INFLUENCE OF ROAD AND TRAFFIC CONDITIONS ON FUEL CONSUMPTION AND FUEL COST FOR DIFFERENT BUS TECHNOLOGIES

by

Ivan S. IVKOVIĆ*, Snežana M. KAPLANOVIĆ, and Branko M. MILOVANOVIĆ

Faculty of Transport and Traffic Engineering,
University of Belgrade, Belgrade, Serbia

Original scientific paper
DOI: 10.2298/TSCI160301135I

In this paper the influences of road and traffic conditions on fuel consumption and fuel costs of conventional diesel, parallel hybrid, and stoichiometric compressed natural gas buses in intercity bus service are analysed. Calculation of fuel consumption and fuel costs for these three different bus technologies was conducted for road network of the Republic of Serbia. Three scenarios were considered. The first scenario includes bus traffic volume carried out on the road network in 2014. The other two scenarios are characterized by the decrease i. e. increase of traffic volume by 20% with unchanged state of road infrastructure in comparison to the year 2014. Obtained results show that in intercity bus service the greatest influence on the fuel consumption of buses has operating speed of the bus, followed by terrain type on which buses operate. The impact of other factors (international roughness index, fluctuation of traffic volume by 20%, and correction factors of fuel consumption) is less pronounced. In various operating conditions the fuel cost savings per 100 km of compressed natural gas buses compared to diesel buses are in the range of €8.84-12.16. These cost saving for hybrid buses compared to diesel buses are in the range of €3.33-7.27.

Key words: *diesel bus, compressed natural gas bus, hybrid bus, costs, fuel consumption, road network*

Introduction

The imperative of sustainable transportation requires increasing efforts to reduce energy consumption from transport sector [1]. For this reason, in many countries constant efforts are being made to create and implement a number of policies and measures to reduce energy consumption and to its efficient use [2]. One of the possible solutions is to replace vehicles that ran on oil-based fuels with alternative fuel vehicles [3], or in this particular case, to replace diesel buses with alternative fuel buses.

The purpose of this research is to highlight the potential benefits of the application of energy efficient bus technologies in intercity bus service. Precisely, the focus is on the fuel consumption of diesel, hybrid, and compressed natural gas (CNG) buses according to various road and traffic conditions. Another aspect of this research is the calculation and comparison of the fuel costs for these three bus technologies. In Serbia, the share of hybrid and CNG bus-

* Corresponding author, e-mail: i.ivkovic@sf.bg.ac.rs

es is very low in both urban and intercity bus service. Consequently, there is considerable scope for their greater use. Also, the possibilities to use more advanced and more expensive bus technologies in Serbia and countries like it are still modest.

Literature review

Numerous studies and experimental research confirmed that CNG and hybrid buses have significant environmental advantages compared to the conventional diesel buses [4-6]. At the same time, numerous studies indicate that hybrid buses have significant potential to reduce fuel consumption and thus fuel costs, compared to conventional diesel buses. Among these are studies that are based on laboratory tests and studies that are based on actual on-road conditions. For example, [5] found that fuel economy for the hybrid bus was more than 50% higher than for the both baseline diesel buses with and without diesel particulate filter. Higher fuel economy, from 30-75%, for the hybrid in comparison to the diesel bus also reported in [6]. Research carried out by [7] revealed that the use of hybrid-drive buses would lead to the more than 20% lower fuel consumption. On the other side, CNG buses have fuel economies 16-25% lowers than diesel buses [8, 9]. Lower fuel economy of CNG buses, also confirmed [10]. But, it is important to underline that the fuel costs savings can be provided both by increasing the buses fuel economy and by using buses that operate on fuels with lower prices. This reflects one of the advantages of CNG buses, since natural gas is considerably cheaper then diesel.

Fuel consumption of buses depends on many factors, including road type, speed, acceleration, road grade, load mass, air conditioning, driving style, *etc.* [11-15]. There are numerous studies which confirm that speed is the one of the most important factor which significantly affects fuel consumption. Among them is the study [12] which stressed that for all analysed buses fuel consumption factors decrease with bus speed increases. Strong influence of average speed on fuel consumption has been confirmed by [13] too. They also revealed that this influence is much stronger when average speed is lower than 30 km/h.

Common for all of the aforementioned studies is that they are related to urban operation conditions. In this research focus is on intercity bus service. Therefore, design speed (V_d – maximum vehicle speed limited by traffic sign), operating speed (V_o – real speed of vehicle in traffic flow), terrain type (flat, hilly, mountainous), international roughness index (IRI – standardized roughness characteristic of the longitudinal profile of road expressed in [mkm^{-1}]), fluctuation of traffic volume, and correction factors of fuel consumption (f_{FC} – correction factor of fuel consumption due to mutual interference between vehicles in the traffic flow, hereinafter referred to as correction factor), were selected as factors that affect fuel consumption and fuel costs. The operating speed, fluctuation of traffic volume, and correction factors were selected as indicators of traffic conditions, while the other three were chosen as indicators of road conditions. Influence of these factors on fuel consumption and fuel costs for three different buses technologies was analysed.

Methodology for estimation of fuel consumption and fuel costs of buses

Research of fuel consumption and fuel costs of different bus technologies (conventional diesel, stoichiometric CNG, and parallel hybrid buses) is carried out at the road network of the Republic of Serbia (all public roads of the IA category, most of the road sections of IB category, and smaller part of the road sections of II category). The whole network includes 260 road sections of a total length of 5,563 km.

The methodological procedure consists of several steps. In the first step it is necessary to collect data on annual average daily traffic (AADT) of the buses on each road section of considered road network. In the second step it is necessary to collect specific operating attributes for each road section: length, design speed, terrain type, IRI, hourly capacity, and flow/capacity (*F/C* – intensity to capacity ratio). In the third step, based on previous data it is possible to calculate the operating speed of buses and correction factor on individual road sections. In relation to the operating speed, the fourth step determines the fuel consumption and the fuel cost of diesel buses for the whole network. Also, it is possible to calculate the fuel consumption and fuel cost per 100 km for each road section. In addition to determining fuel equivalents of alternative bus technologies, in the last step it can be calculated fuel consumption and fuel cost of CNG and hybrid buses.

