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ANALYSIS OF EXTERNAL COSTS OF CO_2 EMISSIONS FOR CNG BUSES IN INTERCITY BUS SERVICE

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Abstract. Within the transport sector, road transport is the largest source of Carbon Dioxide (CO_2) emissions. Greater use of vehicles that run on clean alternative fuels can contribute to reduce CO_2 emissions. This paper gives special attention to the Compressed Natural Gas (CNG) buses and their comparison with conventional diesel buses, which in countries such as Serbia have a dominant share. Justification of using CNG buses in order to mitigate climate changes is measured by realised annual and average external costs of CO_2 emissions. These external costs provide a basis for future use of economic instruments by which negative impacts of transport on the environment can be limited. Research of CO_2 emissions and external costs of CO_2 emissions in intercity bus service was conducted for three technical-technological concepts of CNG buses in comparison to the two types of conventional diesel buses. Analysis was carried out according to four various scenarios that define different operating conditions on the road network of the Serbia. Obtained results show that CNG buses reduce annual external costs of CO_2 emissions by 2…24% compared to conventional diesel buses. Obtained average external costs of CO_2 emissions per 100 bus-kms show to what extent their changes are a result of changes of external costs of CO_2 emissions and to what extent they are due to changes of operating conditions on the road network.

Keywords: CNG bus, diesel bus, CO_2 emission, external cost, intercity bus service, road network.

Notations

Abbreviations:

AADT – annual average daily traffic;
BS2006 – base scenario;
bus-kms – bus kilometres;
CH_4 – methane;
CNG – compressed natural gas;
CO – carbon monoxide;
CO_2 – carbon dioxide;
CS2015 – current scenario;
GDP – gross domestic product;
GHG – greenhouse gases;
GWP – global warming potential;
HC – hydrocarbons;
IRI – International roughness index [m/km];
N_2O – nitrous oxides;
NG – natural gas;
NO_x – nitrogen oxides;
OC converter – oxidation catalytic converter;
OS2030 – optimistic scenario;
PM – particulate matter;
PM_{10} – particulate matter with a diameter of 10 micrometres or less;
PS2030 – pessimistic scenario;
TWC converter – three way catalytic converter;
veh-kms – vehicle kilometres.

Variables and functions:

a, b, c – regression coefficients [–];
$AADT_{Bus}$ – annual average daily traffic of buses [bus/day];
$AEC_{CO_{2j}}$ – average external costs of CO_2 emissions per 100 bus-kms [€/100 bus-kms];
$Bus_{kms\,j}$ – bus-km for scenario j;
ec_{CO_2} – unit values of external costs of CO_2 emission [€/tonne CO_2];
$EC_{CO_{2j}}$ – annual external costs of CO_2 emissions of CNG buses for the whole road network [€/year];

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EMF_{CO_2} – CO_2 emission factors of buses [gr CO_2/m^3 NG] or [gr CO_2/ltr diesel];
Eq_{NG} – consumed natural gas per 100 kilometres [m^3/100 km];
FC_{CNG_i} – fuel consumption of CNG buses on the particular road section [m^3/year];
FC_{CNG_j} – annual fuel consumption of CNG buses for the whole road network for scenario j [m^3/year];
FC'_{Dsl} – fuel consumption of conventional diesel bus in the free traffic flow [lit/100 km]
FEq – fuel equivalent [–];
f_{FC} – correction factor of fuel consumption [–];
i – index of road section;
j – index of scenario (j: BS2006, CS2015, PS2030, OS2030);
k – index of vehicle categories;
L – road section length [km];
n – total number of road sections on the road network (n = 302);
R^2 – coefficient of determination [–];
V_{AVG} – average operating speed for the whole road network [km/h];
$V_{AVG_{bus}}$ – average operating speed of buses [km/h];
V_d – design speed [km/h];
V_{op} – operating speed by road section [km/h].

Introduction

According to the latest data from the International Energy Agency (*https://www.iea.org*), there are two sectors responsible for almost two thirds of the overall CO_2 emissions worldwide in 2012, namely electricity and heat generation sector as the biggest CO_2 emitter, with the share of 42%, and transport sector, with the share of 23% (IEA 2014). Within the transport sector, the primary source of CO_2 emissions is road transport, with the share of even three quarters of the total CO_2 emissions (IEA 2014). Although there are other GHGs emitted in the road transport in addition to CO_2, MacLean and Lave (2000) state that the emissions of other GHGs produced by motor vehicles and their effect on the global warming are minor in comparison with CO_2 emissions, even if taken into account that CH_4 and N_2O have GWP 28 and 298 times greater than CO_2, respectively, over a 100 year time horizon (IPCC 2013). The main reason for the dominant effect of CO_2 on the global warming in comparison with other GHGs relies on the fact that, according to the equation of the stoichiometric combustion process of carbon and hydrogen in the fuel, 12 kg of carbon produces 44 kg of CO_2 (Grote, Antonsson 2009), i.e. 3.7 kg of CO_2 are emitted during the combustion of 1 kg of fuel.

