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STUDY OF THE FUEL EFFICIENCY AND ECOLOGICAL ASPECTS OF CNG BUSES IN URBAN PUBLIC TRANSPORT IN BELGRADE

Slaven Tica, Predrag Živanović, Stanko Bajčetić, Branko Milovanović*, Andrea Nađ
University of Belgrade, Faculty of Transport and Traffic Engineering, Belgrade, Serbia

This paper investigated the fuel efficiency and ecological aspects of CNG (compressed natural gas) buses in urban public transport in Belgrade. For this study, CNG bus equipped with lean burn combustion and OCs (oxidation catalysts), and diesel bus with EGR (exhaust gas recirculation) - CRT (continuously regenerating technology) were tested on four urban public transport lines (55, 58, 74 and 94). Based on the recorded data regarding bus speed, acceleration, deceleration and mileage, for typical stop distance, driving cycle and its parameters is defined for urban public transport lines in Belgrade. Results of this study showed that under identical conditions on the same lines, average consumption of diesel bus was 12% higher than for tested CNG bus, but average energy consumption was 15.7% lower. Applying "Student's t - test" it has been determined that emission of NOX from tested CNG bus is lower than for diesel bus for 40%, CO2 for 21.6%, while emission of HC is higher more than ten times.

Key words: Urban public transport, Fuel, Ecology, Dieseling.

INTRODUCTION

Natural gas is a mixture of different gases where methane is its major component. The combustion of natural gas produces less emission than that of gasoline and diesel fuels due to its simple chemical structure and absence of fuel evaporation [1]. Proponents of CNG claim that because it is an “inherently cleaner” fuel than diesel, use of CNG promises to lower emissions to a greater extent than technologies aimed at cleaning up diesel [2]. The use of natural gas as a transportation fuel is associated with a number of potential benefits to the environment, particularly air emissions and noise. On a “well-to-wheels” basis, CNG is one of the cleanest burning alternative vehicular fuels available in the market today [3].

Following are the main features which conduced to an increased interest to use natural gas as a transportation fuel [4]: wide availability, eco friendly, conventional SI (spark-ignition) and CI (compression-ignition) engines compatibility and low operational cost.

Moreover, some typical disadvantages of a gaseous fuel, such as the low operating range notwithstanding the use of large and heavy storage cylinders are not restrictive for urban buses, since the daily route is limited and the cylinders can be easily placed on board.

The report of Centre for Science and Environment concludes that in cities, facing severe air pollution problems, the use of heavy - duty natural gas engines in place of diesel offers numerous environmental benefits. This has led Teheran, Los Angles, Bangkok, Santiago, Cairo, Beijing and many other major cities to establish natural gas bus programme [5]. In New Delhi, India, one of the most polluted cities in the world, converting the entire transport fleet to CNG in 2000 has resulted in a significant improvement in air quality in terms of suspended particulate matter, CO, SO2 and NOx [6] and [7].

At this moment, natural gas in compressed condition is the leading alternative fuel used for buses in urban public transport. Due to their large size, which facilitates the inclusion of larger engines and fuel tanks, along with their fixed routes and refuelling points, city bus fleets provide excellent opportunities for commercial demonstrations of alternative fuel vehicles (AFVs) [8-16]. Fearghal and Caulfield [17] examined the potential benefits of switching 81 buses in the Dublin bus fleet to alternative fuels. The results show a major decrease in almost all pollutants from the use of CNG buses compared to the Euro II, III and IV diesel buses (except CO and HC).

Clark et al. [18] examined the use of CNG and hybrid electric buses in Mexico City. The results of this study suggest that hybrid electric buses produced significant fuel economy, while CNG buses had the lowest PM emissions. Živanović et al. [19] analyse economic benefits and ecological characteristics of CNG buses in public transport systems in Serbia. Focus of this study is put on the operational costs analysis and possible savings achievable by CNG buses compared to diesel buses. The authors concluded that CNG buses bring significant savings as regards total costs during their operational lifecycle and have a significant ecological potential compared to diesel buses. Milojević [20] analyse benefits and restrictions of natural gas sustainable application as engine fuel in city buses and CNG propulsion system for reducing noise of existing city bus fleet [21].

In previous mentioned studies, special emphasis is given to the economic and environmental effects of introducing CNG buses in urban public transport systems. None of these studies, as part of their experimental research, has not taken into consideration the real load of the tested bus with passengers, which can greatly affect on fuel consumption and emissions of pollutants.

