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Actual emissions from urban buses powered with diesel and gas engines

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Abstract

Due to the growing demand for traditionally sourced fossil fuels such as oil or natural gas, it became necessary to search for new unconventional sources of these raw materials. The latest results of research work targeted the exploration and exploitation of resources of yet another type of fuel – shale gas. According to estimates, Poland alone may have reserves of 5.3 billion cubic meters of natural gas, accumulated in non-conventional sources. This potential can be used in many sectors of the economy, including in transport. Thus, it became reasonable to consider the use of natural gas as an alternative power source for vehicles. The article presents the results of emissions from public buses powered by diesel fuel and compressed natural gas. The study was conducted in real traffic conditions on a regular bus line in Poznan. The measurement of toxic exhaust elements was conducted with the use of a mobile measuring system of exhaust gas analyzers PEMS (Portable Emissions Measurement System). The data obtained were used to determine the average emissions of individual components. Based on the obtained values it can be concluded that the use of different types of fuels to drive public transport vehicles leads to a reduction of air pollutants and thus to improvement in the quality of life in the city.

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Keywords: Bus; CNG; road emission

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1. Introduction

The expected depletion of fossil fuel resources and concerns about the state of the natural environment have significantly increased the interest in alternative sources of energy in the nineties and consequently led to a significant increase in their use in many countries around the world. The depletion of natural resources of hydrocarbon fuels can be greatly accelerated by the rapid growth in demand for primary energy sources, in particular in certain Asian countries like China and India. The depletion of oil resources will result in a dramatic increase in oil prices on world energy markets (Merkisz and Pielecha, 2006). Hence, in the automotive field two main lines of action leading to saving fuel derived from petroleum have emerged: the introduction of internal combustion engines with improved efficiency, including their economical operation and intensified research into implementation of alternative fuels. An additional requirement is the need to reduce emissions of harmful exhaust gases, which, although they represent only about 1.4% of the products of combustion, are the result of a significant share of the automotive industry in environmental pollution and thus affect its degradation (Szlachta, 2002).

It is expected that in the coming years the dominant position of the internal combustion engine as power supply for vehicles will be maintained. Numerous advantages of diesel engines resulted in them being the sole source for propulsion of HDV type (Heavy Duty Vehicle) vehicles, including city buses.

Unfortunately, only large companies can cope with the research and development costs of new constructions, in accordance with legislative requirements currently prevailing in the construction and operation of buses. In some countries, politicians are demanding even "cleaner" vehicles. Trolley buses are still widely used in many countries of Central and Eastern Europe as well as in Italy. A common alternative is compressed natural gas, characterized by lower emissions compared to engines powered with diesel fuel. The problem here is, however, the need to carry this type of fuel in large tanks placed on the roof of the bus, which adds about 1000 kg curb weight and thus reduces the allowed number of passengers. In Stockholm, however, many buses are fueled with ethanol. Emissions of harmful substances are very small, but in order to achieve the same mileage the fuel tanks must be about 60-70% larger than in buses with diesel engines. Furthermore, ethanol production requires a high energy use, it can nevertheless be produced away from urban areas. The disadvantages of ethanol also include its aggressive corrosiveness.

Emission of toxic fumes depends largely on the technical condition of the engine. Therefore, the legislature makes the producers of motor vehicles and engines equipped, among others, in city buses to have procedures for detecting increased emission of toxic fumes. The result was the introduction of the OBD (On Board Diagnostics) system, whose task it is to control the efficiency of vehicle elements responsible for the emission of toxic fumes and the efficiency of elements responsible for the safety of the vehicle.

