Promoting Electric Public Transport

TROLLEY Project

Transport Mode Efficiency Analysis:

Comparison of financial and economic efficiency between bus and trolleybus systems

THIS PROJECT IS IMPLEMENTED THROUGH THE CENTRAL EUROPE PROGRAMME CO-FINANCED BY THE ERDF.

Nowadays trolleybus systems are not as popular in Europe, as they used to be 50 years ago, nevertheless a number of cities run and develop their trolleybus systems. Also some other cities (as for example Leeds) are considering constructing totally new trolleybus networks. On the other hand, closures of the existing lines are also considered, especially in Western Europe.

All this undertakings and decisions raise discussion about the economic efficiency of trolleybus systems. Obviously there is no easy answer what is better – bus or trolleybus. Surely trolleybuses have higher investment and fixed costs of the electricity supply system. On the other hand, trolleybuses offer lower variable costs of energy, as well as some external saving – lower noise emissions and potentially lower CO_2 emissions.

We intuitionally feel, that there are some cases when trolleybuses are reasonable, and some cases when they are not economic. Surely trolleybuses are more efficient, when:

- there is more traffic – as the fixed costs split into the higher number of passengers;
- zero-emission or low-emission electrical energy is available;
- the electrical energy is cheap, compared with petrol; this should be considered in long term, so energy price forecasts should be taken into account;
- there is higher willingness-to-pay for lower emissions (especially noise);
- local conditions are favourable, for example by high share of sloping routes;
- there are some sunk costs of infrastructure or vehicles.

Our aim is to provide a model that provides a framework to assess viability of a trolleybus system in given conditions. As the conditions vary by country or city, the model must be easily fitted to the local conditions, so that a user may easily change the input parameters, such as for example unitary costs of a vehicle, energy, network maintenance or capital expenditures.

On the other hand, a model must provide a clear, easy-to-understand output. In our case, we use a concept of break-even point, i.e. the point of balance between making either a profit or a loss, a point when trolleybus is exactly as efficient, as bus system.

As already mentioned, the biggest difference between buses an trolleybuses from the economic point of view is different cost structure – higher level of fixed costs and lower level of variable costs (this will be proved later in the paper). In such cases, traffic intensity should be the best way to express break-even point.

Therefore, we aim to provide a model, that produces a break-even point for trolleybus system, expressed as minimum traffic intensity, where trolleybus system is not more expensive, than buses, at given assumptions, that are pre-defined in the model, but can be easily change by a user, in order to fit the model to local conditions.

The analysis will be made using two concepts:

- financial analysis – i.e. pure analysis of costs, including maintenance costs and costs of assets;
- economic analysis – i.e. the analysis, when we include also valuation of externalities (such as noise and emission – called also social costs), on the top of financial analysis.

In the following paper we will present:

- in the first chapter – general construction of the model, including location and units of main inputs (that may be re-defined by the user), and some of key calculation methods, that are used in the model (they cannot be easily changed by the user);
- in the second chapter we are going to present and discuss sources of pre-defined inputs of the model; please mind that this inputs may not be relevant to each city, therefore they should be carefully reviewed, before applying the model to a given city.
- in the third chapter we are going to present different outputs of the model, i.e. discuss, how does the break-even point move, when we change some of the assumptions; this will provide us some information, which conditions are favourable for trolleybuses, and which conditions aren't.

This means, that the first two chapters are somehow a 'user manual' to the enclosed model, and the third chapter is an attempt to demonstrate some of the possibilities, that the model offers, as well as an attempt to draw some general conclusions.

Obviously, the model itself is an important attachment to the paper, as it enables the user to change the assumptions, and draw conclusions relevant to a given city. We also strongly encourage users to change the assumptions by themselves, as we did in chapter 3.

1. Basic concept of a model

The model includes six unhidden sheets, as well as number or hidden sheets that are for calculation purpose only.

Three sheets contain input data, those are:

- general parameters (see figure 1) – including: financial and economic discount rate (r), average speed, number of workdays equivalent per year and share of rides in peak hour;
  share of rides in peak hour (see ❶) aims to estimate the number of vehicles needed to serve the connection; shall we have lower share of rides in peak hour, we need less vehicles to serve the line, what influences total costs; share of rides in peak hour should be expressed as a network-average quotient of departures in peak hour (understood as an hour with the highest number of departures), to the total number of departures during entire workday;
  number of workday equivalents per year (see ❷) aims to estimate supply on non-workdays; for example if we assume, that we have 255 (X) workdays and 110 (Y) non-workdays, with 50% (n) daily supply of workdays, we should input X+Y*n = 255+50*50% = 310 workday equivalents / year;

Figure 1. General parameters sheet

	A	B	
1	r - financial	5%	
2	r - economic	8%	
3	av. speed [km/h]	18	
4	share of rides in peak h [%]	10%	← ❶
5	workdays equiv. / year	295	← ❷

- environmental costs, which include unitary values for different pollution emissions and noise (see figure 2);
  the model assumes, that there are two sources of energy available – a conventional source that causes emissions and a zero-emission source; we may define both – emission values for conventional energy for both buses and trolleybuses (❶), as well as share of non-emission energy(❷);

Figure 2. Environmental costs assumptions sheet

	A	B	C	D	E	F	G	H
1								
2								
3	**Emission**	**CO**	**NMHC**	**NOx**	**PM10**	**CO2**		❶
4	Bus Euro 5 [g/vehkm]	0,040	0,110	2,830	0,030	1400,000		
5	Trolley [g/kWh]	0,086	0,000	1,822	0,220	811,300		
6	Trolley [g/vehkm]	0,163	0,000	3,462	0,418	1541,470		
7								
8	kWh/vehkm	1,9	<- if you want to change this parameter, pls go to financial costs					
9								
10	Value [EUR/g]	0,00001	0,00100	0,00440	0,08931	0,00009		
11								TOTAL
12	Bus Euro 5 [EUR/vehkm]	0,00000	0,00011	0,01245	0,00268	0,12180		0,137042
13	Trolley [EUR/vehkm]	0,00000	0,00000	0,01523	0,03733	0,13411		0,186673
14								
15	Share of no-emission-energy	0%			❷			
16								
17	Noise costs bus [EUR/vehkm]	0,06						
18	Noise costs trolley [EUR/vehkm]	0,012						
19								
20	Total externalities bus [EUR/vehkm]	0,20						
21	Total externalities trolley [EUR/vehkm]	0,20						
22								
23	EUR/PLN	4						
24								
25	Total externalities bus [PLN/vehkm]	0,788						
26	Total externalities trolley [PLN/vehkm]	0,795						
27								

- financial costs, which include full infrastructure costs (overhead wires construction and substations)full vehicle costs, energy consumption;
  we also define a number of parameters, referring to the lifetime of assets, such as bus and trolleybus lifetime, as well as residual value of the network, after the 30-years analysis period (we assume, that vehicles are depreciated linearly and may be changed within the analysis period);
  due to different lifetime of assets, they are considered in a model using linear depreciation, and not as one-off spending;
  shall you assume, that the infrastructure is already existing and only maintenance is needed, you should input both overhead wires and substations costs (❶) equal 0;
  please mind, that the model contains two factors of energy price dynamics – bus fuel (diesel) price dynamics (❷) and trolleybus fuel (electricity) price dynamics (❸); we assume that the dynamics is equal in time, but different for both energy sources; they should be expressed as annual, real growth of both prices; the model is very sensitive to both of the values.

Figure 3. Financial costs assumptions sheet

	A	B	C	D
4	Overhead wires [PLN/km]	1 500 000	❶	
5	Substation [PLN]	1 300 000		
6	Substations/km	0,29		
7	Substations [PLN/km]	371 429		
8	Overall construction	1 871 429		
9	Yearly network matainance [PLN/km]	100 000		
10	Network residual value (30 years)	35%		
11				
12	**Vehicles**			
13	Bus - purchase [PLN]	770 000	❹	
14	Trolley - purchase [PLN]	980 000		
15	Bus - lifetime [years]	12		
16	Trolley - lifetime [years]	20		
17	Bus - maintainance [PLN/km]	1,05		
18	Trolley - maintainance [PLN/km]	1,35		
19				
20	**Energy**			
21	Bus - consumption [l/100km]	40		
22	Bus - price of fuel [PLN/l]	4,00	Bus - energy costs [PLN/km]	1,6
23	Bus - real dynamics of energy price [%/year]	4%	❷	
24	Trolley - consumption [kWh/100 km]	190,00	Trolley - energy costs [PLN/km]	0,57
25	Trolley - price of fuel [PLN/kWh]	0,30		
26	Trolley - real dynamics of energy price [%/year]	2%	❸	
27				

We assume, there is only one type of buses/trolleybuses at the network, and those are single (12-m) vehicles, as all trolleybuses in Poland. If you want to consider other types of rolling stock, you may change purchase costs for the type you selected (❹). If you consider a mix of different types, you should input weighted average prices.

