Economic conditions to introduce the battery drive to buses in the urban public transport

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Abstract

For a few years attempts have been made to introduce electric-powered buses to public transportation system. In order to solve this problem rationally, in dependence of local public transport system conditions, models of technical, organizational, economic and ecological links enabling optimal choice of type of propulsion for particular bus line is developed. Technical solutions to enable fully electric busses should be evaluated whether they reflect the prerequisites and requirements of the participating public transport companies. The paper presents a method for evaluating transport system in accordance with the principles of cost-benefit analysis that allows to answer the questions related to the cost-effectiveness of the use of electric drive buses in urban public transport. The model can be used to analyse and design the services of urban public transport in terms of costs generated by the bus fleet equipped with various types of drive. The article presents procedures used to determine the costs used in the method of evaluation of the proposed solutions. The ultimate goal is to find the best technical solution for local public transport companies depending on their real input data (timetable, vehicle operation plan, etc.), which in most cases may mean minimising economic effects, like investment and operational costs.

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

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1. Introduction

Dynamic development of battery electric buses construction (BEB, EV Buses, e-buses) allows to set up their market share growth in urban public transport. According to Topon and Hisashi (2006), various government organisations provide support for installation of charging infrastructure and encourage the adoption of EV Buses for city transportation to promote wide-spread adoption of electric vehicles. One should take into account significant relationship between the technical and organisational aspects of the e-buses implementation. Due to Rogge et al. (2015) battery electric buses neither have a continuous power supply nor generate electricity on-board. Their energy is stored in the battery. The driving range of battery buses is therefore limited and the charging process requires a certain time. Referring to Lei Bao et al. (2013), there are two modes of BEB operation: slow charging mode and battery leasing and displacing mode. In Li at al. (2015) the design of battery swap station for electric battery buses as a solution to replenish energy is presented. According to Varga and Iclodean (2015), the bus should operate with the batteries charged almost to maximum capacity to reduce the risk of being left without energy due to unforeseen circumstances.

The operation of such buses in urban public transport system needs to be adjusted to the requirements of electric drive: organisation of technical facilities of bus depot to ensure reliable and efficient exploitation of the fleet, layout of bus routes network and bus schedule. In CACTUS project deliverable 2.1 (2013) it was assumed that in the near future, there will be no batteries for fully electric busses which provide the daily output of 300 km without needing to be recharged and which would be acceptable in terms of their size, weight and cost as well as there is no technical approach that is currently being investigated that will be equally suitable for all public transport companies. In any case, investment costs for vehicles, in-vehicle components and infrastructures (e.g. battery charging or battery switching facilities) will be very high for public transport companies.

The complexity of the issues to develop functional and operational configuration of transport system which will be optimal in terms of needs and potential of the area require development of the simulation model. In Perotta et al. (2014) simulation method to analyse the energetic profile of an electric bus performing three routes with specific characteristics that has been accomplished by the use of an integrated simulation platform, following the High-Level Architecture (HLA) approach for distributed simulation is presented. A key area of research on introducing battery electric buses to operation in urban public transport companies are economic issues covering various types of costs that should be borne in order to achieve electric-powered buses operation in urban public transport.

2. Model supporting electric-powered buses introduction to urban public transport

2.1. Structure of the model

The research of Yu and Rao (2015) gives scientific basis for decision making process concerning commercial operation of battery electric buses under different physical conditions (vehicle conditions, local conditions and road conditions). In Pejšová (2014) there were three aspects which are essential for the operation of city public transport: financial aspects, performance aspects and aspects of impact on the environment. Kidway at al. (2005) considered the design of bus transit system as a systematic decision process consisting of five stages: network design, frequency setting, timetable development, bus scheduling and driver scheduling. However, the two most fundamental elements, namely, the design of routes and setting of frequencies, critically determine the system’s performance from both the operator and user point of view. Significant savings in resources can be made by reorganization of bus routes and frequency to suit the actual travel demand. Nevertheless, the research team assumed that the transport service being offered for passenger will not be changed as the timetable is constant during the simulation while schedules of the bus may be a subject of optimization. Hence the structure is as follows:
- **Transportation model** comprising road network sub-model (plan and profile of road section, free flow speed, wave speed), bus routes network sub-model (location of bus stops, the route between stops, timetables at the stops, traffic lights, traffic congestion), driving time sub-model (depending on the plan and profile of the route according to traffic stream properties)

