SOME ENERGETIC AND ECOLOGICAL ASPECTS OF DIFFERENT CITY BUS DRIVE SYSTEMS

by

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This paper presents the analysis and comparison of energy and environmental properties of various city bus systems: diesel and compressed natural gas internal combustion engines, trolleybus, and battery electric bus. It is based on experimental research on fuel and energy consumption of city buses with aforementioned propulsion systems carried out under similar driving conditions – on the same city bus lines in Belgrade and Novi Sad, and on evaluation of energy efficiency and CO_2 emission of real electricity production in Serbia. In this way, "tank-to-wheel" and "well-to-wheel" energy consumption and CO_2 emissions of considered bus driving systems have been evaluated and compared. The results show all complexity of the matter since benefits of application of different systems largely depends on bus exploitation conditions and even more of the conditions of electric energy production. The compressed natural gas internal combustion engine compared to the Diesel engine provides obviously benefit in harmful gas emissions. However, CO_2 emissions are on a similar level, while energy efficiency is even less. Electric propulsion systems provide undoubtedly benefit in energy consumption, harmful gases and CO_2 emissions if tank-to-wheel conditions are considered, but well-to-wheel characteristics strongly depend on the condition of electric energy production.

Key words: *efficiency, internal combustion engine, electric vehicle, CO_2 emission*

Introduction

During the first few decades of development of road vehicles, at the end of the 19th century, electricity was the dominant driving power. In the second decade of the 20th century, in fact, when the electric starting of the engine was applied, internal combustion (IC) engines take up the primacy and to this day they are practically the exclusive source of driving power for road vehicles. The characteristics that made IC engine superior to alternative propulsion systems are: high specific power output, availability of fuel and good fuel economy, reliability in operation, reasonable price, *etc*. During the development that lasted longer than a century, these characteristics have been constantly improved so that the exclusivity of IC engine application has remained up to the present days.

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For many years, some negative characteristics of IC engines were ignored. However, when humanity became aware of the increasing environmental pollution, with significant share of motor vehicles, the development of IC engines, in addition to the performance, focused on their environmental characteristics: energy consumption, exhaust emissions, and noise.

In the field of protection against pollution from motor vehicles, the regulations limiting the emissions were adopted firstly in developed western countries and then practically all over the world [1]. These regulations have gradually become more and more severe and provoked very intensive development of technologies for engine emission control, for example: exhaust gas recirculation (EGR) and tree way catalyst (TWC) for spark ignition engines; EGR, diesel oxidation catalyst, selective catalytic reduction, and diesel particulate filter for Diesel engines. As the result, the emission of harmful gases has been drastically reduced, so that modern vehicles emission of harmful gases is on the level of only couple percent of the emission before the beginning of emission control. However, the additional problem is CO_2 emission, which is one of the main gases responsible for the greenhouse effect and global warming of the earth.

Another problem that has been increased in recent decades is the energy efficiency of vehicles because the road transport substantially participates in energy consumption. Energy efficiency is also in close connection with CO_2 emission control.

All these problems have led to intensive research of alternative fuels application and alternative propulsion systems. These alternative systems include: gas turbine, steam engine, Stirling motor, Wankel motor, *etc*. Lately, the research efforts have concentrated to the application of fuel cells, hybrid drive and purely electric drive. Fuel cells technology has not yet reached any commercialization, primarily due to the extremely high prices.

The development of hybrid propulsion systems is much more advanced and renowned manufacturers of vehicles have included models with hybrid drive in their commercial offer. Hybrid drive system includes in addition to IC engine an electric motor and a battery for storing electric energy. The IC engine powers a generator that charges the battery and the wheels of vehicles are powered with electric motor (serial hybrid). In another variant, besides electric motor the wheels are powered with IC engine, if necessary (parallel hybrid). Although good fuel economy and low emissions of hybrid drive has been proven in practice, hybrid vehicles for now occupy practically insignificant share of the fleet of vehicles, primarily due to their still high prices. There are also hybrid vehicles with the possibility of battery charging by connecting to electric network (so called *plug-in hybrid*).

