Selected Issues of the TCO Model for the Conversion of the Conventional Bus Fleet to Electric One

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Abstract National and European transport policy is now moving towards zero-emission transport. One way to achieve public transport policy objectives is to replace conventional buses with electric ones. However, due to the technical characteristics of electric buses, this process will be complicated. Tools are therefore required to support this process. The objective of the research project ERANET Electric Mobility Europe project "PLATON - Planning Process and Tool for Step-by-Step Conversion of the Conventional or Mixed Bus Fleet to a 100% Electric Bus Flee" is to support the stakeholders involved in the process of fleet renewal using an IT tool. Proper development of the tool requires the analysis of many aspects related to the process. The article presents selected elements influencing the total cost of ownership (TCO). The focus of the paper is on the technical and organizational aspects related to the replacement of bus fleet. Authors also shows the main aspects of the structure of TCO analysis.

Keywords electric bus, electromobility deployment, public transport

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1. Introduction

Current developments in public transport aim at the gradual elimination of the conventional bus fleet. The achievement of the intended objectives of replacing conventional buses in public transport with electric buses can be achieved, for example, by replacing conventional with electric buses. Taking into account the provisions of strategic documents (e.g. transport policy) of cities and regions, the process of replacing conventionally driven buses with electric buses may be different from an aggressive approach, consisting in replacing all rolling stock at once, to a mild one, in which vehicles are replaced gradually. Conversion of the bus fleet with conventional propulsion (Diesel or hybrid engines) to electric drive is a process that many cities in Poland face. The fleet conversion process is a remarkably complicated, multithreaded and multifaceted task.

Proper conversion from a fleet of buses in public transport with conventional propulsion to an all-electric fleet will include an analysis of the needs for such an exchange in a given urban agglomeration, and planning future actions to develop conditions for the implementation of these plans, adapted to local needs, implemented according to the degree of importance (attractiveness) and feasibility of the assumed transport tasks. The analysis of the needs for introducing electric buses to public transport may be conducted from the point of view of the political, economic and economic environment in Poland and other EU countries, and the results of this analysis may be different, depending on the policy of a given country or agglomeration. Stakeholders who have an impact on the bus fleet need to define an exchange strategy from the first stage. By indicating, inter alia, the minimum exchange time, the process flow and the financial resources needed in a specific time period. The decisions concerning the definition of the exchange process are supported by various tools which will include the results of the current PLATON project. The development of this tool requires a description of the factors that influence the exchange process of buses.

The aim of the PLATON project is to define the process of planning the conversion of the existing fleet of conventional buses in public transport to 100% share of electric buses and the implementation of this process as an IT tool, based on open-access Internet technologies.

The technical aspects of replacing the bus fleet with electric ones primarily concerns the reliability of the components of the electric bus operation system (including bus, battery and power system, charging stations and the battery charging system, individual components of the technical charging system and the functioning of public transport).

Operational aspects of the implementation process of electric buses are to take strategic decisions on network development. The areas managed by the company are differentiated according to the area served, which takes into account land-use planning, topology and the potential for development from the point of view of the new technologies introduced.

The article discusses technical aspects, general structure of elements, operational aspects, process approach and total cost of ownership (TCO) analysis of the issue of urban bus fleet conversion. It is assumed that the process of fleet conversion may take place in different stages, using various means, taking into account different fleet structure, financial standardization of the company or institution implementing specific measures in the conversion process, as well as the life cycle of the implemented technologies. Within the project "PLATON - Planning process and tool for gradual conversion of conventional or mixed bus fleet into 100% electric bus fleet" it is planned to develop an IT tool to provide economic support in the planned conversion of the fleet for the transport company. Support will include: cost structure and analysis of the TCO of the electric fleet of urban buses.

The article is organized as follows, section 2 provides information about the technical aspects of replacing the bus fleet. The next section presents operation aspects of the TCO in electric buses. Section 4 contains main structure of TCO model. Section 5 of the paper contains conclusions and propositions for future work.

2. Technical aspects

The technical constraints of electric buses concern the following aspects:

- construction of electric buses,
- charging infrastructure and charging stations types
- type of energetic infrastructure.

Construction itself is one of the most important issues as it results in the daily available range of the bus. Electric buses are made of the same vehicle bodies as diesel buses. However, the total weight of the batteries used in electric buses can be several tons. This has a significant impact on the number of passengers to be boarded as well as on the construction of the bus. The weight of a battery is a reason for an apparent conflict between battery capacity and passenger numbers to be boarded.

