Assessment of exhaust emissions from vehicles in real traffic conditions

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Abstract. Every year increase the number vehicle on the road. By 2015 the number of cars on the world was about 1.1 billion. This means that for one car there was 6.5 inhabitants. This number all the time is to increase. It is estimated by 2025 it will exceed 1.5 billion vehicles, and in 2040 it will be already 2 billion. In this case the growth in the global vehicle number and environmental issues requires to reducing the exhaust emissions. The main problem is exhaust emission of vehicles in the city centres but not only, also in extra – urban conditions. Therefore, the focus is on reducing the number of vehicles with significant exhaust emissions and introducing vehicles using alternative fuels. The aim of the article is to present differences in emissions of exhaust gas pollutants using CNG and conventional fuels, from heavy and light vehicles in real traffic conditions.

CNG is considered as an alternative fuel. In Poland is during operation relatively large fleet of vehicles with CNG engines, including buses and passenger cars. An in-depth knowledge of the emissivity of such vehicles is a very important issue. The paper presents too, tests under real traffic conditions two city buses that meet the Euro VI emission standards. Diesel engine of the first bus, was fuelled by diesel oil. Spark ignition engine, of the second bus, was fuelled CNG. Tests buses were conducted in real traffic conditions using PEMS devices. The article presents the comparative results of exhaust emission of passenger car with engine fuelled petrol or CNG, during tests D1 and D2 on the chassis dynamometer, tests registered earlier in real traffic conditions. Test D1 reflects urban traffic conditions while D2 test extra – urban conditions.

1. Introduction

Air pollution and increasingly stringent requirements regarding harmful substances of exhaust emissions make the vehicle fleet in cities, but also in suburban traffic, change significantly. In large urban arteries, concentrations of harmful substances often exceed standards. The best example of this is Cracow. In October 2017, once again there was an alert regarding the exceedance of permissible standards for PM 10 announced. At present, the major problem is the excessive greenhouse gas emissions. Including: first of all, carbon dioxide CO2, methane CH4 and nitrous oxide N2O.[5]. Vehicle companies are already moving in direction reducing these gases, introducing new technical solutions. In terms of cars, one option is to replace traditional vehicles with their alternative equivalents or short-term use of dual-fuel vehicles [3], [5].

The remaining component of natural gas is methane and the rest such as ethane, propane, butane and nitrogen. Natural gas, most often used in compressed form, is characterized by low energy density. At a pressure of 17.7 MPa at 21°C, it is 7 kJ/cm³ (compared to gasoline of 30 kJ/cm³). A comparison of the energy and operating characteristics of natural gas with the selected fuel group is presented in Table 1. A significantly lower density of gaseous fuels, and consequently less energy from the volume unit, requires from the vehicle to be specifically adapted to gas supply. On the other hand, the efficient use of energy contained in gaseous fuel entails the necessity of making changes to the propulsion unit [2], [5],[9-12].
Table 1. The properties of conventional fuels and alternative gaseous fuels[4],[6-8].

|                                | Gasoline | Methane CH₄ | LPG (C₃H₈) | Diesel |
|--------------------------------|----------|-------------|------------|--------|
| The calorific value of the mixture (>= 1) | -3.7 MJ/m³ (fuel from gases) | 3.37 MJ/m³ | =3.66 MJ/m³ | 3.7 MJ/m³ |
| Laminar burning rate [m/s]     | 0.3 – 0.6 (2 um - 22 um) | 0.34        | 0.39 Prop. But. |
| Air requirement/kg of fuel     | 15 kg/kg | 17.2 kg/kg | 15.5 kg/kg | 14.5 kg/kg |
| Octane rating                  | <98      | 110-130    | 100-115    |
| Density [kg/m³] relative to air| (0.72-0.76) kg/dm³ | 0.717 kg/m³ | 2 kg/m³ C₃H₈ | 2.7 kg/m C₄H₁₀ | 0.86 kg/dm³ |
| Flash point T21 [°C]           | Normalna 220 °C | Super 270 °C | 650 °C | 4819- C₃H₁₀ | 4309- C₄H₁₀ | 220 °C |
| Flammability range (practical) K| 0.7- 1.25 | 0.6- 1.9(2) | 0.4- 1.91 C₃H₈ | 0.34- 1.74 C₄H₁₀ | 0.19-0.98 |
| Explosion limit                | (1.3 - 7) % | (5-15)% | (2.1 2-9.35)% P | (1.8-8.5)% B | 0.6 - 6.5 % |

2. Methodology of tests and test apparatus

In the case of buses (Euro VI) the tests were done in real conditions. In real traffic conditions two public transport buses were tested using PEMS measuring equipment. Bus engines were powered with available commercial fuels, compliant with the standards in force in Poland [14].