2. Engines powered with natural gas

Vehicles powered by gaseous fuels are increasingly appearing in our surroundings. The search for alternative fuels as a substitute for the commonly used liquid fuels is driven by the current issues concerning ecology, availability and prices. The very idea of powering a piston of an internal combustion engine with gaseous hydrocarbon fuel dates back to its invention. The world's first internal combustion engine, which was constructed in 1860 by Etienne Lenoir, was powered with coal gas. The first four-stroke engine with spark ignition (SI), built by Nicolaus August Otto in 1876, has a similar background. The construction of the petrol engine (by Carl Friedrich Benz) in the following years caused the use of gaseous fuels in the automotive industry to be mostly abandoned. Interest in hydrocarbon gas as vehicle fuel came back only in the seventies – sparked by the times of energy crisis and it lasts until today (Nowak and Rymaniak, 2002). Gaseous hydrocarbon fuels are an attractive alternative mostly because of their low prices determined by the state. In fact, throughout the world they are cheaper than liquid fuels. This results not only from lower production costs, but also from the tax policy in many countries.

Natural gas is a naturally occurring high-calorie fuel found alone or accompanying reservoirs of crude oil. After extraction it requires only drying and in some cases desulfurization. It is a mixture of light hydrocarbons of paraffin series, coming out of the ground in the form of gas. Its main components are methane (83-90% by volume), ethane, propane and butane (which are usually separated as LPG). Natural gas, depending on the type of deposit, may also contain heavier hydrocarbons and various impurities: hydrogen sulfide, nitrogen, carbon dioxide, air, argon and other compounds in trace amounts (Amann, 1998; Chen, Sun and Zhang, 2002).

Natural gas is non-toxic – it is almost two times lighter than air and can easily be mixed with it, so the presence of any leaks in the vehicle does not pose a large danger.

Manufacturers of engines for city buses require users to use gas with appropriate parameters outlined in the specifications. If the gas composition differs from the expected, engine manufacturers require users to obtain a certificate permitting the use of the gas. Depending on the local quality of the gas it is possible to adapt the engine operating parameters by using appropriate settings of engine control.

The requirements for natural gas are described by the legal standards. The quality of natural gas for combustion engines is determined by the ISO 15403 norm and complemented by the specifications "Requirements regarding the composition of natural gas".

3. Engines powered with natural gas

Measurements of emissions were carried out in real conditions. Tests were performed on two selected routes: urban and suburban. Through the use of mobile measuring equipment, it was possible to compare emissions from public buses powered with CNG and diesel. Selected routes were regular bus lines operated by the city of Poznan communications operator. The choice of route for research was dictated by actual conditions of use of buses for a typical urban area, which is an extensive communications network. City Route 1 ran between Sobieski residential area and a bus loop Debina in Poznan (Figure 1a). It was the line 76, classified by the Municipal Transport Company (MPK) as one of the busiest in terms of length, course and number of passengers. Its length was 16 km and it had 43 stops. The diversified run of line 76 (main thoroughfares, roads in residential areas and the strict city center) determines the high variability of accelerations and the involvement of traffic congestion, which enables the analysis of emissions over a wide range of conditions. The second route chosen for the study was the bus line 98, the length and number of stops are less than the line 76 (Fig. 1b). But it is a route with a large number of passengers carried, because it is a line running through one of the major university campuses in Poznan, where access by public transport is carried out exclusively by a fleet of road vehicles. Its length was 5 km. For each of the test runs four measurements were performed: two on each side of the bus line.