Please mind, that only grey cells should be edited and contain input variables. White cells contain numbers derived from other values.

The three other sheets contain output data, presented on graphs for easier interpretation. The graphs change automatically, every time we change our assumptions, therefore it's important to save entire Excel file for each set of assumption, under a new file name.

Before passing to the output data, please mind, that the model omits some costs, that are equal for bus and trolleybus transport, such as for example personal costs. The model basically presents the data for 1 km of two-directions trolleybus line, i.e. all costs are estimated for such section.

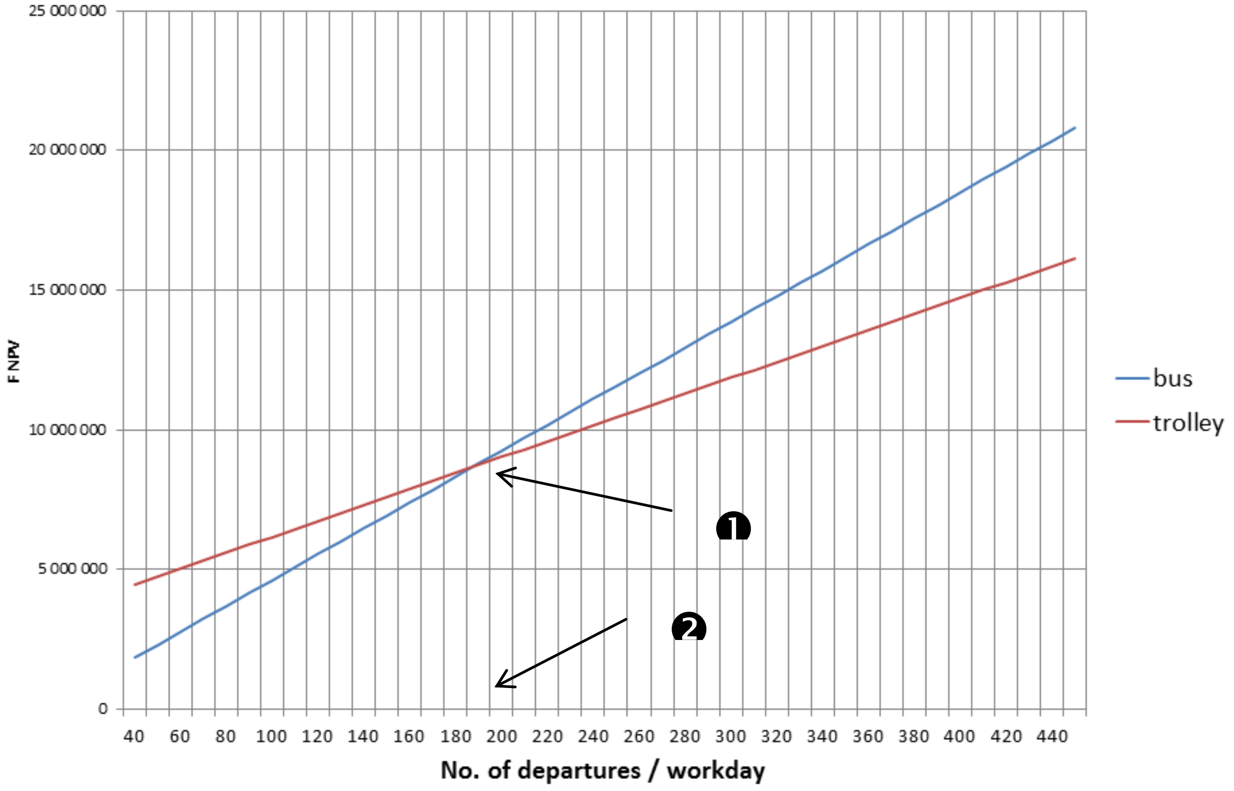
The first of the graphs (figure 4) contains financial analysis output. It shows total discounted costs (infrastructure and vehicle, depreciation and maintenance) of the section, expressed by the formula:

$$FNPV = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t}$$

where:

- t are given time periods (years)
- C_t are costs in a given period (here only 'real', financial costs are considered);
- r is financial discount rate.

Figure 4. Financial analysis output graph



The graph presents FNPV (or total discounted costs – vertical axis) for both bus and trolleybus at different traffic intensity levels (horizontal axis). The level is given as the number of departures over workday at the given section (please mind, that also weekends are considered, due to the "workday equivalent" concept, described earlier).

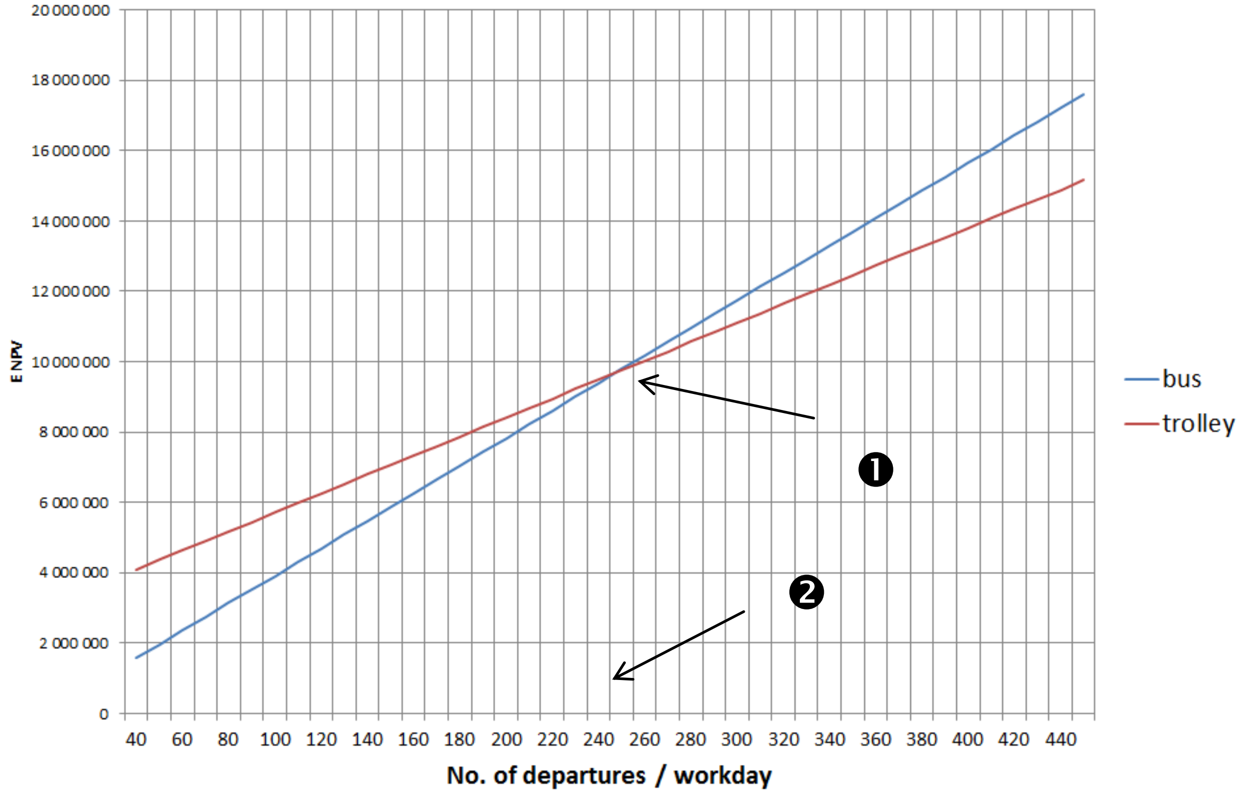
We can easily spot from the figure, that in case of trolleybuses initial costs (red line) are high and then they rise slower. In case of buses (blue line), they are lower, but raise quicker. The point ❶, when the blue and red lines cross, represents break-even point. The level of traffic at the break-even point can be spotted from the horizontal axis at the point ❷.

The second output graph (see figure 5) is based on the similar concept, although it takes into account – as we already wrote – not only financial ('real') costs, but also external (social) costs, namely emissions and noise. Also other (separately defined) discount rate is used, what may influence the results.

ENPV is calculated in the similar way, as FNPV, just with the higher range of costs.

Break-even point (❶) and the critical traffic level (❷) can be spotted in the same way, as before.

