# ОБЩИЕ ПРОБЛЕМЫ МЕХАНИКИ

UDC 629.34:621.3

ALGIN Vladimir B., D. Sc. in Eng., Prof.
Deputy Director General for Research
E-mail: vladimir.algin@gmail.com
Joint Institute of Mechanical Engineering of the NAS of Belarus, Minsk, Republic of Belarus

*Received 05 July 2018.*

## ELECTRIFICATION OF URBAN TRANSPORT. BASIC STAGES IN CREATING ELECTRIC BUSES FLEET

*The paper is of an analytical nature and is devoted to the systematization of approaches that take place in the tasks of creating an urban fleet of electric buses. A holistic view on the problem including comparison of buses with different types of propulsion systems is presented. The paper introduces requirements for data and documents reflecting the main factors and stages of creating a fleet of electric buses. These stages are the following: 1 — analysis of possible variants of "electric bus — charging configuration" for the routes under consideration and ensuring their technical feasibility; 2 — economic analysis of the total cost of ownership for the fleet; 3 — development of a business plan; 4 — support for the transition process on basis of the concept of an "open system". The composition of the initial data and their formats with corresponding examples are given in the framework of the first stage. The key procedure of the first stage is to determine the electric power consumption of an electric bus, taking into account the parameters of its design, charging configuration and route features. Methods and tools for estimating the energy consumption of an electrical bus (cost distance analysis, modelling the operation, etc.) are analyzed and features of the methods are presented. The total cost of ownership (TCO) is assumed as the decisive factor in the second and subsequent stages. Structure and sensitivity of TCO are analyzed. The paper presents part of the ongoing research within the framework of the project PLATON: Planning Process and Tool for Step-by-Step Conversion of the Conventional or Mixed Bus Fleet to a 100 % Electric Bus Fleet. The project was approved for funding in the ERA-NET Electric Mobility Europe Call 2016. Project period is 01.2018–06.2020.*

***Keywords:*** *bus propulsion systems, urban electric bus, route, charging infrastructure, electric bus fleet creation, main stages, data, factors*

### Introduction

The problems with real world emissions from compression igniting combustion engines lead to a focus on urban bus fleets. Many studies consider emissions and costs of buses with different propulsion systems. Diesel buses, Trolleybuses, Hybrid Electric Bus (HEB), Fuel Cell Electric Bus (FCEB), and Battery Electric Bus (BEB) are among them. In the PLATON project, starting with different fleet compositions, network topologies and topography of routes, the feasibility and costs of the different combinations "BEB — charging configuration/technology" will be studied. In some cases, the mentioned investigations are conducted in a joint approach because the efficiency and system cost for BEBs depends on the operational concept, but also the related infrastructure. The lively decrease of the costs for secondary cells as well as technical progress in the development of electric propulsion components lead to the need of constantly monitoring relevant data for decision making and validating various practical applications.

The paper presents a part of the research being in progress within the framework of the project PLATON, which runs from 01.2018 to 06.2020. The project was approved for funding in the framework of the competition Electric Mobility Europe Call 2016. The main objective of the PLATON project is to define a planning process for the conversion of a given diesel or mixed bus fleet to a 100 % electric bus fleet and to implement this process into a web-based software tool. The consortium consists of three research institutions (ifak Magdeburg acting as a coordinator, UIIP-NASB and JIME-NASB), one research-educational institution (SUT), one research consultancy micro company (EUC), two bus manufacturers (BKM, VOLVO), one rail company aiming at the production of electric buses (Stadler-Minsk) and two associated public transport operators (PKM Jaworzno and PKM Sosnowiec). They represent five countries: Germany, Poland, Belarus, Sweden and Austria [1–2]. The paper assumes that the transition to BEBs fleet is a staged process with characteristics, depending on the circumstances. It is important to describe typical stages and the preconditions to realize them.

**The paper objective** is to describe one approach for development of main stages in creating of BEBs fleet; other approaches going more in the PLATON project will be considered in the future. The analysis of the total cost of ownership (TCO) for BEBs provides a base for further decisions.

**The paper contains** a holistic view on the problem of creating an urban fleet of entirely electric buses, including their comparison with the other types of vehicles (section 1). Analysis of basic stages in transition to electric buses fleet is presented (subsection 2.1). The requirements for data reflecting the main factors and stages of creating the fleet of electric buses are formulated (subsection 2.2).

The analysis of the technical feasibility of various transition options to electric buses and charging configurations on specific routes is the most important step, since stranded cost for investment in buses not fit for purpose may be avoided. The best situation takes place when data from manufacturer is available, for example data on battery capacity (kWh) and bus energy consumption (kWh/km). But mentioned data should be evaluated to concrete route where the bus will run. The methods for obtaining the BEB duty cycle data are under consideration too.

These data and methods are used for calculating the TCO as main economic indicator. The typical structure of TCO and a general analysis of TCO sensitivity to various factors are given in section 3.

Conclusions generalizes obtained results.

## 1. Survey of electric buses studies

### 1.1. Holistic review of results

Small pollution and high energy utility (Table 1.1) are the basic advantages of electric vehicles (EV). Main barriers for their wide application are the high initial costs. But if we consider the total cost of ownership (TCO) then EVs become competitive. Usually, TCO is calculated for periods of 12 or 15 years, and for 8 or 20 years in some cases.

For evaluating TCO of electric bus fleet, some economic, social and other aspects should be considered. For example, BEB with supercapacitor needs terminals for charging and an additional time (5–10 min), that increases schedule and reduces commercial bus speed over a route. A fleet of BEB with large batteries needs overnight charging facilities in the depots. When evaluating TCO of the BEB fleet, the system "BEB — charging configuration" should be analyzed. The transition to a 100% electric fleet is a process accompanying by procuring some BEBs and removing some ICE buses from service or using them in a different way. This process should be reflected in a business plan approved and supported by all stakeholders: bus manufacturers, legislators (authorities), municipalities and bus operators.

Basic factors determining operation performances and costs of electric buses, related infrastructure and, as a result, TCO of buses are presented in Table 1.2.

Electric buses studies include [3]:
- Economic aspects such as: capital cost, infrastructure investments, maintenance, and operational costs.
- Energy aspects such as: energy sources, energy consumption, and fuel efficiency.
- Operational aspects such as: range, acceleration, charging time, availability, and infrastructure.
- Environmental aspects such as: greenhouse gas emissions, noise, and air quality.

A holistic view, covering basic aspects of the problem, is presented in Table 1.3 that is based on [5], where data from works published in 2012–2014 are summarized.

**Table 1.1 — Energy utility of vehicles with internal combustion engine (ICE) and the EV (based on [3])**

| Energy way | ICE | EV |
|---|---|---|
| From source to energy storage, Well-to-Tank (WTT)* | 83 % | 38 % |
| From the energy storage to the wheels, Tank-to-Wheel (TTW) | 15–20 % | 65–80 % |
| Total: From the source to the wheels, Well-To-Wheel (WTW) | 12–17 % | 25–30 % |

*WTT includes activities from resource extraction through fuel production to delivery of the fuel to vehicle. Compared to WTW, WTT does not take into consideration fuel use in vehicle operations.

**Table 1.2 — Factors affecting operation performances and TCO (based on [4])**

| Bus model | Duty cycle | Route logistics | Operating environment | Dependability |
|---|---|---|---|---|
| Bus configuration (style)<br>Powertrain architecture<br>Component models<br>Charge methods/Power<br>Battery degradation | Speed<br>Acceleration<br>Grade<br>Deadhead Miles | Length<br>Time duration<br>Schedule<br>Bus Blocking | Environmental conditions<br>Passenger loads | Availability<br>Reliability<br>Road calls |

The TCO estimations (Table 1.3) use a long list of assumptions that include the costs of purchase, financing, operation, infrastructure, and emission penalties. Their findings, based on 60,000 km annual mileage and a 12-year bus lifetime, show that the overnight charged BEB is the most expensive electric alternative for urban buses based on TCO, followed by FCEB, and Opportunity BEB [6].