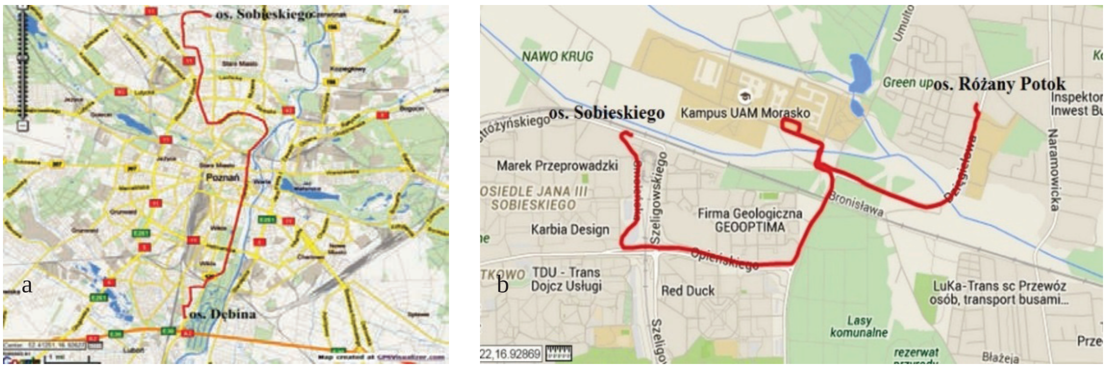


Fig. 1. Research routes used for road tests: (a) the urban route 1; (b) the urban route 2.

The study used two public buses with a length of 18 meters each for diesel and compressed natural gas (Table. 1). Bus using CNG was equipped with an internal combustion engine with a displacement of 8.9 dm^3 and the power of 238 kW executing the Otto cycle (serial type of engine). The vehicle was equipped with triple catalytic converter with a Lambda probe working in a compression feedback loop. 8 composite gas tanks with a capacity of 214 dm^3 each (Fig. 2a) were mounted on the vehicle's roof. The tanks mounted on the vehicle increased its height to 3400 mm, which in many cases can be a serious impediment due to the infrastructure of the urban agglomeration (height of overpasses, low-slung catenary, etc.).

Table 1. Characteristics of tested city buses.

Parameter	Vehicle powered with CNG	Vehicle powered with diesel
Ignition type	spark	compression
Displacement	8,9 dm3	9,2 dm3
Number of cylinders	6	6
Cylinder layout	In-line	In-line
Compression ratio	12	17,5±0,5
Maximum power	239 kW at 2000 rev/min	231 kW at 1900 rev/min
Maximum torque	1356 Nm at 1300 rev/min	1275 Nm at 1100-1710 rev/min
Emission norm	EEV	EEV
Aftertreatment system	TWC	SCR, DPF
Length	18 000 mm	18 000 mm
Height	3400 mm	3050 mm
Curb weight	24 000 kg	24 000 kg

Diesel powered vehicle had an serial type engine with a displacement of 9.2 dm^3 generates a maximum torque of 1275 Nm (Fig. 2b). The vehicle was equipped with selective catalytic reduction SCR and DPF. Both test vehicles comply with the EEV emission standard. They are operated by telecommunication operators mainly in the lines that are characterized by a large number of passengers. Each of the vehicles tested has the capacity of up to 176 people. In this study the buses were loaded with the same weight, which was the average weight of the maximum number of passengers of 70 kg per person. It was meant to simulate the conditions of everyday operation of such vehicles on the busiest routes.

Road emission tests of city buses used a mobile device from the group PEMS - SEMTEH DS's Sensors, Inc., which is a unique combination of apparatus for measuring and recording the following parameters (Bejerlein et al., 2015):

- concentrations of CO and CO_2 (NDIR – Non-Dispersive Infrared analyzer), NO_x = NO + NO_2 (NDUV – Non-Dispersive Ultraviolet analyzer), HC (FID – Flame Ionization Detector analyzer), O_2 (electrochemical sensor);
- thermodynamic parameters of exhaust gases (mass flow, temperature, pressure) – flowmeter using a Pitot tube;
- ambient conditions – atmospheric pressure, temperature, humidity;
- the position and speed of the vehicle – the GPS system;
- data from the vehicle diagnostic network – data transmission protocol CAN SAE J1939/J2284.