Various strategies are developed so as to establish sustainable transport, especially sustainable road transport, which should reduce CO_2 and other pollutant emissions, and thereby negative effects of such emissions to the environment and human health (Andrejszki *et al.* 2014). Sustainable transport strategies can be grouped into two basic groups: preventive strategies (technical-technological-organizational) i.e. those applied "before" providing a transport service, and corrective strategies (primarily economic), i.e. those which refer to the mitigation of the negative effects of transport once the service has been provided. One of the preventive technological strategies, the aim of which is to reduce CO_2 emissions, is based on greater use of vehicles that run on clean alternative fuels, such as CNG. Namely, it is the fuel, which has been attracting all the more attention lately in a number of countries worldwide, all due to its environmental characteristics and abundant reserves of natural gas. In spite of the fact that light-duty vehicles are by far the biggest CO_2 emitters in the road transport, Schipper *et al.* (2009) state that trucks and sometimes buses, are also considered important emitters in low and middle income countries. In particular, the focus of the analysis of this paper is to examine possibilities to reduce CO_2 emissions through the use of environmental friendly buses or in this case in particular – CNG buses. CNG buses and CNG vehicles in general represent bridging technology in low-emission road transportation since zero-emission electric vehicles are not yet market-ready (Wang-Helmreich, Lochner 2012). Besides, electric buses have a lower range with one charge, which constitutes a significant deficiency in intercity operating conditions. Currently, a more widespread use of CNG buses in Serbia, as well as in many other countries, is curbed by high incremental costs, i.e. by high purchase costs of buses and fuelling infrastructure costs (Lowell *et al.* 2003). However, differences between purchase costs of CNG and diesel buses keep reducing, and that for a twofold reason: first, because the costs of conventional diesel buses increase due to the constant tightening of emission standards and second, because investment costs of CNG buses are expected to decrease due to their large scale production and use (Lowell *et al.* 2003; Wang-Helmreich, Lochner 2012; Düsterwald *et al.* 2007). Bearing in mind these trends, as well as the increasing importance of sustainable transportation, a precise quantification of external costs of CO_2 emission for alternative bus technologies, such as CNG buses, is important because it permits us to find out whether and in which time possible savings of external costs of CO_2 emission could compensate for their high capital costs. The main goal of the research in this paper is the use of CNG buses in intercity bus service so that their efficiency could be monitored and determined in terms of reduction of CO_2 emissions and external costs of CO_2 emissions, when compared to conventional diesel buses.

1. Literature review

The tendency to use CNG buses has lately been on the constant increase. This is confirmed by the following data. In fact, worldwide, approximately 185000 buses were in operation in 2008; 308000 – in 2009; 413000 – in 2010; 414000 – in 2011; 702000 – in 2012; 1175000 – in 2013; today 1620000 buses (GVR 2015). The reasons for their increased use are twofold: ecological reasons, which refer to the reduction of CO_2 emissions and air quality improvements, while the other reason rests on energy security benefits, especially in the countries possessing their own natural gas sources.

CNG buses have significant environmental advantages compared to the conventional diesel buses. Such advantages primarily reflect less emission of air pollutants. This is confirmed by numerous studies and experimental research. The aforementioned studies encompass the Wang *et al.* (2011) study, which stresses that CNG buses, when compared to Euro III and Euro IV diesel buses emit considerably less NO_x and PM. The fact that CNG buses emit less NO_x has been confirmed by Zhang *et al.* (2014) too, while Park and Tak (2012) reveal that CNG buses emit considerably less both PM_{10} and CO.

When discussing GHG emissions, especially CO_2 emissions, there are also well-to-wheel studies, which suggest that CNG vehicles generally have lower CO_2 emissions per vehicle kilometre as opposed to the vehicles consuming conventional fuels, petrol or diesel (Hekkert *et al.* 2005; Engerer, Horn 2010). Research carried out by Chan *et al.* (2013) confirms that CNG buses themselves, observed separate from other CNG vehicles, have lower lifecycle GHG emissions in comparison with the diesel or biodiesel-powered buses.

Ryan and Caulfield (2010) have examined how the emission of air pollutants and CO_2 was affected by partial replacement of the Dublin bus fleet. The first variant of such a partial replacement included – new diesel buses, the second variant – CNG buses and finally bio-CNG buses. The relevant results indicate that all three bus concepts lead up to considerable reduction of emissions, especially the latter two, which record identical reduction, with the exception of CO_2 where far more considerable reduction is recorded in bio-CNG buses. Advantages of CNG in terms of CO_2 emissions over diesel buses have once again been confirmed by Nanaki *et al.* (2014) who have drawn such a conclusion upon analysing the Athen's bus fleet. Alam and Hatzopoulou (2014) have also been dealing with the effects on CO_2 emissions made by the operation of transit buses consuming CNG and conventional diesel fuel. They have noticed that CNG decreases GHG emissions by 8…12% in comparison with diesel fuel. Bearing in mind that buses operating along the Montreal busy transit corridor were in the focus of their research, they have noticed that with the higher traffic congestion this decrease reaches up to 16%. On the other hand, Jayaratne *et al.* (2010) have noticed that, when accelerating, diesel bus have approximately 15…20% higher emission rate than CNG bus.