Other studies have argued that the TCO of electric buses is very sensitive, not only to expected cost reductions of electric components (i.e. battery price, auxiliary system), but also to the utilization level of the service. Several studies have echoed that under high, and even moderate utilization scenarios, electric buses can be an economically competitive choice compared to diesel and CNG buses [7–9]. In [6] it is reported that the TCO for some electric buses will drop significantly by 2030 with an average of 30–50 % for FCEB and BEB (Overnight & Opportunity). The TCO for HEB (series and parallel) and diesel buses is also expected to drop by an average of 1–5 % in 2030 as highlighted in Figure 1.1.

**1.2. Specification, systematization and development of data on electric bus themes**

The limitations of the data presented in Table 1.3 (and other similar data) for application in specific problems lie in the fact that they are based on certain

**Table 1.3 — Holistic review of BEB and other 12-meter single-deck buses (data are based on [5])***

| Parameter | Unit | ICE | HEB - Series | HEB - Parallel | FCEB | BEB-Overnight | BEB-Opportunity |
|---|---|---|---|---|---|---|---|
| Engine technology | Type | Diesel | Diesel | Diesel | H-NGSR, WE | Electricity - EU mix, Renewable | Electricity - EU mix, Renewable |
| Economics | | | | | | | |
| Bus price | US$ | 280,000 | 410,000 | 445,000 | 2,000,000 | 590,000 | 530,000 |
| Maintenance cost | US $/Km | 0.38 | 0.24 | 0.26 | 1.20 | 0.20 | 0.20 |
| Running cost | US $/Km | 0.8 | 0.68 | 0.76 | 0.53 | 0.15 | 0.15 |
| Infrastructure cost | US $/Km | 0.04 | 0.04 | 0.04 | 0.16 | 0.15 | 0.26 |
| TCO | US $/Km | 2.61 | 2.98 | 2.895 | 5.71 | 6.83 | 3.97 |
| GHG Emission | | | | | | | |
| WTT | gCo2eq/km | 218 | 172 | 188 | 320, 305 | 720, 20 | 720, 20 |
| TTW | gCo2eq/km | 1004 | 796 | 870 | 0 | 0 | 0 |
| WTW | gCo2eq/km | 1222 | 968 | 1058 | 320, 305 | 720, 20 | 720, 20 |
| Energy Utility/Consumption | | | | | | | |
| WTT | MJ/km | 3.82 | 3.45 | 3.31 | 7, 4.45 | 11.9, 3.57 | 11.9, 3.57 |
| TTW | MJ/km | 16.84 | 10.81 | 12.81 | 10.48 | 6.76 | 6.76 |
| WTW | MJ/km | 20.66 | 15.26 | 16.12 | 17.48, 14.93 | 18.66, 10.33 | 18.66, 10.33 |
| Operation | | | | | | | |
| Range till refueling | Km | 450 | 450 | 450 | 450 | 250 | 40 |
| Acceleration time (0–30 km/h) | Seconds | 7.5 | 8.1 | 7.9 | 9.2 | 10 | 10 |
| Availability | % | 100 | 100 | 100 | 85 | 90 | 90 |
| Refueling/ Recharging time | Minutes | 5 | 5 | 5 | 10 | 240 | 10 |
| Infrastructure | | | | | | | |
| Infrastructure modification | Nominal | As is | As is | As is | Moderate | Moderate | Major |

* in Table:
-Data collected in Euro are converted to USD using an exchange rate of 1 Euro = 1.241 $, and Kilometers are converted to miles using 1.00 km = 0.62137119 mile.
-The cost estimations represent an average of available data in the literature analyzed in [5].
-Running cost is explicitly identified in some studies as fuel cost, while other studies incorporated fuel and maintenance cost as running/operation cost, hence data obtained from these are excluded [5].
-Acronyms: ATR=Auto Thermal Reforming; CAGR=Compound Annual Growth Rate; CNGB=Compressed Natural Gas Bus; CNGHEB=Compressed Natural Gas Hybrid Electric Bus; DB=Diesel Bus; DHEB=Diesel Hybrid Electric Bus; EM=Electric Motor; FCEB=Fuel Cell Electric Bus; GB=Gasoline Bus; GHEB=Gasoline Hybrid Electric Bus; GHG=Greenhouse Gas; GSR=Gas Steam Reforming; GREET=Greenhouse gases, Regulated Emissions, and Energy use in Transportation; HEB=Hybrid Electric Bus; H-NGSR=Hydrogen - Natural Gas Steam Reforming; H-WE=Hydrogen - Electrolysis of Water; MJ=Mega-Joules; NGCC=Natural Gas Combined Cycle; NGSR=Natural Gas Steam Reforming; PHEV=Plugin Hybrid Electric Vehicle; RED=Renewable Energy Directive; SD=Single-deck bus; UCs=Ultra Capacitors; USC=Supercritical Steam Cycle.

averaged conditions, and they cover period till 2014. In addition, electric buses are divided only into two types (BEB-Overnight and BEB-Opportunity) without detailed presentation of their operation and other conditions.

These data need to be updated and detailed, especially in the areas of economics, energy consumption and operation, taking into account new research conducted by scientific, analytical and financial organizations such as Center for transportation & the environment (2016 [4]), U.S. Federal Transit Administration (FTA) with the help of the National Renewable Energy Laboratory (NREL) (2016, 2017 [10–12]), Bloomberg Finance L.P. (2018 [13]) as well as results of EU projects (SeEUS [14], CACTUS [15]), and studies on the assessment of electric urban transport systems in Rome (2012 [16]), Berlin (2014 [17]), etc.

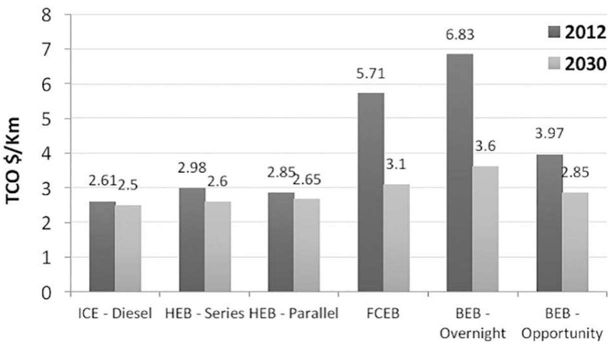


**Figure 1.1 — TCO of buses 2012/2030 [5] with reference to [6]**

It should be noted (1) that day to day more sophisticated approaches and calculated schemes for evaluating effectiveness of technical objects, including electric buses, are developed [15, 18–27]. One of them is *Life Cycle Costing (LCC) calculation tool* [19]. Directive 2014/24/EU significantly innovates the process of tenders awarding, through assigning a relevant importance to LCC. Another typical approach can be presented by a method (Figure 1.2) that has been developed primarily for public transport authorities and operators to be able to analyze what kind of electric bus and charging system has lowest TCO depending on the route or city specific requirements [18]. Companies developing electric buses and infrastructure can also use the method.

It should be noted (2) that any formalized method (like the LCC tool calculator) shall use formalized source data that can be obtained from available concrete, statistical or stable data. So the problem of source data is key.

## 2. Analysis of requirements to basic stages and data in transition to electric buses fleet

### 2.1. Basic stages in transition to electric buses fleet

An analysis of different approaches to problem of implementation of battery electric buses (BEBs) fleet shows that the solution for any practical task from this sphere should be based on four typical stages presented below (Figure 2.1).