* b.milovanovic@sf.bg.ac.rs

The main objective of this paper is to determine fuel efficiency and ecological aspects of CNG buses usage in real operating conditions (with passengers) on selected public transport lines in Belgrade, depending on their route type (tangential, diametral and radial). For this purpose, four typical urban public transport lines that represent real conditions of exploitation of bus subsystem as a whole were selected (urban regime, suburban, routes with gradients, traffic flow influence, peak load of passengers, etc.) on which an experimental tests of driving cycle, fuel consumption and air pollutant emissions were conducted.

The reminder of this paper is organized as follows: Second chapter of this paper gives the temporal and spatial scope of research. Section describes main characteristics of selected lines 55, 58, 74 and 94 (route, length, number of stations, and number of transported passengers). In the next section test fuels and test buses specifications, test engines, driving cycles and measurement protocol, fuel consumption and emission of pollutants measurement procedure are given. Main results of study (driving cycle parameters, fuel and energy consumption and ecological aspects of tested CNG and diesel powered buses exploitation) and discussion of the results is described in fourth chapter. We finish with some concluding remarks and recommendations based on previous presentation.

TEMPORAL AND SPATIAL SCOPE OF RESEARCH

Testing was carried out at real operating conditions in urban public transport system in Belgrade. In order to determine fuel efficiency and ecological aspects of CNG buses in urban public transport in Belgrade, line 55 (Zvezdara-Stari Železnik), 58 (Pančevački most-Novi Železnik), 74 (Bežanijska kosa-Mirijevo 3) and 94 (Blok 45-Miljakovac 1) were selected. Line routes 55, 58, 74 and 94 are presented in Figure 1.

Similar researches in public transport system in Belgrade were carried out on diesel [22], biodiesel powered buses [23] and fully electric buses [24]. Ivković et al. [25] in their paper present multiple attribute decision making of constructional concept bus solutions for achieving sustainable mass public transportation in Belgrade. Line 55 (Zvezdara - Stari Železnik) is tangential urban line with outstanding longitudinal gradients in the part of the route which passes through old part of the city [20]. Total length of the line amounts to 18518 m, number of stations amounts to 34, number of transported passengers

