THEORETICAL ANALYSIS OF THE CUMULATIVE COSTS OF DIFFERENT DIESEL BUS ALTERNATIVES FOR A PUBLIC TRANSPORT IN THE CITY OF BELGRADE

by

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This paper includes comparative analysis of the environmental, energetic, and financial costs of different bus propulsion, possibly applied on the public transport in the city of Belgrade. It considers the modern diesel bus, the trolleybus, the natural gas bus with the spark ignition engine, the electric bus using $LiFePO_4$ *battery, and the electric bus with ultra-capacitor. The results are presented according to the real data and the real electro-energetic situation in Serbia, with the dominantly used lignite coal as primary fuel. This model gives the exact exhaust emission of electric vehicles at the thermal power plant, enables its comparison to the internal combustion engine vehicles. The result in analysis shows that the natural gas bus is the most cost efficient in economical way with overall exploitation price of $87 per 100 km. The trolleybus is more economical then the natural gas powered bus only at high departures rate, higher than 230 per workday.*

Key words: *electric bus, trolleybus, exhaust emission, natural gas propulsion, thermal power plant*

Introduction

Every city with developed public transport needs to do periodical studies about its economic efficiency. Today it is necessary, due to constant technological and market changes. The means of public transport are the capital investments and their choice affects all citizens. It should be done with the scientific and engineering correctness.

Buses are still the core of public transport in Europe, mainly due to the initial price of vehicles as well as the low cost of infrastructure [1]. Today, the choice of bus types and models is so wide, that it is impossible to say which one is the best. A complex algorithm is needed to calculate the optimum for specific transport route. Modern trends force us to think not pure financially, but economically accounting social and ecological costs of transport.

The accent will be on the Belgrade's public transport which mainly uses the diesel buses and the trolleybuses considering all bus types. City owned public transporter decided to buy the five new electric buses powered by ultra-capacitor [2]. The purpose of this paper is to make contribution, dealing with the technical and economic analysis of the problems, to the proper assessment when deciding on the choice of the best variants of the power system at the moment. Some alternative bus propulsion systems will be considered which could possibly

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exchange the diesel ones in the term of economic feasibility. This work will not consider all available the new technologies, but at the already existing technologies which could be applied at our transportation system. Therefore, a brief comparative analysis will be provided where several types of buses will be considered: the electric bus with electrochemical accumulator, the electric bus with ultra-capacitive accumulator, the CNG bus with spark ignition engine, and the trolleybus.

Despite controversies, the trolleybus is still popular means of transport in many European countries [3]. It will be the only bus type where infrastructural cost will be added to cumulative financial costs, rather than the other electric bus types.

This paper gives realistic scenario for Serbia, where lignite coal is used as main energy source for electricity production [4]. The major trends for global price changes will also be calculated in order to provide not only correct, but precise results. This analysis includes two concepts of public transportation costs:

- financial, the costs of vehicle, energy, and maintenance, and
- economic, the financial cost with added social costs (exhaust emission and noise).

The result is mainly achieved by mathematical calculations according to the main principles of physics, based on the well-known mechanic, thermodynamic, energetic, and economical equations.

A lot of well-known models [5, 6] were used and filled with the real data in order to present a clear output. For the simplicity of calculus, this work considers only 12 m long buses. The result will unambiguously show the most profitable bus for public transportation.

There are similar studies in many countries [3], but the uniqueness of every city imposes a separate one. It is important to understand that this work is strongly market-dependent. All variables are valued according Serbian conditions. The computations are done by noted models and the prices are dated on August 11th, 2016. Also, all specific numbers are stated for the public transport in Belgrade.

Proposed financial cost estimation methodology

The financial costs will be based on the energy prices, the vehicle amortization and maintenance, because only those parameters will change with the choice of the vehicle. The infrastructural cost will be neglected except for the trolleybus, where it has significant value.