**Stage 1** (Operational feasibility of different "bus & charging configurations" by routes) is necessary in

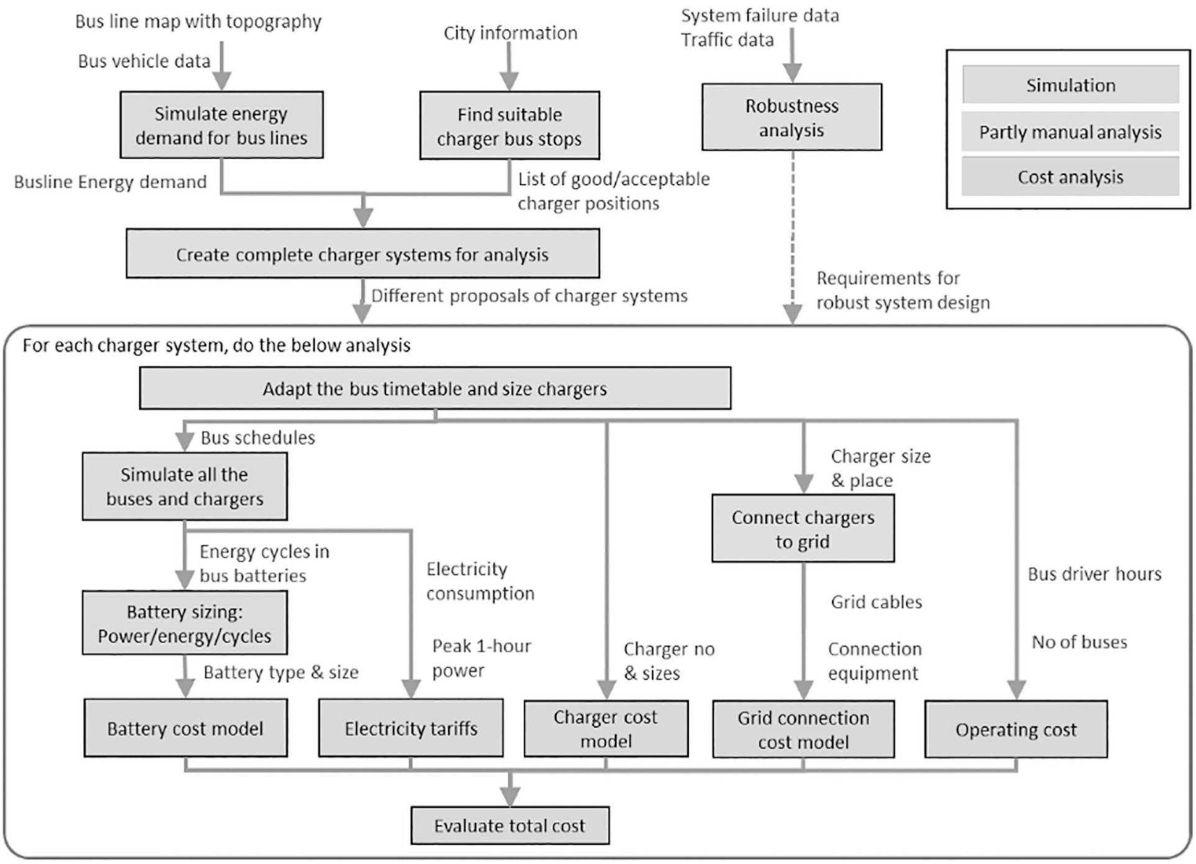


**Figure 1.2 — Schematic picture of the analysis method described in paper [18]**

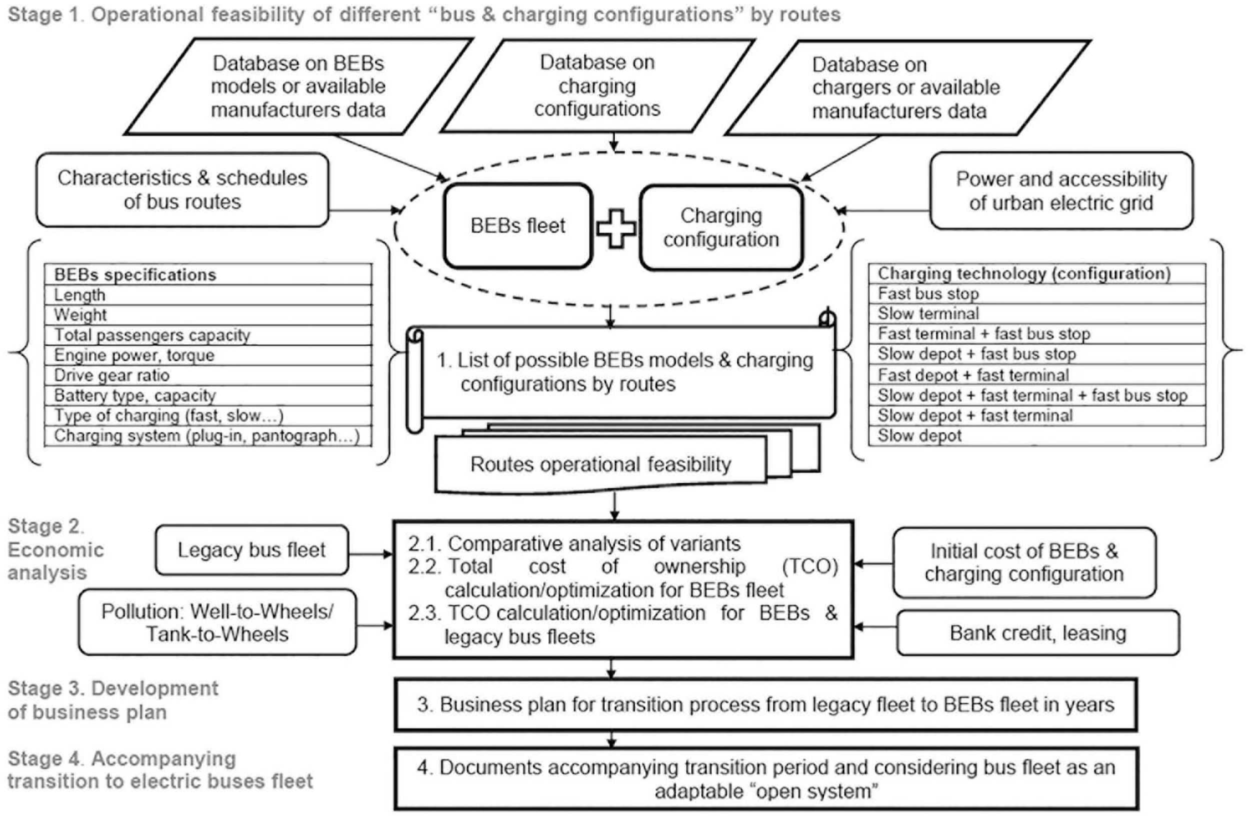


**Figure 2.1 — Basic stages in transition to electric buses fleet**

order to highlight possible solutions in a system "BEBs fleet — Charging configuration". For this matter, the limitations of a particular route network (block "Characteristics & schedules of bus routes") as well as the city electric network for example allowable voltages, locations of the charger positions (block "Power and accessibility of urban electric grid"), should be taken into account. Lists of possible combinations of "bus models — charging technologies" are formed for each route (see Figure 2.1, 1. List ...). Typical specifications for buses and charging configurations accompany this List. After their analysis relatively routes, every route receives some combinations "bus model & set of charging places" under possible charging configuration. (Schedules for electric buses need special attention to synchronize buses into slots at common charge points and also to add dwell time at end stations. Batteries and chargers could be unnecessary large if adequate time for charging is not accounted for).

**Stage 2** (Economic Analysis) includes three types of tasks with an increasing degree of complexity.

The task 2.1 (Comparative analysis of variants) can be solved by considering the differences in the solutions being compared.