Figure 5. Economic analysis output graph



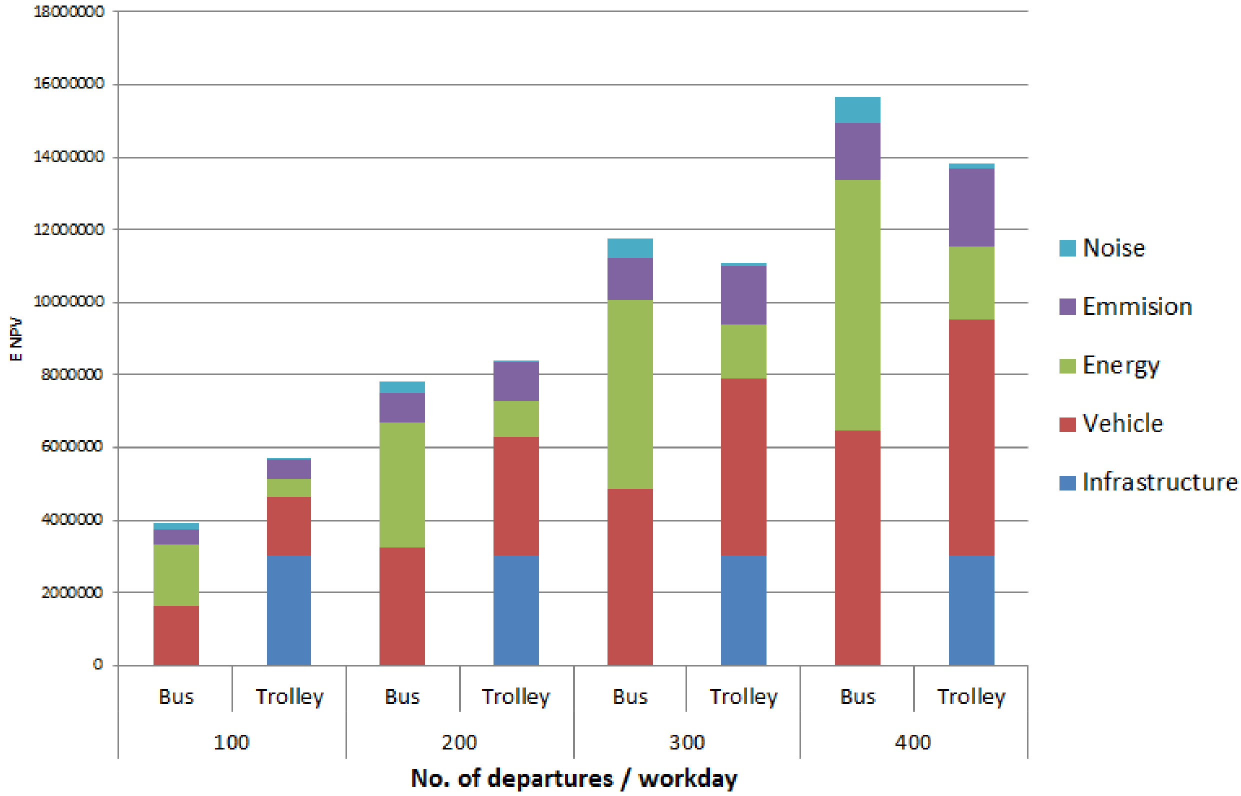
Very useful information is provided by the last output graph, which presents structure of costs in economic analysis (see figure 6).

This graph shows what are exact social and financial costs of both bus and trolleybus transport at four levels of traffic intensity – 100, 200, 300 and 400 departures / workday. The costs are split into five categories:

- infrastructure (costs of construction and maintenance of electrical energy supply system – for buses it's always equal 0);
- vehicle (costs of vehicle depreciation and maintenance);
- energy (costs of diesel or electricity);
- emission (costs of emission of CO, NHMC, NOx, PM2 and CO_2)
- noise.

The two latter – presented on the top of each graph – are externalities, the three other are financial ('real') costs.

Figure 6. Financial and social costs structure



2. Model assumptions

As we already mentioned, the model is pre-parameterised. We tried to find parameters, that are possibly relevant to the Polish trolleybus systems, but each time you draw conclusion for your city, you should check carefully, if you don't have other, more exactly estimated or locally specific values.

The most important assumptions are:

- assumptions on unitary costs of construction and vehicles;
- assumptions on unitary costs of energy;
- assumptions on emissions and their unitary values.

Assumptions of unitary costs of construction and vehicles are based mostly on the experience of Lublin – Polish city of 350 000 inhabitants, that currently is doubling its trolleybus network from 30 km to 60 km, as well as exchanging the fleet and therefore has good orientation in costs.

Also a feasibility study for the project was prepared.

The assumptions referring to infrastructure can be found in table 1. We assume, that one km of overhead wires costs 1 500 000 PLN (ca. 425 000 €)[1] and a

[1] Unless we stated otherwise explicitly, „one km of network" means always 1 km of network in two directions. All prices are net prices (without VAT).

substation costs ca. 1 300 000 PLN (ca. 325 000 €). We need 2,9 substations for each 10 km of two-directions network.

Yearly maintenance of 1 km of the network costs 100 000 PLN/year.

We also assume, that after the 30-years operation period, the infrastructure will be worth 35% of its initial value.

Table 1. Assuptions on infrastructure costs

Overhead wires [PLN/km]	1 500 000
Substation [PLN]	1 300 000
Substations/km	0,29
Yearly network maintenance [PLN/km]	100 000
Network residual value (30 years)	35%

The assumptions referring to vehicle purchase and maintenance costs can be found in table 2.

We assume that a trolleybus is ca. 27% more expensive than a bus, but its lifetime is much longer – 20 years, compared with 12 years lifetime of a bus. Nevertheless maintenance of a bus is over 22% cheaper, than in case of a trolleybus, as longer lifetime requires more effort in servicing, especially at the later stage.

Assumed cost of bus purchase is 770 000 PLN (over 190 000€) and of a trolleybus – 980 000 PLN (ca. 245 000€), what is confirmed by a number of public procurement processes in Poland. We would like to remind, that the pre-defined values refer to single (12 m) vehicles.

Table 2. Assuptions on vehicle costs

Bus - purchase [PLN]	770 000
Trolley - purchase [PLN]	980 000
Bus - lifetime [years]	12
Trolley - lifetime [years]	20
Bus - maintenance [PLN/km]	1,05
Trolley - maintenance [PLN/km]	1,35

Assumptions on energy cost can be found in table 3. We assumed, that a bus consumes 40 l of diesel per 100 km and 1 liter of diesel costs 4,00 PLN (1,00 €). Diesel prices are going to rise 4% per annum in real terms.

A trolleybus consumes 190 kWh/100km and each kWh costs 0,30 PLN (0,075€). Electricity prices are going to rise 2% per annum in real terms.

Table 3. Assuptions on energy costs

Bus - consumption [l/100km]	40
Bus - price of fuel [PLN/l]	4,00
Bus - real dynamics of energy price [%/year]	4%
Trolley - consumption [kWh/100 km]	190,00
Trolley - price of fuel [PLN/kWh]	0,30
Trolley - real dynamics of energy price [%/year]	2%

Assumptions on emissions and noise costs were (see tables 4 and 5) were valuated on a basis of:

- EURO 5 norm for bus emissions;
- a study on emissions of Polish coal power plants, made for the City of Lublin, in case of the trolleybus emissions (we would like to remind, that the third row in table 3 means emissions of pollutions for conventional energy sources, you may separately define a share of non-emission energy, which can be equal up to 100%);
- EU Directive 2009/33[2] for CO2, NMHC and NOx emissions;
- a study by Mayeres, Ochelen and Proost[3] - for other emissions, not valuated in the directive above (noise, PM10);
- trolleybus noise costs was valuated as 1/6 of bus noise costs, estimated by Mayeres, Ochelen and Proost.

Table 4. Assumptions on emissions and their valuation

Emission	CO	NMHC	NOx	PM10	CO2
Bus Euro 5 [g/vehkm]	0,040	0,110	2,830	0,030	1400,000
Trolley [g/kWh]	0,086	0,000	1,822	0,220	811,300
Value [EUR/g]	0,00001	0,00100	0,00440	0,08931	0,00009

[2] Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles, Official Journal of the European Union L 120/5, 15.5.2009

[3] I. Mayeres, S. Ochelen and S. Proost, The marginal external costs of urban transport, Transportation Research Part D: Transport and Environment, 1/1996, p. 111-130.