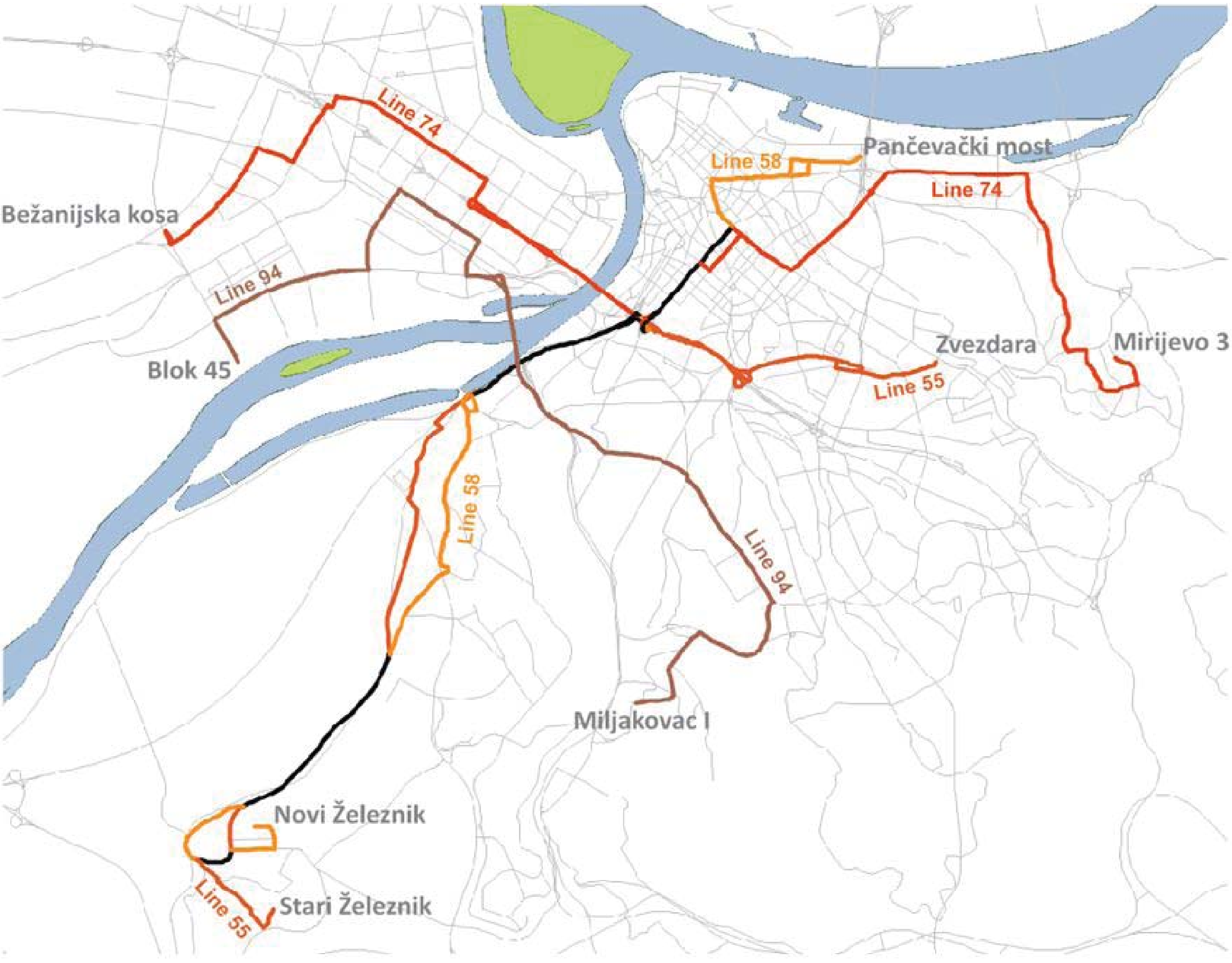

Figure 1: Line routes 55, 58, 74 and 94

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- 22500 per day (9907 in forward and 12593 in backward direction) and the line is served by 12 buses.

Line 58 (Pančevacki most-Novi Železnik) is diametral urban line that passes through central city zone. Line route passes through the most loaded traffic corridors: Boulevard Despota Stefana, Boulevard Kralja Aleksandra, Vojvode Mišića and Kneza Miloša street. Total length of the line amounts to 17975 m, number of stations amounts to 33, number of transported passengers – 14415 per day (6954 in forward and 7461 in backward direction) and the line is served by 9 buses.

Line 74 (Bežanijska kosa-Mirijevo 3) is also diametral line. Line route passes through highly loaded corridors in urban central zone: Ruzveltova street, Boulevard Kralja Aleksandra and Kneza Miloša street. Total length of the line amounts to 21793 m, number of stations amounts to 46, number of transported passengers – 35189 per day (18549 in forward and 16640 in backward direction) and the line is served by 19 buses.

Line 94 (Blok 45-Miljakovac 1) is tangential line that doesn't pass through central urban zone. Route characteristics are high longitudinal slopes through Borska and Boulevard Mira streets, while New Belgrade part of the route is without slopes and with higher traffic flow. The length of line amounts to 16628 m, number of station is 32, number of transported passengers is 19539 per day (10001 in forward and 9538 in backward direction) and the line is served by 13 buses.

EXPERIMENTAL SETUP

Test fuels

For this study two test fuels were used, CNG and diesel. Main physiochemical properties of tested fuels are presented in Table 1.

Table 1: Physiochemical properties of CNG and diesel test fuels

Properties	CNG	Diesel
Octane/cetane number	120	50
Density [kgm-3]	0.705	840
Energy content [MJkg-1; MJL-1]	48.8	36
Molar mass [kgmol-1]	17.3	204
Auto-ignition temperature [^{0}C]	540	316

Tested CNG fuel has a high octane number of 120, higher energy content and auto-ignition temperature than tested diesel fuel. Besides main physiochemical properties, gas composition of CNG fuel is very important. Gas composition is reported on a mole percent basis (Table 2).Tested CNG fuel is characterized by high methane contents of 97.126 mole percent basis. The methods applied in defining the mole percent basis are in accordance with the standards SRPS.H.F8.304 and SRPS.H.F8.306.

