Automated calculation of economic feasibility of using various types of passenger public transport in Russian conditions

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Abstract. Various modes of city passenger transport are being analyzed in the paper. The ecological efficiency of transport based on CO₂ emissions data for vehicles consuming various types of fuel is investigated. An automated calculation algorithm to compare initial and operating costs for conventional and hybrid buses consuming diesel fuel and gas with an electric bus having an autonomous ride range of 15, 60 and 250 km is developed. The calculation used correction factors reflecting the rising cost of fuel and electricity with the reducing cost of lithium-ion batteries per kWh. For the calculation of initial expenses the costs of equipment and charging stations are summed up, and for operating expenses the cost of maintenance, fuel and electricity for traction and heating, and payroll of drivers have been taken into account together with the replacement of batteries considering their limited cycle life.

1. Introduction

At present, a high number of strict environmental requirements are being imposed on urban passenger transit. At the same time, as new sources of energy are developed for transport, a large number of new types of vehicles are being developed differing in the design of power sources. Today in experimental and regular operation there are samples of ICE buses consuming various types of fuel, hybrid buses, trolleybuses, and electric buses with various types of electrical energy storage devices and charging methods. Thus, it becomes necessary to find the most efficient transport modes for given operating conditions.

The main factors affecting the choice of vehicle type are the expenses associated with:
- infrastructure cost;
- vehicle cost;
- fuel and electricity cost;
- durability;
- environmental impact in production and use.

Hu Binxiang et al. [1] conducted a comparative analysis of lifetime costs of fuel, hybrid, and electric buses. In his work the fluctuation of economical efficiency on these three models of vehicle considered the expected technology advance and fuel price change is also studied. The research results allow determination of the most economically effective transit mode for Chinese cities.

Paolo Cicconi et al. [2] also compared traditional and environmentally friendly vehicles. The proposed research focuses on life cycle cost from consumer side in order to evaluate the economic feasibility, using ecological solutions for transportation in EU. Also, different use scenarios are
proposed, considering different vehicle sizes and mileages.

In the paper the electricity consumption of urban public electric transport is being calculated and compared with hybrid and fuel analogues. Also, the initial and operating costs were calculated for the following types of vehicles: conventional and hybrid buses with an internal combustion engine (ICE) running on diesel fuel and compressed gas, and an electric bus with lithium energy storage (ES). These types of transport have been selected for study as the most common in the global bus fleet. They also reflect a wide range of possible power installations from less to more environmentally friendly ones. To calculate initial and operating costs, a specialized algorithm was created that allows estimating possible costs in a selected time period with large amount of corrective factors, such as an increase in the cost of fuel and electricity, a decrease in the cost of lithium batteries, an increase in the electric power consumption of hybrid and electric vehicles due to the added mass of energy storage.

2. Ecological efficiency

In the study performed by the German Association of Energy and Water Industries (Bundesverband der Energie-und Wasserwirtschaft, BDEW) the specific CO$_2$ emissions of cars operating on different types of fuel in Germany were compared [1]. The results are shown in Figure 1.

![Figure 1. CO$_2$ emissions from cars for a mileage of 14,300 km per year](image)

As it can be seen from Figure 1, with the energy structure of the Federal Republic of Germany where the coal power plants produce 38.1% of specific emissions of electric transport, their level is more than 2 times lower than that for a vehicle consuming diesel fuel. The difference between emissions produced by vehicles consuming natural gas, LPG and electricity is relatively small.

Applying this study on Russian infrastructure where the coal electricity generation share is 24%, a slightly smaller difference in CO$_2$ emissions between the vehicle on diesel or gasoline and electric vehicle would be received. Application of hybrid vehicles consuming CNG or LNG may reduce the fuel consumption more than 2 times comparing to non-hybrid vehicles. Consequently, in the conditions of Russia greenhouse gas emissions from electric transport will be higher than that of hybrid analogues consuming natural gas.