The remaining values were assumed at the level, that is typical for Poland, but may not be relevant for other countries – for example in the United Kingdom, discount rate of 3,5% is currently recommended, as the growth perspectives are lower, and the care for future generations is increasing.

Table 5. Other assumptions

Noise costs bus [EUR/vehkm]	0,06
Noise costs trolley [EUR/vehkm]	0,012
r - financial	5%
r - economic	8%
av. speed [km/h]	18
share of rides in peak h [%]	10%
workdays equiv. / year	295

3. Modelling outcomes

In the following chapter, we are going to discuss modelling outcomes, basing on three different sets of assumptions:

- in section 3.1 we discuss modelling outcomes, basing on the possibly realistic assumption for Poland – i.e. we use assumptions, elaborated in chapter 2, with energy deriving from conventional sources;
- in section 3.2 we discuss a zero-emission scenario, i.e. we assume that all energy for trolleybuses origins from environmental friendly sources – all other assumptions remain unchanged;
- in section 3.3 we discuss a zero-emission scenario with higher diesel prices (5 PLN = 1,25 €/litre, instead of 4 PLN/1 €/litre) and higher diesel prices dynamics (5% p.a. in real terms instead of 4% p.a.) – this makes the model more adequate to Western European conditions;
- in section 3.3 we discuss a scenario, basing on section 3.2, but the infrastructure costs are sunk (i.e. there is an existing infrastructure, that only needs maintenance), we call it ‘no-infrastructure-costs-scenario’.

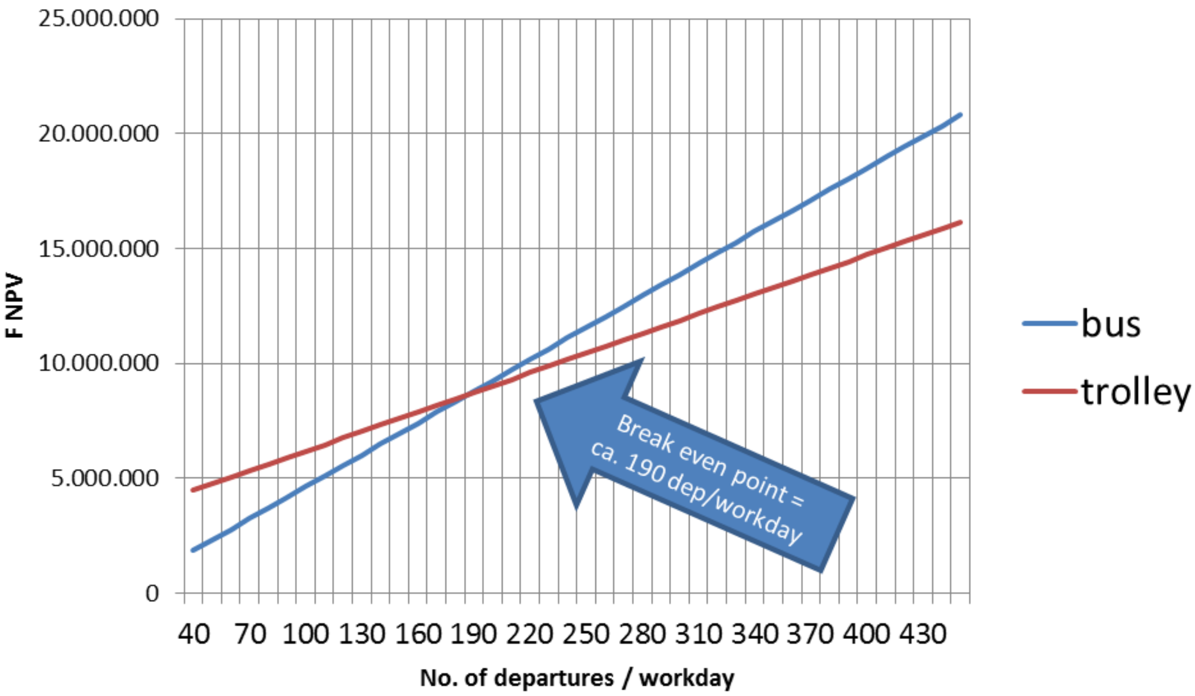
3.1 Realistic scenario for Poland

The modelling output for Poland is presented on figures 6 and 7. We can see, that break-even point in financial terms is ca. 190 departures / workday, what is equal to 5 minutes interval.[4]

This means, that from purely financial point of view, trolleybuses are more efficient then buses, if we introduce them on lines, with interval lower than 5 minutes. The same may apply for a network, when we consider average frequency, weighted by the length of different sections (i.e. some parts – 'branches' –may have 10 minutes interval, and other – 'the root' – 3 minutes).

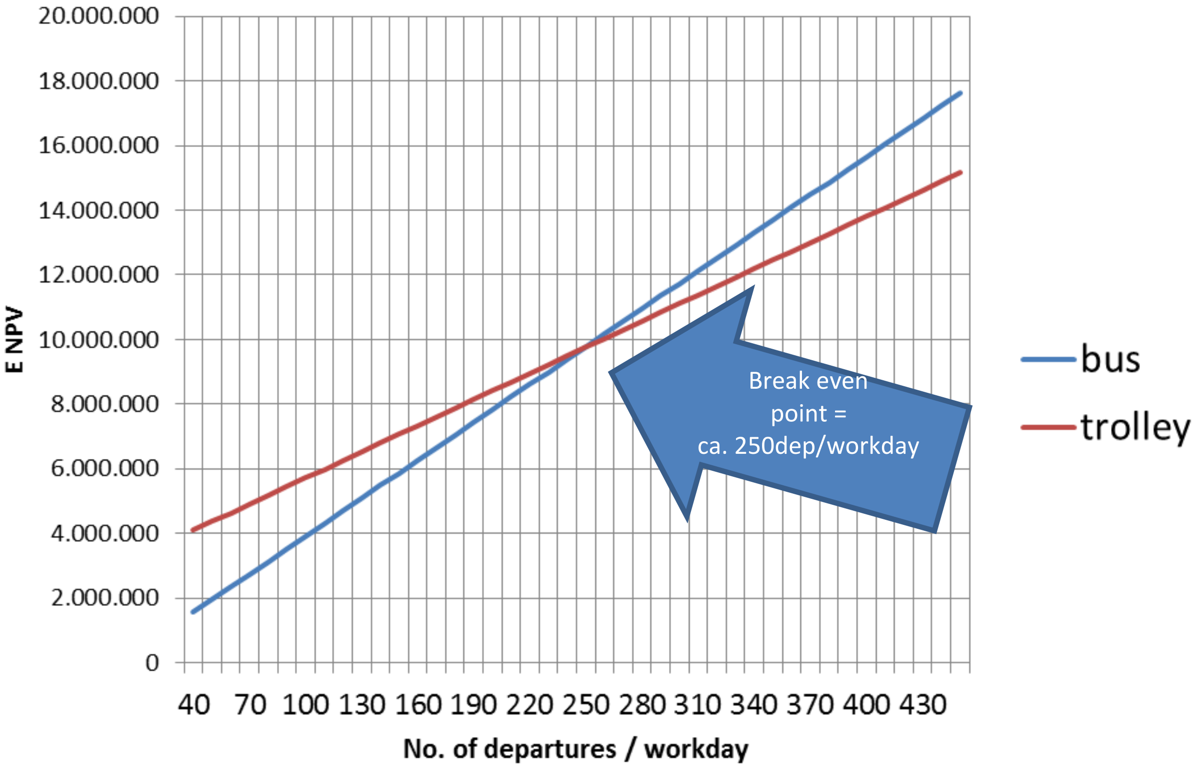
Break-even point in economic terms is surprisingly higher – it equals to 250 departures per day, i.e. ca. 4 minutes interval. This means, that including emissions and noise is – in Polish conditions – unfavourable for trolleybuses.

Figure 6. Realistic scenario for Poland - financial analysis



[4] We give exemplary values of intervals, assuming that trolleybuses run from 6 a.m. till 10 p.m. (i.e. 16 hours) in equal interval.