Test buses

Two buses were used in this study, including a bus equipped with Cummins CGe4 280 CNG engine (MAZ-BIK-203 CNG-S) and a bus equipped with a MAN D2066 LOH 201 diesel engine (IKARBUS IK-112 N). In the Table 3, basic technical data of the buses are given.

Table 3: Technical specifications of the test buses

Manufacturer	MAZ-BIK-203 CNG-S	IKARBUS IK-112 N
Engine type	Cummins CGe4 280	MAN D2066 LOH 201
Gearbox type	Allison T325 (R)	VOITH D 864.5
Vehicle capacity	105 passengers	100 passengers
Vehicle mass	11960 kg	12090 kg
Year of production	2008	2008

Test engines

Basic technical specifications of the test engines are presented in Table 4.

Tested CNG bus was equipped with a lean burn spark-ignited turbocharged Cummins CGe4 280 engine with OCs for controlling THC and CO emissions. Both engines have 6 cylinders and meet Euro 4 emission standard.

Driving cycles

Based on the data of the recorded bus speed, acceleration, deceleration and mileage, for typical stop distance, driving cycle for each line is defined, which represent the real driving conditions on line route. In addition, corresponding calculations for defining of average speed, average acceleration, dwell time and number of stops per kilometre for each line has been performed.

Table 2: Main properties of CNG test fuel

Gas	Methane	Ethane	Propane	I-butane	N-butane	I-pentane	N-pentane	Hexane	N2	CO2
Mole percent basis	97.126	1.164	0.408	0.065	0.066	0.013	0.009	0.009	0.760	0.380

Table 4: Technical specifications of the test engines

Manufacturer	Cummins	MAN
Engine model	CGe4 280	D2066 LOH 201
Fuel Type	CNG	Diesel
Engine type	Lean burn, Spark-ignited, Turbocharged	Turbocharged
Emission standard	Euro 4	Euro 4
Peak torque [Nm]	1152	1250
Displacement [cm3]	8300	10500
Engine power [kW]	209	235
Number of cylinders	6	6
Bore and Stroke [mm]	114 x135	120 x155
After treatment	Oxidation catalyst	EGR – CRT
Weight (dry) [kg]	603	986

Fuel consumption and emission of pollutants measurement

The fuel consumption certainly stays for one of the most important operating elements of each fleet [20]. For the needs of testing the bus MAZ-BIK-203CNG-S, gas tanks was filled every day and kilometres covered were recorded. In order to better comprehend and analyze the consumption of CNG compared to the euro diesel, euro diesel consumption in bus IK-112N was observed in parallel. The measurements included determination of the concentrations of NOx, CO2 and HC (including methane), in vehicle exhaust system on lines 55, 58, 74 and 94 for real driving cycle (with passengers) for CNG and diesel bus (average concentrations of NOx, CO2 and HC per trip). Measured volumetric concentration of the component emissions (in ppm for CO2 and vol % for NOx and HC) is transformed into emissions of vehicles under real operating conditions as functions of the distance travelled (g/km) applying the corresponding calculations. For performing these calculations basic exploitation elements, total measured volume of exhaust gases during tests and data on reference densities of the components has been used.

Table 5: ESC and ETC Test-Upper Limit Values (in g/kWh) ***[26]***

Test method	ESC	ETC
Emission standard	Euro 4	Euro 4
CO	1.5	4
HC	0.46	-
NMHC	-	0.55
NOx	3.5	3.5
CH4	-	1.1
PM	0.02	0.03

Ecological effects of exploitation of CNG and diesel buses have been quantified according to average values of the exhaust emission of selected pollutants per trip for each line separately. The following table show the limit values for emission standard Euro 4 according the two measurement tests methods, European steady state cycle (ESC) for diesel and European transient cycle (ETC) for CNG buses.