Analysing the literature, we can notice that researches were based on the analysis of performances of the buses operated in urban areas. This is due to the fact that the infrastructure has neither been sufficiently developed nor adequate (energy supply, fuel station, reliability of energy storage) for smooth use of alternative bus concepts in intercity bus service. Besides, one can notice that none of the available and analysed studies calculate external cost of CO_2 emissions. Following the previous observations, we can conclude that there is considerable space and a need to carry out research of the use of CNG buses in intercity bus services, to examine effects of the use thereof on CO_2 emissions, as well as to calculate external costs of such emissions. Apart from that, it is also necessary to make a comparison of the results regarding CNG buses with corresponding results regarding diesel buses, which are more numerous in countries like Serbia. The aim of the research is to estimate external costs of CO_2 emissions incurred throughout the intercity bus service provided by CNG buses on the road network of the Serbia.

2. Methodology

In this paper are analysed three technical-technological concepts of CNG buses:

- CNG bus with stoichiometric control of fuel mixture without after-treatment of exhaust gases (named CNG1 bus);
- CNG bus with stoichiometric control of fuel mixture with after-treatment of exhaust gases by using a TWC converter (named CNG2 bus);
- CNG bus with lean burn control of fuel mixture by using an OC converter (named CNG3 bus).

Also, the analysis included conventional diesel bus without after-treatment of exhaust gases (named Diesel1 bus) and diesel bus with the after-treatment of exhaust gases by using an OC converter (named Diesel2 bus). The methodological approach has been demonstrated in seven steps, as presented below. It has been realised through the synergy comprising various research techniques, such as: simulation techniques determining transport demands within the time period in the future, experimental measuring of fuel consumption of CNG buses under real operating conditions in intercity transport, implementation of previous research results, regarding the emission of CNG buses and external cost of CO_2 emissions, taken from the relevant papers, which have been published until now (Pelkmans *et al.* 2001; Hesterberg *et al.* 2008; Maibach *et al.* 2008; Ivković *et al.* 2012).

2.1. Transport demands on the road network

It is essential that we create a multimodal transport network of the Serbia so that we could define road transport demands presented in the form of AADT by vehicle categories (passenger cars, buses, freight vehicles) on the road sections, all according to various scenarios. Multimodality ensures comprehensive research, i.e. adequate distribution of traffic flows by transport modes. The aforementioned is reflected in the existing road network, rail network and network of inland waterways with thereto pertaining attributes, which describe operating conditions of each transport section (road, rail, or inland waterway section) separately. The most important attributes of the road sections are: identification number of road section, road section length, free speed for passenger and freight vehicles, road class, terrain type (flat, hilly, mountain), IRI, number of lanes in each direction, capacity per hour per lane, country border etc. Transport demands have been defined regarding all the four scenarios described, presented through AADT of buses and other vehicle categories, at each road section. A transport model used for the development of "General Master Plan for Transport in Serbia" (Italferr S.p.A. 2009) study has been applied in order to obtain AADT values. The overall concept is a classic four-step (generation, distribution, mode split and assignment) and the system has been adapted for application within the Balkan region. The database within the transport model, in terms of operating conditions, has been updated from 2011 to 2014 through the realization of activities 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" (Grant No TR36027), 2011–2015 financed by the Ministry of Education, Science and Technological Development of Serbia. In addition to AADT, the most important outputs of the transport model runs are operating bus speeds.

2.2. Description of the scenarios

Analysis of the external costs of CO_2 emissions during the use of CNG buses is carried out for the predetermined road network, namely according to four scenarios: Base Scenario (BS2006), Current Scenario (CS2015), Pessimistic Scenario (PS2030) and Optimistic Scenario (OS2030). Scenario BS2006 takes into account operating conditions of the transport infrastructure and defines transport demands on the transport network with regard to the base year. In addition, a transport model for the simulation of the transport demands, described in the next chapter, has been calibrated for 2006 as the base year. Traffic volume on the road network achieved in 2006 is resulted from the transport model run. This value complies with the traffic volume obtained by traffic counting on the road network as carried out by Public Enterprise "Roads of Serbia" (*https://www.putevi-srbije.rs*). Scenario CS2015 defines transport demands on the transport network with regard to the 2015. Operating conditions are identical to those in 2006, since no relevant road infrastructure projects have been carried out throughout this period of time. Scenario PS2030 includes forecasted transport demands with regard to 2030 without development of transport infrastructure in comparison to the previous two scenarios. Scenario OS2030 defines transport demands with considerably improved transport network, with the realized 13 developmental projects in the road sector and 14 developmental projects in the rail sector, defined by the "General Master Plan for Transport in Serbia" (Italferr S.p.A. 2009). According to this document, Figure presents potential developmental projects applied for scenario OS2030. Selected scenarios make it possible to consider and analyse how much operating conditions (road and traffic conditions) affect external costs of CO_2 emissions during the operation of CNG buses in the intercity bus services.

