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Exhaust emissions of an LPG powered vehicle in real operating conditions

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Abstract. The paper contains exhaust emission results for an RDE test drive of a passenger vehicle with a spark ignition bi-fuel engine fuelled with LPG. The tests were performed in accordance with the RDE test requirements, and their results were compared to the emission limits of the applicable EURO norm. The aim of the paper is to investigate the discrepancies in the real exhaust emissions between the gasoline-specific emission norms and real values from vehicle use when powered by LPG.

1 Introduction

Due to the repeated problems of detecting and enforcing the exhaust emission limits on vehicle manufacturers changes to the test methods are introduced continuously. The exhaust emission norms for passenger cars have adopted emission tests in real driving conditions, known as RDE (*Real Driving Emissions*) tests in the recent years. These tests are to increase the reliability of emission data obtained for tested vehicles undergoing the type approval process, especially considering the increasingly more popular direct injection methods and emission problems that come along with them [1]. They are a part of a WLTP (*Worldwide Harmonized Light Vehicle Test Procedure*) drive cycle, which replaced the much simpler NEDC (*New European Drive Cycle*) test. These tests differ significantly, as the newer WLTP test is designed to best mimic emissions in real driving conditions, which is greatly improved by including RDE drive cycle as a part of the emission test. The main differences can be seen in instantaneous acceleration values and the vehicle velocity, which are designed to better reflect the real conditions when driving. Despite that change there are still several aspects of exhaust emission testing that have not been addressed, specifically in the new limits and testing procedures, and are thus not normally measured or tested [2]. One example of such an oversight are bi-fuel vehicles, such as vehicles equipped with an additional fuel supply system for LPG (*Liquified Petroleum Gas*). While not particularly common in vehicles worldwide, this matter is especially significant for the polish transport sector, due to the popularity of adding LPG systems to gasoline vehicles, which significantly reduces the fuel costs for the user [3, 4]. These vehicles are subject to the same exhaust emission tests as all

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other new vehicles but the tests are only performed for drive cycle when the engine is powered by gasoline, even though majority of vehicle operating time in reality would normally be spent powered by the LPG fuel. And while emissions from LPG powered engines have been subject of research to a reasonable degree [5, 6], the emission limits have not been adjusted to account for it. Thus the lack of exhaust emission data for driving when powered by LPG remains a significant problem in consistently assessing vehicle exhaust emissions. This is particularly important for countries with large numbers of LPG powered vehicles, such as Turkey (at about 2 400 000), South Korea (2 300 000), Poland (2 300 000) and Italy (1 700 000) (based on data from WLPGA, 2011).

The goal of the paper is to establish a wider understanding of the environmental impact of LPG powered vehicles, in relation to the emission limits and norms they are subject to. Thus ensuring that powering regular gasoline vehicles with LPG using a non-factory fuel supply system does not result in the vehicle significantly exceeding the emission limits set for it. This information is particularly important when considering solutions aimed at reducing air pollution in urban agglomerations and the fact that the use of non-standard fuels can significantly impact a vehicle's exhaust emissions [7]. Even more so because some of the components of vehicle exhaust emissions can be very harmful to human health as well as the environment. The paper is part of a larger study in testing the real driving emissions of LPG vehicles subject to different emission norms (manufactured in different years). The focus of this paper is the RDE tests of a Euro 5 vehicle with a spark ignition engine when powered with LPG.

2 Test vehicle, method and equipment

The tested vehicle was a Chevrolet Aveo (Fig. 1) equipped with a 1.2 dm^3 displacement spark ignition engine and a rated power of 62 kW. The vehicle was produced in 2011, thus it is expected to meet the Euro 5 emission limits.

Fig. 1. The vehicle used for emission tests.

The RDE test has been performed using a PEMS (*Portable Emission Measuring System*) device SEMTECH DS (Fig. 2), produced by Sensors Inc. The device analysers measured the emission of CO_2 (*Carbon Dioxide*), CO (*Carbon Monoxide*), HC (*Hydrocarbons*) and NO_x

(*Nitrogen Oxides*). Detailed description of the PEMS equipment, its use and its measuring ranges can be found in [8, 9]. A flowmeter was used to determine the volume of exhaust gasses and to enable the calculation of emission values. These devices were mounted on the tested vehicle and fastened firmly to ensure safety (Fig. 3).