Figure 7. Realistic scenario for Poland - economic analysis

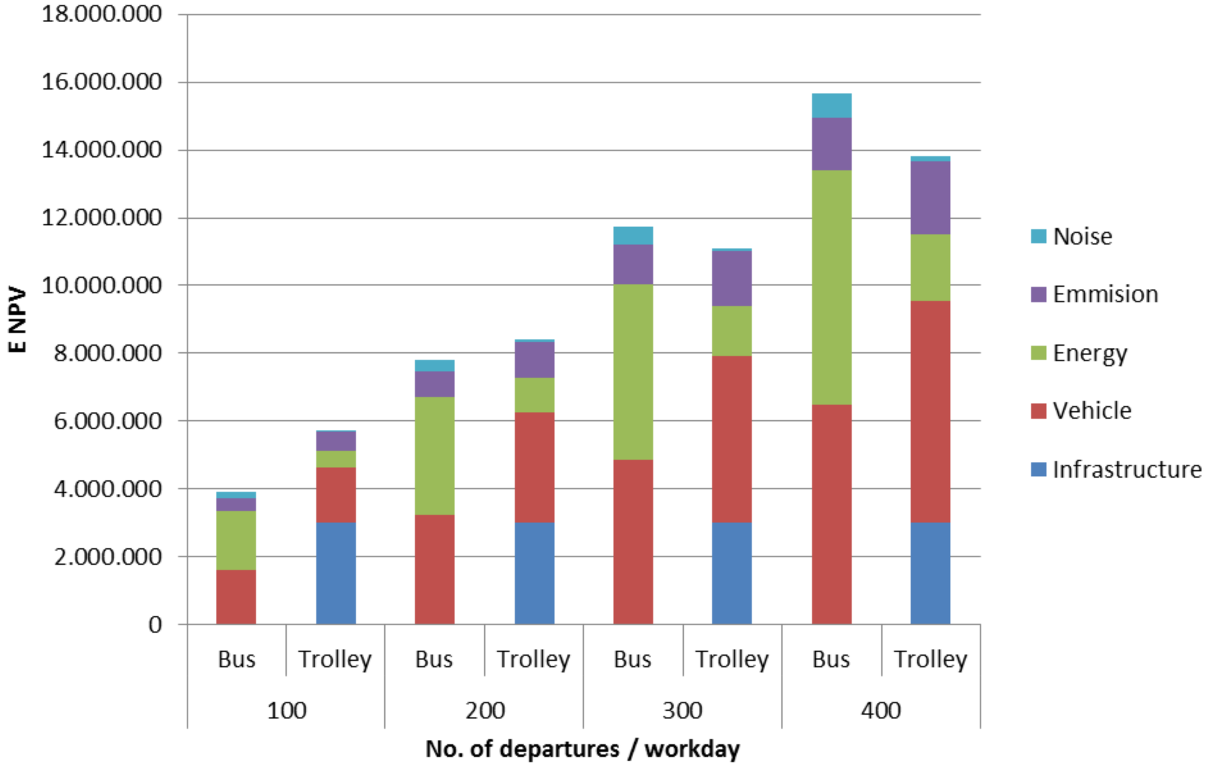


The reasons for the above mentioned phenomenon may be found on graph 8. We can easily spot, that:

- externalities (noise and emissions) do not constitute big share of overall costs, and are not favorable for trolleybuses; although trolleybuses generate lower noise costs, in case of coal-powered electric system, emission costs are lower in case of buses and they offset noise savings; please mind, that our model doesn't include different values of emissions in different locations, although this theoretically may be valuated and may make the results more favorable for trolleybuses;
- the biggest advantages of trolleybuses are low energy costs, and the biggest disadvantage – high infrastructure costs; the energy costs are almost 4 times lower in case of trolleybuses;
- in the long-run vehicle costs are virtually the same for buses and trolleybuses.

Please mind that we take into account only selected costs. If we take full cost model, energy prices are usually equal to 1/4 of the vehicle kilometer price (excluding infrastructure). This means, that according to the model, when we exclude all infrastructure costs, trolleybuses should be ca. 19% cheaper, than buses in purely financial terms.

Figure 8. Realistic scenario for Poland - financial and social costs structure

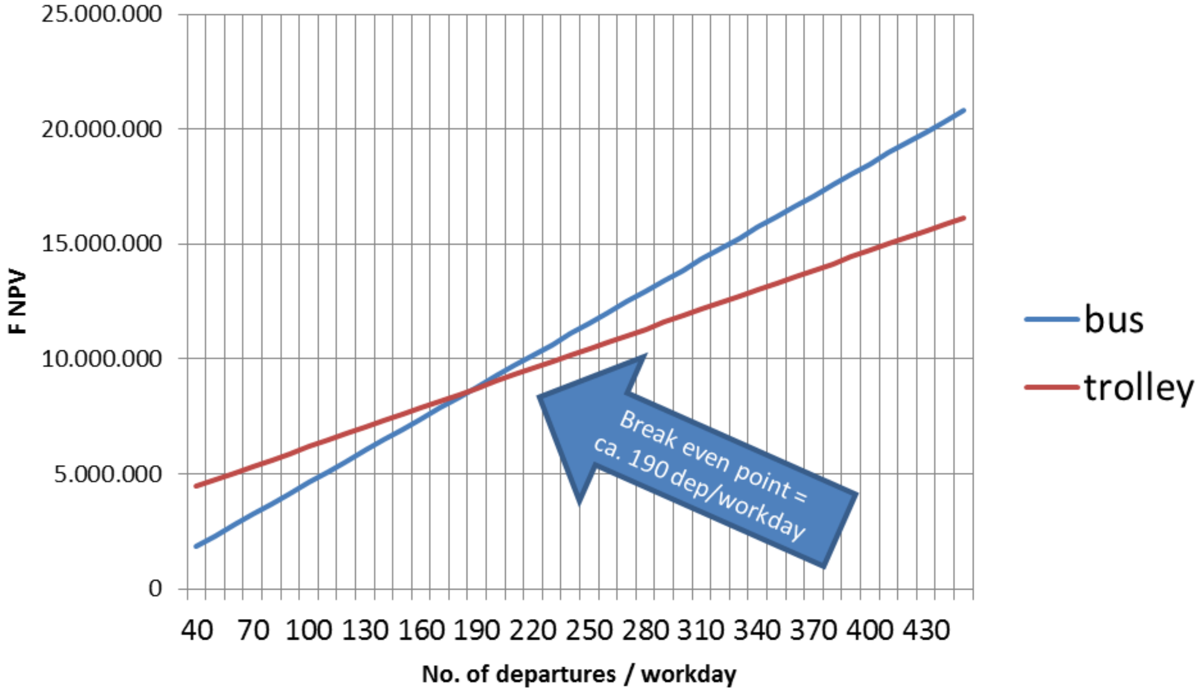


3.2 Zero-emission energy model for Poland

As we know, that a big disadvantage of trolleybuses is pollution, we repeated the modelling, assuming that energy origins from zero-emission sources.

In this case results of financial analysis remain unchanged (see figure 9), because emission does not influence financial costs.

Figure 9. Zero-emission energy scenario for Poland - financial analysis



There are, however, substantial changes in economic analysis results. The break-even point moved substantially down to ca. 170 departures/day, which equals an interval of more than 5.5 minutes.

As we can spot at figure 11, this was caused by 0 emission costs for trolleybuses – in this case only higher infrastructure costs are disadvantageous for this kind of transport.