Presented methodological approach can be used for comprehensive analysis of the mentioned operating conditions on fuel consumption and fuel costs of different bus technologies in rural/non-urban areas. Due to significantly different operating conditions, presented methodology is not applicable in urban areas.

Three scenarios are considered, fig. 1. The first scenario (SC2014) includes bus traffic volume on the road network that is valid for 2014, within the current development of road infrastructure. Necessary data of the AADT for each of the 260 road sections were obtained on the basis of traffic counting conducted by the Public Enterprise *Roads of Serbia* for 2014 [16-18]. The other two scenarios are hypothetical research scenarios. They are related to decrease (scenario SC–20%), or increase (scenario SC+20%) of traffic volume by 20%, tab. 1.

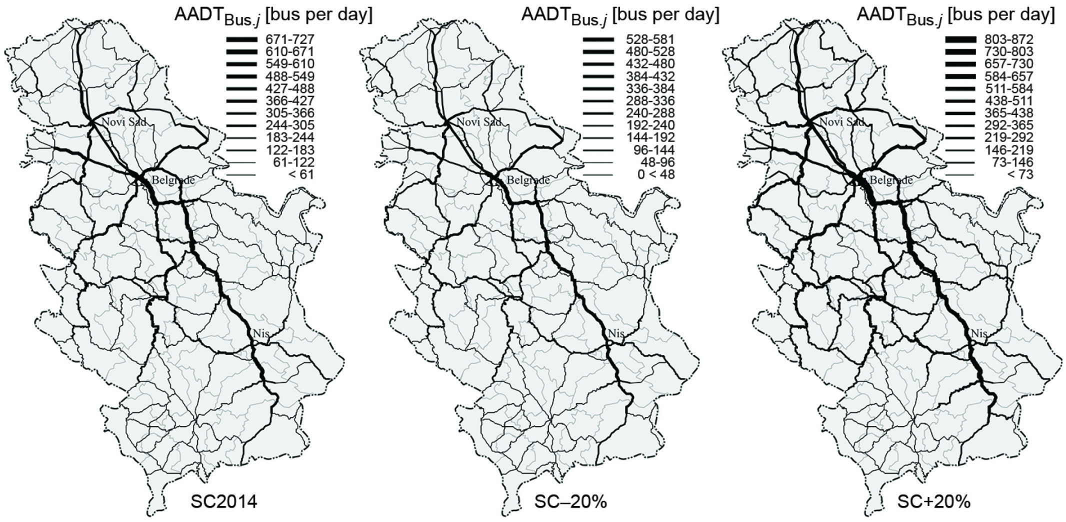

Figure 1. The considered road network of Serbia

Table 1. Bus traffic volumes on the road network in different scenarios

Scenario	SC2014	SC–20%	SC+20%
Traffic volume [km per bus]	312,443,035.90	249,954,428.72	374,931,643.08

At the same time, the state of the road infrastructure is identical as in scenario SC2014. In scenarios SC–20% and SC+20%, the change of AADT causes the changes of:

F/C, operating speeds, and correction factors. The consequences of these changes are reflected in the change of fuel consumption. Hypothetical scenarios are intended to show the extent to which changes in traffic conditions (compared to the unchanged road conditions) affects the fuel consumption of buses.

Annual fuel consumption of buses for the group of road sections with the same IRI and terrain type, $FC_{i,n,k}$, is given by the eq. (1):

$$FC_{i,n,k} = \left[\sum_{j=1}^{n} \mathrm{AADT}_{\mathrm{Bus},j} 3.65 FC_{\mathrm{d},j} \cdot \left(\frac{f_{\mathrm{FC}j}}{100} + 1 \right) F_{\mathrm{eq},i,j} L_j \right]_k \tag{1}$$

where i is the bus technology (diesel, CNG, or hybrid bus), j – the individual road section described by the specific IRI (IRI = 2, 5, or 8 m/km), and terrain type, flat (T1), hilly (T2), and mountainous (T3), k – the scenario, n – the group of road sections with the same IRI and terrain type, $\mathrm{AADT}_{\mathrm{Bus},j}$ – AADT by buses on the road section j, $FC_{\mathrm{d},j}$ – specific fuel consumption of diesel bus per 100 km on the road section j, $f_{\mathrm{FC},j}$ – the correction factor on the road section j due to changes in speed from V_d to V_o, adopted from speed matrix [19], $F_{\mathrm{eq},i,j}$ – the fuel equivalent of bus technologies on the road section j, and L_j – the length of road section j.

The $FC_{\mathrm{d},j}$ from eq. (1) is determined for diesel bus IK104p (six-cylinder engine, displacement 10.35 dm^3, power 160 kW) according to various road conditions of the road section j in the form of a polynomial of second degree, eq. (2):

$$FC_{\mathrm{d},j} = 100(a + bV_{\mathrm{o},j} + cV_{\mathrm{o},j}^2) \tag{2}$$

where a, b, and c are the regression coefficients, tab. 2, $V_{\mathrm{o},j}$ – the operating speed on the road section j calculated by Bureau of Public Roads formula [20], eq. (3).