Internal combustion buses

The first step is to calculate the fuel consumption for buses using internal combustion engines (IC-buses). The energy flow is shown at the schematics bellow, with major energy losses. It is known that the propulsion consists of the engine itself, clutch, and the transmission (in this work, the wheels and losses on them will not be considered as they are the same for all buses) and all of those parts have some energy efficiencies. The overall efficiency is:

$$\eta_c = \eta_{c1}\ \eta_{c2}\ \eta_{c3}\ \eta_{c4} \tag{1}$$

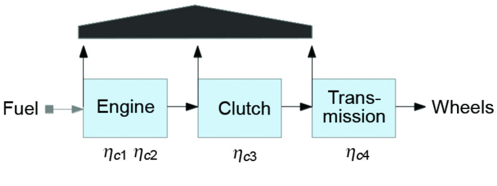

Figure 1. The IC-bus, energy losses

The needed data about buses are found from the catalog of engine and bus manufacturers, as well as from the exploitation, fig. 1. Coefficients η_{c1} and η_{c2} are both stated for engine efficiencies. Value η_{c1} is for the efficiency at full power corresponding from specific fuel consumption given by the manufacturer, and η_{c2} is the efficiency of the engine at variable load normalized to the full power efficiency [5]. Factor η_{c2} is calculated numerically from the graph of specific consumption provided by the engine manufacturer.

For diesel bus, the efficiency factors were calculated using the information from engine manufacturers MAN [7] and Cummins [8], for the engines: D0836LOH and ISB6.7e4245B. The rest of the data are provided by LiAZ [9], MAZ [10], and BIK for the vehicles: LiAZ 5256, LiAZ 5294, and MAZ 203. Calculated factors are:

- $\eta_{c1} = 0.4$ for modern engine at full power,
- $\eta_{c2} = 0.85$ for load variability during normal operation,
- $\eta_{c3} = 0.95$ for clutch due to heat losses, and
- $\eta_{c4} = 0.9$ at gearbox.

After multiplication of those factors, the value $\eta_c = 0.29$ was obtained, as overall efficiency of diesel propulsion.

For spark ignition gas engine the calculation is similar, just the efficiency of engine is different. According MAN and Cummins for the engines E0836LOH01 and CG8.3E4250, it is:

- $\eta_{c1}= 0.35$ for engine at full power and
- $\eta_{c2}= 0.75$ for load variability,

The numbers for clutch and transmission are the same, so the overall efficiency is: $\eta_c = 0.22$ for natural gas propulsion.

Basic equation for vehicles energy consumption is [11]:

$$\chi_t = \frac{e_w m}{\eta_p}, \qquad e_w = 80 \text{ Wh/kmt} \tag{2}$$

where η_p is the overall propulsion efficiency and the variable e_w is approximated for the road speed lower than 50 km/h.

Knowing average loaded single bus weights of about 16 tones and propulsion efficiency, those buses consume 4.41 and 5.82 kWh/km. In a fuel, it is respectably:

- 35 kg per 100 km of diesel, or
- 48 kg per 100 km of natural gas.

These results will be used further to calculate the exhaust emission. Sometimes, in practice, those numbers can differ a bit, depending on the engine model and driving conditions, but average numbers are similar. The actual prices of diesel fuel and compressed natural gas (CNG) are \$1.55 per kg and \$0.67 per kg. Implicated fuel costs of IC-buses are:

- \$54.25 per 100 km for diesel bus, and
- \$32.16 per 100 km for natural gas bus.

There are also maintenance costs and bus amortization costs. The IC-bus is considered as quality if maintenance price is not more than 25% of diesel fuel or 45% of CNG spends [12]. On the other hand, the bus amortization costs are not so easy to calculate. The prices of new Russian buses were used, LiAZ 5256 and LiAZ 52927x (CNG) as they are very competitive at our market. Their resource is about 800000 km and initial costs are \$140000 and \$180000, so the amortization prices are \$17.5 per 100 km and \$22.5 per 100 km. Adding all the aforesaid, the financial costs of IC-buses are:

- \$85.31 per 100 km for diesel bus, and
- \$69.14 per 100 km for CNG bus.

Trolleybus

Next step is a bit more complicated, as it is time for electric vehicles. Again, the start will be – propulsion [11], with energetic part which consists of the switching power supply, motor and differential, fig. 2. The efficiency coefficients of those parts are visible from the schematics. So, the cumulative efficiency of the propulsion is:

$$\eta_{tp} = \eta_{t2}\ \eta_{t3}\ \eta_{t4} = 0.73 \tag{3}$$

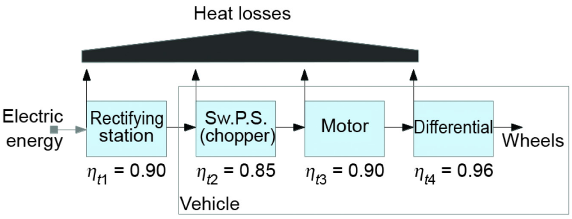

Figure 2. Trolleybus, energy losses

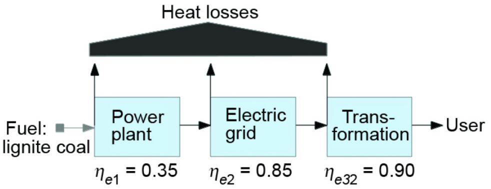

Figure 3. Thermal power plant, energy losses

This is a way higher than the internal combustion engine, but the electrical energy is not the main source of energy. It is generated, basically (around 70%) from the coal in thermal power plants, then transferred by the electrical grid to the consumer [13].

A rough diagram is presented in fig. 3.

It means that the number calculated in the eq. (3) is needed to be multiplied by the efficiency of coal power plant (maximally 0.35), electric grid (0.85) with all transformations (0.9), and finally rectifying station (0.9, from fig. 2), as DC is needed for charging the electric bus or powering trolleybus. Finally, for the electric propulsion, the energy efficiency is:

$$\eta_t = \eta_{tp}\ \eta_{e1}\ \eta_{e2}\ \eta_{e3}\ \eta_{t1} = 0.18 \tag{4}$$

This is even lower than the overall efficiency of the CNG bus propulsion.

For the simplification of the exhaust emission calculations, it will be assumed that power plant *Kolubara* burns only lignite [4], with caloric value of about 7 MJ/kg [4, 14]. In the case of trolleybus, where there are not any other losses, it is possible to determinate the fuel consumption immediately. If its energy needs (on wheels) are also 80 Wh/kmt [11] and the efficiency of energy transfer from coal to the wheel is 0.18, then for 16 tones vehicle the needed mass of lignite coal is 366 kg per 100 km. This number needs to be lower for the amount of the electrical energy produced by hydro-power plants, it is about 30%. Then finally, trolleybus spends 256 kg of lignite coal per 100 km.

From the previous example, it is somehow visible that the ecological impact of electric vehicles is higher than those with internal combustion engine, mainly because of the way of producing the electrical energy in Serbia. Returning to the financial calculus is necessary. For that, what happens from the power plant to the rectifying substation is unimportant, as the public transporter is directly paying only for the delivered energy per known price ($0.06/kWh) [15]. The energy needs for trolleybus from contact grid are 80 Wh/kmt, as it is already mentioned. This number should be multiplied by vehicle mass and then divided by propulsion efficiency and the efficiency of the rectifying stations:

$$\chi_t = \frac{e_w m_t}{\eta_{tp}\eta_{t1}} = \frac{80\ \text{Wh/kmt}\cdot 16t}{0.73\cdot 0.9} = 1.95\ \text{kWh/km} \tag{5}$$

That is 195 kWh per 100 km, transferred into money, it comes to $11.7 per 100 km. Apart from this favorable number, we need to know the maintenance cost, which is $25 per 100 km according to the Trolley project [3] and the trolleybus amortization price. The price of a new vehicle is about $200000 (BKM 321) [16] and its resource is about 20 years or 1600000 km, means that the amortization cost is $12.5 per 100 km. The total financial cost of trolleybus, without its infrastructure is: $49.2 per 100 km.

Infrastructural cost

Infrastructure for trolleybus is a capital investment, basically the one in 30 years and the cost of its maintenance varies very little regarding usage. It implicates that this cost is fixed, so it can not be normalized by the traveling distance of trolleybus. In general, the infrastructural cost will be lower as it is exploited more. In order to compare it with the costs of the other buses, the model which implies the traffic frequency of trolleybuses is needed. In that case, it will be possible to say which number of departures the trolleybus will be more optimal for, than a bus or *vice versa*. That model is complex and it was a part of Trolley Project [17]. It calculates the risk of the infrastructural investment through the net present value (NPV). The model is done for the town of Lublin, Poland, but with small changes of parameters it is also usable for Belgrade. It consists of 3 sets of input parameters: the general, the environmental, and the financial. The general parameters will be:

- the average speed of 16 km/h,
- the number of nominal workdays per year (when the grid will be under the full load) is 295,
- the number of working hours per day is 16,
- the share of rides in peak hours is 10%, and
- the discount rates will be: 5% for financial and 8% for economic present value.

Environmental parameters will be inserted later.