In the case of testing buses, PEMS measuring apparatus was used. Two mobile analyzers Semtech DS were used to measure the content of hazardous compounds in exhaust gases [14]. The equipment was used to measure compounds of harmful exhaust gases, i.e. carbon dioxide, carbon oxide, hydrocarbons and nitrogen oxides and to assess fuel consumption with the carbon balance method. Information in publications regarding the use of mobile exhaust gas analyzers coupled with data recorded by on-board diagnostic systems [1], [7], proved that the evaluation of contamination emission in real conditions of traffic with the use of such equipment was reasonable. The tests were carried out as described above using PEMS instruments equipped with analyzers for CO₂, CO, THC (HC) and NOₓ measurements with specified measurement accuracy [14]. The measurements were repeated several times. Measurement uncertainties would be several percent. Both vehicles moved one after another, which allowed for eliminating errors due to driving style or changeable weather conditions.

The test route combined elements of urban and country driving (Figure1-2). Parameters of the test route are represented in Table 2.
Figure 1. Characteristics of the test route.

Figure 2. Test route.

Table 2. Characteristic of test route.

| Test route |          |
|------------|----------|
| Length     | 26 km    |
| Change of altitude | Minimum 183m maximum -178m |
| Max. slope | 4.7%     |
| Min. slope | -6.9%    |
| Average positive slope | 1.3%     |
| Average negative slope | -1.3%    |

For the passenger cars (Euro 5), the tests were carried out on the chassis dynamometer using the AVL AMA i60 analyzer set, in three different driving cycles. Trade fuels were used, compliant with the standards in force in Poland. The research was conducted strictly in accordance with the requirements of UNECE Regulation 83 [13]. Measurement uncertainties were typical in conducting this type of research. Own tests were conducted as described above on the chassis dynamometer, it is NEDC, D1 and D2 test cycles.

The first one is the European cycle NEDC. It consists of part I (urban) UDC and part II (suburban) EUDC. The course of speed of the vehicle as a function of time in the NEDC cycle is shown in Figure 3 [1], [4], [7], [13].

Figure 3. UDC and EUDC (NEDC) Driving Cycle [13].
Each of them consists of fifteen phases (idle speed, acceleration, constant speed, deceleration, etc.). In contrast, part II of the test consists of one suburban cycle. It consists of 13 phases (idle speed, acceleration, constant speed, deceleration, etc.).

The test consisting of these two parts takes a total of 19 minutes and 40 seconds. During the European driving cycle, measurements of the pollutant concentrations (primarily CO$_2$, CO, THC, NOx) are conducted on the basis of which the emissions of these pollutants are calculated [5].

The next two driving cycles are cycles D1 and D2. They reflect the actual traffic conditions. They were developed at the Motor Transport Institute in Warsaw in Poland. The first of these - D1, reflects urban conditions, while D2 reflects suburban and highway conditions. These are shown in Figures 4 and 5.

![Figure 4. Synthetic cycle characterizing urban type traffic (D1) [7].](image)

![Figure 5. Synthetic cycle characterizing the suburban, highway and express roads type traffic (D2) [7].](image)

Most of the measurements of cars were performed using the set of AVL AMA i60 analyzers mentioned above. Measurements were conducted using conventional IRD (CO, CO$_2$), FID (THC and CH$_4$), CLD (NOx (NO and NO$_2$)) and PMD (O$_2$) analyzers [13].

The driver performing the test on the monitor, so-called the driving indicator, had the course of the test given that they played. To ensure proper cooling of the engine of the tested vehicle, a fan was installed at the front of the car. It was responsible for adjusting the airflow to the speed of the vehicle. Exhaust gases from the exhaust system were supplied to the CVS (Constant Volume Sampler) using a dilution tunnel. It mixes the emissions of the vehicle with the ambient air. Then the mixture is sent to a set of sample bags. In the tests, these were two bags with diluted exhaust gases and two with ambient air for evaluation of the so-called background. Then a sample was taken from the bags and sent to the analyzers [13].

