Technology assessment of an electric urban bus system for Berlin

D. Göhlich, A. Kunith & T. Ly
Department Methods for Product Development and Mechatronics, Technische Universität Berlin, Germany

Abstract

Public transport authorities particularly in conurbations and mega-cities undertake growing endeavours to improve their CO_2 footprint and become less dependent on fossil fuels. Electric buses are an obvious alternative to conventional diesel vehicles. However, public transport authorities face several different options of electric bus technologies and different system solutions to implement electric buses. These options have specific assets and drawbacks concerning technology, capital and operational cost. Despite the importance of this issue only very limited research has been published on that matter so far.

This study presents a technology assessment of battery-electric public bus systems based on technical and economical key performance indicators. The methodology is applied to an electric bus project for the city of Berlin. To facilitate the selection of a suitable technology a step-wise approach is applied. Firstly, an energetic simulation model has been set up to forecast the needed energy for daily service based on bus operating profiles in Berlin. Secondly, a pre-selection of potential electric bus solutions is made by qualitative evaluation of different systems using defined technical and economic indicators. Thirdly, a detailed comparison is made between the remaining technological alternatives taking monetary-based aspects into account. The economic analysis is conducted by means of a total cost of ownership (TCO) approach.

In conclusion the examination reveals that under Berlin conditions inductive opportunity charging technology fulfills the comprehensive system's requirements and shows relatively low TCO values.
Keywords: technology assessment, charging systems strategies, electric urban bus, energy consumption simulation, Total Cost of Ownership.

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1 Introduction

To achieve ambitious climate goals, e.g. the reduction of CO_2 emissions by 40% in 2030 and 60% in 2040 in the European Union [1], "clean technologies" have to be developed and deployed. Electric vehicles have the potential to achieve sustainable results in combination with renewable and non-polluting electric energy sources. Furthermore, the transportation sector in conurbations contributes significantly to urban noise and air pollutants.

Limited recharging infrastructure and high battery costs are the main barriers to the market penetration of electric passenger cars. Since urban buses have regular driving cycles, frequent and predictable stops, it is possible to accurately predict the needed energy and to design energy storage and charging technology accordingly.

Due to the lack of acceptance towards the installation of new overhead wires in cities, grid-bound bus operations are not a feasible option in many metropolitan areas. Additionally, the routing flexibility of the trolley bus concept is limited to the catenary network. Therefore, electric energy has to be stored on-board.

The cost intensive batteries and its unsatisfactory cycle stability and specific power remain critical issues. However, the Boston Consulting Group expect that battery costs will decline by 60% and more from 2009 to 2020 [2].

Considering a relatively lower price increase in future of electricity compared to diesel [3] and additional cost for conventional drive trains due to regulatory decisions such as the application of EURO VI the deployment of electric buses, particularly in urban areas, becomes more attractive.

A fully electric bus can be realized based on different technologies. Several research projects on electric buses with opportunity and overnight charging have been reported but commercial systems solutions are exclusively available for overnight charging systems.

Though, the pertinent literature reveals well-grounded research about alternative transport systems, studies on innovative bus technologies are less documented. Most of the recent researches address the comparison of diesel, hybrid diesel-electric, compressed natural gas, hydrogen fuel-cell and battery electric buses [4–7]. Only very few studies are dedicated to the evaluation of different battery electric bus technologies [8] such as opportunity and overnight charging. However, according to the best knowledge of the authors there are no comprehensive studies made distinguishing different electric charging concepts such as conductive and inductive fast-charging.

This paper presents a technology assessment of battery-electric public bus systems based on technical and economical key performance indicators and evaluates the feasibility of an urban electric bus system in the city of Berlin.

2 E-Bus Berlin project

The "E-Bus Berlin" research project examines whether and how buses in the city center can be operated fully electrically. Trolley bus systems were not considered

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since the city authorities reject a catenary system as detrimental for the urban image. Within the scope of this project a suitable technology has to be chosen and a proof of concept will be given by operating a complete bus route as precursor for the market entry of commercial solutions.

A representative bus line, in cities like Berlin, measures 8 km and features 18 stops. Figure 1 shows a typical velocity profile measured during midday operation in an urban traffic scenario.

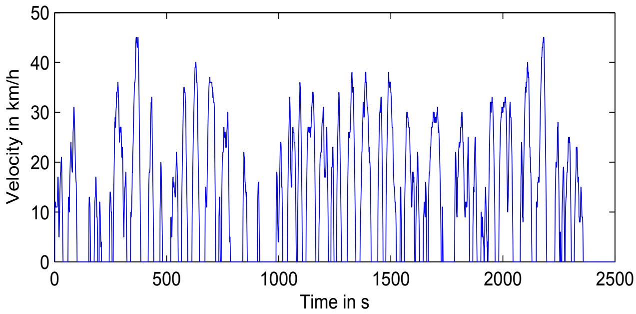

Figure 1: A typical velocity profile measured during midday operation.

The new zero emission electric bus service should have no operational constraints compared with conventional bus system as well as should feature lower emission levels.

Table 1 lists the specification and some characteristic data of the hypothetical line.

Table 1: Specification of the line.

Item	Specification
Single ride [km]	8
Bus stops	18
Route time (single ride) [min.]	39
Average velocity [km/h]	12.2
Distance to Depot [km]	12.0
Turn-around-time at final stops [min]	6–9
Dwell time at bus stops [sec.]	10.0
Headway [min]	10.0
Daily operation time [min/d]	1,080
Annual mileage fleet [km]	515,100
No. of buses in operation	6

It is assumed that service is operated with up to six 12 m buses with a curb weight of 12,650 kg and a maximum additional payload of 5,350 kg. Typically one particular bus is scheduled for 36 daily bus rides. Table 2 outlines the specification of the electric bus.