Concerning financial data about infrastructure, the costs will be assumed as it was not possible to obtain real data from *GSP Beograd* (Belgrade Public Transport Company). For that assumption, the prices for the town of Lublin [17] as the costs of raw materials and labor are very similar to those in Belgrade:

- the new overhead wires, for both direction of the road costs about $350000 per kilometer,
- the rectifying substation is about $320000,
- the number of substations needed per kilometer is 0.29,
- the yearly network maintenance costs about $10000 per kilometer, and
- the network residual value after 30 years is 35%.

The pure financial cost of infrastructure, normalized per kilometer and one year is about $20000.

As you can see, these costs are fixed and large. That's why trolleybuses demand large number of departures in order to be profitable. It is hard to say how many, but after the most optimal bus is found, the relative break-point where trolleybus is cheaper will be calculated.

Electric buses

The coal consumption of electric buses (e-buses) with energy accumulators will be higher for sure, as there are more losses in the system (it will be explained) then in the case of trolleybus [11]. Therefore, the focus with e-buses will be on their financial costs and only if one beats the IC-buses by these criteria that will be pulled through complete economic calculation, fig. 4.

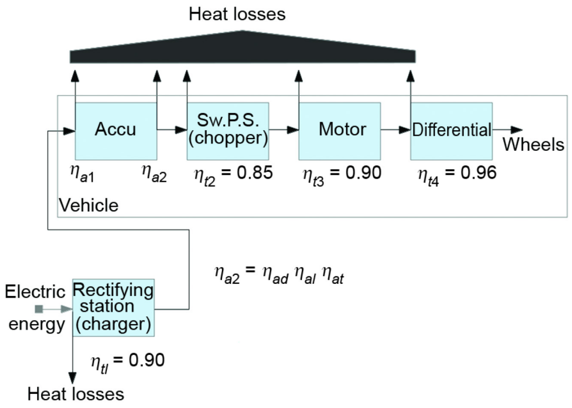

Figure 4. E-bus, energy losses; where η_{ad} is the discharge efficiency, η_{al} – the capacity degradation at the end of life, and η_{at} – the capacity loss at low temperature (–25 °C)

Battery bus

Firstly, will be examined the e-bus with electrochemical accumulator. Today, there are many choices of batteries and our choice will be LiFePO$_4$. It is reliable, and the specific cost of accumulated energy is the lowest regarding the initial costs, the capacity and the number of working cycles. The basic characteristics of those accumulators are [16]:

- nominal voltage: 3.2 V,
- energy density: 80-100 Wh/kg,
- maximal continuous discharge current: 3 × C_n, where C_n is nominal capacity,
- maximal peak discharge current: 10 × C_n,
- life, up to 5000 cycles at nominal conditions,
- capacity efficiency at the end of life: $\eta_{al} = 0.8$,
- working temperature: –25-40 °C, capacity strongly dependent from it,
- capacity factor at –25 °C, $\eta_{at} = 0.85$,
- charging efficiency, $\eta_{a1} = 0.8$,
- discharging efficiency, $\eta_{ad} = 0.9$, and
- price, around \$0.3 per working hour [17].

For optimal dimensioning of the battery, the bus exploitation characteristics are needed. Let us make a few assumptions for our imaginary bus:

- the battery capacity should fulfill daily autonomy of at least 180 km,
- the annual passed distance is minimum 60000 km per bus,
- the bus life should be at least 10 years, so as battery life,
- the lowest working temperature will not go below –25 °C,
- the mass of the average loaded bus without battery should be 16 tones,
- the nominal motor power of 150 kW, regardless the type,
- the nominal voltage of the engine is 700 V, and
- the energy consumption of power train (from the data for trolleybus) is 1.74 kWh/km.

After including information from accumulator producer [16], there are enough data to design the battery and find out its cost. That was done numerically by a few iterations. Simplified steps would be the following:

(1) The calculation of battery discharge efficiency for the worst working conditions, which are:

- the old battery with 5000 cycles behind (capacity efficiency is 0.8), and
- the winter condition, outside temperature is –25 °C (capacity efficiency is 0.85).

When those two coefficients are multiplied with the battery discharge efficiency, then the overall accumulator efficiency, regarding available capacity is $\eta_{a2} = 0.612$.