2.3. Fuel consumption of CNG buses on the road network by various scenarios

Fuel consumption of CNG buses on the particular road section by year for scenario *j* is obtained as follows:

$$\left(FC_{CNG_i}\right)_j = \left(\left(365 \cdot AADT_{Bus} \cdot \frac{FC'_{Dsl}}{100} \cdot L \cdot f_{FC} \cdot FEq\right)_i\right)_j, \quad (1)$$

while, annual fuel consumption of CNG buses for the whole road network for scenario *j* is given:

$$FC_{CNG_j} = \sum_{i=1}^{n} FC_{CNG_{i_j}}. \quad (2)$$

Fuel consumption of conventional diesel bus in the free traffic flow is determined according to different attributes of road sections (terrain type and IRI) in the form of a polynomial of the second degree:

$$FC'_{Dsl} = 100 \cdot \left(a - b \cdot V_{op} + c \cdot V_{op}^2\right). \quad (3)$$

This variable represents fuel consumption of diesel buses [ltr/100 km] at certain values of operating speed (ranging from the minimum to the maximum, in the steady driving mode). Regression coefficients, adopted from Ivković *et al.* (2012), are given in Table 1.

FC'_{Dsl} is corrected by f_{FC} due to mutual interference between vehicles in the traffic flow. The dependencies of f_{FC} for buses as a function of speed change (due to the change at the design speed to operating speed) are given on the basis of the speeds matrix (Kuzović 1994) in the form of a polynomial of the second degree:

$$f_{FC} = a + b + V_{op} + V_{op}^2. \quad (4)$$

Calculated regression coefficients are given in Table 2.

FEq is a measure of how much Eq_{NG} [m^3/100 km] is consumed in relation to diesel consumption [ltr/100 bus-kms]:

$$FEq = \frac{Eq_{NG}}{FC'_{Dsl}}. \quad (5)$$

It is determined by comparing the fuel consumption of CNG bus with the fuel consumption of diesel bus. Fuel consumption of CNG bus is obtained from experimental measurements on road sections of two intercity itineraries in Serbia "Belgrade–Jagodina" and "Belgrade–Vrnjacka Banja". Fuel consumption was measured regarding the bus model IKARBUS IK 104CNG (stoichiometric combustion engine, power 190 kW). The total length of the itinerary "Belgrade–Jagodina" is 159 km in one direction. There were 30 passengers on the bus in both directions. Average consumption of natural gas amounted to 28.93 m^3/100 km, that is to say 28.55 m^3/100 km in each respective direction. The total length of the itinerary "Belgrade–Vrnjacka Banja" is 215 km in one direction. There were 11 passengers on