The task 2.2 (TCO calculation / optimization for BEBs fleet) requires consideration of the initial cost of buses and the cost of the charging infrastructure (block "Initial cost of BEBs & charging configuration"). A typical solution is the use of bank loans, leasing, etc. (block "Bank credit, leasing"). In some models, economic consequences on a city or country scale can be taken into account (for example, pollution penalties) [block "Pollution: WTW (Well-to-Wheels)/ TTW (Tank-to-Wheels)"].

Task 2.3 (TCO calculation / optimization for BEBs & legacy bus fleets) provides for TCO calculation taking into account the new fleet of electric buses and the operating fleet of buses (block "Legacy bus fleets"). This problem statement reflects the real situation and gives a comprehensive economic evaluation. The decommissioning or use of buses from the existing park can be reproduced. The TCO should be calculated for the entire system including in the general case of a mixed bus fleet and in time covering the transition period.

**Stage 3** (Development of business plan) provides for the development of a business plan, in which an economic part is required based on the results of the TCO analysis.

**Stage 4** (Accompanying transition to electric buses fleet) is the process of accompanying the period of the introduction of the electric bus fleet.

Some publications consider the transition in one step seeing the fleet of electric buses as a complete unchangeable system. An approach based on the concept of "open systems" should be developed. ("Open systems" are those systems that operate for extended periods of time while modifying themselves to accommodate change in their environments and objectives [28]). Under this concept the bus fleet is viewed as an open system, changing under the influence of external and internal factors and adapting

**Table 2.1 — Example of characteristics for Route *N***

| Route ID | Length of bus line, km | Average commercial speed, km/h | Total distance per day, km | Altitude, m, min/max | Season temperatures, °C, min/max | Passengers traffic | Route profile |
|---|---|---|---|---|---|---|---|
| *N* | 7.5 | 19.0 | 110 | 300/500 | –10/+25 | Data from local authorities |  |

**Table 2.2 — Possible placement of chargers along the Route *N***

| Place 1, m | Place 2, m | Place 3, m | ... | Place M, m | Depot, m |
|---|---|---|---|---|---|
| 200–400 | 700–900 | 1,300–1,500 | ... | 7,500–8,000 | 2,000 |

to them. The system includes non-electric and electric buses. The task is reduced to ensuring the maximum efficiency of this system during the transition phase and the subsequent operation in a purely electric version. It is important to have the uniform understanding of the problem by stakeholders: bus manufacturers, legislators (authorities), municipalities and bus operators (operating organizations).

**2.2. Data in detail**

**2.2.1. Stage 1. Operational feasibility of different "bus & charging configurations" by routes**

Typical shapes and data formats for stage "Operational feasibility" are presented below. They illustrate basic sub-stages of getting required data.

*New route.* If the route is new (without existing stops), the data about it in the most general form can be presented as shown in Table 2.1. The possible charging places should be indicated for each route as primary source information from local authorities for this (Table 2.2) and all the following cases.

*Existing route (route with designated stops)*. An example of data for existing route is presented in Table 2.3. The incline significantly changes the energy consumption on the stretch of road. For example, in [25] the data shown in Table 2.4 is given.

The description of the route in addition to the topography should also be accompanied by additional factors, such as road conditions, temperature, traffic lights and incidents, congestion, interaction with other vehicles that affect energy consumption.

*Bus & charger data.* The main objective of Stage 1 is to determine the locations of the chargers along the route, taking into account the characteristics of each prospective bus and charging configuration.

Typical data from a bus manufacturer are given in Table 2.5 [23]. As alternative, the buses' specifications from available databases may be formed.

Typical charging configurations that were established based on data analysis [14] are shown in Table 2.6.

Battery capacity and operational conditions (as well as some others additional factors) determine bus energy consumption and as consequence the places on route for chargers. Options determining bus energy consumption comprise usage of:
- data from manufacturers,
- statistics from transportation companies,
- data from test runs by researchers,
- cost distance analysis (for example, this approach is used for optimal routing and charging procedures for electric buses in [25]),
- modelling.

**Table 2.3 — Example of characteristics for existing Route *N* [25]**

| Bus stop | Time | Distance (m) | Topography |
|---|---|---|---|
| Giæverbukta | 05:57 | 0 | Flat |
| Postterminalen | 05:59 | 928 | Flat |
| Sjølundvegen | 06:00 | 336 | Flat |
| Fiolvegen | 06:01 | 374 | Flat |
| UNN, ˚Asg˚ard | 06:02 | 645 | Flat |
| Lars Eriksens veg | 06:02 | 372 | Uphill 5.2 % |
| Holtvegen | 06:03 | 480 | Uphill 5.2 % |
| Barduvegen | 06:04 | 304 | Uphill 5.2 % |
| Elverhøy | 06:05 | 158 | Uphill 5.2 % |
| Sommerlyst skole | 06:05 | 301 | Uphill 5.0 % |
| Kirkeg˚arden | 06:06 | 145 | Uphill 5.0 % |
| Vervarslinga | 06:06 | 280 | Uphill 5.0 % |
| Trykkbassenget | 06:07 | 211 | Uphill 5.0 % |
| Myrengvegen sør | 06:07 | 244 | Uphill 5.0 % |
| Myreng | 06:08 | 264 | Uphill 5.0 % |
| Grimsbyvegen | 06:09 | 217 | Uphill 5.0 % |
| Skoglyst | 06:10 | 283 | Uphill 5.0 % |
| Maristuen | 06:10 | 190 | Downhill 4.6 % |
| Snarvegen | 06:11 | 342 | Downhill 4.6 % |
| Petersborggata | 06:12 | 569 | Downhill 4.6 % |
| Kongsbakken | 06:13 | 360 | Downhill 4.6 % |
| Wito | 06:15 | 166 | Downhill 4.6 % |
| Sjøgata S1 | 06:20 | 318 | Downhill 4.6 % |
| Skippergata | 06:21 | 353 | Uphill 8.0 % |
| Tromsdalen Bruvegen | 06:23 | 1301 | Bridge |
| Novasenteret | 06:24 | 732 | Downhill 8.0 % |
| Pyramiden | 06:25 | 383 | Flat |

**Table 2.4 — Increasing of energy consumption depending on incline [25]**

| | |
|---|---|
| Consumption increases going uphill 5 % incline | approximately by 4.5 times |
| Consumption increases going uphill more than 5 % incline | approximately by 7.3 times |

**Table 2.5 — Typical data on a bus & charger from the manufacturer (based on [23])**

| Characteristic | Specification of electric bus | Cost (2018), € |
|---|---|---|
| Bus | Custom made 100 % electric, 12 m long | 330,000 |
| -Bus energy consumption | 0.9 kWh/km | |
| -Driving range | 250 km | |
| Battery | | 45,000 |
| -Battery capacity | 242 kWh | |
| -Battery type | Lithium iron phosphate | |
| Charger | Normal charger (3.5 hours full charge) | 9,000 |
| -Charger lifetime (technical) | 10 years | |
| -Charging rate | 100 kW | |

*Typical data from manufacturer* are presented in Table 2.5 (see position "Bus energy consumption").

*Typical data from public transportation company* are presented in [26]. The public transportation company VL has provided information on the following design parameters: maximum bus energy consumption, bus frequencies, time at the end stations, total drive time on the routes and route distances. VL estimates the dimensioning energy demand to be **1.6 kWh/km** and **2.3 kWh/km** for buses of 12 m and 18 m, respectively [26].

If such data are not available, the other methods mentioned above may be used.

Under using "cost distance analysis" and "modelling", repeated starts and stoppings must be reproduced as special feature in movement of urban bus.

Methods of modeling can be divided into two categories: 1 — methods in which the speed profile on a route is pre-determined, 2 — methods that reproduce the actions of the driver along the route. In the latter case, it is necessary to develop a driver actions algorithm.