RESULTS AND DISCUSSION

Driving cycle parameters

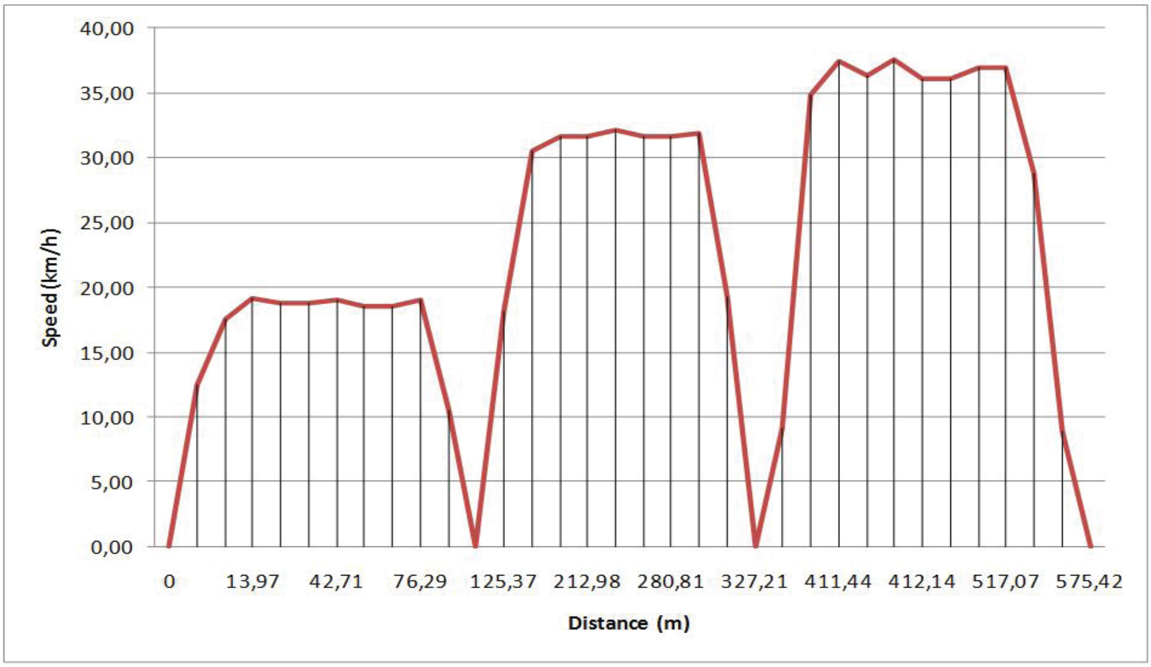
Based on measurements of bus speed, acceleration, deceleration, vehicle load impact and mileage, driving cycle parameters on each line route has been defined. Twenty seven tests were run on line 55 and 94 for each (CNG and diesel) fuel, twenty eight on line 58 for diesel fuel and on line 74 for both fuel, while twenty nine tests were run on line 58 for CNG fuel. Results of basic driving cycle parameters for selected lines are presented in Table 6.

Table 6: Basic driving cycle parameters for lines 55, 58, 74 and 94

Line	Average load [%]	Average speed [kmh-1]	Average acceleration	Stops/km [-]	Dwell time
55	28	22.20	0.72	1.8	28.3
58	24	19.29	0.70	1.8	24.6
74	24	20.12	0.74	2.1	29.5
94	18	19.92	0.73	1.9	26.7

Based on the results shown in table 6 it can be concluded that the type of line route do not affect the average speed, which is the result of traffic conditions on line route. The previous statement is supported by the fact that the deviation of dwell time per line (in %) is less than 5%.

Figure 2: Driving cycle for typical stop distance



In Figure 2 driving cycle for line 58 is presented, which is similar to driving cycles on the other research lines. The driving cycle consisted of a three phases of acceleration reaching speeds of 18, 33, and 37 km/h, including two stopovers due to traffic conditions and stopping at the next bus stop, alone typical stop distance of 576 m. The driving cycle is characterized by an average speed of 19.29 km/h, a maximum speed of 37.51 km/h, an average acceleration of 0.70 m/s2 (average deceleration of 0.72 m/s2), and a maximum acceleration of 1.02 m/s2 (maximum deceleration of 0.85 m/s2).

Fuel and energy consumption

On the basis of statistical processing of the representative specimen, the results were shown in the Table 7. Sample size (n) represents number of trips in both line directions (forward and backward), average consumption rate for diesel bus is expressed in (l/100km) and in (kg/100km) for CNG bus.

Applying "Student's t - test", (p=0.05) on equivalence of average values of the two sets, it can be concluded:

- Average CNG consumption per line was in the range from 37.66 kg/100 km (line 55) to 45.06 kg/100 km (line 74), which was caused by a traffic conditions on the lines. Therefore average fuel consumption for all lines of CNG was 40.77 kg/100km.
- Under identical conditions on the same lines, euro diesel consumption was in the range from 44.68 litres/100 km (line 55) to 47.68 litres /100 km (line 58). Average consumption of euro diesel for all lines was 46.5 litres/100 km, which is 12% higher than for CNG.