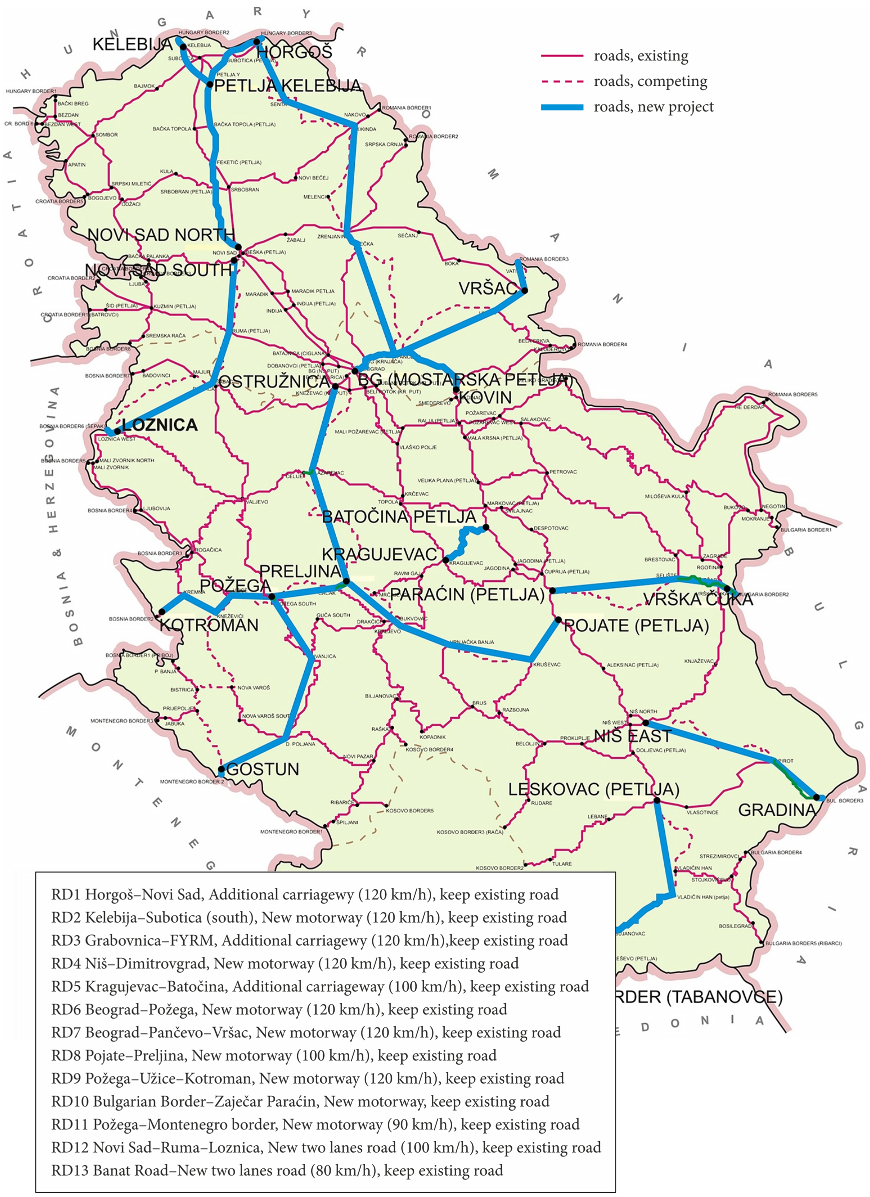

Figure. Potential road developmental projects applied for scenario OS2030

Table 1. Regression coefficients for determining fuel consumption of diesel bus

	Terrain type – flat				Terrain type – hilly				Terrain type – mountain			
IRI	*a*	*b*	*c*	R^2	*a*	*b*	*c*	R^2	*a*	*b*	*c*	R^2
2	0.349117	0.00638	0.000059	0.977954	0.347710	0.00595	0.000056	0.990012	0.359716	0.004460	0.000043	0.965232
5	0.365289	0.00668	0.000061	0.975478	0.363594	0.00621	0.000058	0.988547	0.369716	0.004471	0.000043	0.971257
8	0.387864	0.00708	0.000065	0.985632	0.380856	0.00517	0.000049	0.992154	0.391856	0.005077	0.000049	0.989754
12	0.388856	0.00506	0.000049	0.999652	0.4235996	0.00681	0.000073	0.993252	0.432599	0.006719	0.000073	0.999752

Table 2. Regression coefficients for determining the correction factor of fuel consumption

V_d [km/h]	100	90	80	70	65	60	50
a	2.289429	1.790479	1.438914	1.318200	1.286200	1.256200	1.206200
b	–0.009756	0.000389	0.001417	–0.002440	–0.002440	–0.002440	–0.002440
c	–0.000031	–0.000102	–0.000087	–0.000030	–0.000030	–0.000030	–0.000030
R^2	0.989205	0.999130	0.995837	0.999806	0.990617	0.997609	0.998452

the bus in the direction "Belgrade–Vrnjacka Banja". In the other direction "Vrnjacka Banja–Belgrade" there were 43 passengers on the bus. Average consumption of natural gas amounted to 25.54 m^3/100 km, i.e. 30.37 m^3/100 km in each respective direction. The amount of gas in reservoirs was read off while the bus was operated in intercity conditions; to be more precise, partial operation of the bus in urban conditions within these itineraries was excluded from the analysis. These results were partially published in 2003 (Stevanović 2003) and described in detailed in 2012 (Ivković *et al.* 2012). Fuel consumption of diesel bus is calculated by applying Equations (3) and (4) on the same itineraries. According to Ivković *et al.* (2012), accepted values for the whole road network are: FEq = 1.031 for CNG1 and CNG2 buses. Fuel consumption of CNG3 buses is higher than CNG1 buses by 5% (Hesterberg *et al.* 2008). Therefore, the adopted value for this bus concept is FEq = 1.082. Based on the determined values of fuel equivalents, we have established the correlation between experimental data and calculated data of fuel consumption of CNG buses (Equation (1)).

2.4. CO_2 emission factors of CNG and diesel buses

CO_2 emission factors of CNG buses comprise CO_2 emission [gr/consumed m^3] of NG. CO_2 emission factors of CNG buses have been adopted according to Pelkmans *et al.* (2001): $EMF_{CO_2} = 2403\,gr_{CO_2}/m^3$ NG for CNG2 buses, $EMF_{CO_2} = 2352\,gr_{CO_2}/m^3$ NG for CNG3 buses. The data are compatible since they have been obtained based on the on board measures of CO_2 emissions under real operating conditions in intercity transport. $EMF_{CO_2} = 2157\,gr_{CO_2}/m^3$ NG is the value adopted for the concept – CNG1 bus. This value is less than the EMF_{CO_2} value of CNG2 bus since the concept CNG1 bus does not include TWC converter. Namely, TWC converter reduces NO_x, CO and HC emissions, while on the other hand its by-product is the increase in CO_2 emission. According to the Hesterberg *et al.* (2008) research, TWC converter causes CO_2 emission to increase by about 9%, which is taken into account when setting the EMF_{CO_2} value for CNG1 bus. In order to ensure comparison and carry out analysis of external costs of CO_2 emissions of CNG buses and conventional diesel buses, the following CO_2 emission factors have been adopted for diesel buses: $EMF_{CO_2} = 2603\,gr_{CO_2}/\text{ltr diesel}$ for Diesel1 buses (Pelkmans *et al.* 2001), $EMF_{CO_2} = 2917\,gr_{CO_2}/\text{ltr diesel}$ for Diesel2 buses (Hesterberg *et al.* 2008).