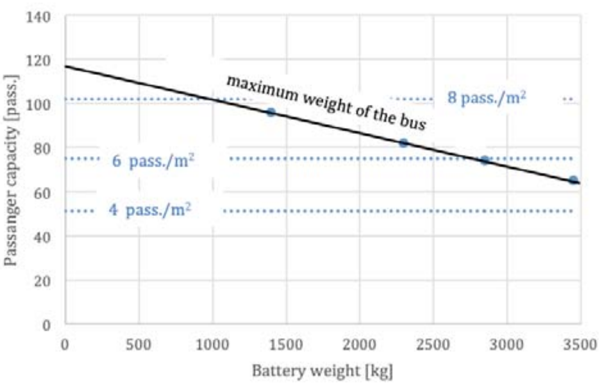

Figure 1. Passenger capacity of a 12 m bus as a function of added battery weight, and passenger capacity [1].

Designing the bus for a passenger capacity determined by floor space leave sample weight reserve for traction batteries even under crowded conditions, as Figure 1 illustrates for a 12 m electric bus [1]. In this example, even assuming a passenger density of 8 per square meter, we can add battery weighing above to 1 ton.

A typical electric bus configuration consists of an energy source (e.g., battery pack), a single traction motor with a controller and a final drive differential gearbox [1]. Performance parameters such as passenger capacity, vehicle unload weight, lighting system, air conditioning systems have a significant impact on energy consumption. Other bus parameters that influence the energy consumption, are – inter alia – aerodynamic shape of the bus, the thickness of insulation in walls, precent of glazing, and etc.

Batteries are another fundamental technical aspect. The basic battery parameter is energy capacity, determined in kilowatt-hours (kWh). The operating parameters of electric buses are energy consumption per kilometre (kWh/km). Most bus operators report common energy consumption per kilometre in the range from 1 kWh/km to 1.4 kWh/km for 12-meter buses, and up to 1.8 kWh/km for 18-meter buses. This parameter is often incorrect for operating situations because in usage it depends on many factors, such as route profile, number of stops, the mass of passengers, driver's driving style, activation of additional bus devices or the current weather [2, 13].

At present, the most popular types of cells that are being used in battery electric buses are:

- cells based on lithium titanium oxide (LTO)
- cells based on manganese cobalt oxide (NMC)
- lithium phosphate-based cells (LFP).

LTO cells allow to use the highest charging power of all the technologies mentioned above, but due to their relatively low density, they have the lowest capacity as well. LTO ones may be used only in opportunity charging systems, frequently implemented at important bus stations. NMC cells provide the highest capacity and high charging power, so they are proper for slow and long-term use. LFP cells can only be used in slow charging methods [3, 14].

The second main technical aspect is chargers and electric energy infrastructure. Almost all chargers are connected to the low-voltage (220-400V) power grid and the current is converted using transducers and correcting systems. As a result, at the point of connection to the battery consumption control system of the bus, there is high power current, which value is from 600 to 800V DC (direct current). It is also possible to connect chargers to the medium voltage grid (from 1 kV to 60 kV) or high voltage (from 60 kV to 200 kV). If charging stations are located near the existing tram infrastructure, it may be possible to use direct current coming directly from traction, without the need for additional transformer stations [4]. However, safety regulations may not allow this solution in some countries.

Charging a large number of buses at a time may significantly affect the energy network parameters, e.g. cause overloading of network elements. This is undoubtedly a challenge when we are to exchange a larger number of vehicles, striving to a 100% electric bus fleet.

Electric buses may be charged in three major methods:

- conductive charging
  - plug-in
  - pantograph
- inductive charging
- battery swapping.

The first one – conductive – uses a physical connections between the charger and a bus. Technological solutions like plug-in or a pantograph needs this type of electrical connection. The main advantage of such a systems is their high efficiency, but tried and tested technology and relatively low price advocates for this technology. The drawbacks include maintenance costs of battery using systems. Another problem of the abovementioned technical solution is the necessity for the user to connect and disconnect during each charging cycle and the resulting potential risk of electric shock, what in combination with connection difficulties during the winter season and the possibility of destruction to the charging station by hooligans, makes conductive charging not ideal [5].

Another method is inductive charging. In this solution, electrical energy transfers by creating a magnetic field in the transmitter and then converting the magnetic field into an electric current in the receiver. The inductive charging system may provide up to 95% of the energy transmitted through a similar conductive system [8]. Such a high efficiency is achieved by short distances between the coils of the charger and the bus, precise positioning of coils in relation to each other and by frequencies reaching tens or hundreds of kHz [5].

The third method, that is also possible to be used, is battery-swapping systems. Yet for the time being, such systems are not in use. This method requires a spare battery that can be replaced at the depot. A simple version requires only mechanically and electrically trained personnel with an elevator that can lift heavy batteries on the roof of the bus or elsewhere. Otherwise, we can use a fully automated battery exchange station. Such a solution requires costly investments, including advanced vehicle automation solutions as well as a special construction of the bus in order to adapt it to the requirements of battery swapping.