Fig. 2. The SEMTECH DS mobile emission analyser.

Fig. 3. The SEMTECH DS measurement equipment with the flowmeter mounted on the vehicle.

The road emission measurement was conducted in line with the RDE test requirements. The drive cycle comprised of three sections: urban, rural, and motorway, defined by their different speed profiles. In accordance with the procedure each section constitutes approx. 23–43% of the total drive distance, and each section needs to be longer than 16 km. The average vehicle speed ranges for each section are 15–40 km/h, 60–90 km/h, and above 90 km/h for the urban, rural and motorway sections respectively.

3 Results

The results of RDE test cycles have been analysed and presented as diagrams representing the share of the vehicle engine operating time based on its emission value of a given exhaust component as a function of velocity and acceleration intervals. The total share of driving time spent in each velocity-acceleration interval has been shown (Fig. 4). The obtained results do not deviate from expectations, especially the notable share of idling for when the vehicle is stationary (v = 0 km/h and a = (-0.5 m/s^2, 0 m/s^2〉), constituting the highest individual share of drive time at approx. 17%. The other three highest shares all fall in the same acceleration range but for higher velocities, indicating situation of idle engine speed when slowing down, mostly before the brakes are applied, or engine braking.

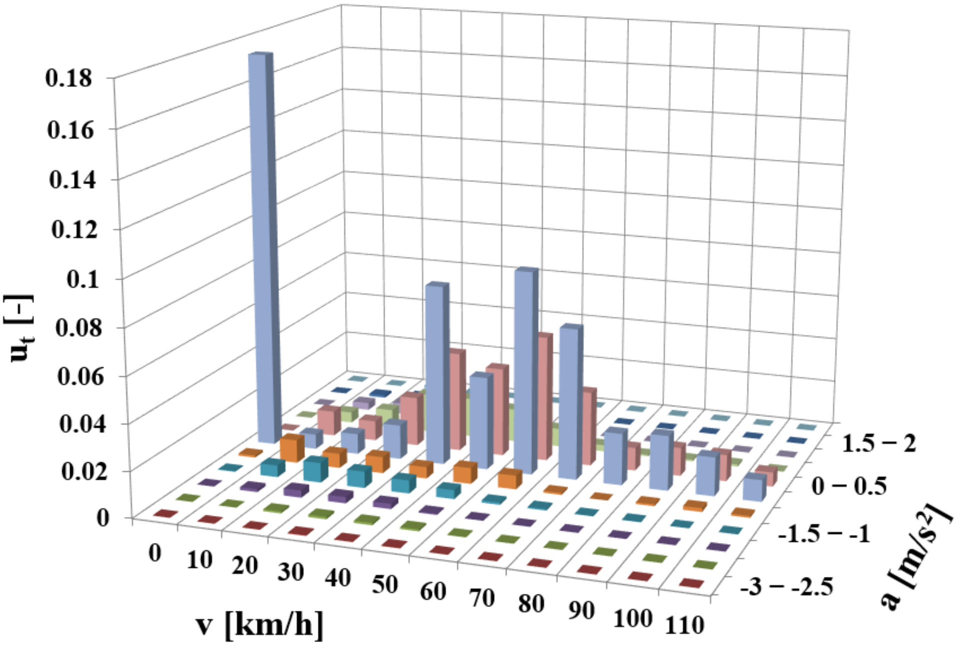

Fig. 4. Share of engine operating time in velocity-acceleration intervals.

The CO_2 emission (Fig. 5) could further be used as a reference for other types of exhaust emissions for a set of results that could be comparable between different vehicle types, as described in [10]. The results indicate a stable level of CO_2 emission for the range of low velocity values, which can be used to establish the carbon dioxide emission for the engine at idle speed. In this case these emissions reach about 0.5 to 1 g/s of CO_2 as measured by the PEMS device. Similar values for the higher velocity ranges with negative net acceleration reflect the driver's driving style, which consisted of using idle engine speed and brakes rather than engine braking for deceleration. Hence the total measured CO_2 emission could have been lower with slight variation to the driving style, as indicated in the eco-driving principles described in [11]. The highest recorded values of CO_2 emission were observed for the highest positive acceleration intervals of (2 m/s^2, 2.5 m/s^2〉**.** Emission of carbon dioxide is strictly related to the vehicle fuel consumption, thus a reduction in this parameter would also result in a decreased fuel consumption and thus a better fuel economy.