3. Own tests

3.1. City buses

The results of studies could be evaluated owing to a positive result of the comparison of test routes and their large time consistency. This is because the portion of time of vehicle’s driving phases was determined in the test (with values rounded to full units). The compared values for acceleration, fixed velocity, braking and stopover of vehicles are presented below (Table 3).
Table 3. Values of respective driving phases of tested buses.

| Value          | Bus powered by CNG fuel | Bus powered by diesel fuel |
|----------------|-------------------------|----------------------------|
| Acceleration % | 38                      | 40                         |
| Fixed velocity % | 19                      | 9                          |
| Braking %       | 28                      | 35                         |
| Stopover %      | 15                      | 17                         |

With the test results, it was possible to determine the content and intensity of flow, depending on the route. Figure 6 presents the results for CO₂ with reference to the road, for both tested buses (the buses fulfilling Euro VI emission standard. The bus with diesel engine was characterized with engine of capacity 10,518 [cm³] and a nominal power of 235 [kW], while the bus with spark ignition engine powered by CNG, was with engine of capacity 12,816 [cm³] and a rated power of 228 [kW]).

Figure 6. Concentration and intensity of CO₂ emission with reference to the completed road:
- I bus (CNG-fuelled), — II bus (diesel fuelled)

Figure 7. Presents temporary and average fuel consumption, also with reference to the route of both vehicles.

Figure 7. Characteristics of temporary and average fuel consumption with reference to the completed road:
- I bus (CNG-fuelled), — II bus (diesel fuelled)

Owing to the tests it was possible to determine time courses for the intensity of emission of hazardous substances of exhaust gases for both buses. Hence, correlations were developed characterising the impact of dynamic properties of public transport buses on the emission of harmful compounds. Dynamic properties of vehicles were included indirectly, using the entire velocity range and the range of measured acceleration in urban traffic for a matrix of intensity of emissions of respective pollutants. Those figures were averaged in respective velocity and acceleration ranges.
Therefore, characteristics of operation in respective ranges and the matrix of emission of harmful compounds had been determined.

Figure 8. Two-dimensional histograms of vehicle’s operating time in relation velocity – acceleration:

- I bus (CNG-fuelled), - II bus (diesel fuelled)

According to data presented in Figure 8 there is a similarity in the portion of operating time for the tested buses. Also, a greater portion of operation is observed in the area of minimum driving speed (stopover) and high driving speeds (10-18 m/s) and zero bus acceleration.

Two-dimensional histogram of intensity of CO₂ emission [mg/s] in the relation velocity – acceleration is presented in Figure 9. It represented indirectly the fuel consumption during the tests. The bus fuelled with CNG was comparable. Histograms of intensity of CO₂ emission during the tests for averaged velocities are represented in Figure 10.

Figure 9. Two-dimensional histograms of CO₂ emission intensity during the tests in relation velocity – acceleration:

- I bus (CNG-fuelled), - II bus (diesel fuelled)

Figure 10. Histograms of CO₂ emission intensity during the tests for average velocity:

- I bus (CNG-fuelled), - II bus (diesel fuelled)
In case of the CNG-fuelled bus, attention must be given to NO\textsubscript{X} emission, which is lesser than in the diesel-fuelled bus. Figure 11 presents a two-dimensional histogram of NO\textsubscript{X} emission intensity during the tests in the relation velocity – acceleration. The figures shown in Figure 12 prove the above.

![Figure 11](image1)

**Figure 11.** Two-dimensional histograms of NO\textsubscript{X} emission intensity during the tests in relation velocity – acceleration:

- I bus (CNG-fuelled), II bus (diesel fuelled)

![Figure 12](image2)

**Figure 12.** Histograms of NO\textsubscript{X} emission intensity during the tests for average velocity:

- I bus (CNG-fuelled), II bus (diesel fuelled)

Also, in case of HC emission intensity, the CNG-fuelled bus manifests lower emission than the diesel-fuelled bus. This is reflected in Figure 13.