- **Technical sub-model** describing the parameters obtained from transportation model (network, speed and distance profiles, driving time), mechanical characteristic of e-buses and the batteries as the input data while the output parameters include the optimization of the fleet choice for declared route while keeping the established timetable and the ability to simulate: the battery life (driving time, speed changes), charging stations geographic distribution and the battery charging strategy

- **Ecological sub-model** that contains the requirements the relevant legislation on air quality (e.g. Directive 2008/50/EC) as the input data and environmental impact in formula of emissions volume for different type of bus propulsion (Diesel buses, CNG, LNG, Hybrid buses)

- **Economic sub-model** showing the relationship between financial factors (loans, leasing, cash), the purchase of the rolling stock costs as well as infrastructure maintains and exploitation costs, bus fleet structure (fully electric or mixed), energy supply strategy (charging, charging and recharging, exchanging of the battery).

![Fig. 1. The structure of public transport network.](image)

Fig. 1. depicts the dependents between subsequent sub-models. The main objective of the authors’ research team was to develop the economic sub-model which is mainly dependent and influences the technical sub-model. Effects of sub-models’ cooperation can be analysed in a structural model of the transport network for the urban public transport service area.

### 2.2. Main issues of the economic sub-model

Due to the research of CACTUS project team as well as Herrmann et al. available technical approaches and solutions must be considered separately against the prerequisites and requirements of every single public transport company in terms of transportation, technical, economic and environmental aspects. Only on this basis can a decision for a technology that optimally meets the requirements of a public transport company be made as in CACTUS (2014).

<table>
<thead>
<tr>
<th>Input data</th>
<th>Output data</th>
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<tbody>
<tr>
<td>Transportation model</td>
<td>Investment and operational costs</td>
</tr>
<tr>
<td>Input data from transport organiser</td>
<td>Life cycle of the batteries depending on the charging strategy</td>
</tr>
<tr>
<td>Needs of e-bus manufacturer</td>
<td>Battery charging, recharging, exchanging stations</td>
</tr>
<tr>
<td></td>
<td>Costs of vehicles and infrastructure implementation and exploitation</td>
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In order to develop a proper economic model of electric-powered buses introduction to the public transport system there is a need to specify the input and output data. The comparison of the input and output data to the economic model is shown in Table 1.

There are many questions of an economic nature concerning electric-powered buses implementation in urban public transport system. A public transport companies have to evaluate the costs the electric drive in comparison to traditional one (combustion engines), costs that involve purchasing and maintaining technical infrastructure in the depot and on the network (charging, recharging or exchanging stations) which are essential for e-buses operation as well as the external costs of such solutions comprising the costs of noise pollution, the costs of emissions of harmful substances in the high-populated areas. Considering the economic conditions of electric buses’ introduction one should also take into account the costs of recycling of used batteries and the possibilities of ‘second life’ of the battery. Topon (2014) claims that the major hurdle for large-scale adoption of EV Buses is the cost of the buses as well as the installation cost of the charging infrastructure. A sensitivity analysis of total costs of ownership for a fleet consisted of electric-powered buses, including three scenarios for two different types of electric buses, is presented in Nurhadi et al. (2014). In Litman (2011) there were twenty-three transportation costs evaluated under cost-benefit analysis. Benefits which are generated by the use of electric-powered buses in public transport should be evaluated after calculating the costs related to compared variants of transport using a method of assessing the proposed solution based on an economic model. The cost-benefit analysis with the use of simulation models was conducted for an electric bus fleet being able to compare different bus applications in terms of life cycle costs in Lajunen (2014). According to the authors of this article, the costs of public transport based on bus fleet can be divided into the following:

- **Prime costs** – costs which are incurred by the public transport organisers and bus operators
- **Transport infrastructure costs** – costs of building and exploitation of transport infrastructure which are neither covered by the transport organisers nor are subsided from the local government
- **External costs** – environmental costs which have not been covered by the users and the costs of road accidents
- **Time cost** – costs borne by the users of transport due to loss of time.

The economic model and the method of selecting the type of propulsion based on this model is essential for the analysis of the viability of the use the battery drive in public transport. The analysis indicates the relationship between input data and effects generated by the application of electric drive in public transport buses. The most important criterion in the economic model is the option of operation by conventional diesel buses or electric buses – in the second case possible technical and operational solutions such as en-route battery recharging are also considered. Economic aspects have to be preceded by an analysis of energy consumption of the battery depending on the load of the bus due to profile of elevation of the route, passengers weight and power consumption by on-board systems (e.g. lighting and air conditioning). On the basis of the analysis it is possible to identify appropriate routes and therefore estimate the number of electric buses as a part of buses fleet to service of urban transport networks according to Karoń and Janecki (2014).

The formula (1) describes a present economic value of the calculated variant. It is the total cost of electric-powered buses ownership, exploitation and adaptation to their needs and way to exchange and charging the battery less for present value of the proceeds of liquidation.

\[
KCW = KA + KO + KI + KZ - PL \ [\text{EUR}]
\]  

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>KA</td>
<td>present value of the acquisition costs of bus</td>
</tr>
<tr>
<td>KO</td>
<td>present value of the operational costs</td>
</tr>
<tr>
<td>KI</td>
<td>present value of the infrastructure costs</td>
</tr>
<tr>
<td>IE</td>
<td>present value of the external costs</td>
</tr>
<tr>
<td>PL</td>
<td>present value of the proceeds of liquidation</td>
</tr>
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</table>
The benefits which are generated by battery electric buses operation is to be considered as well as the costs associated with the introduction these buses to urban public transport. Taking into account the overall form of the model it should be noted that the effects arising from the e-buses introduction to public transport are twofold:

- Direct economic benefits associated with the operation of transport variant using the method based on the economic model (existing conventional fleet, mixed fleet that consists of conventional buses and battery electric buses, pure electric fleet)
- Benefits identified in the urban environment which are the subject of evaluation based on the ecological model.
There are economic effects that are possible to achieve after a period of the EV buses’ exploitation which size is determined by the market value of the vehicle. The computational procedure comprises the calculation of the nominal proceeds of liquidation based on nominal cost of acquisition of bus and the value of percentage rate of residual value as well as the calculation of present value of the liquidation proceeds.

3. Tool

The algorithm which is presented in Fig. 2. is a part of the CACTUS Tool – the software supporting the process of electric-powered buses introduction to public transport system. It’s major feature are battery charging points, charging tracks or exchanging station localisation optimisation using the methods presented in CACTUS Deliverable 3.1 (2014). The tool supports the proper planning process of introducing electric-powered buses to operation in urban public transport. The algorithm has been developed for public transport authorities (organisers of public transport) or operators (municipal public transport companies), and allows to enter technical and economic requirements of the specific situation. Simulating a variety of options allows the company to rank the bus routes regarding their capability for electrification (being operated by battery electric buses). The interfaces’ print screens of the tool are presented in Fig. 3.