For using mentioned methods, the detail data on bus (some of them are in Table 2.7) are necessary as well as route peculiarities.

*The method of the first category* is presented in [27]. To reflect extensive real-world bus driving conditions, the Oak Ridge National Laboratory (ORNL) MD conventional bus database (https://www.autonomie.net/) was used. The database covers one year of real-world second-by-second measurements from three Class-7 diesel buses operated by the Knoxville Area Transit (KAT) in Knoxville, TN. The key measured data included fuel consumption, vehicle speed and acceleration, engine speed and torque, vehicle weight, and global positioning system (GPS) spatial location information.

The GPS altitude data were used to estimate road grade, which can have a significant impact on vehicle powertrain performance and energy consumption. Then, using these data (in particular, the speed profile and the road grade) as well as the electric bus data the energy consumption was calculated. However, this

**Table 2.6 — Typical charging configurations**

| ID | Description |
|---|---|
| 1 | Flash (15–20 sec) |
| 2 | Fast bus stop (1–3 min) |
| 3 | Fast terminal (5–10 min) |
| 4 | Slow terminal (1– 2 hours) |
| 5 | Fast depot (1–2 hours) |
| 6 | Slow depot ( 2– 8 hours) |
| 7 | Fast terminal + fast bus stop |
| 8 | Slow depot + fast bus stop |
| 9 | Fast depot + fast terminal |
| 10 | Slow depot + fast terminal + fast bus stop |
| 11 | Slow depot + fast terminal |

**Table 2.7 — Example of some basic bus mechanical characteristics**

| Weight including passengers, kg | Length, m | Tire radius, m | Front surface area, $m^2$ | Aerodynamic drag coefficient | Maximum driveline efficiency | Gear Ratio | Rolling resistance coefficient (for concerned route or its part) |
|---|---|---|---|---|---|---|---|
| 16,000 | 12 | 0.5 | 8.36 | 0.70 | 0.93 | First: 3<br>Second: 1<br>Main: 8.83 | 0.012 |

approach is not suitable for cases when the route is being developed for the first time or its speed profile is unknown.

It should be noted that the standardized drive cycles do not include road grade. Thus, obtaining the speed profile in combination with the road grade is an independent typical task within the framework of the said first method.

*The method of the second category is used in [29].* In order to define the routes, data was collected and further made available to the authors directly from the Portuguese urban transportation company STCP (Sociedade de Transportes Colectivos do Porto — Oporto Society of Public Transports) (STCP, 2011). This data accounts for all the geographic coordinates of bus stops for each routes. It was assumed that the bus would stop in every bus stop and would stay there for 20 seconds, which is the average time provided by STCP. *The speed profile of the bus is defined by the technical characteristics of the motor and the maximum speed, by the regulation*. It is important to state that an ideal traffic flow was considered, which means that the buses were on free-flow roads.

An essential restriction for the above version of the method is the motion in the free route, using all engine capabilities and maximum speed mode. Thus, the actual route schedule is not respected, and it is impossible to reproduce the energy consumption for a real/aggressive style of driving an electric bus, taking into account the strict order of traffic on a schedule.

*Additional method of energy consumption evaluating*. As addition to above presented ways, one more method for evaluation of electric bus energy consumption is proposed. It uses the data on fuel consumption by an ordinary diesel bus under the same route. The volume of this fuel serves for calculation of the energy expended, taking into account the losses "Tank-to-Wheels". Then this energy is recalculated into the energy consumption by the electric bus, taking into account its losses "Tank-to-Wheels". The effect of energy recuperation for the electric bus during braking is also to be taken into account, this effect can reach 25 %.

*Example*. Initial data for diesel bus: fuel consumption is 39 litres/100 km; calorific value of diesel fuel is 43.12 MJ/litre; TTW1 = 20 %; for electric bus: gross weight corresponds to the gross weight of the diesel bus; TTW2 is 65 %; the degree of energy recuperation in the route is 10 %.

The energy expenditure of a diesel bus per 1 km of the route:

$$(39/100) \cdot 43.12 = 16.82 \text{ MJ/km}.$$

The energy expenditure of the bus per 1 km of the route to overcome the resistance to the movement:

$$16.82 \cdot (20/100) = 3.36 \text{ MJ/km}.$$

Energy consumption of the electric bus in the same route:

$$[3.36/(65/100)]\,(1 - 10/100) = 4.66 \text{ MJ/km} = 1.29 \text{ kWh/km}.$$

These data are consistent with the data in Tables 1.1 and 1.3.

*In complex cases*, the road conditions, the season, temperature, altitude of the route, driving style and other external factors that affect the energy consumption can be taken into account by means of using related coefficients. It is necessary to evaluate the worst case in terms of energy consumption (passengers' maximum load, temperature, etc.).

*Final data-blocks for Stage 1.* Forming operational feasibility for every route (numerous tables like Table 2.8) is final action for the Stage 1.

*Basic strategy for Stage 1.* The key procedure of the first stage is to determine the energy consumption of the electric bus, taking into account the parameters of its design, the charging configuration and the features of the route.

The worst case in season temperature and the most intense day of the week are reproduced.

In the case of charging configurations "slow depot (overnight charging)" the daily amount of work for bus (full timetable) is simulated. The simulation reproduces the daily energy consumption of the electric bus and determines the required battery capacity.

In cases of other charging configurations "opportunity (on-route)" with charging/recharging on the route, the most intensive mode of movement along the route is played with a full load of the bus by passengers.

If the specified locations of the chargers are given, then the required battery capacity is determined to reach all chargers on the route.

If battery capacity is given, the locations of the chargers are determined, taking into account the available places for their placement.

If the specified locations of the chargers and battery capacity are given, then technical feasibility of a selected variant "electric bus + charging configuration" is confirmed (or is not confirmed) for the route.

"The worst case" is a possible combination of all the unfavorable factors that affect the operation of

**Table 2.8 — Final elementary data-block for Stage 1 on a route *N* (Variants of operational feasibility for route *N* with bus model *K* for charging configurations)**

| Bus model ID | Charging configuration ID | Number of chargers | Location of chargers along a route: numbers of bus stops/terminals | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *K* | 1 (Flash) | 7 | 1 | 4 | 7 | 11 | 14 | 17 | 20 |
| *K* | 3 (Fast terminal) | 2 | 1 | 20 | | | | | |

the battery. One of them is an aggressive driving style with high acceleration, which can increase energy consumption up to two times. This case must reflect hard but real operation conditions. Therefore, the additional problem is to choose a *rational calculated level of energy consumption* on the route using the data obtained by various method, tools, sources.

Stage 1 is difficult for complete formalization. Such actions as the choice of possible places for installing chargers must be coordinated with local authorities. Then these decisions should be processed and presented in a formal form. The results of the first stage contain possible technical options for implementing the system "electric buses — charging configurations" for the routes. They serve as a basis for further choice of solutions, including economic optimization tasks.

**Stage 2.2.2. Economic analysis: input data**

Typical input variables are presented in Table 2.9. For determining initial (fixed) costs under some item of expenses, relative (specific) values may be used (Table 2.10 and 2.11).

In solving economic problems, including the reproduction of working cycles of electric buses, the results of calculations of energy consumption obtained in Stage 1 for various routes, electric buses and charging configurations can be used. Economic analysis can consider different time options for the commissioning of electric buses on the routes and, accordingly, the phased use of the invested costs. Credit and leasing can also be taken into account. The closest to reality is the situation when the joint existence of electric and non-electric bus fleets is considered. The available examples of economic analysis show that among the investment costs the largest are the costs for the purchase of electric buses, and among operation costs these ones are the wages of drivers.