![Figure 13](image3)

**Figure 13.** Two-dimensional histograms of hydrocarbons emission intensity during the tests in relation velocity – acceleration:

- I bus (CNG-fuelled), II bus (diesel fuelled)

In Figure 14 presents the results of fuel consumption and road emission of exhaust gases in the course of tests and a comparison of fuel consumption and exhaust emissions during tests.
3.2. Passenger cars

It was prepared by the manufacturer to be supplied by CNG and conventional petrol fuel. Emissions of harmful substances have been tested on a chassis dynamometer under specified conditions (temperature: 20-30 degrees Celsius, humidity: 5.5-12.2 gH₂O/kg of dry air), from a vehicle with an engine (with a capacity 1984 cm³, with three-way catalyst and fulfilling Euro V emission standard) powered by natural gas CNG and gasoline. Figure 16-19 shows the comparison of pollutant concentrations in the NEDC driving cycle carried out according to Regulation No. 83 EKG ONZ [7].

As shown by the results of the tests, the car powered by CNG is characterized by lower concentrations (CO₂, CO, NOₓ and THC) compared to the values of concentrations mentioned above occurring when fuelled with gasoline [7].
In addition to the tests mentioned above, for VW Caddy 2.0l, the pollutant concentrations of this CNG- and gasoline-powered vehicle were also tested in the tests reflecting the actual traffic conditions D1 and D2, developed at the Motor Transport Institute in Warsaw in Poland. The differences in the course of concentrations of the D1 driving cycle, depending on the type of fuel for the warm engine of the tested vehicle are shown in Figure 19-22. The results show that, during the entire D1 driving cycle, CO\(_2\) concentrations are lower than for gasoline, while the NO\(_x\) and THC concentrations are slightly higher when powered by CNG [7].

![Figure 19](image1.png)

**Figure 19.** Comparison of CO\(_2\) concentrations in the D1 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

![Figure 20](image2.png)

**Figure 20.** Comparison of CO concentrations in the D1 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

![Figure 21](image3.png)

**Figure 21.** Comparison of NO\(_x\) concentrations in the D1 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

![Figure 22](image4.png)

**Figure 22.** Comparison of THC concentrations in the D1 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

Below, the figures 23-26 are shown the course of concentrations for the VW Caddy 2.0l in the D2 driving cycle, reflecting suburban, highway, and express roads cycle, both for petrol and CNG engines. The D2 test concentration values for the VW Caddy 2.0l are characterized by the same course as the D1 test, i.e. the CO\(_2\), CO and THC values are lower, and the NO\(_x\) values are slightly higher when powered by CNG [4].
Figure 23. Comparison of CO₂ concentrations in the D2 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

Figure 24. Comparison of CO concentrations in the D2 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

Figure 25. Comparison of NOₓ concentrations in the D2 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

Figure 26. Comparison of THC concentrations in the D2 driving cycle at warm start of tested VW Caddy 2.0l engine powered by CNG and petrol [7].

The tests conducted also allowed to determine the average values of the road emission of the polluting components in the individual driving cycles. These results are shown in Table 4 below.

| Average road emission | CO₂   | CO    | NOₓ   | THC   |
|-----------------------|-------|-------|-------|-------|
| D1 (CNG supply)       | 177.2 g/km | 272.7 mg/km | 9.5 mg/km | 28.4 mg/km |
| D1 (PB supply)        | 235.7 g/km | 276.5 mg/km | 8.8 mg/km | 27.7 mg/km |
| D2 (CNG supply)       | 153.7 g/km | 343.3 mg/km | 14.2 mg/km | 34.7 mg/km |
| D2 (PB supply)        | 194.7 g/km | 1037.8 mg/km | 10.0 mg/km | 56.9 mg/km |

Table 4. Average values of road emissions for passenger car VW Caddy 2.0l [7].
4. Summary

The results of the tests carried out indicate that in the case of a car powered by CNG, the road emission in the NEDC cycle is smaller than when supplied with petrol in relation to CO₂, CO, NOₓ and THC. Comparing the road emission of this car in cycles D1 and D2 with CNG power supply, it can be concluded that the road emission is lower than when supplied with petrol for CO₂, CO and THC, and higher in the case of NOₓ, which may have been the result of engine regulation using this fuel.

In turn, the differences in emissions of individual components for the heavy vehicles tested are presented below.