![Fig. 3. Interface of the tool (a) startup screen of the economy model; (b) economy model values.](image)

To run a simulation one need the input data collected from sources listed out in Table 1 which are stored in batch files written in Extensible Markup Language (XML) format that provides proper clarity and the possibility of dynamic swapping the data in case of feedback in the end of simulation. The batch file in which economic input data are stored is ‘Economy.xml’.
The scheme shown in Fig. 4. shows the assignment of input data to the respective sub-models. After the simulation is over, a ‘Report on Economic Impact’ is generated by the program which includes the most important output data from the calculation. The results are the total cost of ownership in use of electric buses and adapt to their needs and way to exchange and charging the battery less for present value of the proceeds of liquidation.

‘Economy.xml’ file contains the definitions of the various cost types (in Euro) such as present value of acquisition, operational, infrastructure and external costs which are included in the <CostType> tag. General acquisition costs are the costs of the bus fleet: bus costs itself and the costs double-layer capacitor taking into account subsides and external finance rate. Category ‘annuity costs’ refers to financial conditions of the investment in electric buses. Credit period, loan interest rate, market interest rate and repayment terms are taken into account in this category as well as Different types of propulsion extort different units: [kWh/km], [EUR/kWh] for e-buses, [l/km], [EUR/l] for diesel buses (for petrol and AdBlue). Costs of the maintenance are the subject of category ‘Maintenance Costs’, annual operational use is taken into account as well. These costs depend on the fleet size (number of buses), additional equipment, age of the fleet, etc. Wage costs are in category ‘Salary’ which contains costs generated by bus drivers as well as their training and maintenance. Tire costs depend on the schedule speed expressed in [km/h]. Noise and pollution emissions are assigned to the category ‘External costs’ (the unit is [EUR/km]). In the category “Battery Swapping Costs” the numbers of additional batteries, battery capacity and the costs of the battery capacity are defined. These costs which were not assigned to categories previously described are presented in category “Other costs”. The above mentioned are the costs of insurance, costs of supply, costs of vitality of the fleet, maintenance of infrastructure as well as funding of infrastructure costs.

<table>
<thead>
<tr>
<th>Table 2. Costs related to technical model.</th>
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<tr>
<th>Charging at points</th>
<th>Charging on tracks</th>
<th>Exchanging batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs of installation charging facilities</td>
<td>Costs per installation for each track</td>
<td>Costs for installation swapping facilities for each bus stop</td>
</tr>
<tr>
<td>Cost per meter of installation for each track</td>
<td>Cost per swap for each bus</td>
<td></td>
</tr>
<tr>
<td>Capacity measured in batteries per hour for each bus stop</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2 presents selected costs which are needed to declare in which are associated with technical aspect of electric-powered buses introduction to urban public transport. Costs and lifetime of the battery (and spare battery) as well as the capacity of the battery are essential for further calculations in the model. Another technical solutions which are necessary to compute the economic model are obtained from technical sub-model.

4. Exemplary calculation

4.1. Input data

The example which is mentioned in this article has been calculated for the 12-meter long electric-powered bus having 85 seats for passengers (including 34 seated). The bus is retailing at 425 000 € and its expected lifetime is 20 years. During the exploitation the bus will be having assumed averaged mileage of 63 000 km/year and the average speed of 25 km/h. Energy consumption has been assumed to be 1.5 [kWh/km] while the unit cost of energy to be 0.14 €/kWh.

The bus is charged at points (conductive charging). In-depot charging station powered 32 kW cost is assumed to be 12 500 €, the cost of additional re-charging facility located in the network is assumed to be 75 000 € while the connection cost is 15 000 €. Exploitation costs is assumed to be 375 € for in-depot charging station and 1250 € for re-charging station located in the network. Annual conductive charging maintenance costs are assumed to be 1625 €. The original battery will be replaced after 10 years of exploitation. The cost of additional battery with the capacity of 120 kWh is assumed to be 350 €/kWh.

Loan interest rate is 0.07 while market interest rate is 0.0316. The credit period and repayment term amount to 5 years, 5 instalment are also established. External finance rate is assumed for 0.8. The subsides for the bus from the authorities is assumed to be 297 500 €.