2.5. Unit values of external costs of CO_2 emission

The unit values of external costs of CO_2 emission are obtained from Maibach *et al.* (2008): 25 €/tonne CO_2 for 2010, 40 €/tonne CO_2 for 2020, 55 €/tonne CO_2 for 2030, 70 €/tonne for 2040 and 85 €/tonne CO_2 for 2050. According to these values, unit values of external costs of CO_2 emission for particular scenarios are adopted: =19 €/tonne; $ec_{CO_2(2015)}$ = 32.5 €/tonne CO_2; $ec_{CO_2(2030)}$ = 55 €/tonne CO_2.

2.6. Annual and average external costs of CO_2 emissions

Annual external costs of CO_2 emissions of CNG buses for the whole road network for scenario *j* are obtained by summing annual external costs of CO_2 emissions for all road sections according for the scenario *j*:

$$EC_{CO_{2j}} = \left(\sum_{i=1}^{n} FC_{CNG_i} \cdot EMF_{CO_2} \cdot ec_{CO_2} \right)_j. \quad (6)$$

Average external costs of CO_2 emissions per 100 bus-kms for different bus concepts for scenario *j* are calculated:

$$AEC_{CO_{2j}} = \frac{EC_{CO_{2j}}}{Bus_{kms\,j}} \cdot 100. \quad (7)$$

3. Results and discussion

3.1. Basic indicators of transport and traffic in the road network

Table 3 presents traffic volumes based on the methodological step three, and they refer to the transport results achieved for the whole road network according to the relevant scenarios.

According to scenario BS2006, 7974 million veh-kms was the total transport volume achieved by all vehicle categories in 2006. Passenger cars had the highest share in the total transport volume, while buses reached the transport volume of 259 million veh-kms.

According to the scenario CS2015 forecast, the total transport volume in 2015 will increase in comparison with the one in 2006 by 27.36%, i.e. it will reach 10156 million veh-kms. Increase of the transport volume has been recorded for each vehicle category, and for the buses it records 21.49%. Both unchanged road conditions on the whole road network and increased transport demands lead to the increase of flow/capacity ratio on the road sections. Therefore, the average operating speed for the whole road network per all vehicle categories is decreased, for

Table 3. Transport demands on the road network according to various scenarios [×1000 veh-kms]

Scenario	Passenger cars	Buses	Total passenger vehicles	Light-medium trucks	Heavy trucks	Articulated trucks	Total freight vehicles	Total all vehicles
BS2006	6595228	259058	6854286	300976	349253	469890	1120119	7974405
CS2015	7964137	314731	8278868	504493	585415	787625	1877533	10156400
PS2030	21586620	320326	21906945	764913	887607	1194198	2846718	24753664
OS2030	25346956	213088	25560044	734691	852536	1147014	2734240	28294285

buses from 62.83 to 60.62 km/h. The average operating speed for the whole road network for vehicle categories *k* is calculated as follows:

$$V_{AVG_k} = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} \frac{L_i}{V_{op_{k_i}}}}. \quad (8)$$

According to scenario PS2030, the achieved transport volume will record increase concerning all vehicle categories in 2030, in comparison with 2015. With regard to the matter, passenger cars will be leading, while 1.78% will be the rate of increase for buses. Considerably less percentage of the increase of bus-kms, in comparison with the increase of passenger car veh-kms, indicates that passengers will opt for another choice when it comes to the means of transport for trips. Besides, increase of flow/capacity ratio for the whole road network will also be recorded in this period, and for that reason the tendency of decrease of average operating speed will continue, if compared to 2015. Decrease of average operating speed for all vehicle categories is about 25%. The causes for this all are minimal investments in the transport infrastructure, on the one hand, and increased transport demands, due to improved socio-economic indicators, primarily GDP, on the other hand.

Increase of the total traffic volume by 14.3% is typical for scenario OS2030 in comparison with scenario PS2030. Traffic volume of passenger cars increases by 17.42%, while the achieved bus-kms decrease by 33.48%. Even more striking redistribution of a certain number of passengers from one transport mode – by bus to another transport mode – by passenger car is due to the improvement of operating conditions on the road network made through the implementation of 13 potential developmental projects in the road sector, in comparison with scenario PS2030. Both the development of road infrastructure and redistribution of freight traffic flows from road to rail sector, due to the implemented rail infrastructural projects, lead to the decrease of flow/capacity ratio for the whole road network, in comparison with PS2030. This all causes an increase of average operating speed. $V_{AVG_{bus}}$ has increased from 44.99 km/h (PS2030) to 53.59 km/h (OS2030).