3. Operation aspects of the TCO in electric buses

The type of bus fleet used in the organizational system of public transport determines the solutions in the range of [6, 7, 8]:

- the organisation of the technical facilities of the bus depot, the task of which is to ensure the efficient, reliable and effective day-to-day operation of the vehicles,
- the system of the bus line network in the urban area and spatial development structure,
- organization of bus work on bus lines, including the implementation of the timetable.

The process of operating electric buses is associated with problems concerning the **type of amenities of the technical facilities** necessary to operate them and the problems of spatial arrangement of **various types of supplying devices for the charging the electric buses** - on the route (for example at stops or inter-stopping points) or at end points (at end stops or loops). Analysing the functioning of bus transport, we are looking for answers to questions related to the susceptibility of existing bus lines to handling electric buses.

An important issue is the process of planning the bus transportation system (the route of the line) and the process of planning the service of bus lines with a specific fleet of buses. One of the main factors in this case is the terrain, with lines running on hillsides, which significantly increase the electric energy consumption from the battery by the drive system while driving on a hill and thus significantly shorten the range (course) of the bus between successive cycles of battery charging.

Traffic conditions also have an impact on the interval between recharging of electric bus batteries. It entails a specific profile of electricity consumption when driving at low speed and with frequently stopping of the bus in the queue of vehicles waiting at the inlet of an intersection without traffic lights and with traffic lights without priority for buses and with priority.

The advantages of electric buses due to their local lack of emissions and very low noise level predispose them to serve a specific type of area with limited or closed traffic, e.g. the city centre, the old town, the park and leisure areas. On the other hand, the additional energy consumption of on-board installations (e.g. heating in winter, air conditioning in summer and lighting together with audio-video systems) indicates the need to take into account the division into urban, suburban and urban lines - from the point of view of the location of charge points on the route.

The impact of the total mass of passengers carried on board the bus on the energy consumption of the battery is important. In this respect, the factors of influence are the dispersion of transport needs, driving frequency and capacity of the bus, in relation to the size of passenger flows - actual and forecast. As a result, when justifying the operation of specific routes by electric buses, the type of bus should be taken into account in terms of its capacity - e.g. light, one-piece, low capacity, extended driving time between energy refills or medium and high capacity, i.e. shorter driving time between recharging of batteries due to higher total weight (mass of passengers) [9].

The analysis of transport needs should also include the communication of bus routes with other transport systems using electric traction - the possibility of potential power supply from the tram, trolleybus or railway substations (including stationary chargers of bus battery or chargers built in vehicles). It is a search for the possibility of installing devices supplying electric energy to buses, also depending on the type of objects served, which are sources of traffic streams, e.g. near a shopping centre, tram terminal, railway station, bus station.

The presented problems with the operation of electric buses affect the total costs of ownership (TCO), mainly in terms of the number and type of battery charging points and the type of buses in terms of their capacity [10, 11, 12, 15].

4. Main structure of TCO model

The analysis of the basic components constituting the TCO was performed. The figure 2 shows the cost components constituting of the TCO.

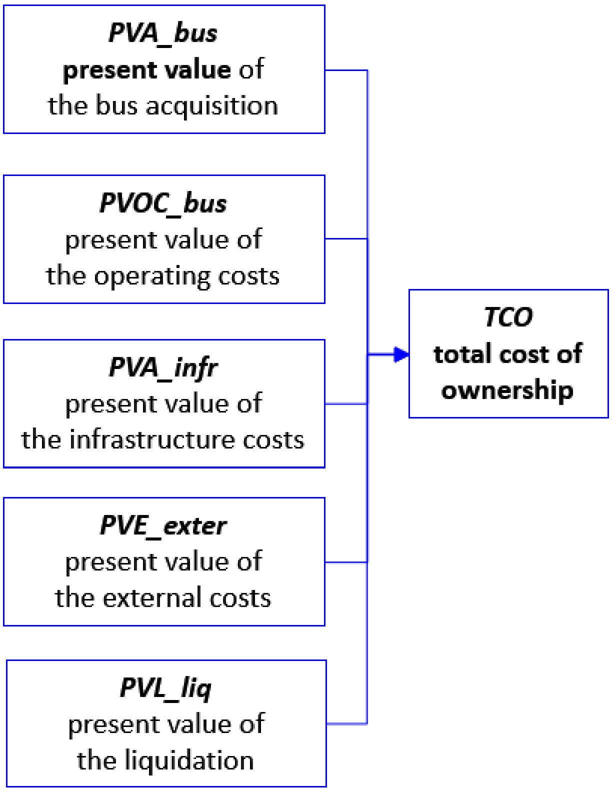

Figure 2. Cost components constituting of the TCO

The basic components of TCO, referring to Fig. 2) are the following:

- PVA_bus – present value of the bus acquisition,
- PVOC_bus – present value of the operating costs,
- PVA_infr – present value of the infrastructure costs,
- PVE_exter – present value of the external costs,
- PVL_liq – present value of the liquidation.