Figure 10. Zero-emission energy scenario for Poland - economic analysis

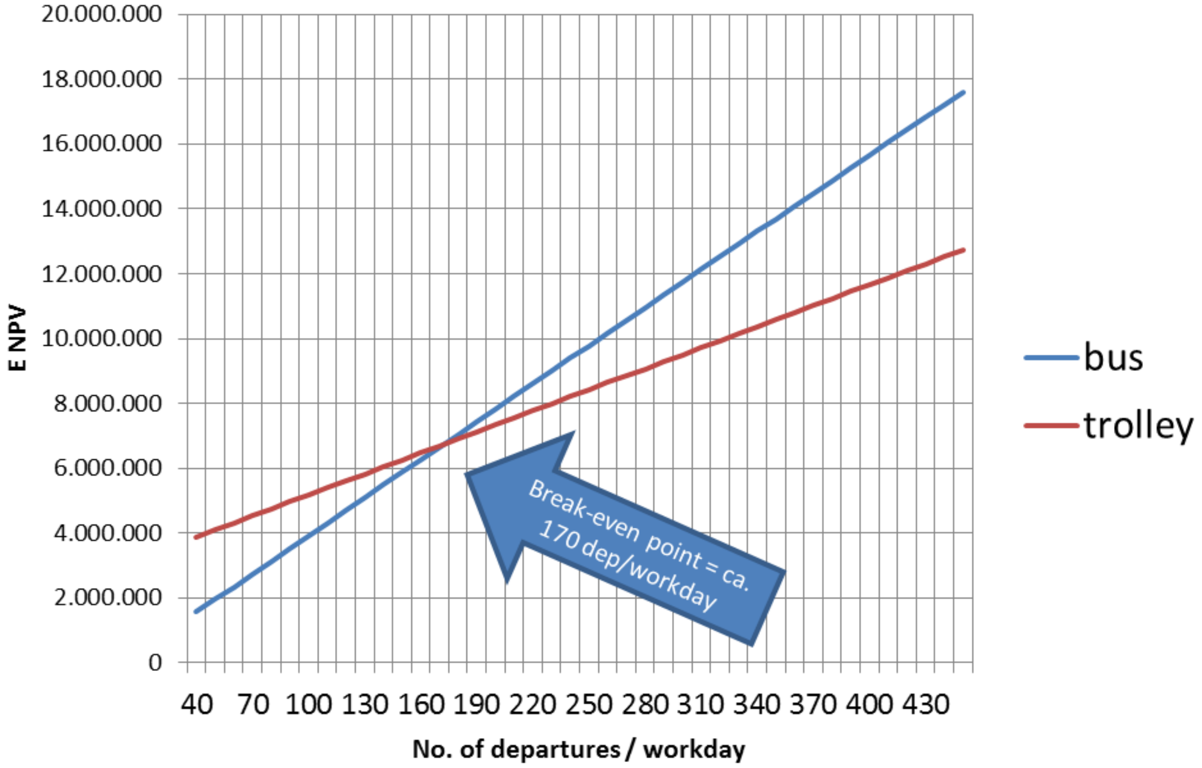
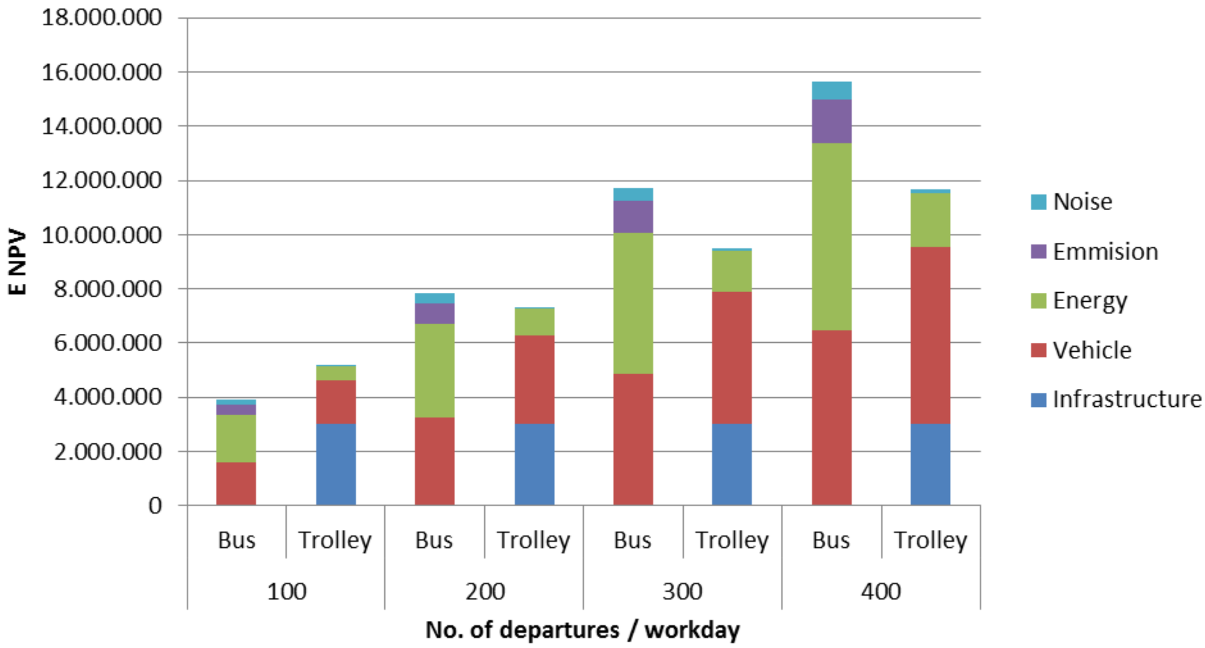


Figure 11. Zero-emission energy scenario for Poland - financial and social costs structure

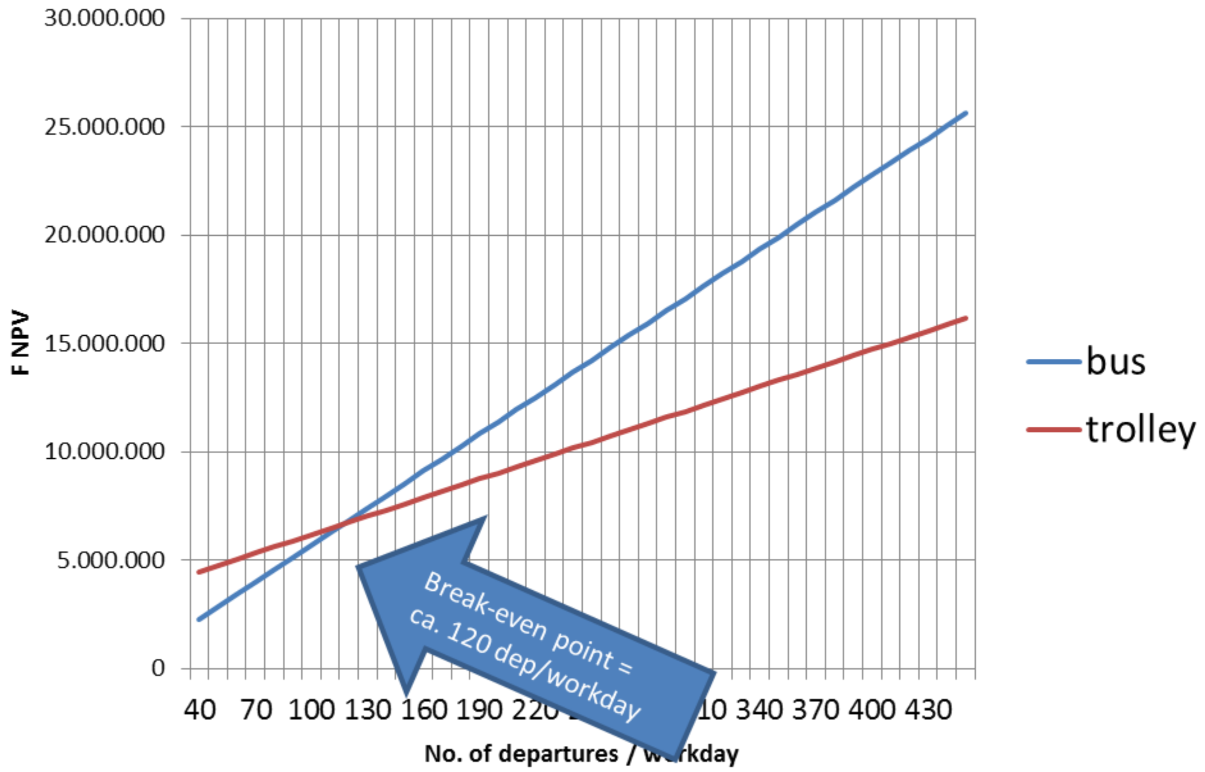


3.3 High-diesel prices scenario

In the above scenarios we included relatively low diesel costs of 1€/litre. In most of the Western European countries this price is however higher. In the last scenario, we assume initial net price of diesel of 1.25€ and its higher dynamics.