3.2. CO_2 emissions and external costs of CO_2 emissions on the road network

Table 4 shows annual CO_2 emissions in intercity bus service for different bus concepts, all according to various scenarios. These data, presented for the whole road network, are obtained by summing of CO_2 emissions for all road sections.

Judging by the data stated in Table 4, one can notice that, in all four scenarios, Diesel2 buses equipped with an OC converter have the highest CO_2 emissions on the road network. It is also obvious that all three concepts of CNG buses have lower total CO_2 emissions in comparison with conventional diesel buses, as well as that CNG1 buses are major contributors to the sustainable road transport.

According to scenario BS2006, Diesel2 buses have the emissions of 178.8 thousand tonnes per year for the whole road network, while Diesel1 buses without an OC converter emit by about 19.2 thousand tonnes less CO_2 per year. The lowest CO_2 emissions are typical for CNG1 buses; on the annual level, these buses have lower CO_2 emissions than Diesel1 and Diesel2 buses, namely by 42.47 and 23.23 thousand tonnes respectively. CNG2 and CNG3 bus versions also emit less CO_2 in comparison with both concepts of diesel buses. In addition, an OC converter makes the concept of CNG3 bus less efficient than CNG bus equipped with a TWC converter.

21.49% increase of the traffic volume of buses in comparison with 2006 is typical for scenario CS2015. As a consequence, there is higher fuel consumption on the whole road network, and thereby higher CO_2 emissions. Concepts of CNG1 buses and Diesel2 buses show the biggest difference in the emitted CO_2, at the amount of 51.86 thousand tonnes, while the less difference is to be seen between CNG3 buses and Diesel1 buses, at the amount of 4.34 thousand tonnes.

Scenario PS2030 foresees highest bus traffic volume in comparison with all other scenarios, which consequently means the highest quantity of the emitted CO_2. According to this scenario, the emitted CO_2 quantity will be higher by 31.92, 8.03 and 45.27% in comparison with the years 2006, 2015 and 2030 (OS2030), respectively. In this scenario, use of CNG buses in intercity bus services will ensure the most considerable reduction of CO_2 emissions. CNG buses decrease CO_2 emissions by 4.68…30.65 thousand tonnes in comparison with Diesel1 buses i.e. 30.07…56.03 thousand tonnes in comparison with Diesel2 buses.

As juxtaposed other scenarios, minimum CO_2 emissions are to be noticed in scenario OS2030, namely as a direct consequence of the realised minimum traffic volume of buses on the whole road network. Use of CNG1 buses ensures decrease of CO_2 emissions by 21.1 thousand tonnes in comparison with Diesel1 buses i.e. 38.56 thousand tonnes in comparison with Diesel2 buses. Use of CNG2 buses and CNG3 buses ensure lowest decrease of CO_2 emissions, both in comparison with appropriate diesel buses and also with all other scenarios, which have been taken into consideration.

Table 5 presents annual external costs of CO_2 emissions for different bus concepts according to various scenarios for the whole road network, calculated using the Equation (6). According to scenario PS2030, there will be maximum annual external costs of CO_2 emissions in 2030, as a consequence of the highest realised bus traffic volume, but also of the highest unit values of external costs of CO_2 emission.

According to scenario OS2030, higher annual external costs of CO_2 emissions for the whole road network in 2030, in comparison with 2006 and 2015, will come exclusively as a consequence of the increase in unit values of external costs of CO_2 emission, since the minimum CO_2 emissions is foreseen by the optimistic scenario for 2030.

Table 4. Annual CO_2 emissions for the whole road network for different bus concepts according to various scenarios [tonnes/year]

Scenario	CNG1 bus	CNG2 bus	CNG3 bus	Diesel1 bus	Diesel2 bus
BS2006	136358.29	151909.58	156040.49	159591.52	178832.95
CS2015	166494.69	185482.96	190526.84	194862.68	218356.65
PS2030	179872.21	200386.15	205835.29	210519.51	235901.17
OS2030	123812.72	137933.22	141684.07	144908.39	162379.52

Table 5. Annual external costs of CO_2 emissions for the whole road network for different bus concepts according to various scenarios [€/year]

Scenario	CNG1 bus	CNG2 bus	CNG3 bus	Diesel1 bus	Diesel2 bus
BS2006	2590807.42	2886281.98	2964769.26	3032238.88	3397826.10
CS2015	5411077.58	6028196.31	6192122.35	6333037.22	7096591.01
PS2030	9892971.64	11021238.22	11320941.12	11578573.15	12974564.21
OS2030	6809699.33	7586327.07	7792623.70	7969961.37	8930873.80

Table 6. Average external costs of CO_2 emissions per 100 bus-kms for different bus concepts according to various scenarios [€/100 bus-kms]

Scenario	CNG1 bus	CNG2 bus	CNG3 bus	Diesel1 bus	Diesel2 bus
BS2006	1.00009	1.11415	1.14444	1.17049	1.31161
CS2015	1.71927	1.91535	1.96743	2.01220	2.25481
PS2030	3.08841	3.44063	3.53420	3.61462	4.05043
OS2030	3.19572	3.56018	3.65699	3.74022	4.19116