**3. TCO sensitivity to different factors**

The total cost of ownership (TCO) is the main economic indicator that is used in the second and subsequent stages of the project to assess its effectiveness. The typical structure of this indicator and a General analysis of its sensitivity to various factors are given below. In the future, a detailed analysis of each of the components of the TCO is planned.

**3.1. TCO structure**

To represent the typical TCO structure, an example from [15] is cited (*the format of the numeric data of the original [15] is retained here*): "The example 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 of 120 kWh 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

**Table 2.9 — Input data for electric bus with 1 extra battery and 2 normal chargers (based on [23])**

| Input variables in present worth (2018–2025 as example) | Value |
|---|---|
| Investment cost including battery, € | 375,000 |
| 1 Extra battery cost, € | 44,000 |
| 2 Normal chargers cost , € | 1,530 |
| Maintenance cost & helping maintenance per year, € | 153,000 |
| Energy cost per year, € | 72,000 |
| Carbon tax per year, € | 1,460 |
| Distance driven per year, km | 93,000 |
| Operational time, years | 8 |
| Real interest rate, % | 1 |

**Table 2.10 — Use of relative (specific) values for battery and charging infrastructure (based on [18])**

| Fixed costs | Relative (specific) values |
|---|---|
| Bus charger | 1 €/W |
| Electricity substation | 0,8 €/kW |
| Cabling in low/medium/dense parts of cities | 100/200/300 €/m |
| Power optimized batteries | 1130 €/kWh |
| Energy optimized batteries | 540 €/kWh |

**Table 2.11 — Use of relative (specific) values for maintenance and electricity costs (based on [18])**

| | |
|---|---|
| Driver cost including dwell time and downtime | 35 €/h |
| Maintenance cost per electric bus (without drivers wages) | 0,183 €/km/year |
| Maintenance cost per bus charger | 2 % of bus charger cost/year |
| Electricity subscription fee per year 400 V/10 kV | 520 €/year / 930 €/year |
| Power tariff, highest entry per month 400 V/10 kV | 4,12 €/kW/month / 3,42 €/kW/month |
| Variable energy fee 400 V/10 kV | 0,0068 €/kWh / 0,0031 €/kWh |
| Energy costs | 0,075 €/kWh |

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 instalments 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 are modelled. The costs listed in the example are hypothetical and for a specific example in Polish conditions and may vary depending on local predispositions".

*Results analysis*

Table 3.1 presents a fragment of the Report of Economic Impact which is the output of the CACTUS Tool [15]. 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 €.

Demonstrative percentage of the cost structure is depicted in Figure 3.1.

If we assume that this structure is typical, then the most attention should be paid to the component KO. The remaining components can be represented on the basis of approximate generalized characteristics without detailed modeling.

**Table 3.1 — Report of Economic Impact [15]**

| Costs type | Symbol | Cost value |
|---|---|---|
| Present value of the acquisition costs of bus | KA | 169 680.68 € |
| Present value of the operational costs | KO | 584 922.26 € |
| Present value of the infrastructure costs | KZ | 185 189.77 € |
| Present value of the external costs | KI | 57 323.96 € |
| Present value of the proceeds of liquidation | PL | 0.00 € |
| Total | KCW | 997 116.67 € |

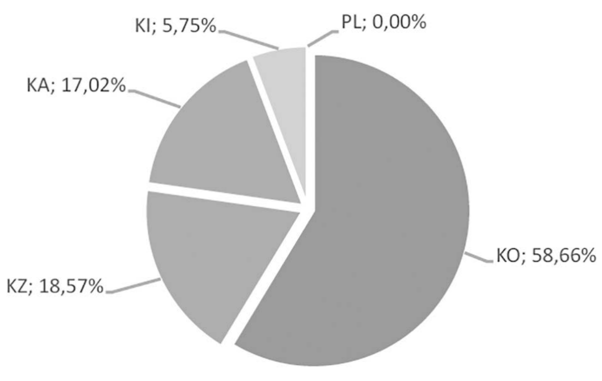


**Figure 3.1 — The percentage of subsequent costs in the total cost [15]**

**3.2. Driver cost, the purchasing cost of vehicles and batteries**

Feature of [18] is the wide system prospective and optimization of the total costs of operating an entire bus line. The analysis [18] visualizes that apart from the driver cost, the purchasing cost of vehicles and batteries account for an important part of the total cost. It highlights that increased costs as a result from added time needed to recharge the vehicles is an essential cost factor. Additionally, the cost of charging system and energy is shown to have a lower annual cost impact.

Results are presented in Figure 3.2. A bus with similar cost characteristics as a diesel bus but runs on hydrogenated vegetable oils (HVO) is hereon used for having reference cost. As can be seen, the investment cost for the battery electric buses are estimated to be at least twice the cost for the comparative ICE bus system.

Analysis of electric bus traffic on two city bus lines and calculation of the annual cost of operation [18] indicate the importance of reducing battery costs and ultimately to optimize the use of the buses and the drivers. The analysis shows that it is less important to reduce infrastructure costs or optimize usage of the chargers.

Results indicate that the cost for the charging system and electricity connection have a low impact

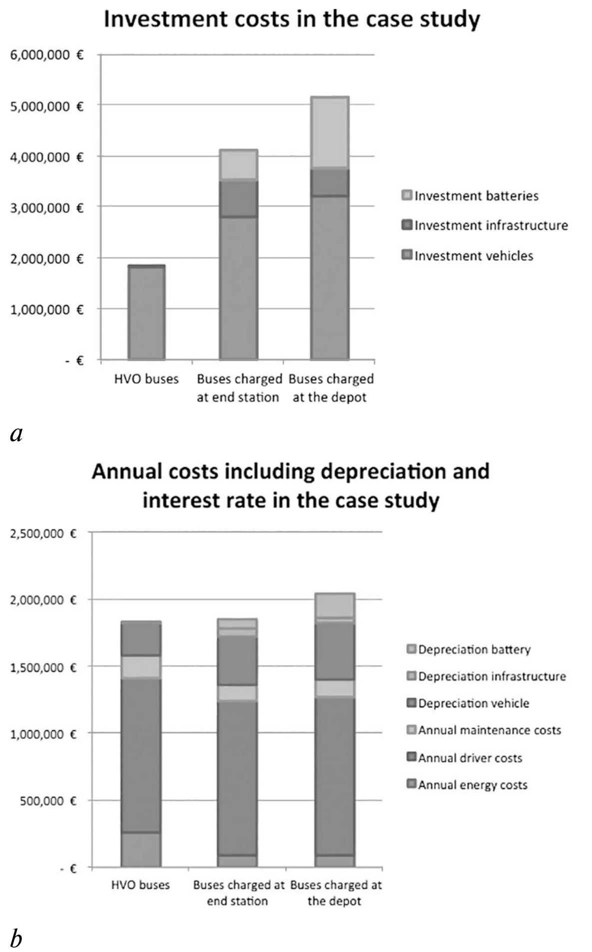


**Figure 3.2 — Investment cost for the investigated bus system (*a*) and Annual operating costs in the case study: 10-years depreciation time for both buses (*b*) [18]**

on the total annual operating costs for electric buses in general and especially when comparing electric bus system alternatives. Solely comparing investment costs might thus give a wrong indication what type of electric bus system result in the lowest total cost for operating the bus lines.

The analysis [18] also highlights the importance of looking at the total cost for the bus operation instead for an optimum of isolated problems such as in the tradeoff between battery capacity and charger power. Reducing the size of chargers and batteries to a minimum could increase the charge time and require an additional bus to operate the bus line to keep up bus frequency. Operator costs stand out clearly as a significant cost item.

**3.3. Sensitivity of TCO to charging configuration and distance**

A sensitivity analysis of TCO for electric public bus transport systems in Swedish medium sized cities is presented in [23]. Initial data on electric buses & charger from the manufacturer are presented above in Table 2.3; a typical set of input data for operation stage is given in Table 2.7.