The research and development of pure electric drive vehicles was strongly motivated by their environmental characteristics (*zero emission* and low noise) and some attempts date from 1970 [2]. Research efforts are numerous and the examples are: La Roshelle (France), Berlin and island Rugen (Germany), Mendrisio (Switzerland), Amsterdam (Holland). However, the problems such as: great weight, high costs, small battery capacity and consequently small driving autonomy, long period of charge and necessity of battery replacement, did not allow practical application. Last decade, the interest for electric vehicles has significantly grown, primary due to the development of a new battery systems, and a lot of manufacturers of passenger cars, and even city buses, have included in their offer the vehicles with purely electric drive.

Energy efficiency and emission characteristics of electric vehicles

Electrically driven vehicles are without a doubt energy efficient and with *zero emission*, if so called tank-to-wheel (TTW) efficiency and emission are considered. In other words, the vehicle itself is very efficient and does not produce any emission. However, the whole process of electricity production and transmission to the battery charging place should be taken into account and so called well-to-wheel (WTW) efficiency and emission are important in order to estimate global impact to the environment. With respect to the protection of the environment, only CO_2 emissions will be evaluated and compared in this paper. The reason is that the emission of harmful pollutants (CO, HC, NO_x, PM, *etc.*) can be very efficiently reduced and controlled by modern technologies, especially in the field of motor vehicles. On the other hand, CO_2 emissions can not be reduced by any technology since it is a product of complete combustion of carbon in fuel, and the only possibility is to reduce fuel consumption or to use fuel with less carbon content.

While the efficiency and exhaust emission of the vehicles driven by IC engines are more or less similar in all countries, especially in developed countries, the efficiency and emission of electricity production vary largely, even in these countries. The production of electric energy can be in thermal power plants (TE) with various fuels: coal, oil fuel or gaseous fuel, with different efficiency and emission. On the other hand, hydro, and nuclear-electric plants do not produce any emission, which is even more the case when using the energy of Sun or wind. In most countries, electricity production is a combination of several different systems. Therefore, the comparison of efficiency and emission of conventional drive and electric drive can largely vary from country to country. As the illustration, fig. 1 shows the *standard CO_2 emission factors* and *life cycle assessment (LCA) emission factors* of electricity consumption of EU countries [3]. The authors added standard and LCA CO_2 emission factors of Serbia calculated on the bases of data given in next section of this paper. Standard emission factor includes only the emission that occurs directly or indirectly due to electricity production within local authority while LCA emission takes under consideration all emissions of the supply chain (fuel exploitation, transport, processing, *etc.*).

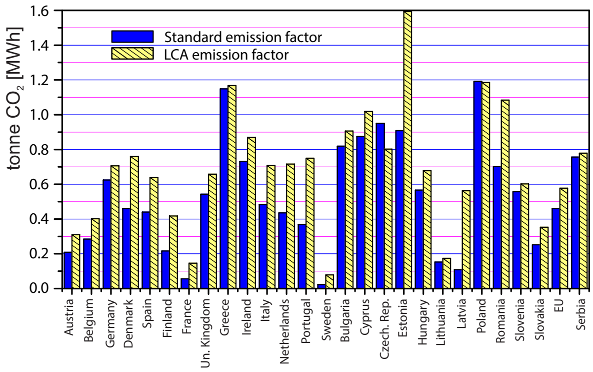


Figure 1. Standard CO_2 emission factors and LCA emission factors of the EU countries [3]

As it can be seen, the variations of emission factors between countries are extremely high, from very low in the countries with predominantly nuclear, or hydro-electricity production (France, Sweden) to very high in the countries with TE (Greece, Poland).

Figure 2 shows the benefit in CO_2 emission of electric and hybrid city buses *vs*. diesel bus (Euro 5) as a baseline [4]. The source is the report of Ricardo Institute, one of the world leading institutions in the field of IC engines and motor vehicles research. The estimation is based on United Kingdom current CO_2 specific emission of electricity production of 164 g CO_2 eq/MJ (590 g/MWh). The estimated WTW benefit of approximate 30% in the case of battery electric buses is significant. However, it implies the ability of electricity production with relatively low CO_2 emission.