Table 2. Regression coefficients for determining specific fuel consumption of diesel buses [21]

IRI	Terrain – flat				Terrain – hilly				Terrain – mountainous			
	a	*b*	*c*	R^2	*a*	*b*	*c*	R^2	*a*	*b*	*c*	R^2
2	0.349117	–0.00638	0.000059	0.978	0.347710	–0.00595	0.000056	0.990	0.359716	–0.004460	0.000043	0.965
5	0.365289	–0.00668	0.000061	0.976	0.363594	–0.00621	0.000058	0.988	0.369716	–0.004471	0.000043	0.971
8	0.387864	–0.00708	0.000065	0.986	0.380856	–0.00517	0.000049	0.992	0.391856	–0.005077	0.000049	0.989

$$V_{\mathrm{o},j} = \frac{L_j}{t_{\mathrm{free},j} \left[1 + c \left(\frac{F}{C} \right)_j^d \right]} \tag{3}$$

where $t_{\mathrm{free},j}$ is the travelling time in the free traffic flow, $(F/C)_j$ – the intensity to capacity ratio on the road section j, c and d – the coefficients (for motorways c = 0.45, d = 4, for two-lane roads c = 0.50, d = 2.5, for rural roads c = 0.80, d = 1.5).

On the basis of the coefficients (a, b, and c) and operating speeds, fig. 2, shows a diagram of the specific fuel consumption of diesel buses for different operating speeds in various road conditions.

The curves are calculated for nine combinations of terrain type and IRI, tab. 3.

Table 3. The considered nine combinations of terrain type and IRI [mkm^{-1}]

Road conditions	Terrain – flat			Terrain – hilly			Terrain– mountainous		
	IRI = 2	IRI = 5	IRI = 8	IRI = 2	IRI = 5	IRI = 8	IRI = 2	IRI = 5	IRI = 8
Label	T1-IRI2	T1-IRI5	T1-IRI8	T2-IRI2	T2-IRI5	T2-IRI8	T3-IRI2	T3-IRI5	T3-IRI8

In eq. (1), in the case of CNG buses, $F_{\mathrm{eq},i,j}$ represents a value which indicates how much the equivalent cubic meters of natural gas where consumed in relation to the consumption of diesel in litres per 100 km. According to our previous research [21], adopted value is $F_{\mathrm{eq,CNG}}$ = 1.08. This fuel equivalent was obtained on the basis of experimental research of fuel consumption of CNG bus IK-104CNG (six-cylinder engine, stoichiometric combustion, displacement 10.35 dm^3, power 190 kW) on the real intercity lines in Serbia: Belgrade-Jagodina, Belgrade-V. Banja, and Belgrade-Loznica. In the case of hybrid buses, $F_{\mathrm{eq},i,j}$ is the reduction percentage of fuel consumption of diesel buses due to the use of electric motor in various operating conditions at different operating speeds. According to [22], based on four months testing of hybrid bus Volvo 7700-Hybrid (parallel hybrid system, four-cylinder Diesel engine, displacement 4.76 dm^3, power 158 kW and electric motor, power 120 kW) in real intercity operating conditions, the adopted values are: $F_{\mathrm{eq,HB}}$ = 100% (V_o = 0-20 km/h), $F_{\mathrm{eq,HB}}$ = 50% (V_o = 20 – 40 km/h); $F_{\mathrm{eq,HB}}$ = 30% (V_o = 40 – 60 km/h), and $F_{\mathrm{eq,HB}}$ = 15% (V_o = 60-maximum speed).

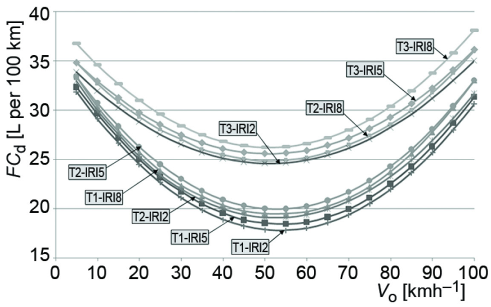

Figure 2. Specific fuel consumption of diesel buses

Based on the calculation of fuel consumption, it is possible to determine the average fuel costs of different bus technologies per 100 km in various road and traffic conditions – $\mathrm{AC}_{\mathrm{FC},i,n,k,100\mathrm{km}}$, eq. (4):

$$\mathrm{AC}_{\mathrm{FC},i,n,k,100\ \mathrm{km}} = \frac{FC_{i,n,k}\, p_\mathrm{f} 100}{\mathrm{Bus\ kms}_{n,k}} \tag{4}$$

where Bus $\mathrm{kms}_{n,k}$ is the traffic volume of buses per day for characteristic operating conditions n and scenario k, p_f – the fuel price, and f – the fuel type (diesel or CNG).

Results and discussion of fuel consumption and fuel cost of buses

Analysis of fuel consumption in scenario SC2014

Table 4 presents results of the fuel consumption of different bus technologies according to various road and traffic conditions in scenario SC2014, obtained by eq. (1). The total traffic volume of 312 million Bus-kms has been achieved in this scenario. The highest traffic volume was achieved on road sections within operating conditions T1-IRI2. The major part of the road sections on which design speeds are high (80-100 km/h) is encompassed by operating conditions T1-IRI2. Average fuel consumption of diesel buses is 25.06 litres per 100 km. Based on the determined fuel equivalent value, average fuel consumption of CNG buses is by 8% higher than fuel consumption of diesel buses. Fuel consumption of hybrid buses is by 17% lower than of diesel buses.

Table 4. The fuel consumption of different bus technologies in scenario SC2014

	Bus kms [10^6 per year]	Aver. V_d [kmh^{-1}]	Aver. V_o [kmh^{-1}]	f_{FC} [%]	Diesel bus [10^6 L per year]	CNG bus [10^6 m^3 per year]	Hybrid bus [10^6 L per year]	Diesel bus [L per 100 km]	CNG bus [m^3 per 100 km]	Hybrid bus [L per 100 km]
T1-IRI2	153.40	76.23	72.15	5.30	38.45	41.52	31.89	25.06	27.07	20.79
T1-IRI5	12.96	65.31	61.84	2.53	2.58	2.78	1.85	19.86	21.45	14.26
T1-IRI8	0.040	80.00	67.78	13.46	0.009	0.010	0.008	23.45	25.32	19.93
T2-IRI2	55.76	65.65	58.61	7.44	12.27	13.25	9.23	22.00	23.76	16.55
T2-IRI5	56.82	61.32	57.19	4.24	12.14	13.11	8.81	21.36	23.07	15.51
T2-IRI8	0.634	54.90	49.91	3.10	0.164	0.178	0.121	25.96	28.03	19.11
T3-IRI2	12.92	61.50	52.71	6.95	3.43	3.70	2.36	26.55	28.67	18.26
T3-IRI5	18.47	52.60	50.89	1.80	4.88	5.27	3.26	26.39	28.50	17.63
T3-IRI8	1.44	60.00	58.49	1.22	0.386	0.417	0.270	26.80	28.94	18.76
Network	312.44	64.99	60.71	5.18	74.29	80.23	57.79	23.78	25.68	18.50