In conducted laboratory tests the main unit of the SEMTECH DS device was placed inside the bus and secured against any uncontrolled movement. A flowmeter for measuring thermodynamic parameters of the exhaust gas with a diameter of 4 inches was attached to the vehicle body, which was connected and sealed to the exhaust system of the engine. The GPS and the sensor of atmospheric conditions, which were connected to the main unit of the instrument, were located on the roof of the bus. The connection to the diagnostic bus network was implemented through a special module for data transmission using the SAE J1939/J2284 protocol dedicated to vehicles in the HDV category.

a) b)

Fig. 2. Public buses with a length of 18 meters being prepared for the test: (a) a vehicle fuelled by CNG; (b) a vehicle fuelled by diesel oil.

Exhaust sample to be analyzed was collected from the flowmeter and transported through a heated conduit kept at a temperature of ~190 °C. This is to prevent condensation of hydrocarbon on the walls of the duct. The sample is then passed through the filter and goes to the FID, where the measurement is the concentration of hydrocarbons. After cooling down to 4 °C the sample exhaust gas is passed sequentially to the NDUV and NDIR analyzers. Then the concentration of nitrogen oxides (NO and NO_2) and carbon monoxide and carbon dioxide are measured. The measurement of the concentration of oxygen is done last using an electrochemical sensor. The control and monitoring of the SEMTECH DS device was executed by a portable computer connected to the main unit via a wireless network. The device can also communicate using a local area network. In this study this form of communication has not been used.

4. Results

The speeds of vehicles were recorded with on-board diagnostics systems. Their value was verified on the basis of information obtained from the GPS. Urban operating conditions contributed to the speed profile characterized by high volatility. The average speed on test route 1 (Fig. 3) for conventional fuel-powered buses amounted to 18.9 km/h (with a maximum of 68.9 km/h), while for the other vehicle the value was 19.8 km/h (with a maximum of 57.3 km/h). Test route 2, was characterized by shorter and fewer stops compared to the route 1, while in the measurement cycles carried out included a greater average number of passengers. Velocity profiles obtained show that for both routes there was a large variation in speed, due to the need to use stops, intersections and traffic congestion (Fig. 4). The bus powered by conventional fuel moved at an average speed of 17.6 km/h (with maximum speed of 46.4 km/h) and the second researched bus had an average speed of 18.5 km/h (reaching up to 42.3 km/h). To obtain the relative speed difference of 5% for vehicles covering equal distances, demonstrates the similarity of the tests carried out and becomes a justification for implementation of a comparative analysis of the ecological aspects of the tested vehicles.

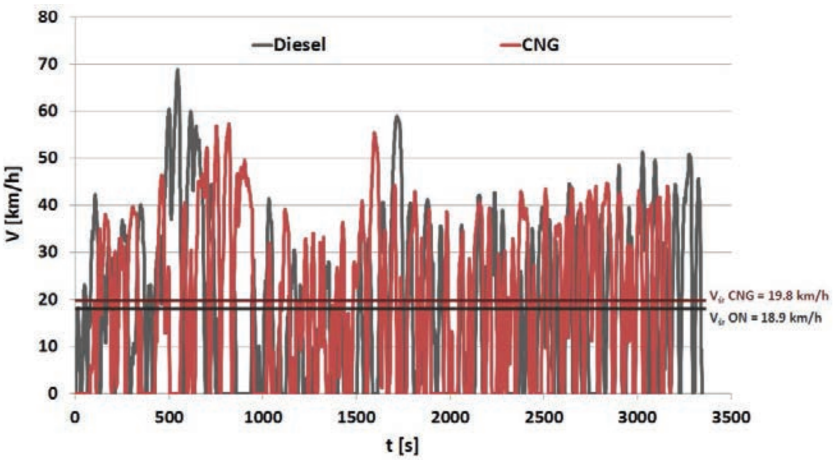


Fig. 3. Speed profiles for buses powered with CNG and diesel tested in real traffic conditions on test route 1.

