<td>CNG</td>
<td>0.743</td>
<td>181.1</td>
<td>17.23</td>
<td>23.15</td>
<td>66.47</td>
<td>3.248</td>
</tr>
</tbody>
</table>

Though a direct comparison between measured results and EURO4 emission standard is not fully adequate since test conditions and mainly the total vehicle mass were not identical to those required by standard, some interesting conclusions can be extracted from Table 4. It is discernable that for the analyzed vehicle moderate load increase results in exceeding the CO limits for both fuels that use gasoline ECU settings. Therefore, only the CNG fuelled vehicle complies with the CO limits when the total vehicle mass is increased. It is furthermore discernable from the table that THC emissions per km are far below the limits for all three fuels despite low THC conversion rate in the TWC of the CNG fuelled vehicle and despite rich A/F ratio operation of the gasoline and LPG fuelled vehicle during the high speed acceleration. The highest NO\textsubscript{x} emission per km of the LPG fuelled vehicle can be explained by the poor tuning of the retrofitted system (lean A/F ratio during steady-speed cruising). The second highest NO\textsubscript{x} emission per km of the CNG fuelled vehicle can be explained by the large spark advance and by the lower NO\textsubscript{x} conversion efficiency in the TWC as analyzed above. For all fuels, higher vehicle mass also contributes to higher NO\textsubscript{x} emissions per km through larger in-cylinder NO\textsubscript{x} production.

The CO\textsubscript{2} emissions per km reflect mainly the H/C ratios of fuels as addressed above. It is also discernable form the Table 4 that the CNG fuelled vehicle features the highest TtW efficiency that is paved through the CNG optimized compression ratio and spark advance. It is also worth mentioning that measured CO\textsubscript{2} emissions per km agree well with the manufacturer data of the tested vehicle (155 g/km of CO\textsubscript{2} for the CNG fuelled vehicle and 196 g/km of CO\textsubscript{2}}
for the gasoline fuelled vehicle), while it needs to be considered that analyses were performed on an open air test polygon with warmed-up vehicle carrying higher load and thus CO₂ emissions per km are not directly comparable. Due to the fact that starting the test with the warmed-up vehicle decreases fuel consumption and due to the fact that higher vehicle load increases the fuel consumption it might be concluded that good agreement in measured and manufacturer’s data of the CO₂ emissions per km confirms adequacy of the performed analysis.

Table 4
Emission results for NEDC compared to EURO4 emission standard

<table>
<thead>
<tr>
<th>NEDC</th>
<th>CO</th>
<th>CO₂</th>
<th>THC</th>
<th>NOₓ</th>
<th>fuel consumpt.</th>
<th>energy consumpt.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(g/km)</td>
<td>(g/km)</td>
<td>(mg/km)</td>
<td>(mg/km)</td>
<td>(g/km)</td>
<td>(MJ/km)</td>
</tr>
<tr>
<td>gasoline</td>
<td>4.573</td>
<td>196.3</td>
<td>20.82</td>
<td>45.84</td>
<td>64.26</td>
<td>2.795</td>
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<tr>
<td>LPG</td>
<td>2.982</td>
<td>185.1</td>
<td>1.97</td>
<td>170.87</td>
<td>62.83</td>
<td>2.884</td>
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<tr>
<td>CNG</td>
<td>0.668</td>
<td>153.5</td>
<td>45.53</td>
<td>100.19</td>
<td>56.38</td>
<td>2.755</td>
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<tr>
<td>EURO4 (M)</td>
<td>1.0</td>
<td>/</td>
<td>100.00</td>
<td>80.00</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

Vehicle features the lowest energy consumption when CNG is used as a fuel, which leads to the highest TtW efficiency. This is made possible due to the CNG optimized compression ratio and due to the large spark advance when utilizing CNG. The lowest CO₂ emission per km of the CNG fuelled vehicle is mostly influenced by higher H/C ratio of the fuel and to a lesser extent to higher TtW efficiency. Fast degradation of the methane conversion efficiency in the TWC results in the highest THC emissions per km of the CNG fuelled vehicle. High NOₓ emissions per km are also characteristics for CNG powered vehicle, which can be attributed to higher engine out NOₓ emission due to larger spark advance and mainly to higher breakthrough of NOₓ in the TWC due to the presence of methane. The CNG fuelled vehicle features the lowest CO emissions per km.

When gasoline is used as a fuel the vehicle features lower TtW efficiency than in the case of using the CNG fuel, which is mainly related to the smaller spark advance, whereas higher CO₂ emissions per km are mainly related to lower H/C ratio of the fuel. The CO emissions per km of the gasoline fuelled vehicle exceed the NEDC limit. This is mainly due to very high CO emissions during the high speed accelerations in the EUDC where engine entered rich A/F ratio operation due to high vehicle mass that approached the maximum allowed total vehicle mass and was thus higher than the mass of the vehicle specified for the NEDC. Although rich A/F ratios resulted also in the THC emissions peak, THC conversion efficiency in the TWC is still sufficient to keep the THC emission per km below the EURO4 limit. Gasoline powered engine features the lowest NOₓ emissions per km due to lower spark advance, adequate A/F ratios and exhaust gas composition that enables favorable NOₓ conversion rate.

Retrofitted LPG fuel supply system features the largest A/F ratio variations that result in the lowest TtW efficiency, whereas CO₂ emission per km is again mainly driven by the H/C ratio of the fuel. The highest NOₓ emissions per km of the LPG fueled vehicle can mainly be attributed to the lean A/F ratios during the steady-state operation of the engine. High CO emissions per km that exceed the EURO4 limit originate from the low A/F ratios during the high speed acceleration in the EUDC. The highest THC conversion rate in the TWC is characteristic for the LPG fuelled vehicle.
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