Average fuel consumption of diesel and CNG buses within operating conditions T1-IRI5, with respective values 19.86 L per 100 km and 21.45 m^3 per 100 km, is considerably lower than it is the case within operating conditions T1-IRI2. In spite of worse road conditions (IRI value higher by 3 m/km), average fuel consumption has decreased. Lower design speeds are the major cause of the aforesaid, that is to say, lowers operating speeds on particular road sections which imply less specific fuel consumption (difference between average operating speeds within operating conditions T1-IR5 and T1-IRI2 is about 10.5 km/h). Hybrid buses averagely consume by 28% less fuel within operating conditions T1-IRI5 than diesel buses do within the same conditions, which is the consequence of more intensive use of electric motor than within operating conditions T1-IRI2.

Average fuel consumption of diesel and CNG buses is by 6.5% lower within operating conditions T1-IRI8 than within operating conditions T1-IRI2. The *F/C* ratio of road sections is higher within operating conditions T1-IRI8, as indicated by a more considerable difference between average design and operating speed (about 12 km/h). Correction factors are higher due to higher *F/C* ratio (average value is about 13.5%). However, higher values of IRI and correction factors can not make influence strong enough to make average fuel consumption of diesel and CNG buses higher than in case of operating conditions T1-IRI2. This is due to the dominant influence of lower operating speeds on fuel consumption decrease. Average fuel consumption of hybrid buses within operating conditions T1-IRI8 is by 15% lower than of diesel buses within the same operating conditions. Making a comparison between average fuel consumptions of hybrid buses on the road sections T1-IRI8 and T1-IRI5 we can notice that the fuel consumption on road sections T1-IRI8 is by 39% higher. The primary cause whereof is less intensive use of electric motors at higher operating speeds. The higher operating speeds on particular road sections are indicated by difference between average operating speeds – 67.78 km/h – T1I-RI8 and 61.84 km/h – T1-IRI5, tab. 4. The secondary cause is higher specific fuel consumption at higher IRI and higher values of correction factors.

Lower design and operating speeds of buses are more typical of hilly road sections (T2-IRI2, T2-IRI5, and T2-IRI8) than of flat road sections. Yet, the minimum specific fuel consumption on hilly road sections is registered at lower speeds. Consequently, the range of speeds which imply higher specific fuel consumption is wider. The minimum of specific fuel consumption curves is shifted more to the left, fig. 2. To be precise, speeds which imply minimal specific fuel consumption are by 2 km/h lower than the equivalent speeds within flat road operating conditions. In addition, specific fuel consumption curves typical of hilly road sections are above the curves referring to flat road sections. These are the main reasons for which fuel consumption per 100 km of diesel and CNG buses is by 7.5% and 10.7% higher within operating conditions T2-IRI5 and T2-IRI8, respectively, than within operating conditions T1-IRI5 and T1-IRI8. Correction factors influence the registered fuel consumption increase up to 2%. To the contrary of the previously stated, average fuel consumption of diesel and CNG buses within operating conditions T2-IRI2 is lower than average fuel consumption within operating conditions T1-IRI2. This comes as a consequence of distinctively higher operating speeds (average value is 72.15 km/h) on particular road sections within operating conditions T1-IRI2. Average fuel consumption of hybrid buses on the road sections T2-IRI2, T2-IRI5, and T2-IRI8 is by about 25-27% lower than the fuel consumption of diesel buses under the same operating conditions.

Average fuel consumption of diesel and CNG buses is higher within mountainous operating conditions (T3-IRI2, T3-IRI5, and T3-IRI8) than within flat and hilly operating conditions. Generally speaking, the increase in average fuel consumption fluctuates in range of 3-33% depending on the operating conditions that are being compared. Road conditions reflected primarily in a bus driving within hilly conditions, which are typically characterized by an increase in specific fuel consumption per 100 km (specific fuel consumption curves which refer to hilly road sections are positioned above other curves, fig. 2), are the basic cause. Within mountainous operating conditions, average fuel consumption of hybrid buses is by 30-31% lower than of diesel buses. Such a decrease is even more noticeable than within hilly operating conditions.

Analysis of fuel consumption in scenario SC–20%

Traffic volume decreases by 20% in scenario SC–20%. The total fuel consumption of diesel and CNG buses on the level of the whole road network is by 20.32% lower than it is the case in scenario SC2014. The difference of 0.32% also indicates that average fuel consumption of diesel and CNG buses on the level of the whole road network is lower in scenario SC–20%.

Since operating speeds on each section of the road network are by 20% higher due to less traffic volume, higher fuel consumption is expectable. This standpoint is indicated by the fact that the average operating speed on the level of the whole road network (62.44 km/h, tab. 5) is higher than operating speeds which register minimum specific fuel consumption (50-54 km/h, fig. 2). However, lower values of correction factors are the main reason due to which fuel consumption does not increase in respect to scenario SC2014. More precisely, in scenario SC–20% such values cause increase in the fuel consumption within the limits 0.79-8.34%, while in scenario SC2014 the values in question are almost double as much (1.22-13.46%).