Table 7: Results of fuel consumption measurement

Fuel	Line 55			Line 58		
	Sample size	Average consumption rate	Standard deviation	Sample size	Average consumption rate	Standard deviation
Diesel	27	44.68	1.80	28	47.68	1.92
CNG	27	37.66	1.05	29	39.86	1.22
Fuel	**Line 74**			**Line 94**		
	Sample size	Average consumption rate	Standard deviation	Sample size	Average consumption rate	Standard deviation
Diesel	28	47.49	1.68	27	46.37	1.75
CNG	28	45.06	1.15	27	41.18	1.24

Based on the previous analysis, it can be concluded that an important factor that affects fuel consumption is average speed, which is the result of traffic conditions on the line routes. In addition to average speed, average load (coefficient of vehicle capacity utilization) affects on fuel consumption, which was confirmed by the results of fuel consumption on the line 74 on which the average load is 6% higher compared to the line 94 and the fuel consumption is 5% lower. In order to determine energy consumption of the CNG and diesel bus, the applied data for diesel fuel were energy content 36 MJ/litre and density 840 kg/m3 and for CNG fuel energy content 34.4 MJ/m3 (48.8 MJ/kg) and density 0.705 kg/m3.

Results of energy consumption are presented in Table 8.

Table 8: Results of energy consumption measurement

Fuel	Energy consumption [MJkm-1]			
	Line 55	Line 58	Line 74	Line 94
Diesel	16.08	17.16	17.10	16.69
CNG	18.34	19.41	21.95	20.06

Based on the results presented in the Table 8 it can be concluded that the tested CNG bus has a higher average energy consumption than diesel bus for 15.7% (from 11.5% on line 58 to 22.1% on line 74), despite that average fuel consumption of CNG bus is 12% lower.

This is due to the fact that CNG buses have lower energy efficiency (by about 25%) compared to diesel buses.

Despite the fact that the energy consumption of tested CNG bus is higher than for diesel bus, the authors consider that significant financial benefits in fuel consumption can be achieved using CNG buses (higher fuel efficiency), taking into account the current market price of fuel, which has a direct impact on reducing of operating costs.

Ecological aspects of tested CNG and diesel powered buses exploitation

In Table 9 average NOx emissions from CNG and diesel bus for lines 55, 58, 74 and 94 are presented. Sample size (n) represents number of trips in both line directions (forward and backward), average NOx emission is expressed in (g/km).

Based on the data presented in the table 9 (applying "Student's t - test", (p=0.05) it can be concluded that emission of NOx from CNG bus is relatively high (from 10.89 g/km (line 55) to 11.01 g/km (line 94) but it's much lower than for diesel bus (by about 40%).

This is result of shortcoming of lean-burn engines in which the oxidation catalyst cannot reduce NOx emission under lean-burn conditions.

Also, measured emission of CO2 is lower for tested CNG bus than for diesel bus, because CNG buses do not give a significant benefit in terms of CO2 reductions (Table 10). The reason is that CNG engines, owing to their lower energy efficiency, annul the effect of lower CO2 emissions, which has natural gas compared to diesel fuel [19]. Sample size (n) in table 10 represents number of trips in both line directions (forward and backward), average CO2 emission is expressed in (g/km).

Applying "Student'st - test", (p=0.05), it can be concluded:

- Average CO2 emission from tested CNG bus per line was in the range from 1220 g/km (line 55) to 1240 g/km (line 58). Therefore average CO2 emission for all lines was 1228.75 g/km.
- Under identical conditions on the same lines, average CO2 emission from tested diesel bus was in the range from 1550 g/km (line 55) to 1580 g/km (line 58 and line 94).
- Average CO2 emission for tested diesel bus is 21.6% higher than for CNG bus.