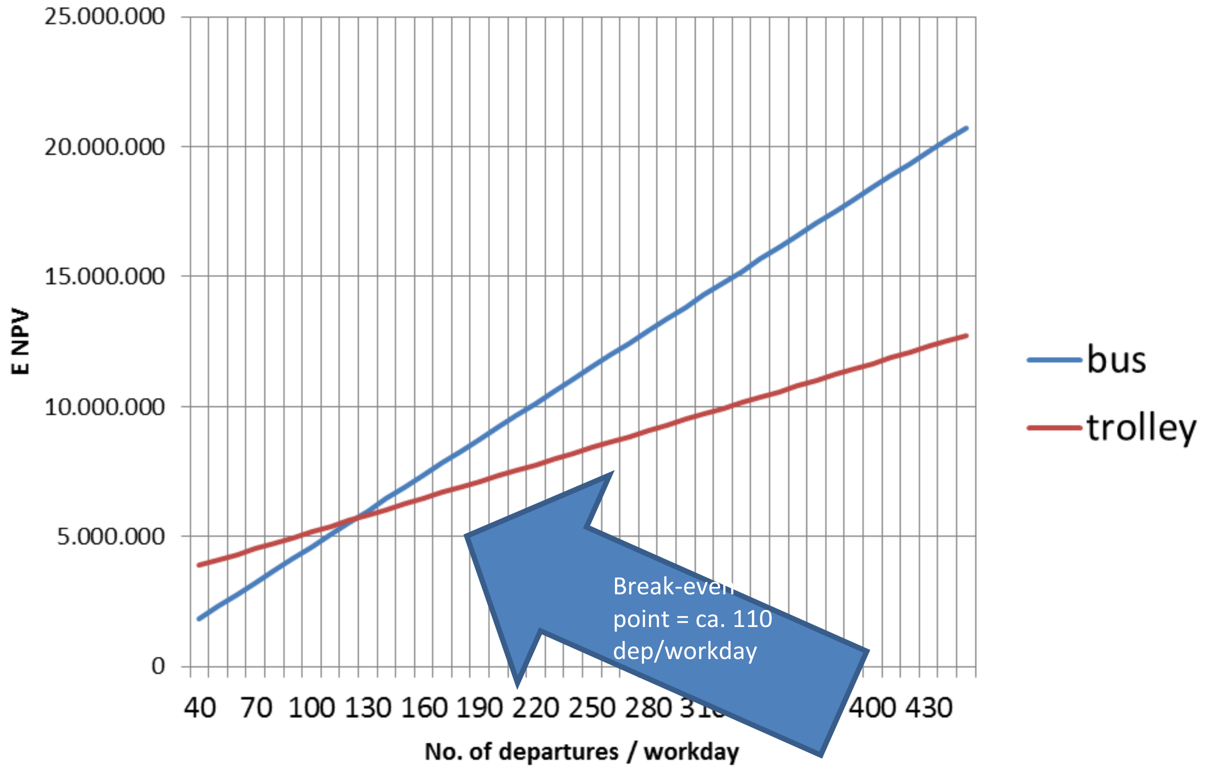
In this case, the results of financial analysis changed substantially – break-even point is now equal to 12 departures/workday what is equivalent to 8 minutes interval. This means, that the model is very sensitive to diesel prices and their dynamics.

Figure 12. High-diesel prices scenario- financial analysis



When we include also social costs, in this scenario break-even point is a bit lower (ca. 110 departures/workday), but still equals to ca. 8 minutes interval.

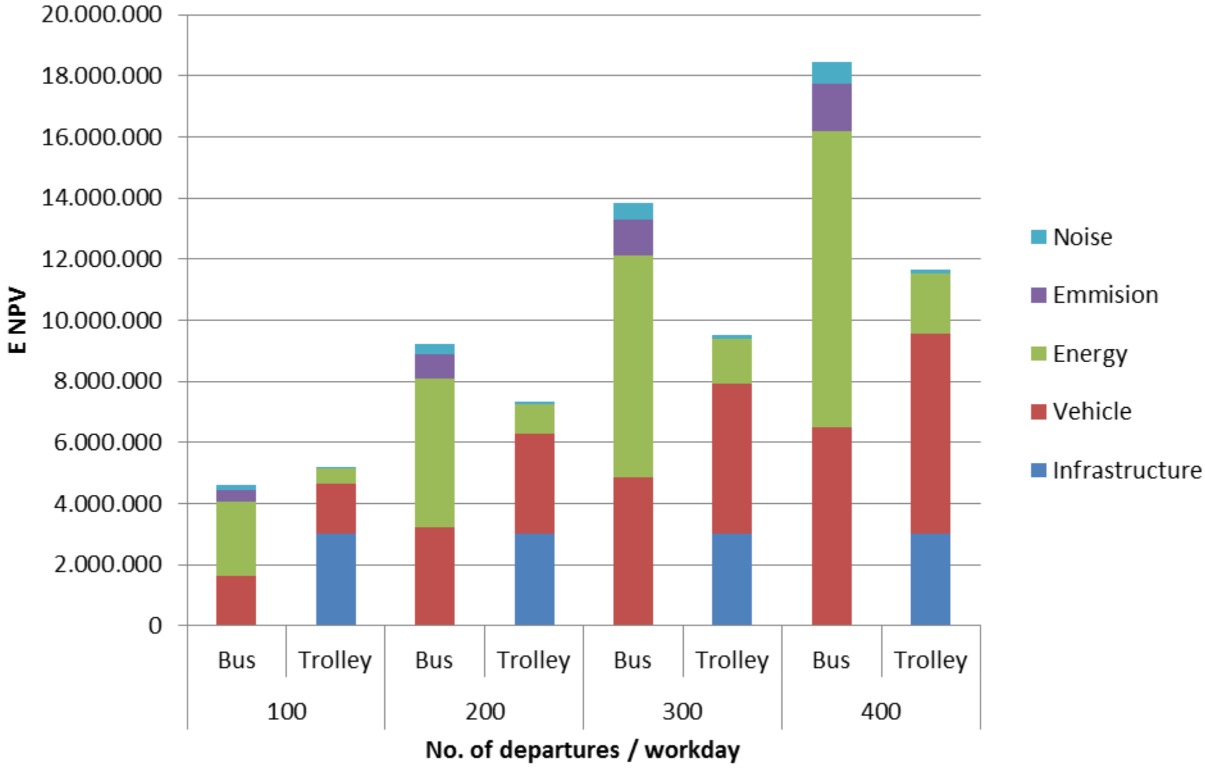
Figure 13. High-diesel prices scenario- economic analysis



When we analyse the full structure of social and financial costs (see figure 14), we can see, that in this case energy costs of energy in case of buses are ca. 5 times higher, than in case of trolleybuses.

Please mind that the model is very sensitive to diesel prices, but less sensitive to electricity prices, as they have lower share in total cost structure. Electricity prices in most of the countries are also less variable, than diesel prices.

Figure 14. High-diesel prices scenario - financial and social costs structure



3.4 'No-infrastructure-costs' scenario

In the last scenario, we assume that there is trolleybus infrastructure existing in a city. We return to 'low' diesel prices, but we assume that electric energy origins from zero-emission sources (exactly as in section 3.2).

This may be relevant also for a case, when the infrastructure is financed (or co-financed) from external grants, such as government or European funds.

In this scenario we still include infrastructure maintenance costs.

The results of the modelling show, that in this case break-even point falls even lower, than in section 3.2, down to ca. 95 departures/workday when we consider financial costs (see figure 13), and ca. 80 departures/workday, when we add social costs (see figure 14). This is respectively equivalent to ca. 10 and 12 minutes interval.