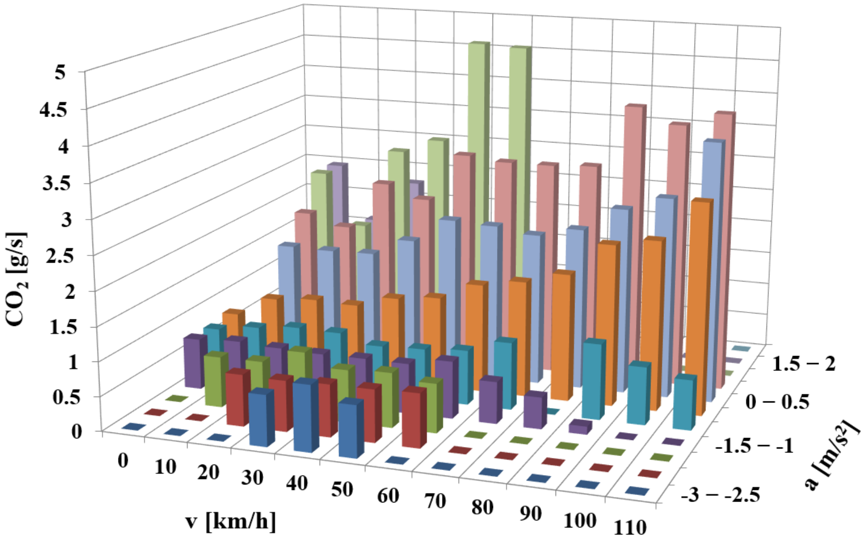

Fig. 5. CO_2 emission per second characteristics in velocity-acceleration intervals.

Emission results of carbon monoxide (Fig. 6) indicate high values for all positive acceleration intervals, largely regardless of vehicle velocity. The highest emission values were observed for acceleration intervals between ⟨0.5 m/s^2, 1.5 m/s^2⟩. Equally high values were reached for the interval ⟨1.5 m/s^2, 2 m/s^2⟩ but only for low velocity ranges ⟨0 km/h, 30 km/h⟩. This is mostly the result of the vehicle power limit when travelling at high speeds. CO emission is strongly influenced by acceleration, as a result of worsening combustion conditions in the cylinder.

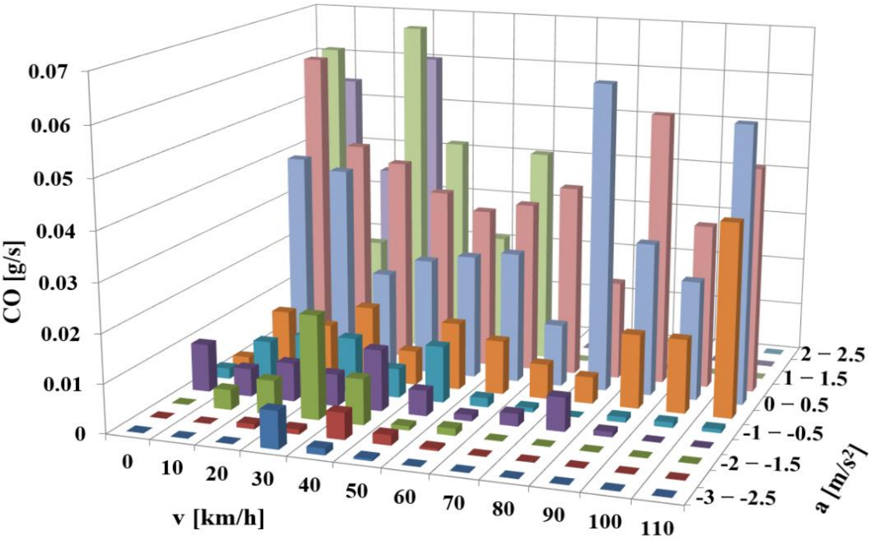

Fig. 6. CO emission per second characteristics in velocity-acceleration intervals.