No exceptional boundary conditions is modelled. The costs listed in the example are hypothetical and for a specific example in Polish conditions and may vary depending on local predispositions.

4.2. Results

Table 3 presents a fragment of the Report of Economic Impact which is the output of the CACTUS Tool. The table shows that the largest group of expenses are operating expenses, which amount to 584 922.26 € during its 20-years’ operation. It should be noted that in the assumptions of this example is the support of the battery electric purchase by government subsides which significantly reduces the costs incurred by the operator. Costs of acquisition incurred by the public transport company amounts to 169 680.68 €.

<table>
<thead>
<tr>
<th>Costs type</th>
<th>Symbol</th>
<th>Cost value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present value of the acquisition costs of bus</td>
<td>KA</td>
<td>169 680.68 €</td>
</tr>
<tr>
<td>Present value of the operational costs</td>
<td>KO</td>
<td>584 922.26 €</td>
</tr>
<tr>
<td>Present value of the infrastructure costs</td>
<td>KZ</td>
<td>185 189.77 €</td>
</tr>
<tr>
<td>Present value of the external costs</td>
<td>KI</td>
<td>57 323.96 €</td>
</tr>
<tr>
<td>Present value of the proceeds of liquidation</td>
<td>PL</td>
<td>0.00 €</td>
</tr>
<tr>
<td>Total</td>
<td>KCW</td>
<td>997 116.67 €</td>
</tr>
</tbody>
</table>

Demonstrative percentage of the cost structure is depicted in Fig. 5. Due to the lack of data present value of the proceeds of liquidation are not taken into account thus its share in total cost structure is zero. Significant variations in the cost structure depending on the method of financing, fleet size, the specifics of the urban transport company and local conditions are observed.
The results presented above are the first important economic output data obtained from CACTUS simulation tool and present the usefulness of the tool from public transport companies’ point of view. In the near future the results in a systemic approach will be presented for varied operational variants which are to be defined by the companies planning to implement electric buses to operation in urban public transport system.

5. Conclusions

The approach to the issue of economic conditions to introduce the battery drive to buses in the urban public transport that is presented in the article enables the creation of practical application to assess the variants of urban public transport company behaviour (operator). Economic sub-model, that has been carried out within the ERA-NET Electromobility+ project, acronym CACTUS, pull together with another sub-models which were implemented by the partners of consortium and can be a basis to rational choose of propulsion variant in urban public transport on the basis of answering the questions related to the cost-effectiveness of the use of battery electric buses by the urban transport company.

Replacing conventional Diesel buses with the alternative fuel buses (incl. electric buses) is a long-lasting process which could be aided by the computer simulation. The application makes use of a simulation technique that allows the optimal choice of the propulsion type for analysed public transport taking into account technical, organizational, economic and ecological aspects of battery electric buses introduction to urban public transport system. An important consideration throughout the method is the assumption that the transport service being offered for passenger will not be changed as the timetable is constant during the simulation. However, schedules of the bus may be a subject of optimization.

It is possible to plan a multistage process of battery buses introduction by ranking the bus routes that may be electrified depending on available funds on the basis of the output data from the simulation. The tool help the user (public transport authorities, organiser, operator) to plan the process of electric buses introduction to operation properly by taking into account unique economic needs of the company. It is possible that the company can afford to electrify (replace conventional buses by electric-powered buses) only a fragment of the network (selected bus lines) the tool helps the company choose the bus routes that are most suited for this purpose. Certainly, the variant of replacing conventional buses by electric ones in the whole network is possible to assess in the economic sense.

Due to the simulation many economic uncertainty factors from the decision-making process to introduce the battery drive to buses in the urban public transport can be estimated.
References


Li, W., Li, Y, Ma, G. Design and Simulation of a Battery Swap Station for Electric Battery Buses. ICTE 2015: pp. 48–57.