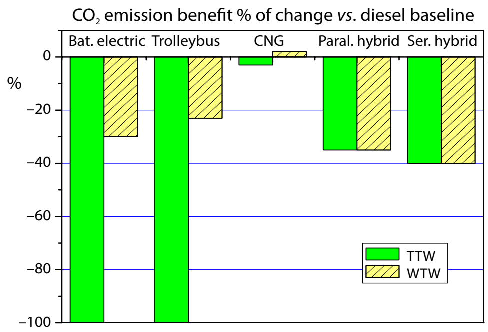


Figure 2. Comparison of WTW and TTW CO_2 emission benefits of alternative drive systems *vs.* diesel baseline [4]

Comparison of energetic and emission characteristics of electric and fossil fuel vehicles regarding the conditions in Serbia

For energy consumption and CO_2 emission evaluation in a particular country the estimation of whole energy supply chain efficiency is required. Figures 3 and 4 show the estimation of well-to-tank (WTT), TTW, and total WTW efficiencies in the cases of classic vehicle drive using IC engine and battery electric vehicle drive with respect to the condition in our country. These estimations are crucial for proper energy consumption and CO_2 emission evaluation and comparison of different vehicle drive systems.

In the case of diesel fuels the energy consumption WTT (exploitation, transport, and fuel processing) is usually estimated as approxomate 12.5% of fuel energy content at the well (or 14% of available energy in the tank) and the efficiency WTT can be estimated as 87.5% [3, 5]. The estimation of average TTW efficiency of Diesel engines in city bus driving conditions is a very complex task. The efficiency of modern bus Diesel engines achieves 35-45% at engine optimal operating point. Under city bus driving conditions the efficiency is much lower. Having in mind the age of vehicle fleet in our country, the estimation of average efficiency in exploitation 28 % seems to be reasonable.

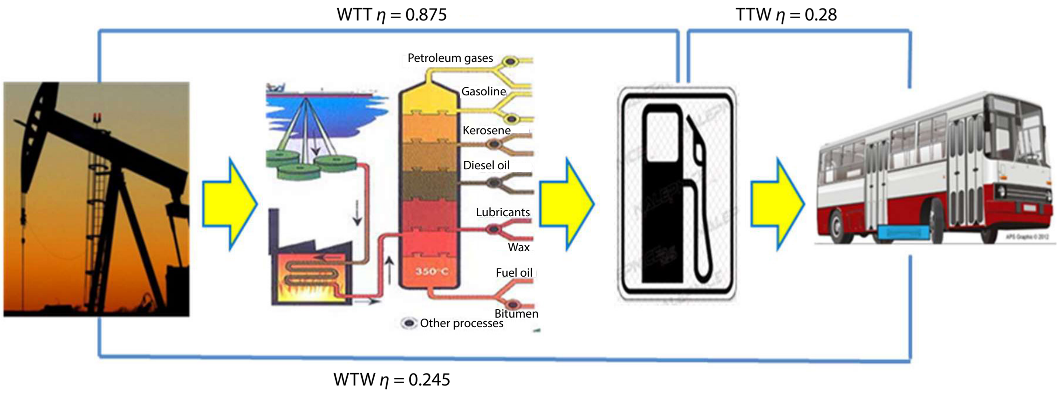
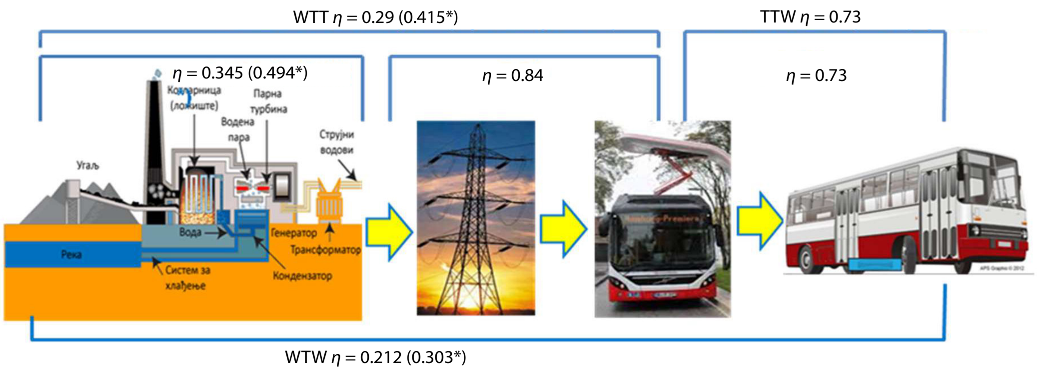


Figure 3. The estimation of whole supply chain average efficiency in the case of diesel IC engine city bus drive (fuel exploitation, transport, processing, and combustion)