(2) Determination of the battery capacity regarding the bus power train energy consumption and desired autonomy. Including upper efficiency coefficient, but disregarding battery

mass. The result will be 512 kWh, with the mass of maximally 4.5 tones. This will enlarge the bus energy consumption linearly for 1.28 times. Now, for higher consumption, this step has to be done iteratively a few times. The final result is 650 kWh, with mass increase of about 5.8 tones. Effective capacity is not less than 400 kWh and it is available for daily travel.

(3) This step is for calculation of battery amortization. Simply find the battery price of about \$195000. Then, according its lifetime of about 13.7 years and daily average travel of 160 km, found from daily autonomy according nominal workdays [3], the battery amortization price is about \$24 per 100 km.

The upper cost is only the price of the battery, without the energy transfer through it. The charging costs for filling up the 400 kWh of effective capacity, normalized to electric grid are higher for energy losses at charger and battery:

$$Q_C = \frac{Q_e}{\eta_{a1}\eta_{ad}\eta_{t1}} = \frac{400\ \text{kWh}}{0.8\cdot 0.9\cdot 0.9} = 617\ \text{kWh} \tag{6}$$

It comes that daily charged energy to the bus is 617 kWh. From daily travel of 180 km, the energy spend per 100 km is 343 kWh. For the electricity price of about \$0.06 per kWh, the energy cost is \$20,6 per 100 km. Including the battery amortization cost, the cumulative fuel-equivalent price for the battery e-bus is \$44.6 per 100 km. This is the cost which is comparative to the fuel costs of IC engine buses.

The maintenance cost is the same as for trolleybus (\$25 per 100 km) with additional 5% for regular battery inspections, but the amortization is much higher. This is due to higher mass of the vehicle which leads to the faster body fatigue. It will be assumed that the bus price without the battery is around the trolleybus price, close to \$200000 (BKM 321) [18] and the resource is in the range of battery (say 1000000 km), then the amortization of the vehicle is \$20 per 100 km.

Total financial cost of $LiFePO_4$ battery powered e-bus is \$90.85 per 100 km including the battery and vehicle amortization, the electricity cost and the maintenance. Obviously, this price is even higher than for diesel bus.

Electro-capacitive bus

Ultra-capacitors, especially those developed by Maxwell, have recently become very popular as an alternative to electrochemical accumulators, basically as a power support in hybrid electric vehicles. The world's biggest production facilities for those capacitors are in Shanghai (Maxwell, Aowei), so it is not a surprise why electro-capacitive (EC) buses are so popular in China. Those buses use only ultra-capacitors as energy storage and fill it at both, or one terminal point. Also in last decade, many new Chinese producers appear offering low-cost, but short life-cycle capacitors. The most popular is Aowei [19], whose products are in use in Hong Kong public buses. As its price is optimal regarding capacity and working life, we will use it in our imaginary bus.

Ultra-capacitors are relatively new technology, regarding their intensive use in transport. It means that only the theory of electrostatic accumulators [20, 21] and the producers' data [19] can be used as a source of information for this work. Schematic demonstration of EC-bus also corresponds to the fig. 4.

Basic characteristics of ultra-capacitors are following [19, 22]:

– energy density: 5.5 Wh/kg, for useful energy,

- power density: 120 W/kg,
- operating temperature: from –20-65 °C, $\eta_{at} = 1$,
- working life 10 years, regarding electrolyte loss at temperature of 25 °C,
- cycle life over 50000 cycles,
- shelf life 4 years at 25 °C,
- capacity loss at the end of life: 20% of initial value, $\eta_{al} = 0.8$,
- charge/discharge efficiency factor, $\eta_{ad} = \eta_{\mathrm{a1}} = 0.9$, and
- price, \$12/Wh of useful energy.

This is electrostatic energy accumulator, not electrochemical. In general that means that voltage strongly depends on the state of charge, which is not optimal for traction usage. In order to have desired autonomy for a vehicle, the capacity must be over-dimensioned.

The imaginary EC-bus will have following characteristics:

- capacitor capacity should fulfill the distance between terminal stations, say 8 km,
- number of working hours per day: 16,
- annual passed distance is minimum 80000 km per bus,
- bus life should be at least 10 years, so as capacitor life,
- the lowest working temperature will not go below –25 °C,
- mass of the average loaded bus without capacitor should be 16 tones,
- motor nominal power of 160 kW, regardless type,
- nominal voltage of the engine is 700 V, maximal 750 V, minimal useful is 435 V, and
- the energy consumption of power train (from the data for trolleybus) is 1.74 kWh/km, for 16 tones.