Table 5. The fuel consumption of different bus technologies in scenario SC–20%

	Bus kms [10^6 per year]	Aver. V_d [kmh^{-1}]	Aver. V_o [kmh^{-1}]	f_{FC} [%]	Diesel bus [10^6 L per year]	CNG bus [10^6 m^3 per year]	Hybrid bus [10^6 L per year]	Diesel bus [L per 100 km]	CNG bus [m^3 per 100 km]	Hybrid bus [L per 100 km]
T1-IRI2	122.72	76.23	74.00	2.86	30.83	33.30	25.62	25.12	27.13	20.88
T1-IRI5	10.37	65.31	63.28	1.78	2.04	2.21	1.47	19.72	21.30	14.21
T1-IRI8	0.032	80.00	72.52	8.34	0.008	0.008	0.006	23.44	25.31	19.92
T2-IRI2	44.61	65.65	61.46	4.37	9.71	10.49	7.72	21.77	23.52	17.30
T2-IRI5	45.45	61.32	58.76	2.81	9.59	10.36	7.08	21.11	22.80	15.57
T2-IRI8	0.507	54.90	51.25	2.47	0.130	0.141	0.096	25.73	27.79	18.95
T3-IRI2	10.33	61.50	56.14	4.69	2.68	2.90	1.93	25.97	28.05	18.66
T3-IRI5	14.78	52.60	51.47	1.29	3.88	4.19	2.59	26.25	28.35	17.54
T3-IRI8	1.15	60.00	59.13	0.79	0.308	0.333	0.216	26.74	28.88	18.72
Network	249.95	64.99	62.44	3.02	59.19	63.93	46.72	23.68	25.58	18.69

Yet, regardless of all previously stated, more favourable traffic conditions do not cause considerable decrease in average fuel consumption within various operating conditions (from T1-IR5 to T3-IRI8). Bearing in mind the common, yet adverse influence of the increase in operating speeds and lower values of correction factors, decrease in the average fuel consumption of diesel and CNG buses does not exceed 2.15%. It should be pointed out that, only in case of operating conditions T1-IRI2 in connection with scenario SC–20%, average fuel consumption of diesel and CNG buses is higher in comparison with scenario SC2014, due to very high values of operating speeds on particular road sections (average value is 74.00 km/h, tab. 5).

The total fuel consumption of hybrid buses on the level of the whole road network is lower by 19.14% in scenario SC–20% than in scenario SC2014. One can notice that decreasing the traffic volume by 20% does not necessarily lead to the proportionally equal decrease in the fuel consumption. This fact indicates that average fuel consumption of hybrid buses on the level of the whole network is higher than in scenario SC2014. If we make a comparison between average fuel consumptions of hybrid buses, assuming the same operating conditions yet in different scenarios (SC2014 and SC–20%), one can see that within certain operating conditions in scenario SC–20% there has been an increase while in others there has been a decrease in average fuel consumption. More intensive use of diesel motor on certain road sections is considered to be the cause of an increase in average fuel consumption registered within some operating conditions. Within operating conditions which register decrease in average fuel consumption the cause is almost as much use of Diesel motors on characteristic road sections in two scenarios (SC2014 and SC–20%), and lower values of correction factors in scenario SC–20%. Changes in average fuel consumption, whether we talk about an increase or a decrease therein, do not exceed 4.6%.

Analysis of fuel consumption in scenario SC+20%

The 20% increase in the traffic volume is typical of scenario SC+20%. The total fuel consumption of diesel and CNG buses on the level of the whole road network is by 20.97%

higher than in scenario SC2014. These data indicate that average fuel consumption of diesel and CNG buses on the level of the whole road network is higher than in case of scenario SC2014. If we make a comparison between average fuel consumptions of diesel and CNG buses, assuming the same operating conditions in two different scenarios (SC2014 and SC+20%), one can notice that average fuel consumption is higher for all operating conditions in scenario SC+20%. Bigger influence of the correction factor is considered the main reason thereof. Within different operating conditions, correction factors separately affect an increase in the fuel consumption of buses, from 1.79-18.91% on average, tab. 6. Still, bearing in mind the equivalent value of correction factors in scenario SC2014 (1.22-13.46%), an increase in the average fuel consumption of diesel and CNG buses, within various operating conditions (from T1-IR2 to T3-IRI8) in scenario SC+20%, does not exceed 3%.

Table 6. The fuel consumption of different bus technologies in scenario SC+20%

	Bus kms [10^6 per year]	Aver. V_d [kmh^{-1}]	Aver. V_o [kmh^{-1}]	f_{FC} [%]	Diesel bus [10^6 L per year]	CNG bus [10^6 m^3 per year]	Hybrid bus [10^6 L per year]	Diesel bus [L per 100 km]	CNG bus [m^3 per 100 km]	Hybrid bus [L per 100 km]
T1-IRI2	184.08	76.23	69.52	8.42	46.13	49.82	37.64	25.06	27.07	20.45
T1-IRI5	15.56	65.31	60.01	3.35	3.12	3.37	2.20	20.03	21.63	14.13
T1-IRI8	0.049	80.00	62.29	18.91	0.011	0.012	0.010	23.67	25.56	20.12
T2-IRI2	66.91	65.65	55.10	10.98	14.99	16.18	10.71	22.40	24.19	16.01
T2-IRI5	68.18	61.32	55.25	5.81	14.83	16.02	10.53	21.76	23.50	15.44
T2-IRI8	0.760	54.90	48.49	3.77	0.199	0.215	0.147	26.21	28.30	19.28
T3-IRI2	15.50	61.50	48.69	9.23	4.24	4.58	2.83	27.34	29.53	18.29
T3-IRI5	22.17	52.60	50.20	2.34	5.89	6.36	3.85	26.58	28.70	17.35
T3-IRI8	1.73	60.00	57.65	1.79	0.464	0.502	0.325	26.89	29.04	18.82
Network	374.93	64.99	58.47	7.78	89.87	97.06	68.24	23.97	25.89	18.20