* fictive overall efficiency when electricity production TE and HE plants is considered

Figure 4. The estimation of whole energy supply chain average efficiency in the case of battery electric city bus drive (electricity production, electricity transmission and distribution network, battery charging and electric motor); in parentheses a fictive overall thermal efficiency is calculated using total electric energy production (TE + HE) and coal consumption in TE plants

In the case of battery electric vehicle, fig. 4, the WTT efficiency consists of the efficiency of electricity production in electric plants and the efficiency of electricity transmission network. The assessments are based on the actual situation in our country. The average efficiency of TE is approximate 34.5% (see tab. 1). The data for electricity transmission losses in different countries can be found in the report of World Bank [6]. According to this data the electricity transmission losses in our country are approximate 16%. The average efficiency of battery electric drive TTW can be estimated at the level of 73% [5]. This includes: approximately 88-90% for the charger and 85-95% for the charging and discharging cycle with lithium batteries, 96-98% for the electronic engine management, and 90-95% for the electric motor.

For the evaluation of WTW energy efficiency and CO_2 emission of city buses with electric drive, the data of electricity production, fuel (coal) consumption and coal characteristics are required. The emissions of CO_2 are calculated under the assumption that the entire carbon from the fuel is burned into CO_2. In other words the emissions of CO and unburned HC are neglected as much smaller. In this case CO_2 emission can be calculated using very simple relation:

$$m_{CO_2} = m_f g_c \frac{44}{12} \tag{1}$$

where m_{CO_2} is the mass of CO_2, m_f – the mass of fuel burnt, g_c – the mass content of carbon in fuel, and 44 and 12 molar masses of CO_2 and carbon, respectively.

The CO_2 emissions of city buses with conventional drive using IC diesel and CNG engines are calculated in the same way.

Electricity production conditions in Serbia

Table 1 shows the production of electricity and the quantity of coal used in 2015 in Serbia. Data were taken from the official annual report of the Electric Distribution Company of Serbia [7]. These data can be considered as a representative of the state of electricity production in our country, since for many years the share was approximately 70% in TE and 30% in HE, with very small deviation.

Table 1 also shows the calculated values for thermal efficiency and specific CO_2 emissions based on data for coal characteristics from relevant literature [8]. Thermal efficiency for total electricity production is fictive, calculated as the ratio of total energy produced (TE + HE) divided by the chemical energy content of coal used in TE. In TE it is assumed that 3% of energy is used for extraction, preparation and transport of coal [3], and this has been taken into account.

Table 1. Electric energy production and coal consumption in Serbia 2015, source [7]; calculated CO_2 emission from TE in Serbia 2015; source for coal mass analysis [8]

	Units	TE			HE	Total TE+HE
		TENT	Kostolac	Total TE		
Produced electric energy	GWh	19028	5989	25017	10599	35616
Quantity of coal (lignite)	t	27695581	8189724	35885305		
Carbon content	$kgCkg^{-1}Fuel^{-1}$	0.198	0.221	0.2035		
Net (lower) caloric value	$MJkg^{-1}$	6.8	8.0	7.08728		
Thermal efficiency	–	0.353	0.3192	0.345		0.494*
CO_2 emission	t	20106992	6636406	26743398		26743398
CO_2 LCA emission factor of electricity production	$gkW^{-1}h^{-1}$	1089	1142	1102		774

* Fictive global thermal efficiency of electricity production (calculated as total produced electric energy divided by chemical energy of used coal in TE plants).

Experimental results of fuel and energy consumption measurements

The testing of fuel and energy consumption was realized in the cooperation of the Vinca Institute of Nuclear Sciences VINCA and City Public Transport Company of Belgrade. By analysing topography of the lines of public city transport in Belgrade, including the available infrastructure, from the aspect of future development of appropriate systems for fast charging of electric buses and trolleybus, line 41 (Studentski trg-Banjica II) was selected. This line was considered to be appropriate for testing the buses having different bus subsystems including fully electric bus. The experimental measurements of energy consumption were taken on the line 41 for three different bus subsystems: diesel bus (IK-112N), trolleybus (BKM-321), and fully electric bus (BYD E-12).