The next question is how to choose the capacitor. For this purpose, the basic equation for the energy accumulated in capacitor was used:

$$E = \frac{C\,U^2}{2} \tag{7}$$

where C is the capacity, and U – the voltage.

Regarding capacitor basics, where voltage drops linearly with the state of discharge and knowing that final discharge voltage is not 0, as minimal useful voltage for powering the motor is needed, it is clear that the capacity over-dimensioning is necessary. Luckily, the producers of ultra-capacitors already are selling their products by useful accumulated energy, where the discharge voltage is 60% of nominal [26]. If needed energy capacity is 13.9 kWh, the capacitor with this useful energy is needed to be bought, divided by ageing factor ($\eta_{al} = 0.8$) and discharge efficiency factor ($\eta_{ad} = 0.9$). That is 19.3 kWh, with the mass of 3.5 tones. This mass increment will linearly increase the energy consumption, the same like with $LiFePO_4$ battery, so we need the iterations again. Final useful energy capacity of the ultracapacitor is 25 kWh, with the mass of 4.5 tones.

The procedure for financial cost calculation is the same as for electrochemical battery. From the previous data, the overall price of the capacitor is \$300000. For the given number of cycles it is \$6 per cycle. It gives the price of \$0.75 per km, or \$75 per 100 km and the working life of about 7 years.

The consumed energy from the electric grid is lower than for the electrochemical accumulator, as the losses of the capacitor are lower. Calculation is analogue as for the battery. It will be the energy consumption of the vehicle with included mass of the capacitor, enlarge for the losses of the charger (10%) and the capacitor itself (10% for charging and 10% for discharging). Finally, the consumed electrical energy from the grid is 306 kWh per 100 km, with the price of $18.4 per 100 km. Maintenance cost are the same as for battery bus, about $26.3 per 100 km as well as the vehicle amortization cost of $20 per 100 km. The total financial cost of electric bus with ultra-capacitive accumulator is $139.7 per 100 km.

Keep in mind that the infrastructural cost was not included, which exists as high power charging stations are needed at each bus terminal stations. But, in the ratio with all other costs, it could be neglected.

The summary of financial costs

The next step is to see financial costs of the entire buses one more time, then to find the most optimal one and compare it with the trolleybus including infrastructural cost. That is easier from tab. 1.

Table 1. Summary of financial costs

Bus	Diesel bus	CNG bus	E-bus, battery	EC-bus	Trolleybus*
Financial cost	85.31 $/100 km	69.14 $/100 km	90.85 $/100 km	139.7 $/100 km	49.2 $/100 km

* Infrastructural cost is not included.

As you see, the CNG bus is the cheapest bus after trolleybus. It is the best candidate for analysis by the following comparative model with trolleybus including its infrastructure. After that, the number of departures (or flow frequency) of vehicles will be known, where one vehicle will be more optimal then the other.

It is time to continue the story from the upper paragraph about trolleybus infrastructural cost. The mentioned model [23] is discrete, it divides fixed infrastructural cost with the number of departures and calculates characteristic break point. As infrastructure is a 30-years investment, it is necessary to include the price changes as well as other uncertainties. The commonly used model is the calculation of NPV, which is implemented here. The NPV is presented for annual period of time, for 1 km in both traveling directions and given number of departures.

As seen in fig. 5, the break point is at 165 departures per day, for 16 hours of exploitation, it is 6 minutes average interval. That is real in a city center, but keeps in mind that this is only financial cost.

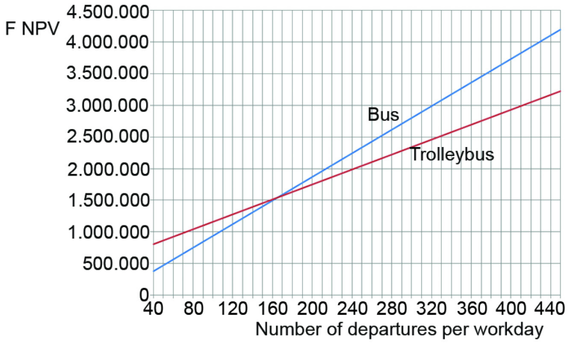

Figure 5. Trolleybus *vs.* CNG bus – financial feasibility (F)

Economic model

Economic costs in this work will be presented as financial costs of vehicles with their environmental costs, where the pollution by noise and exhaust gases will be observed. The noise is easy to estimate and it will be done according Trolley project [3, 23], but the air pollution is not such an easy task.