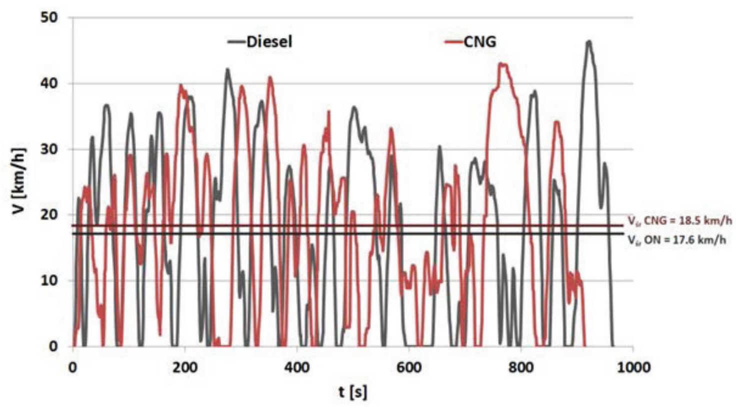


Fig. 4. Speed profiles for buses powered with CNG and diesel tested in real traffic conditions on test route 2.

Based on studies conducted under real operating conditions of buses the road emissions of tested vehicles were determined and compared (Fig. 5). The vehicle powered by CNG was characterized by a greater road emission of CO, THC and CO_2. For these exhaust gas constituents differences amounted to 78%, 1843% and 18% (Fig. 6) respectively. NO_x emissions for that bus was lower by 87%. The characteristics of route 1 reflects urban driving conditions and the results show that none of the mobile SORT standard tests used to certify the buses cannot fully reflect the characteristic parameters for this route. Moreover, the impact on the values of obtained emission of pollutants was mainly driven by the properties of fuels and the type of thermodynamic cycle, in which the combustion engines worked.

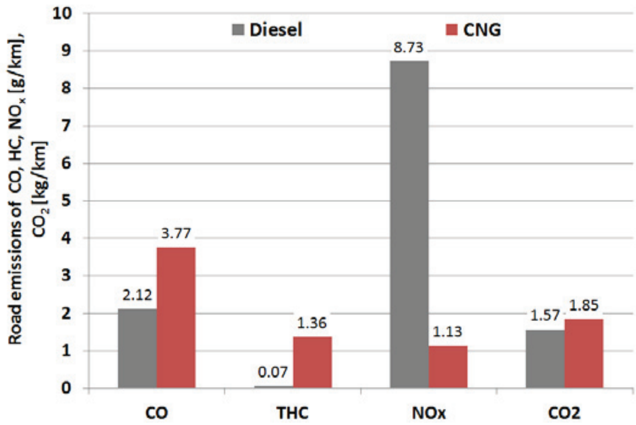


Fig. 5. Comparing road emissions obtained on urban test route 1.

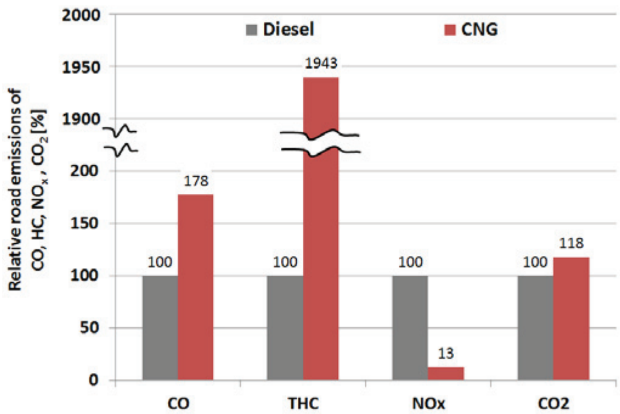


Fig. 6. Comparing the relative road emissions obtained on urban test route 1.

Comparison of the obtained road emission values indicates that the vehicle powered by diesel was characterized by a lower emission of CO, THC, and CO_2 (Fig. 7). For all of harmful substances lower values were obtained for both buses on the test route 1. Taking into account the greater load caused by passengers in the vehicle, it can be concluded that the reason for getting lower emission values was primarily due to the driving profile of the measured section of the route – as it required braking and acceleration less often. Vehicles powered by CNG emitted more pollutants per unit of the road: for CO about 71%, for THC by 2320% and for CO_2 by 11% (Fig. 8). However, emissions of NO_x was about 90% lower compared with the conventional solution.