Fuel consumption measurement of diesel bus was realized using flow-meter MR 1000 which registers the difference between fuel-flow toward the engine and back flow to fuel tank. The display of the instrument is digital and the accuracy is ±0.25%. In addition, fuel tank filling and discharging depending on the route travelled was precisely monitored and compared with flow-meter reading.

The measurement of electric energy consumption of trolleybus was carried out using the direct current meter that is built into this type of trolleybus. The accuracy class of the counter is ±0.5 % and it registers both the consumed electricity (withdrawn from the net) and the return eclectic energy due to the recuperation.

In the case of battery electric bus the measurement of electric energy consumption was realised by precise registering of battery state of charge using incorporated battery management system depending of the distance travelled. The accuracy of reading is 1% and the methodology E-SORT (Cycles for electric vehicles) was applied.

The results of fuel and energy consumption measuring are analysed and already published [2]. In [2] can be also found more details about city line 41 characteristics and topography and test procedure. Here only basic characteristics of the buses and final experimental results that were used for the analysis of environmental impact in relation to the conditions of electricity production are given in tabs. 2-4. The results of fuel consumption of diesel bus, tab. 2, and battery electric bus, tab. 4, are the average of six measurement in both directions (approximate 58 km), while the results of trolleybus energy consumption, tab. 3, are the average of the whole working day (245 km).

Comparative testing of fuel consumption of city buses with diesel and CNG drive systems was comprehensive and carried out with several diesel and CNG buses of different manufacturers. This investigation was realized in cooperation with the Institute of Nuclear Sciences

Table 2. Technical characteristics of diesel bus and the results of fuel and energy consumption measurements [2]

Diesel bus IK-112N								
Technical characteristics							Experimental results	
Engine	Power [kW]	Torque [Nm]	Gear box	Length/ Width/ Height [mm]	Curb weight [kg]	Vehicle capacity	Fuel consumption [l/100 km]	Energy consumption [kWhkm^{-1}]
MAN D2066 LOH 201 Euro 4	235	1100	VOITH D 864.5	11940/2525/2802	12090	105	48.2	4.82

Table 3. Technical characteristics of the trolleybus and the results of energy consumption measurements[2]

Trolleybus BKM-321						
Technical characteristics					Experimental results	
Electric motor drive	Power [kW]	Length/ Width/ Height [mm]	Curb weight [kg]	Vehicle capacity	Energy consumption with heating [kWhkm^{-1}]	Energy consumption without heating [kWhkm^{-1}]
Asynchronous	180	11825/2550/3680	11100	101	1.796	1.46

Table 4. Technical characteristics of battery electric bus and the results of energy consumption measurements [2]

Battery electric bus BYD E-12							
Technical characteristics							Experimental results
Electric motors	Power [kW]	Torque [Nm]	Length/ Width/ Height [mm]	Curb weight [kg]	Battery capacity LiFePo4 [kWh]	Autonomy [km]	Energy consumption [kWhkm^{-1}]
Asynchronous AC	2 x 90	2 x 350	12000/2550/3360	14300	324	250	1.24

Table 5. Technical characteristics of diesel bus and the results of fuel and energy consumption measurements [9]

Diesel bus IVECO IRISBUS CROSSWAY LE						
Technical characteristics					Experimental results	
Engine	Power [kW]	Gear box	Vehicle capacity	Emission standard	Fuel consumption [l/100 km]	Energy consumption [kWhkm^{-1}]
Iveco Cursor 8	243	VOITH D 864.5 automatic	101	Euro 5	45.4	4.54

Table 6. Technical characteristics of CNG bus and the results of fuel and energy consumption measurements [9]

CNG bus SOLARIS Urbino 12							
Technical characteristics						Experimental results	
Engine	Power [kW]	Gear box	Vehicle capacity	Exhaust after treatment	Emission standard	Fuel consumption [kg/100 km]	Energy consumption [kWhkm^{-1}]
Iveco Cursor 8	200	Automatic Voith Diwa 854.5	91	TWC	Euro 5	42.6	5.78

VINCA, City Public Transport Company of Belgrade, and City Public Transport Company of Novi Sad. The results were analysed and published in [9] where also can be found the detailed characteristics of tested buses and selected city lines in Belgrade and in Novi Sad, as well as the test procedures. Among the results published in [9], here are selected those obtained on line 9 in Novi Sad, because the measured fuel consumption of the diesel bus is more similar and thus comparable with the results for the diesel bus given in tab. 2. Tables 5 and 6 show basic bus characteristics and results of fuel consumption measurements for diesel and CNG buses tested on line 9 in Novi Sad.