These basic components require the determination of indirect cost components. For the **present value of the bus acquisition [PVA_bus]** can contain, inter alia:

- nominal acquisition costs of bus [AC_bus_nom],
- acquisition costs with subsidies [AC_bus_sub],
- acquisition costs of bus with self-financing [AC_bus_self],
- acquisition costs with bank credit [AC_bus_kred],
- annual annuity of bank credit [AC_bus_cred_ann],
- discounted annual annuity acquisition [DAC_bus_cred],
- discounted costs of spare battery [DAC_bat2],
- self-financed costs of spare battery [DAC_bat2_self].

Determination of the **present value of the operating costs [PVOC_bus]** shall include, inter alia, the following components:

- discounted value of operating costs [DOC],
- annual energy costs [OC_ener],
- annual maintenance costs [OC_maint],
- annual daily energy supply [OC_energy_supply],
- annual insurance [OC_insur].

Determmination of the **present value of the infrastructure costs [PVA_infr]** shall include the following components:

- credit costs - as for the purchase of a bus [DAC_bat_add_cred],
- acquisition costs of battery swapping to meet the range requirement of up to 300 km per day [AC_bat_add],
- acquisiton costs of depot charging [AC_Depot],
- acquisiton costs of pantograph charging [AC_Panto],
- acquisiton costs of on bus-stop charging [AC_Stop],
- acquisiton costs of in-motion charging [AC_Induct].

Determination of the **present value of the external costs [PVE_exter]** shall include, inter alia:

- discounted value of external costs [DEC],
- costs of noise emission [Noise_Cost],
- costs of pollutant emission [Pollutant_Cost].

The last component, **present value of the liquidation [PVL_liq]**, shall include, inter alia:

- discounted value of liquidation [DVL],
- nominal acquisition costs [AC_bus_nom],
- residual value of bus [RES_bus].

It should be noted that the above-mentioned cost elements may vary according to local conditions. It may happen that some of them will not be present in some transport networks. Therefore, before proceeding with the calculations, the specificity of the area concerned should be taken into account.

The basic components and intermediate components of the model for TCO calculations mentioned above, are connected with many inputs to this model model. The most important of these - at a general level – include:

- battery capacity [Bat_cap],
- cost of battery unit capacity [Bat_unit_Cost],
- number of additional batteries [Bat_add_n],
- bus costs [Bus_Cost],
- subsidies value for bus [Bus_sub],
- rate of self-finansing [Bus_self_r],
- credit period [Bus_cred_per],
- loan interest rate [Bus_lir],
- number of interest rate [Bus_nir],
- repayment term acquisition [BusBat2_rta],
- market interest rate [BusBat2 _mir],
- battery lifetime [Bat2_life],
- useful life of bus [Bus_life],
- annual operational use [Bus_oper_ann],
- energy consumption [Ener_cons],
- energy cost rate [Ener_Cost],
- tax relief [Tax_rel],
- cost rate workshop staff [Work_Staff_C],

– supply cost rate [Energy_supply_cost_rate].

A great challenge when calculating TCO will be the fact that electric buses will in most cases be purchased in lots, but not necessarily from the manufacturer. This means that the in TCO calculations will have to be taken into account that the implementation of electric buses in the transport network will be in different phases at different timeframes. What is more, the fact that there is no commitment to a single manufacturer, may result in a multiplication of certain technical solutions used in electric buses within a single transport network.

5. Conclusions

The article describes some elements connected with the process of replacement of the fleet of conventional buses with electric buses. This process seems to be complex and multithreaded.

Selected technical aspects related to the construction of buses and the charging infrastructure are presented in the paper. Three ways of charging electric buses and their influence on the operation of buses in the transport system are described. The operational factors are also presented in the following section as well.

The basic analysis of operational aspects of the TCO calculation in electric buses was presented. Two main operational problems related to concerning the type of amenities of the technical facilities necessary to operate them and the problems of spatial arrangement of various types of sup-plying devices for the charging the electric buses were distinguished.

The primary structure of the total cost of ownership model is presented as well. Detailed components analysis of the five basic components of the TCO model are presented in the paper. Future works on this model will include the development of mathematical formulas for calculating the costs of individual components.

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