Table 9: Average NOx emissions from CNG and diesel bus

Fuel	Line 55			Line 58		
	Sample size	Average NOx emission	Standard deviation	Sample size	Average NOx emission	Standard deviation
Diesel	27	17.93	0.45	28	18.05	0.52
CNG	27	10.89	0.13	29	11.00	0.16
Fuel	Line 74			Line 94		
	Sample size	Average NOx emission	Standard deviation	Sample size	Average NOx emission	Standard deviation
Diesel	28	18.00	0.48	27	18.12	0.44
CNG	28	10.94	0.11	27	11.01	0.15

Table 10: Average CO2 emissions from CNG and diesel bus

Fuel	Line 55			Line 58		
	Sample size	Average CO2 emission	Standard deviation	Sample size	Average CO2 emission	Standard deviation
Diesel	27	1550	50	28	1580	44
CNG	27	1220	31	29	1240	27
Fuel	Line 74			Line 94		
	Sample size	Average CO2 emission	Standard deviation	Sample size	Average CO2 emission	Standard deviation
Diesel	28	1560	37	27	1580	33
CNG	28	1225	28	27	1230	22

Table 11: Average HC emissions from CNG and diesel bus (''Student's t - test'', (p=0.05))

Fuel	Line 55			Line 58		
	Sample size	Average HC emission	Standard deviation	Sample size	Average HC emission	Standard deviation
Diesel	27	0.02	0.00024	28	0.03	0.00045
CNG	27	0.35	0.00385	29	0.37	0.00481
Fuel	Line 74			Line 94		
	Sample size	Average HC emission	Standard deviation	Sample size	Average HC emission	Standard deviation
Diesel	28	0.04	0.00056	27	0.03	0.00054
CNG	28	0.39	0.00468	27	0.37	0.00518

Regarding emission of HC (table 11), it can be seen that tested diesel bus have much lower emission than diesel bus for all tested lines.

Relatively low level of HC emission for tested CNG bus compared to other CNG buses is due to the built in oxidation catalyst. Sample size (n) in table 11 represents number of trips in both line directions (forward and backward), average emission HC is expressed in (g/km).

Based on the data presented in the table 11, it can be concluded:

- Average HC emission from tested CNG bus per line was in the range from 0.35 g/km (line 55) to 0.39 g/km (line 74). Therefore average HC emission for all lines was 0.37 g/km.
- Under identical conditions on the same lines, average CO2 emission from tested diesel bus was in the range from 0.02 g/km (line 55) to 0.04 g/km (line 74).

CONCLUSIONS

In this paper study of the fuel efficiency and ecological aspects of CNG buses in urban public transport in Belgrade is presented. For this study two bus types were selected, CNG one equipped with lean burn combustion and OCs, and diesel bus with EGR – CRT. Buses were tested on four typical urban public transport lines (55, 58, 74 and 94) in terms of their route, length, number of stations, number of transported passengers. Tests carried out show that CNG can be successfully used as fuel for buses in urban public transport in Belgrade. Results presented in the paper showed that CNG bus under identical conditions on the same lines has better fuel efficiency than diesel bus (average consumption of CNG bus was 12% lower). Average energy consumption of tested CNG bus was 15.7% higher, which can be explained due to the fact that CNG buses have lower energy efficiency (by about 25%) compared to diesel buses.

Applying ''Student's t - test'' it has been determined that emission of NOX from tested CNG bus is lower than for diesel bus for 40%, also emission of CO2 is lower for 21.6%, but emission of HC is higher more than ten times. The presented analysis shows all the specifics of CNG powered buses exploitation in comparison with conventional diesel buses and it proved better fuel efficiency and ecological aspects (except emission of HC) of implementation.

As a proven ecological "clean" vehicles, CNG powered buses contributed to the improvement of sustainable development. Use of these vehicles in environmentally vulnerable urban corridors in Belgrade (Kneza Miloša street, Boulevard Despota Stefana, Boulevard Kralja Aleksandra) would be manifested through reduced emissions of pollutants. Experimental exploitation of MAZ-BIK-203CNG-S bus is the first step before the widespread use of this type of fuel in urban public transport in Belgrade. Following the world trends in the development of buses for urban public transport sector (hybrid, electric, fuel cell) the use of CNG buses in Belgrade would be a good solution in the next medium term considering financial possibilities of operator and taking into the consideration facts that cited sophisticated high technologies has yet to prove their validity, feasibility and choose of development concept.This discussion also recaps a series of outcomes that this analysis does not address. First, this analysis does not address purchase price and disposal of CNG buses. Second, it does not address safety issues (in particular, the explosive potential of CNG) or the potential for environmental contamination (e.g. if diesel fuel is spilled and soaks into the ground) and noise emission.

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