3. Trends in the development of transport

Figure 2 presents a diagram of the use of different fuel types by different types of vehicles according to their degree of environmental impact. Buses typically consume diesel or gas fuel and have the highest levels of greenhouse gas emissions. The next technological development stage would be hybridization of ICE and ES, or of ES and electric double layer capacitors (EDLC) and transition to environmentally friendly transport based on hydrogen. The diagram in Figure 2 shows the direction of a gradual transition from one type of transport to another over the development of technologies and tightening of emission standards.
In most cities, bus service is still prevailing over other transit modes. Since the introduction of buses, infrastructure has been developed and a wide base for maintenance and repair has been formed. Due to the tightening of environmental standards and rising fuel cost, the new models consuming natural gas are being introduced. This solution is the simplest and most economical, but does not significantly reduce the amount of greenhouse gas emissions [2].

The next step is the hybridization of classic bus and electric transport. Using electric motor for motion and ICE as the main energy source reduces fuel consumption by 1.5...2 times as compared with a gasoline bus [3]. However, this type of vehicle has a high cost caused by increase in number of structural elements, i.e. electric motor, generator, converter and buffer storage unit (BSU). Also, it increases the total mass of the vehicle [3].

The advantages of electric buses are zero emissions from vehicle itself and highest energy efficiency compared to common and hybrid buses. Their main difference from hybrid power installation is the replacement of serial connection of ICE, generator and BSU by ES, which reduces the number of structural elements and simplifies the power plant design. As the main energy source an ES based on a lithium-ion battery (LIB) is usually applied. Contrasting to the previous vehicle types, ES requires a long time to recharge, and consequently the development of infrastructure, including a network of charging stations. In addition, the specific energy of modern ES is still much less than of diesel or gas fuel. Thus, the placement of a large number of batteries on the vehicle is needed to maintain operating temperature of batteries and to ensure an acceptable travel range in the real traffic conditions. According to average estimates, the mass of ES contains up to 25% of the total mass of unloaded electric bus. In addition, having a high cost of kWh, ES based on a LIB makes up 50% of vehicle initial cost [4].

4. Calculation of initial and operating cost

Table 1 shows the total cost of transport and basic equipment. The cost of ES for electric buses with different range of travel per one charge is determined from the electricity consumption per km, the maximum depth of discharge, the length of the autonomous motion range and cost of kWh of a Li-Ti battery (for electric buses with an autonomous range of 15 and 60 km) and cost LiFePO₄ (for an electric bus with an autonomous range of 250 km). For the basis of the model was taken the LiAZ–5292 low floor 12-m city bus with the capacity of 112 people, which was subsequently converted into a hybrid bus or electric bus. The number of working days is assumed to be 320.

For buses and hybrid buses, infrastructure development costs are assumed equal zero, since now there is already a network of fuelling stations. For electric buses, the cost of production and installation of charging station capable to charge up to 10 vehicles simultaneously was taken as 98 million rubles [5].

Operational costs consist of fuel or electricity consumption for traction, heating the passenger compartment, maintenance of equipment and charging stations, the payroll of drivers, and replacement of ES. The rise in prices for fuel and electricity is modeled by correction coefficients that increase the
cost: electricity – by 6% per year, diesel fuel and CNG – by 7% per year. The values of the coefficients are obtained from the data of increase in price of fuel and electricity for the period from 2012 to 2018. In the calculation, it was assumed that the cost of diesel fuel for 2019 is 45 rub/l, CNG – 17 rub/m³, electricity – 3 rub/kWh.

The fuel and electricity consumption rates are presented in Table 2. Hybridization allows the use of ICE in the highest efficiency modes, and recover a part of braking energy back to BSU, which reduces fuel consumption by up to 40% compared with models without hybridization [6 - 10]. The electric bus can also recover 17 ... 25% of the braking energy in ES [11].

Heating of the passenger compartment is carried out by increasing diesel fuel or gas consumption by 8% in the case of bus and hybrid bus, or using a 15 kW diesel generator in the case of electric bus. It is also accepted that heating is used for six months each year.