The emission values for hydrocarbons (Fig. 7) indicate an increase in emission values for higher velocities, mainly in velocity ranges ⟨80 km/h, 110 km/h⟩. This steady increase in HC

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emissions per second indicate that for these intervals the engine was running on a rich mixture rather than, as it would be expected for LPG vehicles, a lean mixture. The highest emission value of 0.0042 g/s, however, was found for the interval a = (1.5 m/s^2, 2 m/s^2⟩ and v = (20 km/h, 30 km/h⟩. It is an operating point at a large acceleration value but relatively low vehicle velocity, implying a situation of dynamic acceleration.

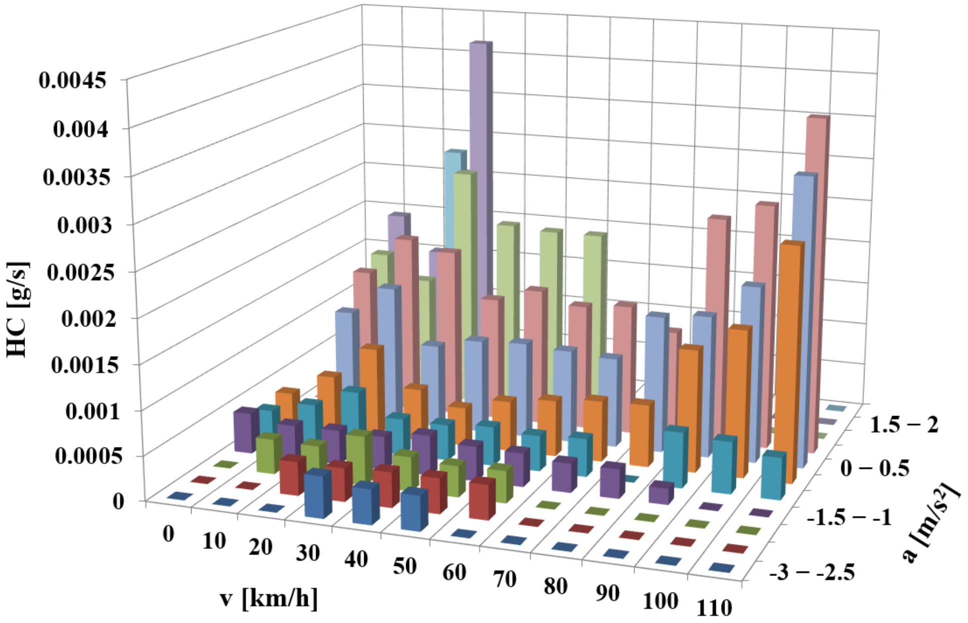

Fig. 7. HC emission per second characteristics in velocity-acceleration intervals.

Emission of nitrogen oxides indicates a strong impact of velocity and acceleration (Fig. 8). The highest NO_x emission values (of up to 0.0028 g/s) were observed in the intervals v = (80 km/h, 110 km/h⟩ and a = (0 m/s^2, 1 m/s^2⟩. This indicates high temperature during the combustion process, as resulting from the richer air-fuel mixtures. Unlike for gasoline or diesel oil, which require thermal energy from the combustion chamber to evaporate, LPG fuel does not decrease the thermal energy of the combustion chamber as significantly (which is also reflected by the problems of cylinder head overheating in such systems). Hence leading to increased NO_x emissions.

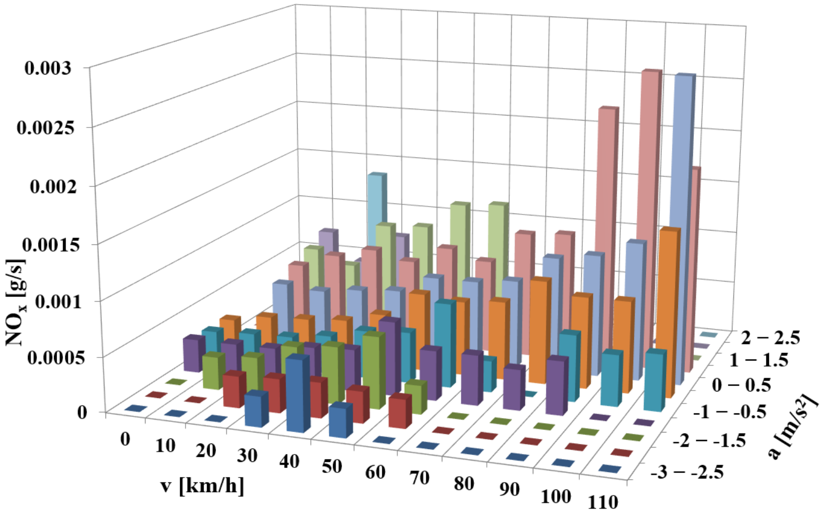

Fig. 8. NO_x emission per second characteristics in velocity-acceleration intervals.