Exhaust emission

The exhaust emission of the combustion engines is a known fact and it can be easily calculated for a bus per a passed kilometer. In order to transfer it into real cost and make it addable to the numbers above, EC Directive 33/2009 [24] and the work of Mayeres, *et al.* [25] were used as a worldwide adopted tool.

For CNG powered buses, the data from the Vinča Institute of Nuclear Sciences, Belgrade, were used, from the Center for Engines and Vehicles. They initiated the measurement of bus emission performance under the real driving conditions [1]. The representative data for diesel buses shown in the study of Mišanović [26] were used, as well as in the study about trolleybus efficiency [23] from Trolley Project.

The coal power plant exhaust is much harder to calculate. As real data was not obtainable, the authors used several mathematical models and presented the average results. The representative fuel was found to be *Kolubara* lignite, as about 55-60% of all electrical energy in Serbia comes from it [14]. The coal characteristics [4, 14] are put into models explained in forward books by Mooney [27], Djurić *et al.* [14], as well as into two similar models provided be MAERS [28] and CIAB [13].

The analysis of energy efficiency from coal to the rectifying station, *i. e.* from coal to the electro-meter will be repeated, given in the paragraph about trolleybus financial cost. In ideal electro-powering system there are further top efficiencies, fig. 3:

- of the thermal power plant: $\eta_{e1} = 0.35$, including alternator,
- of the electric grid: $\eta_{e2} = 0.85$, and
- of the transformations: $\eta_{e3} = 0.9$.

This is a simplified calculation where all similar-origin losses are collected under one factor. The overall efficiency is 0.27 and it will be used for e-bus exhaust emission. The caloric value of the used lignite fuel is about 7 MJ/kg (1.94 kWh/kg). Also, the share of the energy produce by hydro-power plant is about 30%. It means that for each 0.75 kWh of the paid electricity 1 kg of coal is burnt.

However, it is idealized and goes in the favor of electric transport which has other high costs, so in the interest of promoting clean city center, we decided to use these data. The computed results are presented in tabs 2-5.

Table 2. Repetition of fuel consumption for all buses

Bus type	IC-bus	IC-bus	E-bus, battery	EC-bus	Trolleybus
Fuel	Diesel	CNG	Lignite	Lignite	Lignite
Consumption	35 kg/100 km	48 kg/100 km	457 kg/100 km	407 kg/100 km	256 kg/100 km

Table 3. Exhaust emission (in g/km for one vehicle)

Emission	CO	HC	NO_x	PM*	CO_2
IC-diesel	0.04	0.15	3.40	0.04	1140
IC-CNG	0.30	0.20	1.45	0.00	1300
E-bus, battery	0.36	0.18	3.86	0.88	2399
EC-bus	0.32	0.16	3.44	0.78	2140
Trolleybus	0.20	0.10	2.16	0.49	1344

* PM – particulate matter emission is theoretical for noted lignite coal, without concerning filters or any other treatment.

Table 4. Cost of the emission (EC Directive 33/2009 [24] and Mayeres *et al.* [25])

Emission	CO	HC	NO_x	PM	CO_2
Cost, $/kg	0.01	1.04	4.58	92.9	0.09

Table 5. Applied environmental emission costs, per vehicle

Bus type	Diesel bus	CNG bus	E-bus, battery	EC-bus	Trolleybus
Cost, $/km	0.123	0.118	0.316	0.280	0.177

Pollution by noise

The noise cost is estimated in Trolley Project [3, 23]:
- $0.062 per km for bus with internal combustion engine, and
- $0.012 per km for electric bus, including trolleybus.

Total economic costs

After addition of environmental costs to the financial costs, the final price of the analyzed buses is shown in tab. 6.

Table 6. Total economic cost [$/100 km]

Bus	Diesel bus	CNG bus	E-bus, battery	EC-bus	Trolleybus*
Financial cost	85.31	69.14	90.85	139.7	49.2
Environment cost	12.3	11.8	31.6	28	17.7
Noise cost	6.2	6.2	1.2	1.2	1.2
Total	103.81	87.14	123.65	168.9	68.1

* Infrastructural cost is not included

The infrastructural costs are added on the same way as at the end of our financial analysis. The final result of comparative economic efficiency between the CNG bus and the trolleybus is presented in fig. 6. Now the real picture is shown, where the break number of departures is 230, giving the average time interval, only 4.2 minutes between the departures. This is hardly needed in Belgrade, but it is up to the Directorate for Public Transport to decide. One should keep in mind that used economical discount rates in our model are assumed as those in similar countries and for more precise data these should be adequately determined.