On the level of the whole network, hybrid buses consume by 1.58% less fuel per 100 km in scenario SC+20% than in scenario SC2014. If we compare scenarios SC2014 and SC+20%, average fuel consumption in SC+20% is higher within particular operating conditions (T1-IRI2, T1-IRI5, T2-IRI2, T2-IRI5, T3-IRI5), while it is lower within other operating conditions (T1-IRI8, T2-IRI8, T3-IRI2, T3-IRI8). Decrease in average fuel consumption occurs mainly as a consequence of more intensive use of electric motor (due to lower operating speeds) to the point that the increased correction factors can not make crucial influence causing the achieved average fuel consumption to be higher than in scenario SC2014. Within operating conditions which register increase in average fuel consumption the cause is almost as much operation of Diesel motors on characteristic road sections in two scenarios (SC2014 and SC+20%), and higher values of correction factors in scenario SC+20%. Average fuel consumption variations of hybrid buses, whether an increase or a decrease is in question, do not exceed 3.3%.

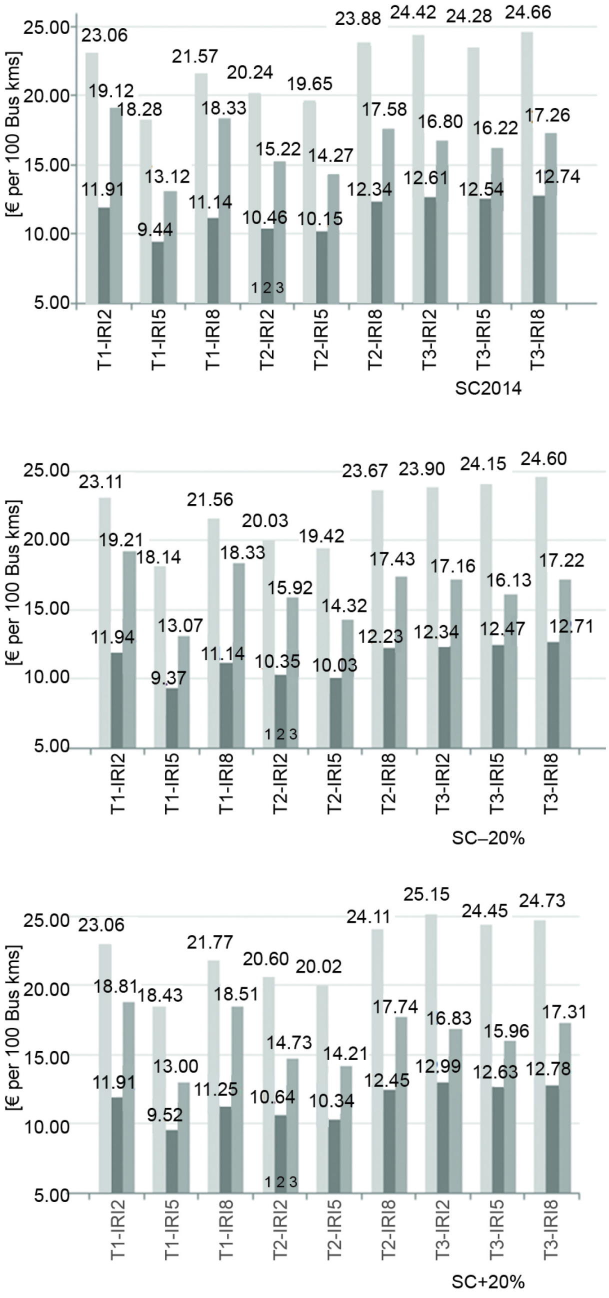

Figure 3. The fuel costs for different bus technologies per 100 km: *1 – diesel bus, 2 – CNG bus, 3 – hybrid bus*

Analysis of fuel costs

The aim of this chapter is to quantify fuel costs of different bus technologies within various road and traffic conditions. Bearing that in mind, fig. 3 presents average fuel costs of buses, per 100 km. As you can see from the fig. 3, CNG buses incur the lowest fuel costs. Although their fuel consumption, expressed in m^3/100 km, is higher than of diesel buses whose consumption is expressed in L/100 km, the main reason for the lowest fuel costs of CNG buses is the price of CNG, which costs by 52% less than diesel. According to [23] regressed price of one litre of diesel for legal entities in October 2015 was €0.92. According to the same source, the total price of one m^3 of natural gas was €0.44 (taking into account the additional expenditure of compression to 200 bar).

In scenario SC2014, these buses reach the highest average fuel costs per 100 km within operating conditions T3-IRI8, T3-IRI2, T3-IRI5, T2-IRI8, and T1-IRI2 (€11.91-12.74). The lowest average fuel costs of €9.45 are achieved within operating conditions T1-IRI5. In case of SC2014, hybrid buses reach the highest average fuel costs within operating conditions T1-IRI2, which amount up to €19.12, while the lowest costs of €13.12 are achieved within operating conditions T1-IRI5. In scenario SC2014, the highest average fuel costs of about €24.50 per 100 km are reached of diesel buses on hilly road sections.

Changes in traffic conditions in terms of increasing or decreasing traffic volume by 20% (scenario SC–20% and scenario SC+20%) have such an influence that changes in average fuel costs, of particular bus technology within particular operating conditions and with regard to scenario SC2014, reach the maximum value of 4.60%. In scenario

SC–20% the biggest change in fuel costs occurs in case of hybrid buses, within operating conditions T2-IRI2, noting their increase by 4.57%. In all other cases, when it comes to the comparison of fuel costs changes of different bus technologies, which appear within various operating conditions, deviations do not exceed 2.15%. The biggest change of fuel costs of diesel and CNG buses, in scenario SC+20%, occurs within operating conditions T3-IRI2, when the costs increase by 2.98%. In case of hybrid buses, the biggest change occurs within operating conditions T2-IRI2 when fuel costs increase by 3.23%. In all other cases, when we make a comparison between fuel cost changes of different bus technologies, which appear within various operating conditions, deviations do not exceed 1.90%. In the end, tab. 7 shows fuel cost savings per year of different fuel technologies, according to various operating conditions and in three discussed scenarios.