Figure 13. 'No-infrastructure-costs' scenario - financial analysis

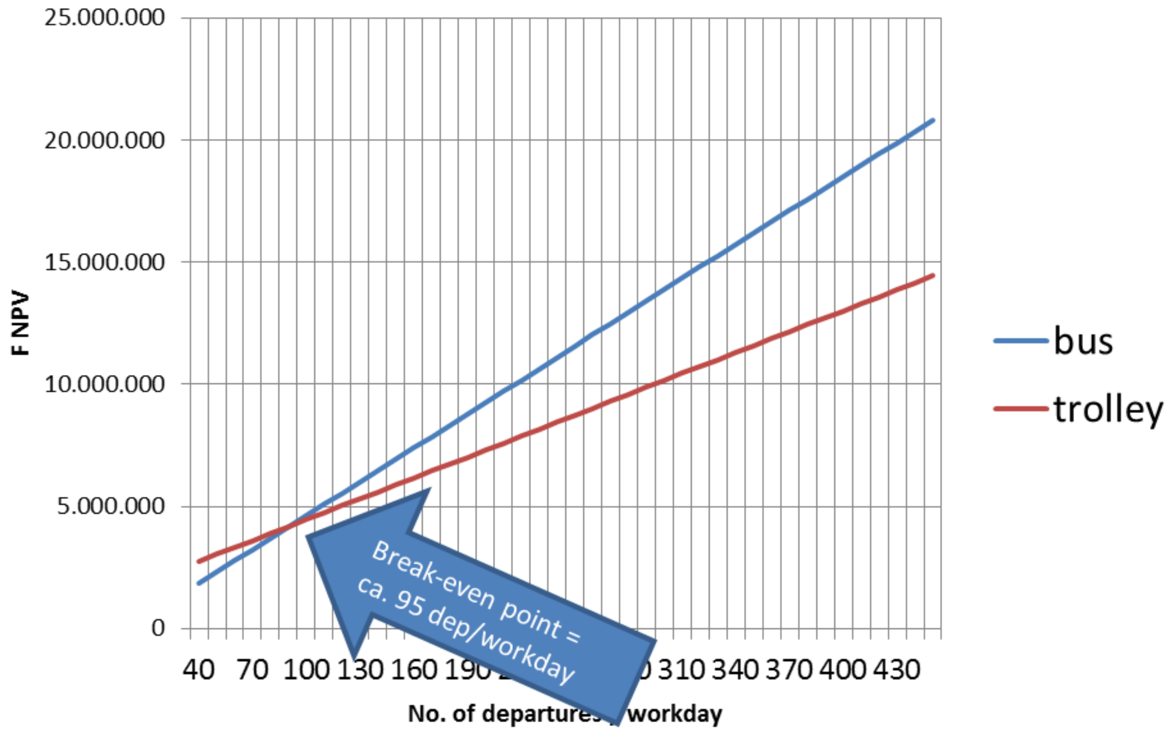
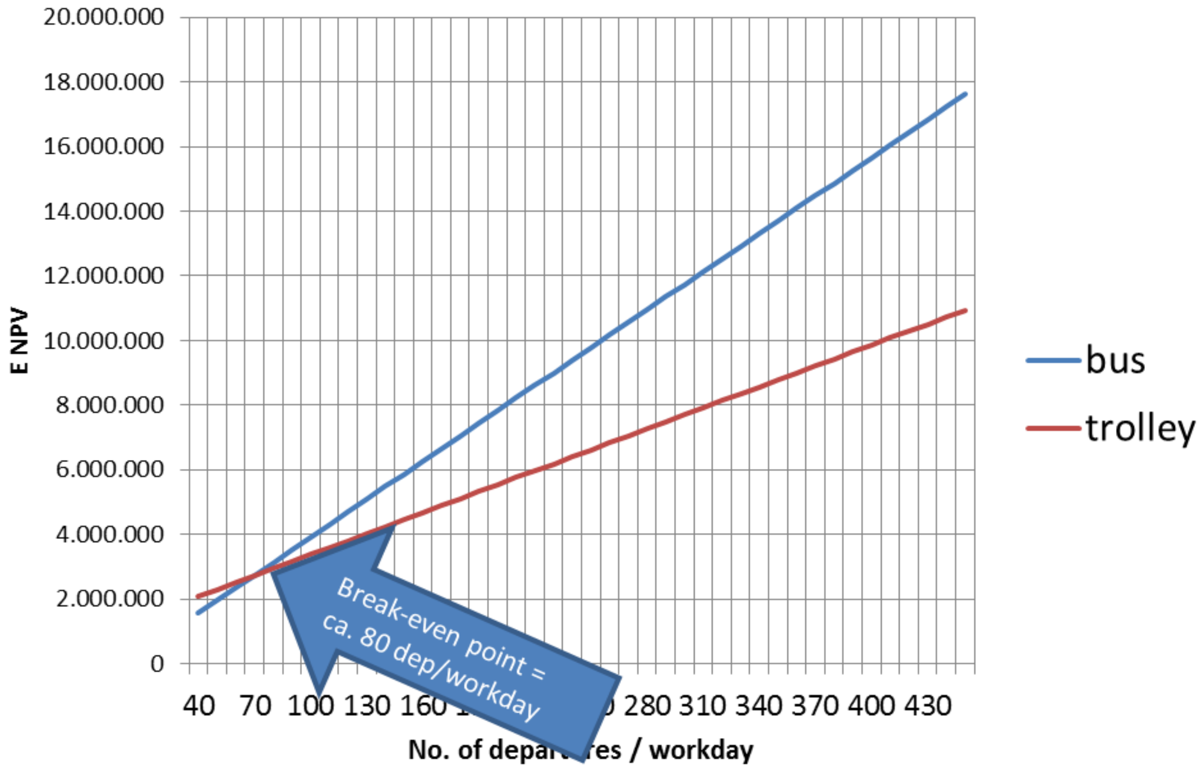


Figure 14. 'No-infrastructure-costs' scenario - economic analysis

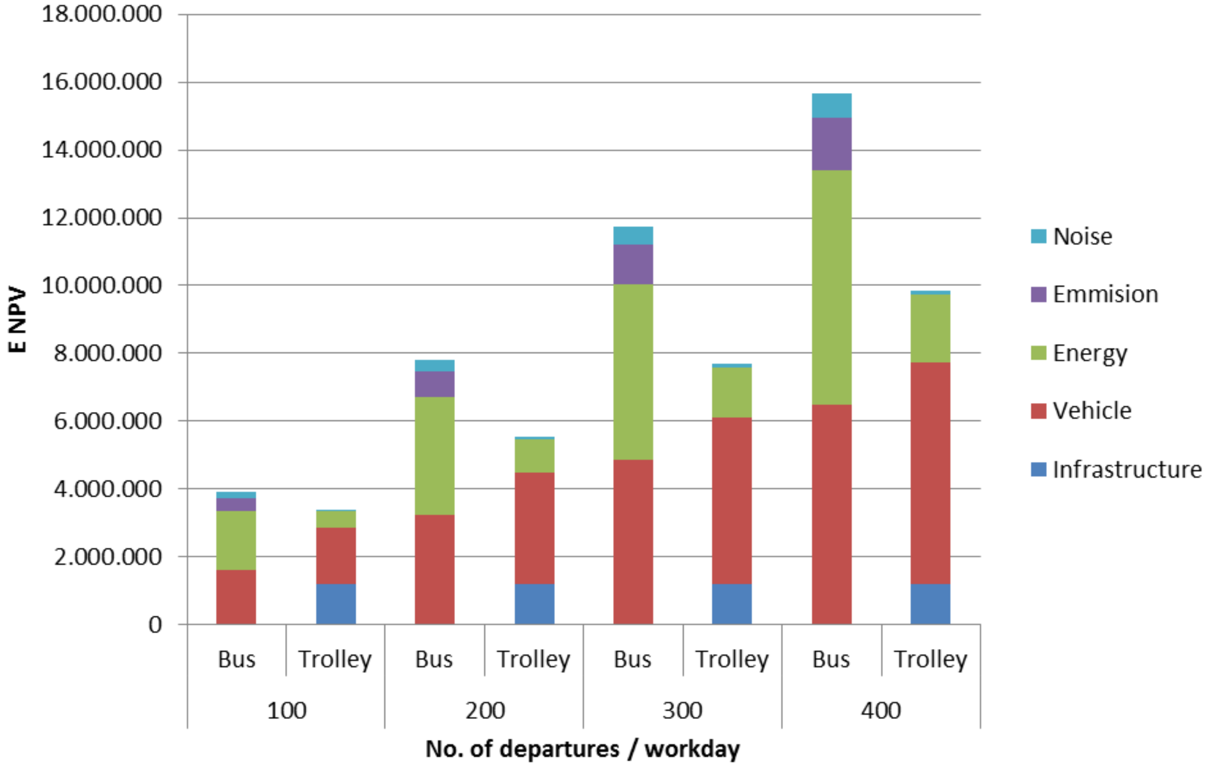


In this scenario infrastructure maintenance is still remarkable component of the total cost of trolleybus transport, but its share is smaller, than before (see figure

14). Above the break-even point, vehicle costs are the biggest part of trolleybus total cost.

In case of very strong traffic (300 departures/day), trolleybuses may provide savings over 20% in 'real' costs, and almost 25% including social costs.

Figure 14.' No-infrastructure-costs' scenario - financial and social costs structure



4. Conclusions

Concluding we may state, that in case of newly-built networks we usually should have an average interval of 4-8 minutes during workdays, in order to provide efficiency (see table 6). If some of the infrastructure or vehicle costs may be considered as sunk or is covered from an external grant, the break-even point is obviously more favourable for trolleybuses and then critical traffic may be below 100 departures/workday (below 10 minutes interval).

Table 6. Modelling outcomes

	Realistic scenario for Poland	0-Emission Energy scenario	0-Emission Energy, High diesel costs scenario	0-Emission Energy, no infrastructure investment scenario
Financial Break Even [departures/workday] (average interval)	190 (5 min.)	190 (5 min.)	120 (8 min.)	95 (ca. 10 min.)
Economic BreakEven [departures/workday] (average interval)	250 (4 min.)	170 (5.5 min.)	110 (8 min.)	80 (ca. 12 min.)

The most important factor, influencing cost of trolleybuses are diesel prices, which are very difficult to forecast. According to the scenario, energy prices in case of bus transport are 4-5 times higher, than in case of trolleybuses.

On the other hand, the most important component of trolleybus total cost is infrastructure. This cost is not so variable and may be easily predicted. In many cases it can be also externally co-financed, what constitutes an additional advantage.

Finally, we must stress, that the model can be further improved by adding different values for urban and extra urban emissions. This could additionally decrease break-even point, but the change will be rather slight, as the emission cost is a small component of the total costs.