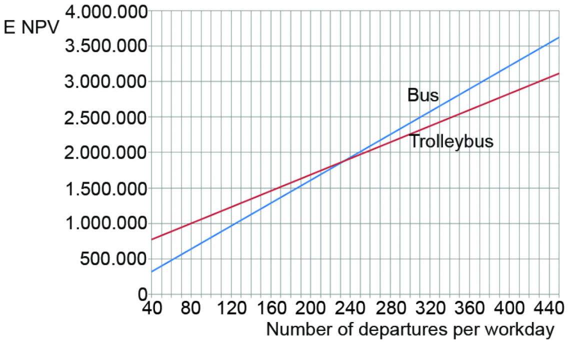

Figure 6. Trolleybus *vs.* CNG bus – economic feasibility (E)

Conclusions

In the case of Belgrade, the natural gas powered bus is the most cost effective transport, regarding all road vehicles. The total price for exploitation of such bus is $87 per

100 km, including direct and indirect costs. That is about two times lower than the exploitation cost of e-bus powered by ultra-capacitor. The environmental costs of both electric buses are also about two times higher than the costs of vehicles powered by IC engine (according to the EC Directive 33/2009 [24] and Mayeres *et al.* [25]). Even diesel buses are more eco-friendly than the electric vehicles powered, mainly by coal power plant. That is not the reason to prevent the development of electrical transport. It is only the reason for more careful approach to its design and optimization. For example, the trolley lines should be redesigned in order to have certain number of departures for the case of economic feasibility. According to this paper, it will be around 230 departures per day.

The conclusion of the paper is that the CNG buses and the trolleybuses should be looked again as the transport alternatives in city center. Also, Serbian professional community should think again about their choices. The electrical buses with energy accumulators in our conditions do not have the economic sense, at this moment. It means that periodical, preliminary feasibility studies are needed to be taken in order to remove any potential doubts.

Nomenclature

C – capacity of a capacitor, [F]
C_n – nominal current capacity of an energy accumulator, [As]
E – accumulated energy at a capacitor, [Ws]
e_w – specific energy consumption of a road vehicle, [Wsm^{-1}kg^{-1}]
m – mass of a vehicle, [kg]
m_t – mass of an electric vehicle, without energy accumulator, [kg]
Q_c – charged energy from the electric grid to the energy accumulator, [Ws]
Q_e – energy capacity of an energy accumulator, [Ws]
U – voltage, [V]

Greek symbols

$\eta_{\mathrm{a}1}$ – energy efficiency of an accumulator at the process of charging
$\eta_{\mathrm{a}2}$ – overall capacity efficiency of an accumulator at the discharge process
η_{ad} – energy efficiency of an accumulator at the discharge process
η_{al} – capacity efficiency of an accumulator at the nominal end of life
η_{at} – capacity efficiency of an accumulator at the low temperature (–25 °C)
η_c – overall energy efficiency of internal combustion propulsion
η_{c1} – energy efficiency of an internal combustion engine at full power
η_{c2} – energy efficiency of an engine at variable load, normalized to the full power efficiency
η_{c3} – clutch energy efficiency, applicable for internal combustion propulsion
η_{c4} – energy efficiency of a gearbox, applicable for internal combustion propulsion
η_{e1} – power plant energy efficiency
η_{e2} – energy efficiency of the electric grid
η_{e3} – cumulative energy efficiency of all electric transformations
η_p – propulsion energy efficiency
η_t – cumulative energy efficiency of electric propulsion
η_{t1} – energy efficiency of the rectifying station or the charger
η_{t2} – energy efficiency of a switching power supply unit for vehicle traction motor
η_{t3} – energy efficiency of vehicle traction motor
η_{t4} – energy efficiency of a transmission, applicable for electric vehicle propulsion
η_{tp} – cumulative energy efficiency of electric propulsion, normalized to the electric grid
χ_t – energy consumption of a road vehicle, [Wsm^{-1}]

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