Bus fleet characteristics: five city-buses (line 1 and 7 in Karlskrona, Sweden) with average speed profiles (25 km/h) and average load profiles, with a stop in almost every bus stop that was based on drive cycles of 93 000 km/bus/year. A timeframe of 8 years was used, as this was stipulated by Swedish procurement of public bus authority. In relation to that, 8 years is not the technical lifetime of the bus, which the bus can be used longer time. For TCO, the energy price was assumed to increase annually by about 6 %, based on the history of energy price development in the last 10 to 15 years (Svenska Petroleum och biodrivmedelinstitutet; pool 2012) and with a real interest rate of 1 %.

The result (Figure 3.3) suggests that the electric bus A would be more preferable in term of cost effectiveness since the normal chargers are cheaper and allows a longer battery life. This might be a good solution for a city or suburb where a fully charged electric bus can be available as a back-up after a bus has been driving for 200–300 km. Electric bus B could be an intermediate solution for a city that runs on tight schedule since it charges within 10 minutes.

The TCO of electric bus A is 13 to 30 % higher while the TCO of electric bus B increase 12 to 30 %, if the travel of line distance is decreased by 10 to 30 % [23]. It is shown that the mileage is the most influential factor when calculating TCO.

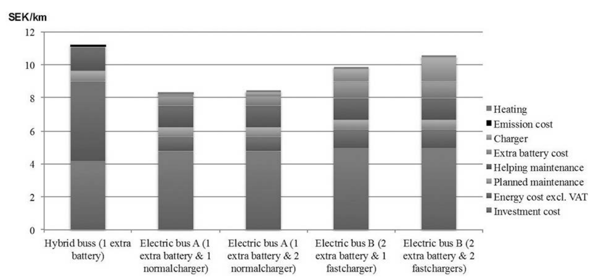


**Figure 3.3 — How cost varies depending on electric buses configuration compared to hybrid [23]**

**3.4. TCO vs. bus annual mileage**

Analysis and results of [13, 18] shows that the TCO of any vehicles depends heavily on their annual mileage if the period for calculating TCO is fixed. This is usually done.

To describe the trend of "TCO vs. bus annual mileage" it is suggested to use the following approach. First, a typical mathematical dependence is constructed. Before using this dependence, it is adjusted to a certain TCO value corresponding to the annual run. The dependency graph can be shifted vertically as a result of the adjustment. Then, the corrected dependence is used for the prediction.

It is suggested to describe typical mathematical dependence in the form

$$y = ax^b + c, \tag{3.1}$$

where $x$ = annual mileage (km), $y$ = TCO ($/km).

The values of parameters $a$ and $b$ are presented in Table 3.2.

For using dependence (3.1) it is necessary to have supporting point ($x_0$, $y_0$). If TCO $y_0$ is known (or determined) for the annual mileage $x_0$, then the parameter $c$ is equal to

$$c = y_0 - ax_0^b. \tag{3.2}$$

Figure 3.4 shows lines 1 and 2, which are plotted for the values $x_0$ = 33km and $y_0$ = 1,539$/km (line 1) as well as for $x_0$ = 33km and $y_0$ = 1.830 $/km (line 2).

In presented cases, there are $c$ = 0.258 (line 1) and $c$ = 0.318 (line 2) respectively. The above parameters can be used if any information (supporting point) is absent.

**Conclusions**

Many publications consider the prospective fleet of electric buses as an image of a complete unchangeable system, to which the one-stage transition should be implemented. In this paper the typical stages for transient mode to BEBs fleet is highlighted. They comprise:

- analysis and ensuring technical feasibility,
- economic analysis of the total cost of ownership for the fleet,
- development of a business plan,
- support for the transition process on basis of the concept of an "open system".

A typical list of initial data for the implementation of the first stage is presented. The key procedure of the

**Table 3.2 — Parameters *a*, *b* for electric buses with different battery capacities***

| Trend line | Battery capacity, kWh | *a* | *b* |
|---|---|---|---|
| 1 | 110–250 | 39,156 | –0,978 |
| 2 | ≥350 | 59,157 | –1,049 |

*The choice of the typical mathematical dependence and the determination of the coefficients *a* and *b* have made by V. Shportko.

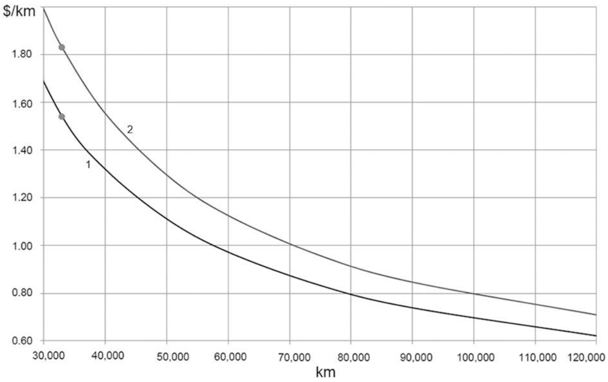


**Figure 3.4 — TCO ($/km) vs. bus annual mileage (km)**

first stage is to determine the energy consumption of the electric bus, taking into account the parameters of its design, the charging configuration and the features of the route. The methods and tools for estimating the energy consumption of the electric bus (cost distance analysis, modelling, etc.) have been analyzed and methods peculiarities have been demonstrated. Methods of modeling have been divided into two categories: 1 — methods in which the speed profile on a route is pre-determined, 2 — methods that reproduce the actions of the driver along the route. In the latter case, it is necessary to develop a driver actions algorithm. Additional method for evaluation of electric bus energy consumption have been proposed. It uses the data on fuel consumption by an ordinary diesel bus under the same route.

Examples and ways of determining the initial data for calculating TCO as the main economic indicator for the second and subsequent stages are shown. Typical structure of TCO for electric buses and TCO dependence on annual mileage are given. The way for adjustment of this dependence to the available concrete data is shown.

The paper presents the part of the research being in progress within the framework of project PLATON (01.2018–06.2020) that was approved for funding in the Electric Mobility Europe Call 2016.

*Acknowledgements. The author is grateful to the partners of the project PLATON, first of all to Dr. Gerfried Cebrat (EUC) and to Dr. Boris Rosin (UIIP NAS of Belarus), for valuable recommendations and comments on improving the paper.*

*Автор выражает признательность партнерам по проекту PLATON, в первую очередь доктору Герфриду Цебрату (EUC) и доктору Борису Розину (ОИПИ НАН Беларуси), за ценные рекомендации и замечания по улучшению статьи.*