Other results include the cumulative CO_2 emission for the entire RDE test cycle. It amounted to just over 10 kg, which averages out at approx. 150 g/km. This value exceeds the EU passenger cars 2015 CO_2 target of 130 g/km. The highest rate of cumulative CO_2 increase can be seen around the 1500–2500 s time period. This period corresponds to the vehicle switching from rural drive section to the motorway section, thus requiring a significant increase in speed to match the motorway cruising speed of other vehicles. Especially since for the purposes of the RDE testing motorway section is assessed based on the average vehicle speed being over 90 km/h. Highest recorded values of CO_2 emission reached 5 g/s, while the average value for the whole drive was determined to be around 2 g/s.

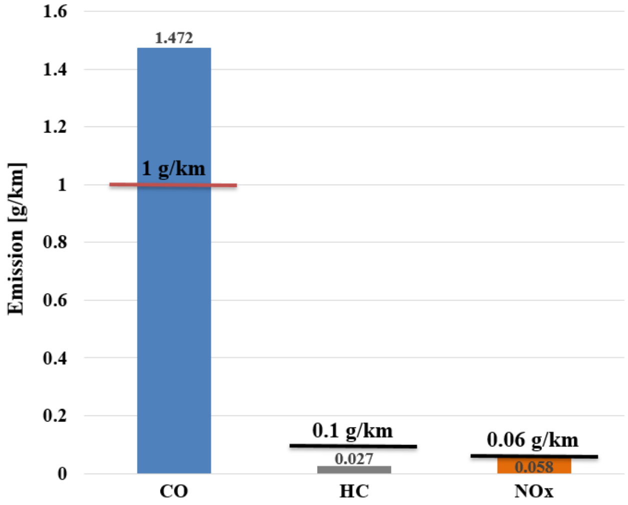

Fig. 10. Measured road emission values for CO, HC and NO_x in relation to the Euro 5 limits.

The test results indicate a relatively similar set of emission characteristics of an LPG powered vehicle to the emission limits set for regular gasoline powered vehicles (Fig. 10). These results have been compared to the Euro 5 emission norms.

4 Conclusions

As a general conclusion it should be noted that despite not being subject to testing, the emissions of vehicles powered by LPG fuel are reasonably within the limit values, even in the case of CO the RDE test emission results are permitted to reach 210% of the limit value due to the introduction of “conformity factor” equal to CF = 2.1. Although the conformity factor was introduced only recently to RDE tests in newer emission norms (Euro 6), it provides a good reference for older vehicles that RDE testing doesn’t legally apply to. Use of RDE tests are also intended to compliment rather than supplement stationary dynamometer tests, however, their improved accuracy in representing real emissions does impact the use and utility of stationary tests [12].

The specific conclusions for the tested vehicle include:

1. The vehicle NO_x emissions at their highest points were higher than expected. The total amount of NO_x emitted in the test drive was nearly 4 grams, and the peak emission value reached was just under 0.01 g/s. Despite that the emission limit value was not exceeded (Fig. 10). Problems in meeting the NO_x emission limits tend to be a more common issue for vehicles equipped with compression ignition engines, as shown clearly in a comprehensive study by O’Driscoll et. al [13].
2. The HC emission was significantly below the limit value, despite the mixture being richer than expected for high velocity and acceleration intervals. Average road HC emissions were recorded at only 0.027 g/km compared to the limit value of 0.1 g/km.
3. The CO emission exceeded the limit value by approx. 47%. Thus a conformity factor of 1.5 would be needed for the test to have yielded acceptable values [14].
4. High CO emission indicates that either the air intake was insufficient (mixture too rich) or the aftertreatment systems failed to adequately reduce the emitted CO.

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