Table 7. Fuel costs savings per year of different bus technologies (in €)

	SC2014		SC–20%		SC+20%	
	CNG bus/ Diesel bus	Hybrid bus/ Diesel Bus	CNG bus/ Diesel bus	Hybrid bus/ Diesel Bus	CNG bus/ Diesel bus	Hybrid bus/ Diesel Bus
T1-IRI2	17,100,703	6,035,631	13,713,250	4,794,332	20,520,142	7,814,960
T1-IRI5	1,145,425	668,309	909,578	525,598	1,386,068	844,133
T1-IRI8	4,221	1,310	3,376	1,047	5,113	1,586
T2-IRI2	5,457,709	2,800,509	4,320,434	1,835,810	6,665,640	3,930,334
T2-IRI5	5,397,990	3,057,314	4,267,541	2,316,578	6,598,006	3,959,993
T2-IRI8	73,160	39,925	58,019	31,624	88,639	48,435
T3-IRI2	1,525,196	984,447	1,193,862	695,719	1,884,863	1,290,353
T3-IRI5	2,168,563	1,489,900	1,725,495	1,184,759	2,620,400	1,881,198
T3-IRI8	171,607	106,483	136,977	84,995	206,585	128,187
Network	33,044,574	15,183,829	26,328,532	11,470,462	39,975,455	19,899,178

Conclusions

Fuel consumption and fuel costs of buses depend on a number of factors which have been presented in this research. Operating speed of a bus and terrain type of the road section on which a bus is driven, respectively, have the biggest influence on the fuel consumption. The IRI influence on the fuel consumption change is the least prominent. To be precise, less influence of IRI on the fuel consumption is especially noticeable on flat road sections with minimum value of IRI in all three discussed scenarios. Due to a high operating speed within these operating conditions, fuel consumption and fuel costs are very similar to the appropriate values achieved within the most unfavourable operating conditions (all mountainous road sections and hilly road sections with higher IRI). This statement applies to all bus technologies in all three scenarios. Making a comparison among different scenarios, correction factor changes are more prominent when traffic volume on the road network increases. That is to say, on the level of the whole road network, correction factors are in average higher by about 50% in scenario SC+20% rather than in scenario SC2014. In scenario SC+20% they influence fuel consumption of buses to increase in range of 2-19%. In scenario SC–20%, on the level of the whole road network, correction factors are in average by about 42% less than in scenario SC2014. In this scenario they influence fuel consumption of buses to increase in range of 1-8%. In comparison with the fuel consumption of diesel and CNG buses within the all discussed operating conditions, the biggest decrease in average fuel consumption of hybrid buses is typical of scenario SC+20%. Due to a bigger traffic volume achieved in scenario SC+20%, operating speeds are lower; therefore the electric motor use is more intensive. In case of the road network of Serbia, this fact is especially noticeable within mountainous operating conditions, when fuel consumption decreases by 30-35%.

The CNG buses represent by far the most efficient bus technology from the viewpoint of the effectuated fuel costs. When these buses are used in intercity bus service, the following fuel cost savings are registered: in scenario SC2014, savings of CNG buses per 100 km range from €8.84-11.92 in comparison with diesel buses, *i. e.* from €3.67-7.21 in comparison with hybrid buses; in scenario SC–20%, savings per 100 km range from €8.77-11.89 in comparison with diesel buses and from €3.66 to €7.27 in comparison with hybrid buses; in scenario SC+20%, savings per 100 km range from €8.91 to €12.16 in comparison with diesel buses and from €3.33 to €7.26 in comparison with hybrid buses. The previously displayed fuel cost savings indicate that fluctuations in the traffic volume generally have very little influence on the fuel cost changes per 100 km, assuming the same operating conditions which are observed in various scenarios. If CNG buses operate on the observed road sections, there will be the total annual fuel cost savings (in respect to the operation of diesel buses) in range of €26-39 million, depending on the realised traffic volume. If on the other hand hybrid buses operate on the observed road sections, there will be the total annual fuel cost savings (in respect to the operation of diesel buses) in range of €11-19 million, depending on the realised traffic volume.

Assessment approach for the influence of road and traffic conditions on fuel consumption and fuel costs presented in this research is adaptable, *i. e.* it is applicable both on other alternative bus technologies and other vehicle categories. From the viewpoint of fleet owners, certain ideas and observations can be used in the procedure of choice of vehicles, especially in segment of determining of fuel costs, which represent the key component of vehicle operating costs.

Acknowledgment

This paper is based on the project *Software development and national database for strategic management and development of transportation means and infrastructure in road, rail, air and inland waterways transport using the European transport network models*, No. TR36027, 2011-2016. Ministry of Education, Science and Technological Development of Republic of Serbia.

Nomenclature

$\mathrm{AADT}_{\mathrm{Bus},j}$ – annual average daily traffic by buses on the road section j, [buses per day]
$\mathrm{AC}_{\mathrm{FC},i,n,k,100\,\mathrm{km}}$ – average fuel costs of different bus technologies per 100 km, [€ per 100 km]
a, b, c – regression coefficients, [–]
Bus $\mathrm{kms}_{n,k}$ – traffic volume of buses per day in conditions n in scenario k, [bus kms]
c, d – coefficients of the road section type, [–]
$(F/C)_{,j}$ – intensity to capacity ratio on the road section j, [–]
$FC_{\mathrm{d},j}$ – specific fuel consumption of diesel bus on the road section j, [L per 100 km]
$FC_{i,n,k}$ – annual fuel consumption of buses, [L per year or m^3 per year]
$F_{\mathrm{eq,CNG}}$ – fuel equivalent of CNG bus, [–]
$F_{\mathrm{eq,HB}}$ – fuel equivalent of hybrid bus, [%]