Table 7. Average external costs of CO_2 emissions per 100 bus-kms for different bus concepts according to various scenarios [€/100 bus-kms, ec_{CO_2} from 2015]

Scenario	CNG1 bus	CNG2 bus	CNG3 bus	Diesel1 bus	Diesel2 bus
BS2006	1.71068	1.90578	1.95759	2.00215	2.24354
CS2015	1.71927	1.91535	1.96743	2.01220	2.25481
PS2030	1.82497	2.03310	2.08839	2.13591	2.39344
OS2030	1.88838	2.10374	2.16095	2.21013	2.47659

Table 6 shows average external costs of CO_2 emissions per 100 bus-kms for different bus concepts according to various scenarios calculated by Equation (7).

As expected, upon analysing Table 6 within all four scenarios, it has been confirmed that all three concepts of CNG buses, in comparison with conventional diesel buses, show better CO_2 emission performances, i.e. lower average external costs of CO_2 emissions per 100 bus-kms, as well as that CNG1 buses show the best CO_2 emission performances.

Table 7 shows calculated average external costs, according to adopted unit value of external costs of CO_2 emissions from 2015 for all four scenarios. This allows to eliminate the effect of change in unit value of external costs of CO_2 emission and to present only the effect of the change of operating conditions (traffic and road conditions) on average external costs of CO_2 emissions per 100 bus-kms.

Upon analysing Table 7, we have clearly noticed that, apart from the adopted higher unit value of external costs, an increase in the average external costs of CO_2 emissions has been affected by additionally altered operating conditions. Besides, it is noticeable that improvement of operating conditions does not always lead to the decrease in average external costs of CO_2 emissions. In fact, one can notice that average external costs of CO_2 emissions, realised in scenario with the lowest level of service (PS2030), are higher than the equivalent values realised in scenarios BS2006 and CS2015. Simultaneously, one can also notice that the highest average external costs of CO_2 emissions are related to scenario OS2030, which provides a higher level of service than in scenario PS2030. In other words, it is clear that implementation of developmental infrastructural projects in scenario OS2030 has caused average external costs of CO_2 emissions to increase in comparison with scenario PS2030. This can be reasoned by the fact that, even if the level of service has increased in terms of higher speeds achieved in particular road sections, buses consume more fuel just at such particular higher speeds, whereby average external costs of CO_2 emissions are higher.

Conclusions

CNG buses operating in intercity bus service incur less annual external costs of CO_2 emissions than conventional diesel buses. Percentage of decrease in annual external costs of CO_2 emissions ranges from 2 to 24%. If a bus is taken as an element of the transport system and as a direct consumer of fuel, the saving of external costs of CO_2 emissions will be higher or lower due to the use of CNG and it will depend on a technical-technological bus concepts, i.e. engine type, preparation mode of the combustion mixture and use of compatible devices for the after-treatment of exhaust gases. The lowest external costs of CO_2 emissions are recorded during the operation of CNG buses without the after-treatment of exhaust gases. Therefore, one can draw a conclusion that such buses are most adequate for intercity bus services, with respect to external costs of CO_2 emissions. CNG buses concepts equipped with OC converter or TWC converter emit less HC, CO and NO_x, which are not the primary causes of the global warming, but the emitted quantity of CO_2 increases due to chemical reactions, whereby external costs of CO_2 emissions increase as well. However, when such buses are put into operation, it is still possible to make less external costs of CO_2 emissions, especially if they substitute conventional diesel buses, which are also equipped with OC converter. In this case, annual external costs come less by about 12…15%.

Methodological approach presented in this paper has been carried out with regard to the four scenarios, distinct in the scope of transport demands within the road network, operating conditions and unit value of external costs of CO_2 emission. We can conclude that increase of the level of service through the realization of developmental infrastructure projects within the transport sector does not automatically mean decrease of external costs of transport; rather to the contrary, it can also affect an increase in external costs of CO_2 emissions for the whole network. The underlying reason for the aforementioned is increased operating speed of buses to the extent that average external costs of CO_2 emissions per 100 bus-kms (for the whole road network) increase in comparison with the equivalent external costs incurred due to the slower movement of buses caused by the lower level of service. In such a case, increased average external costs of CO_2 emissions especially relate to the road sections with higher design speed (about 90…100 km/h) and a small value of flow/capacity ratio.

In this paper, the analysis of external costs of CO_2 emissions for CNG buses has initially taken into account the following road and traffic conditions of particular road sections: speed in traffic flow, terrain configuration, international roughness index and correction factors of fuel consumption. Apart from these factors, the analysis can be extended to encompass other factors such as weather conditions, bus weight and number of passengers. In addition, one of the goals in the future research is to determine individual influence of each of the diverse factors, which were mentioned previously, on fuel consumption and external costs of CO_2 emissions for CNG buses.

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