Evaluation and comparison of energy efficiency and CO_2 specific emission with respect to the conditions of production of electricity

Based on the fuel and energy consumption measurements given in tabs. 2-4, and the characteristics of production of electricity, tab. 1, the TTW and WTW efficiency and specific CO_2 emissions were evaluated and the results are shown in tab. 7. For battery electric bus, the measured energy consumption is increased by 10%, since the measurements were based on battery discharge, and the TTW energy losses include charger and battery efficiencies, which were not taken into account here. These losses are estimated at 10%. In the case of trolleybus, the energy consumption measured on the vehicle is increased by 5% (estimated losses in the rectifier station). For diesel bus, the same energy for vehicle traction and auxiliary devices is assumed as for a trolleybus without energy recuperation. Although relatively realistic, these assumptions are still arbitrary and the purpose is only rough estimation of global efficiency.

Table 7. The TTW and WTW energy consumption and CO_2 emission for bus drive systems under consideration; situation without vehicle heating

	Units	Diesel bus	Trolleybus	Battery of electric bus
Fuel (diesel) consumption TTW	kgkm^{-1}	0.4035		
Energy consumption TTW	kWhkm^{-1}	4.82	1.46/0.95 = 1.54	1.24/0.9 = 1.38
Fuel (diesel) consumption WTW	kgkm^{-1}	0.4609		
Energy consumption WTW	kWhkm^{-1}	5.5		
Energy consumption at electric plant	kWhkm^{-1}		1.83	1.643
Fuel (coal) consumption WTW (electricity production TE+HE)	[kgkm^{-1}		1.9	1.705
Energy consumption WTW	kWhkm^{-1}		3.74	3.356
Overall efficiency WTW	–	0.317*	0.467	0.52*
Specific CO_2 emission WTW	gkm^{-1}	1453.4	1417	1272
WTW CO_2 emission benefit (% of change *vs*. diesel baseline)	%	0	–2.5	–12.5

* For diesel bus and battery electric bus the same energy for vehicle traction and auxiliary devices is assumed as for trolleybus without energy recuperation

Lower heating values and carbon contents of diesel fuel and CNG used for efficiency and CO_2 specific emission evaluation are given in tab. 9.

As expected, the energy efficiency of electric driven vehicles is much better. It should be noticed that evaluated values of efficiency are greater than the estimations based on the literature and given in the section *Comparsion of energetic and emission characteristics of eletric and fosill fuel vehicles regarding the conditions in Serbia*, figs. 3 and 4, especially for electrically driven vehicles. The reason could be the fact that the estimations in this section for electric drive do not include energy recovery by vehicle braking. According to the results reported in [2] recuperated amount of energy in the case of trolleybus was at the level of 13.7%. The advantage in TTW CO_2 emission is 100% since TTW emission of electric vehicles is zero.

When considering WTW efficiencies and CO_2 specific emissions, the situation is rather different. The benefits in WTW CO_2 specific emissions, specified as percent of change *vs*. diesel bus baseline, are graphically shown in fig. 5(a). The figure also shows the benefits of

CO_2 specific emissions for CNG bus evaluated in tab. 9. Electric vehicles are still in advantage (trolleybus –2.5% and battery electric bus –12.5%) but the difference is relatively small, as the consequence of the actual conditions of production of electric energy.

It is interesting that if WTW CO_2 specific emissions of tested vehicles were calculated with specific CO_2 emission of electricity production in Great Britain, 590 g/kWh (as in example in fig. 2), instead of 774 g/kWh what is actual for our country, the results for benefit in CO_2 emission of electric vehicles would be similar as in example given in fig. 2 (–33% for battery electric bus and –26% for trolleybus).

Table 3 contains the data for energy consumption of trolleybus with vehicle heating. This provides the possibility to compare energy consumption and CO_2 emission under winter conditions. The testing of battery electric bus was carried out in summer part of the year and energy consumption for vehicle heating was not included in overall consumption. According to the first approximation, it can be assumed that required energy for heating electric bus can not much differ than in trolleybus. In the case of the buses driven by IC engine (diesel and CNG), vehicle heating is realized using engine waste heats (for engine cooling and exhaust gases), and there is no additional fuel and energy consumption for this purpose. Table 8 shows the results when trolleybus and battery electric bus energy consumption is with vehicle heating. As can be seen the situation is quite different than in the case without heating. The advantage of WTW energy efficiency is still on the side of electrically driven vehicles, although the difference is smaller, but WTW specific CO_2 emission is greater than for diesel and CNG buses. The results of the change of WTW specific CO_2 emission expressed as the percentage versus diesel baseline are shown in fig. 5(b).