$F_{\mathrm{eq},i,j}$ – fuel equivalent of bus technology on the road section j, [–]
f_{FC} – correction factor of fuel consumption, [%]
$f_{\mathrm{FC},j}$ – correction factor of fuel consumption on the road section j, [%]
L_j – length of road section j, [km]
p_{f} – fuel price of CNG or diesel, [€ per m^3] or [€ per L]
R^2 – coefficient of determination, [–]
$t_{\mathrm{free},j}$ – travelling time in the free traffic flow the road section j, [h]
V_{d} – design speed, [kmh^{-1}]
V_{o} – operating speed, [kmh^{-1}]
$V_{\mathrm{o},j}$ – operating speed on the road section j, [kmh^{-1}]

Acronyms

AADT – annual average daily traffic
CNG – compressed natural gas
F/C – flow/capacity ratio
IRI – international roughness index

Subscripts

f – fuel type (diesel or CNG)
i – different bus technology (diesel, CNG, or hybrid bus)
j – individual road section
k – scenario (SC2014, SC –20%, or SC–20%)
n – number of road section with the same road conditions

References

[1] Uhlik, K., *et al.*, Elaboration of a Program to Facilitate the Implementation of the Directive 2009/33/ec on the Promotion of Clean and Energy-Efficient Road Motor Vehicles, *International Journal for Traffic and Transport Engineering, 2*, (2012), 3, pp. 170-177
[2] Medar, O. M., *et al.*, Assessing the Impact of Transport Policy Instruments on Road Haulage Energy Efficiency, *Thermal Science, 18* (2014), 1, pp. 323-337
[3] Wang-Helmreich, H., Lochner, S., The Potential of Natural Gas as a Bridging Technology in Low--Emission Road Transportation in Germany, *Thermal Science, 16* (2012), 3, pp. 729-746
[4] Alam, A., Hatzopoulou, M., Reducing Transit Bus Emissions: Alternative Fuels or Traffic Operations?, *Atmospheric Environment, 89* (2014), June, pp. 129-139
[5] ***, Technical Assessment of Advanced Transit Bus Propulsion Systems for Dallas Area Rapid Transit, Battelle, Columbus, O., USA, 2002
[6] Chandler, K., Walkowicz, K., King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results, Technical Report NREL/TP-540-40585, National Renewable Energy Laboratory, Golden, Col., USA, 2006
[7] De Almeida d'Agosto, M., Ribeiro, S. K., Performance Evaluation of Hybrid-Drive Buses and Potential Fuel Savings in Brazilian Urban Transit, *Transportation, 31* (2004), 4, pp. 479-496
[8] Barnitt, R., Chandler, K., New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses. Final Evaluation Results, Technical Report NREL/TP-540-40125, National Renewable Energy Laboratory, Golden Col., USA, 2006
[9] Chandler, K., *et al.*, Washington Metropolitan Area Transit Authority: Compressed Natural Gas Transit Bus Evaluation, Technical Report NREL/TP-540-37626, National Renewable Energy Laboratory, Golden, Col., USA, 2006
[10] Pelkmans, L., *et al.*, Influence of Vehicle Test Cycle Characteristics on Fuel Consumption and Emissions of City Buses, SAE technical paper 2001-01-2002, Society of Automotive Engineers, Warrendale, Penn., USA, 2001
[11] Frey, H. C., *et al.*, Comparing Real-World Fuel Consumption for Diesel – and Hydrogen-Fueled Transit Buses and Implication for Emissions, *Transportation Research Part D, 12* (2007), 4, pp. 281-291
[12] Wang, A., *et al.*, On-Road Pollutant Emission and Fuel Consumption Characteristics of Buses in Beijing, *Journal of Environmental Sciences, 23* (2011), 3, pp. 419-426
[13] Zhang, S., *et al.*, Real-World Fuel Consumption and CO_2 Emissions of Urban Public Buses in Beijing, *Applied Energy, 113* (2014), Jan., pp. 1645-1655
[14] Ma, H., *et al.*, Effects of Driving Style on the Fuel Consumption of City Buses under Different Road Conditions and Vehicle Masses, *Transportation Research Part D, 41* (2015), Dec., pp. 205-216
[15] Mišanović, S. M., *et al.*, Energy Efficiency of Different Bus Subsystems in Belgrade Public Transport, *Thermal Science, 19* (2015), 6, pp. 2233-2244
[16] ***, Public Roads of the IA Category in the Republic of Serbia – Average Annual Daily Traffic-AADT in 2014 (in Serbian), Public Enterprise "Roads of Serbia", Belgrade, 2015

[17] ***, Public Roads of the IB Category in the Republic of Serbia – Average Annual Daily Traffic-AADT in 2014 (in Serbian), Public Enterprise "Roads of Serbia", Belgrade, 2015
[18] ***, Public Roads of the II Category in the Republic of Serbia – Average Annual Daily Traffic-AADT in 2014 (in Serbian), Public Enterprise "Roads of Serbia", Belgrade, 2015
[19] Kuzović, Lj., *Evaluation in Management of Development and Exploitation of Road Network* (in Serbian), Faculty of Transport and Traffic Engineering, University of Belgrade, Belgrade, 1994
[20] ***, Highway Capacity Manual, 2000, Transportation Research Board
[21] Ivković, I., *et al.*, Research into the Costs of Vehicle Exhaust Gases from the Standpoint of Using Natural Gas-Powered Buses, *African Journal of Business Management*, *5*, (2011), 22, pp. 9304-9321
[22] ***, Hybrid Postbus Passes Practice Test, 2010, www.postauto.ch
[23] ***, Maximum Fuel Prices-Oct. 2015 (in Serbian), NIS Petrol, Novi Sad, Serbia, 2015

Paper submitted: March 1, 2016
Paper revised: March 18, 2016
Paper accepted: May 24, 2016