Technical inspection and maintenance (TI) is carried out for the body, ICE and gearbox, gas equipment, traction motor and converter, and charging station. The calculation takes into account the growth in the cost of servicing an annual inflation rate of 5%.

In Table 3 the costs of maintenance for various equipment types are presented.

### Table 1. Costs of equipment

| Transport mode | Equipment | Vehicle cost, mln. rubles |
|---------------|-----------|--------------------------|
| Hybrid bus (diesel) | Body | 10.6 |
| Hybrid bus (CNG) | ICE + transmission | - |
| Electric bus (15 km) | ICE + generator and gear | 1.4 |
| Electric bus (60 km) | CNG equipment | - |
| Electric bus (250 km) | Traction motor + converter | 1.7 |
| ICE bus (diesel) | BSU + Converter | 3.8 |
| ICE bus (CNG) | LIB+ BMS | - |
| Hybrid bus (diesel) | | 18.5 |
| Hybrid bus (CNG) | | 19 |
| Electric bus (15 km) | | 14.8 |
| Electric bus (60 km) | | 19.4 |
| Electric bus (250 km) | | 25.2 |
| ICE bus (diesel) | | 12 |
| ICE bus (CNG) | | 12.5 |

### Table 2. Fuel and electricity consumption rates

| Vehicle type | Consumption per 100 km |
|--------------|------------------------|
| Hybrid bus (diesel) | 29.4 l. |
| Hybrid bus (CNG) | 36 m³ |
| ICE bus (Diesel) | 49 l. |
| ICE bus (CNG) | 60 |
| Electric bus (without energy recuperation) | 3.4 kWh |

As a result of batteries cost analysis we have established that the price for LIB is annually reduced by 8.6%. Therefore, for an objective calculation of the cost of replacing BSU and ES, the coefficient of annual reduction of the LIB have been taken into account.
Table 3. Cost of technical inspection

| Equipment                                      | Cost  |
|-----------------------------------------------|-------|
| TI of charging station, ths. rub / year       | 100   |
| TI of body, ths. rub / year                   | 600   |
| TI of ICE+gearbox, ths. rub / year            | 300   |
| TI of Gas equipment, ths. rub / year          | 50    |
| TI of traction electrical equipment, ths. rub / year | 150  |

The service life of BSU in a hybrid power installation is determined in accordance with the number of required charge-discharge cycles, the installed energy capacity of BSU and operating modes. Thus, the life cycle of a BSU based on a Li-Ti battery for a hybrid bus will be up to 5 years, after which it would be necessary to replace it. In electric buses with a short range of autonomous traction (15 and 60 km), it is also expedient to apply Li-Ti batteries which are the most adapted to the frequent recharging regimes. For electric buses with an autonomous motion range of 300 km a battery based on LiFePO₄ was chosen, since it has a higher specific energy capacity (100 kWh/t for LiTi, 220 kWh/t for LiFePO₄). It was accepted that the battery durability for an electric bus with a range of 15 km would amount up to 5 years while for an electric bus with a range of 60 and 250 km up to 8 years.

As a result of calculation for the operation period from 2019 to 2034, the total costs for the submitted modes of transport are obtained. Figure 3 shows a diagram with the initial and operational costs for various types of transport. In Figure 4 there is relationship between the various types of operating costs during the first year of operation.

![Figure 3. Total initial and operating costs of various types of vehicles](image)

![Figure 4. Operating costs (in 2034)](image)
5. Conclusions
The comparison of the hydrocarbon emissions amount depending on mileage was performed for various transport modes. It was found that under the existing energy system structure in Russia, the greenhouse gases emissions of electric transport were comparable with those of hybrid analogs consuming natural gas.

Comparison of initial and operational costs between bus and hybrid bus consuming different fuels and electric buses with batteries of different energy capacity showed the comparability of costs for hybrids and electric buses. Considering conventional bus as not energy efficient and environmentally friendly, a transition to fully electric buses became necessary. However, application of electric buses with the increased autonomous traction range of 250 km led to significant increase in weight and capital costs while electric buses with small autonomous course of 15 km and 60 km would require the deployment of the distributed charging station network.

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