## References

1. *Electric. Mobility. Europe*. Available at: https://www.electricmobilityeurope.eu/projects (accessed 11 May 2018).
2. *PLATON*. Available at: http://www.energie-umwelt.at/PLATON (accessed 28 May 2018).
3. Nikolić Z., Živanović Z. The Contribution and Prospects of the Technical Development on Implementation of Electric and Hybrid Vehicles. *New Generation of Electric Vehicles*, 2012, ch. 2, pp. 27–66.
4. Hanlin J. Battery Electric Buses Smart Deployment, *Zero Emission Bus Conference*, London, 2016. Available at: http://www.cte.tv/wp-content/uploads/2016/12/5_Hanlin.pdf.
5. Mohamed M., Garnett R., Ferguson M.R., Kanaroglou P. Electric Buses: A Review of Alternative Powertrains. *Renewable and Sustainable Energy Reviews*, 2016, vol. 62, pp. 673–684.
6. *Urban buses: alternative powertrains for Europe*. The Fuel Cells and Hydrogen Joint Undertaking, 2012. Available at: http://gofuelcellbus.com/uploads/20121029_Urban_buses,_alternative_powertrains_for_Europe_-_Final_report.pdf.
7. Lajunen A. Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, 2014, vol. 38, pp. 1–15.
8. Feng W., Figliozzi M. An economic and technological analysis of the key factors affecting the competitiveness of electric commercial vehicles: A case study from the USA market. *Transportation Research Part C: Emerging Technologies*, 2013, vol. 26, pp. 135–145.
9. Feng W., Figliozzi M. Conventional vs Electric Commercial Vehicle Fleets: A Case Study of Economic and Technological Factors Affecting the Competitiveness of Electric Commercial Vehicles in the USA. *Procedia – Social and Behavioral Sciences*, 2012, vol. 39, 702–711.
10. Eudy L., Jeffers M. *Foothill Transit Battery Electric Bus Demonstration Results: Second Report*. Technical Report NREL/TP-5400-67698. 2017. 59 p.
11. Prohaska R., Eudy L., Kelly K. Fast Charge Battery Electric Transit Bus In-Use Fleet Evaluation. No. NREL/CP-5400-66098. *IEEE Transportation Electrification Conference and Expo (ITEC)*. Dearborn, 2016. Available at: https://www.nrel.gov/docs/fy16osti/66098.pdf.
12. *King County Metro Battery Electric Bus Demonstration — Preliminary Project Results*. 2017. Available at: https://www.afdc.energy.gov/uploads/publication/king_county_be_bus_preliminary.pdf.
13. *Electric Buses in Cities. Driving Towards Cleaner Air and Lower $CO_2$*. 2018. Available at: https://c40-production-images.s3.amazonaws.com/other_uploads/images/1726_BNEF_C40_Electric_buses_in_cities_FINAL_APPROVED_%282%29.original.pdf?1523363881.
14. *ZeEUS eBus Report #2. An updated overview of electric buses in Europe*. 2018. Available at: http://zeeus.eu/uploads/publications/documents/zeeus-report2017-2018-final.pdf.
15. Krawiec S., Karoń G., Janecki R., Sierpiński G., Krawiec K., Markusik S. Economic conditions to introduce the battery drive to busses in the urban public transport. *Transportation Research Procedia*, 2016, vol. 14, pp. 2630–2639.
16. Fusco G., Alessandrinia A., Colombaronia C., Valentinic M.P. A model for transit design with choice of electric charging system. *Procedia — Social and Behavioral Sciences*, 2013, vol. 87, pp. 234–249.
17. Göhlich D., Kunith A., Ly T. Technology assessment of an electric urban bus system for Berlin. *Urban Transport XX. WIT Transactions on The Built Environment.*, 2014, vol. 138, pp. 137–149.
18. Olsson O., Grauers A., Pettersson S. Method to analyze cost effectiveness of different electric bus systems. *Proceedings of EVS29 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, Montréal, Québec, Canada, 2016. Available at: https://www.viktoria.se/sites/default/files/pub/www.viktoria.se/upload/publications/method_to_analyze_cost_effectiveness_of_different_electric_bus_systems.pdf.
19. *Life-Cycle Costing (LCC) calculation tool.* Available at: http://ec.europa.eu/environment/gpp/pdf/09_06_2015/Life_cycle_costing_calculation_tool.pdf (accessed 05 July 2018).
20. Rogge M., Wollny S., Sauer D.U. Fast charging battery buses for the electrification of urban public transport – a feasibility study focusing on charging infrastructure and energy storage requirements. *Energies*, 2015, vol. 8(5), pp. 4587–4606.
21. Lindgren L. *Full electrification of Lund city bus traffic – a simulation study.* Lund, Lund institute of technology, 2015. 51 p.
22. *TOSA buses power up for less*. Available at: http://actu.epfl.ch/news/tosa-buses-power-up-for-less/ (accessed 16 June 2014).
23. Nurhadi L., Borén S., Ny H. A sensitivity analysis of total cost of ownership for electric public bus transport systems in

Swedish medium sized cities. *Proceedings of the 17th Meeting of the EURO Working Group on Transportation, EWGT2014*. Sevilla, 2014, pp. 818–827.
24. Mohamed M., Farag H., El-Taweel N., Ferguson M. Simulation of Electric Buses on a Full Transit Network: Operational Feasibility and Grid Impact Analysis. *Electric Power Systems Research*, 2017, vol. 142, pp. 163–175.
25. Masliakova K. *Optimal routing and charging procedures for electric buses*. Master Thesis. Narvik, 2016. 78 p.
26. Andersson M. *Energy storage solutions for electric bus fast charging station. Cost optimization of grid connection and grid reinforcements*. Master Thesis. Uppsala. 72 p.
27. Gao Z., Lin Z., LaClair T.J., Liu C., Li J.-M., Birky A.K., Ward J. Battery capacity and recharging needs for electric buses in city transit service. *Energy*, 2017, vol. 122, pp. 588–600.
28. Tokoro M. Open Systems Dependability and DEOS: Concept, Retrospect and Prospects, *Proceedings of Sixth Workshop on Open Systems Dependability*. Tokyo, 2017, pp. 1–4.
29. Perrotta D., Macedo J.L., Rossetti R.J., Freire de Sousa J., Kokkinogenis Z., Ribeiro B., Afonso J.L. Route planning for electric buses: a case study in Oporto, *Proceedings of the 16th Meeting of the EURO Working Group on Transportation, EWGT2013*. Porto, 2013. Available at: https://paginas.fe.up.pt/~niadr/PUBLICATIONS/2013/EWGTrans_RoutePlanning.pdf

УДК 629.34:621.3

В.Б. АЛЬГИН, д-р техн. наук, проф.
заместитель генерального директора по научной работе[1]
E-mail: vladimir.algin@gmail.com
Объединенный институт машиностроения НАН Беларуси, г. Минск, Республика Беларусь

*Поступила в редакцию 05.07.2018.*

# ЭЛЕКТРИФИКАЦИЯ ГОРОДСКОГО ТРАНСПОРТА. ОСНОВНЫЕ ЭТАПЫ СОЗДАНИЯ ПАРКА ЭЛЕКТРОБУСОВ

*Статья имеет аналитический характер и посвящена систематизации подходов, которые имеют место в задачах создания городского парка электробусов. Представлен целостный взгляд на проблему, включая сравнение автобусов с различными типами силовых установок. Сформулированы требования к данным и документам, отражающим основные факторы и этапы создания парка электробусов. Основные этапы: 1 — анализ технической осуществимости возможных вариантов «электробус — зарядная конфигурация» для рассматриваемых маршрутов, 2 — экономический анализ общей стоимости владения парка; 3 — разработка бизнес-плана; 4 — сопровождение процесса перехода на основе концепции «открытой системы». Рассмотрен состав исходных данных и их форматов с соответствующими примерами. Представлен типичный список исходных данных для реализации первого этапа. Ключевой процедурой первого этапа является определение потребления электроэнергии электробусом с учетом параметров его конструкции, конфигурации зарядки и особенностей маршрута. Проанализированы методы и инструменты для оценки энергопотребления электробуса (анализ путевых затрат, моделирование и т. д.) и продемонстрированы особенности методов. Общая стоимость владения (TCO) рассматривается как определяющий фактор на втором и последующих этапах. Анализируется структура и чувствительность TCO. В статье представлена часть исследований, проводимых в рамках проекта PLATON: процесс планирования и инструмент поэтапного преобразования обычного или смешанного автобусного парка в 100%-ный парк электробусов. Проект одобрен для финансирования в рамках программы ERA-NET Electric Mobility Europe, объявленной в 2016 году. Период проекта 01.2018–06.2020.*

***Ключевые слова:*** *силовые установки автобусов, городской электробус, маршрут, зарядная инфраструктура, создание парка электробусов, основные этапы, данные, факторы*