The tests in real road traffic conditions resulted in the following conclusions:

• consumption (natural gas) 59.1 m³/100 km (CNG-fuelled bus) and 41.7 dm³/100 km (diesel-fuelled bus),
• CO emission: 1.01 g/km (CNG-fuelled bus) and 0.95 g/km (diesel-fuelled bus),
• HC emission: 0.23 g/km (CNG-fuelled bus) and 0.39 g/km (diesel-fuelled bus),
• NOₓ emission: 0.37 g/km (CNG-fuelled bus) and 1.11 g/km (diesel-fuelled bus),
• CO₂ emission: 1114.73 g/km (CNG-fuelled bus) and 1133.11 g/km (diesel-fuelled bus).

Attention should be given to the fact that despite positive results of using compressed natural gas for fuelling public transport buses, in terms of road emission of – in particular – nitrogen oxides, as proved by tests, also in other aspects the use of methane fuel is reasonable. This applies particularly to compressed bio-methane used instead of CNG, with CO₂ emission in the life cycle is almost null.

Because of those aspects the use of vehicles fuelled with methane (CNG, LNG and biomethane) in bus fleets is reasonable.

References

[1] Merkisz J, Pielecha J, Radzimirski S, 2014 New Trends in Emission Control in the European Union. Springer International Publishing Switzerland
[2] Merkisz J, Pielecha J, Nanoparticle Emissions from Combustion Engines. Springer Tracts on Transportation and Traffic 8, 1-139 (2015), DOI: 10.1007/978-3-319-15928-7
[3] Bonnel P, Weiss M, Provenza A, 2011: In-use emissions requirements in the new and future European motor vehicle emissions regulations: state of play. In: 8th Annual SUN Conference, Ann Arbor
[4] Commission Regulation (EC) No. 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No. 595/2009 of the European Parliament and of the Council with respect to emissions from heavy-duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council. OJ L 167/1 (June 25, 2011).
[5] Deutsche Energie Agentur GmbH: Erdgas und Biomethan im künftigen Kraftstoffmix – Handlungsbedarf und Lösungsansätze für eine beschleunigte Etablierung im Verkehr (The role of natural gas and methane in the fuel mix of the future in Germany), DENA, Berlin 2010.
[6] Directive 2005/55/EC of the European Parliament and of the Council of 28 September 2005 on the approximation of the laws of the Member States relating to the measures to be taken against the emission of gaseous pollutants from positive – ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles. Official Journal of the European Union L 275/1.
[7] Gis M.: Engineer dissertation titled: Ograniczenie emisji dwutlenku węgla z silników spalinowych pojazdów kategorii M i N przez zastosowanie biometanu. Warsaw 2013
[8] Gis W, Zółtowski A, Majerczyk A, Taubert S: Badanie emisji zanieczyszczeń z pojazdów w rzeczywistych warunkach eksploatacji. ITS Study No. 6105/COŚ.
[9] Merkisz J, Pielecha J, Conversion of the exhaust emission results obtained from combustion engines of heavy-duty vehicles. Scientific Conference on Automotive Vehicles and Combustion Engines (KONMOT 2016), IOP Publishing, IOP Conf. Series: Materials Science and Engineering 148, UNSP 012078 (2016), doi:10.1088/1757-899X/148/1/012078

[10] Merkisz J, Pielecha J, Radzimirski S, Type Approval of Heavy-Duty Vehicles for Emission of Pollutants. Springer Tracts on Transportation and Traffic 4, 67-90 (2014), DOI: 10.1007/978-3-319-02705-0_4

[11] Merkisz J, Idzior M, Pielecha J, Gis W, Emission tests in city buses under real road conditions. WIT Transactions on the Built Environment 111, 181-189 (2010), DOI: 10.2495/UT100171

[12] Merkisz J, Fuc P, Lijewski P, Pielecha J, Actual emissions from urban buses powered with diesel and gas engines. Transportation Research Procedia 14, 3070-3078 (2016), DOI: 10.1016/j.trpro.2016.05.452

[13] Regulation No 83. Revision 4. Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements. E/ECE/324/Rev.1 Add.82/Rev.4 – E/ECE/TRANS/505/Rev.1/Add82/Rev.4.

[14] Sensors SEMTECH-DS. On Board Vehicle Emissions Analyzer. User Manual. Document: 9510-086. Revision: 1.15.