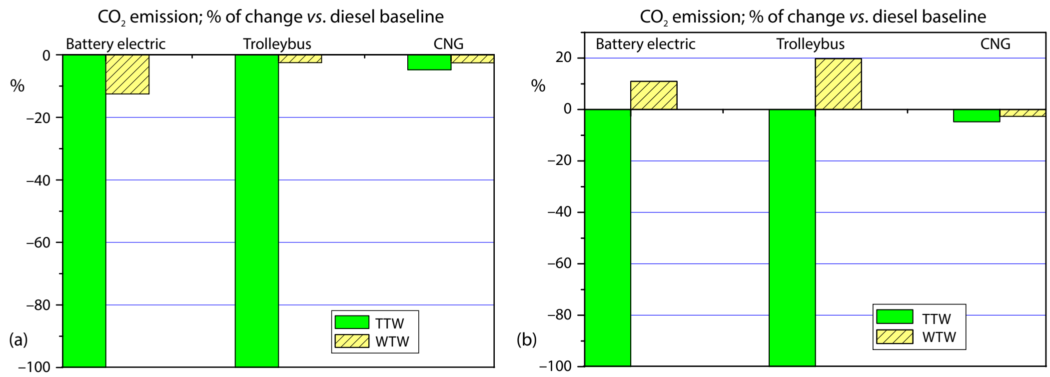


Figure 5. Comparison of WTW and TTW CO_2 emission benefits of considered drive systems *vs.* diesel baseline; (a) situation without vehicle heating, and (b) situation with vehicle heating

The previous consideration takes into account only the energy consumption and the CO_2 emission in the phase of vehicle use. In order to make complete comparison of energetic and environmental characteristics of different driving systems (LCA analysis), it is necessary to take into account energy consumption and equivalent CO_2 emission of vehicle manufacturing and recycling. Although precise data are hardly accessible, especially for city buses, it is known that the manufacturing of electric vehicles requires more energy and produce higher equivalent CO_2 emission, especially the production of batteries. According to some data for passenger cars [10, 11], electric vehicles have approximative twice higher equivalent CO_2 emission in manufacturing phase. The manufacturing of classic car with IC engine is associated with approximative 43 g CO_2-eq/km (grams CO_2 equivalent per kilometre, projected to expected vehicle

Table 8. The TTW and WTW energy consumption and CO_2 emission for bus drive systems under consideration; situation with vehicle heating

	Units	Diesel bus	Trolleybus	Battery electric bus
Fuel consumption TTW	l/100 km	48.2		
Fuel consumption TTW	kgkm^{-1}	0.4035		
Energy consumption TTW	kWhkm^{-1}	4.82	1.796/0.95 = 1.89	1.576/0.9 = 1.751*
Fuel (diesel) consumption WTW	kgkm^{-1}	0.4609		
Energy consumption WTW	kWhkm^{-1}	5.5		
Energy Consumption at electric plant	kWhkm^{-1}		2.25	2.084*
Fuel (coal) consumption WTW (electricity production TE + HE)	kgkm^{-1}		2.34	2.163*
Energy consumption WTW	kWhkm^{-1}		4.55	4.22*
Specific CO_2 emission WTW	gkm^{-1}	1453.4	1742	1613*
WTW CO_2 emission benefit (% of change versus diesel baseline)	%	0	+19.8	+11.0*

* The energy required for vehicle heating is assumed to be the same as for trolleybus

Table 9. The TTW and WTW energy consumption and CO_2 emission for diesel and CNG bus driving under consideration