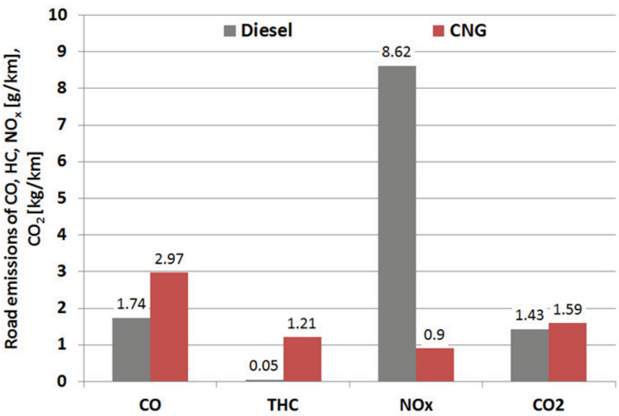
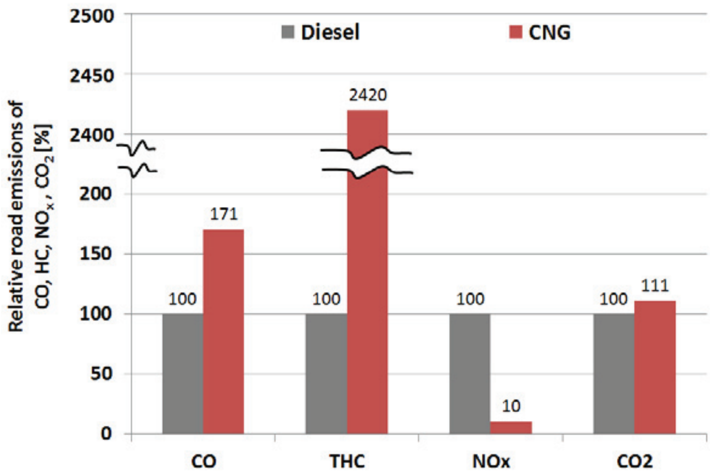


Fig. 7. Comparing the road emissions obtained on urban test route 2.

Fig. 8. Comparing the relative road emissions obtained on urban test route 2.



5. Conclusions

Based on the research results it can be noted that, between the conventional and the alternative drive considerable differences in relative values of road emissions were achieved. It has been proven that the use of natural gas to power city buses relatively slightly increases CO_2 emissions. Increased CO_2 emissions (also associated with fuel consumption) were the result of lower efficiency of the engine work cycle. Furthermore, due to the obtained excess-air ratio the CO emissions were higher. It was noted, however, that it had a particularly negative effect on emissions of THC (a 20-fold increase). The largest share of emissions among hydrocarbons belonged to methane, which is not a toxic compound, additionally the Euro VI emission norm expects separate limits for it. The conventional diesel vehicle was fitted with a SCR system the conversion rate of which is influenced by a variety of factors such as the exhaust gas mass flow and temperature. During on-road tests there is a high oscillation of accelerations, which is related to significant changes in the exhaust gas flow and its temperature. This fact has a substantial impact on the reduction of the conversion rate of the SCR system – hence the high differences in the emission of nitric oxides between the conventional and the alternative drive. Detailed changes in these values have been shown in Table 2.

Table 2. A comparison of changes in the relative emissions for a bus powered by CNG and by diesel.

	Test route 1	Test route 2
CO	+78%	+71%
CO_2	+18%	+11%
THC	+1843%	+2320%
NO_x	–87%	–90%

Research done for the purpose of this study also showed that the most effective method of assessing the emissions of vehicles used in public transport, powered by combustion engines, is by using the results of measurements performed under real operating conditions.

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