	Units	Diesel bus	CNG bus
Fuel consumption TTW	l/100 km	45.4	
Fuel consumption TTW	kgkm^{-1}	0.38	0.426
Fuel consumption WTW	kgkm^{-1}	0.434	0.498
Lower heating value	MJkg^{-1}	43	48.8
Energy consumption TTW	kWhkm^{-1}	4.54	5.78
Energy consumption WTW	kWhkm^{-1}	5.18	6.76
Fuel carbon content	kgCkg^{-1}Fuel^{-1}	0.86	0.73
Specific CO_2 emission TTW	gkWh^{-1}	1198.3	1140.3
TTW CO_2 emission benefit (% of change *vs.* diesel baseline)	%	0	–4.8
Specific CO_2 emission WTW	gkWh^{-1}	1368.5	1333.0
WTW CO_2 emission benefit (% of change *vs.* diesel baseline)	%	0	–2.6

lifespan 150000 km). In the case of electric vehicle this is 87-95 g CO_2-eq/km, of which battery production contributes roughly 40%. For each kilowatt-hour storage capacity in the battery, emissions of 150 to 200 kilograms of CO_2 equivalent are generated, already in the factory [11].

With average European CO_2 LCA emission factor of electricity production it is further estimated that from its production until its retirement, un electric vehicle still produce 10-12% less equivalent CO_2 emission than an diesel powered car [10]. Based on these data and with supposed average diesel car fuel consumption and average electric car energy consumption, simple calculation shows that with the purpose to estimate car total equivalent CO_2 emission (manufacturing and operating phases), the operating emission should be increased by approximate 20-25% for diesel car and even by approximate 70-75% for electric car.

Of course, upper analysis can not be simple applied in the case of city buses. First, city buses have far longer operating lifespan and consequently the contribution of manufacturing phase CO_2 emission per kilometre is less. On the other hand, estimated battery lifespan (150000 km) is too optimistic and during city bus operating lifespan batteries probably should be changed several times, what, as already said, generates additional considerable contribution to CO_2 emission. Although without relevant data it is hard to precisely quantify the contribution of manufacturing phase to total city bass CO_2 emission, it certainly considerable decrease positive environmental effects of electric drive application.

Recycling of electric vehicle batteries is, as a whole, expensive yet feasible. There is little incentive for manufacturers to recycle electric vehicles batteries when Lithium – their *main ingredient* – costs five times more to recycle than to produce [10].

The results for diesel and CNG buses are shown in tab. 9. The benefit of CO_2 specific emissions for CNG bus is graphically shown in fig. 5, together with electric vehicles. As can be seen, the advantage in CO_2 emission of CNG bus is a very small percentage, despite considerable lower carbon content in fuel as a consequence of higher fuel consumption.

Conclusions

- Trolleybus and battery electric bus have much better TTW efficiency than the buses with IC engines (diesel and CNG). Considering WTW efficiency, electric vehicles are still more efficient, but the difference is much smaller.
- Trolleybus and battery electric bus have zero TTW CO_2 emission. However, under the current conditions of electric energy production in our country their WTW CO_2 emissions are just slightly lower than the buses with IC engines (diesel and CNG). Comparing WTW CO_2 emissions of diesel and CNG buses the advantage of CNG is very small as a consequence of higher fuel consumption.
- The situation is quite different during winter conditions when additional energy for vehicle heating is required. The buses with IC engine use for heating engine waste heat (cooling heat and exhaust gases heat), while electrically driven vehicles must use a considerable amount of additional energy for heating. The advantage in efficiency is still on the side of the electric vehicle, but the difference is smaller. Under these conditions, WTW CO_2 emissions of electrically driven vehicles are even higher compared to the buses with IC engines.
- All upper conclusions do not include energy consumption and CO_2 emission of vehicle manufacturing end recycling. This part of environmental impact is considerably less favourable for electric vehicles and this fact should be taken into account for total LCA comparison of different city bus driving systems.
- All comparisons are made considering the current situation of electricity production in our country: 70% in TE, with coal (lignite) as a fuel, and app. 30% in HE. The chances for a significant increase in hydro potentials are very small and only real possibility of increase of electricity production in the foreseeable future is through TE. This means that with the increase of the share of electricity production in thermal plants, the advantages of electric vehicles will decrease, especially under winter conditions of vehicle exploitation.

Nomenclature

CNG – compressed natural gas
HE – hydro-electric plants
IC – internal combustion
LCA – life cycle assessment
PM – particulate matter
TE – thermal power plants
TTW – tank-to-wheel
TWC – tree way catalyst
WTT – well-to-tank
WTW – well-to-wheel

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