Table 2: Specification of the electric bus.

Item	Specification
Bus type	Low Floor, 12 m, 2 doors
Vehicle weight [kg]	12,650
Maximum payload (battery + maximum occupants) [kg]	5,350
Full height [mm]	3,350
Overall width [mm]	2,550

3 Simulation and TCO model

The technology assessment is backed by a simulation and TCO model.

3.1 Methodology

For the assessment, several technological alternatives have been taken into consideration. A fully electric bus could be endued with different base technologies. Since trolley buses are precluded in Berlin, on board storage of electric energy is required as shown in Figure 2.

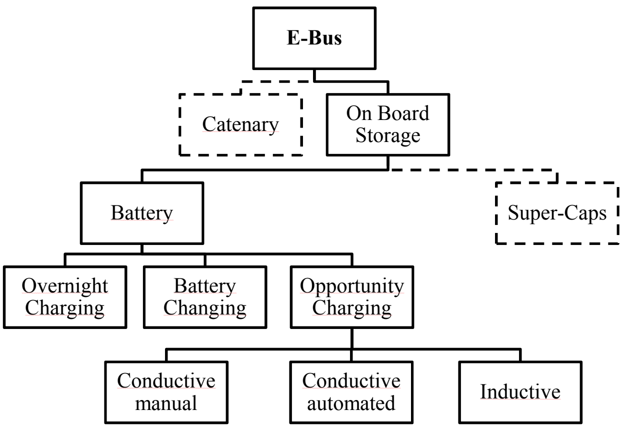

Figure 2: Storage and charging system alternatives for a full electric bus.

The relatively low specific energy of super capacitors requires very frequent charging points. This could be realized at every bus stop but additionally the route to and from the depot has to be covered. Under the assumed conditions in Berlin super capacitors are not a feasible option and were not investigated further. Electric energy has to be stored on board in batteries but the battery system and charging approach remains to be assessed. Therefore, a step-wise methodological approach has been applied.

At first the needed energy to cope with the bus line requirements has to be identified. Thus, a simulation model has been set-up. Second, the battery-system strategy has to be determined and is qualitatively done based on technical indicators such as required battery capacity, range to fulfill the scheduled service, etc. as well as economic indicators expressed in battery cost, infrastructure cost and additional expenditures. Third, after the exclusion of alternatives in the previous steps, a total cost of ownership (TCO) approach is applied for the remaining charging technologies. The economic assessment is conducted supporting the non-monetary assessable decision criteria.

3.2 Energy flow model

The energy consumption is the most determining parameter for the technology assessment of electric buses if onboard energy storage is deployed. In order to forecast the needed energy an appropriate simulation model has been developed. The MATLAB Simulink model in Figure 3 is composed of several sub-models.

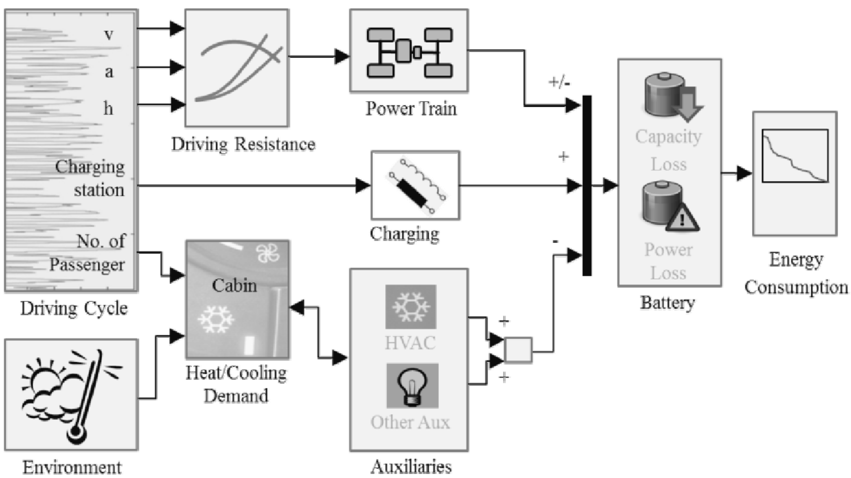

Figure 3: Simulation model.

The mechanical model accounts for the driving resistance referring to [9].

$$F_{res} = (\lambda_m m_{vehicle} + m_{payload})\ddot{x} + mgf_R + \frac{1}{2}\rho_L c_W A v^2 + mg\sin(\alpha) \qquad (1)$$

The auxiliary model includes the complete heat flow for heating, ventilation and air conditioning (HVAC) of the bus as well as other auxiliaries like light, door operation, lifting devices etc.

$$\dot{Q}_d = \dot{Q}_{Passenger} + \dot{Q}_{Conduction} + \dot{Q}_{Radiation} + \dot{Q}_{Doors} + \dot{Q}_{HVAC} \qquad (2)$$

The electrical model includes the power train, charging devices and battery system with internal resistance and power loss due to thermal effects (derived from [10, 11]).

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Aside from the energy consumption for driving, cooling and especially heating are additional important issues when designing electric buses. The energy for climate control has to be fully provided by battery since there is no heat release of an internal combustion engine. According to a VDI guideline the temperature range in Germany should be assumed from -20°C to 35°C [12].

In the year 2012 the weather station of Freie Universität Berlin has measured the ambient temperature in Berlin. Figure 4 shows the measured temperature distribution.

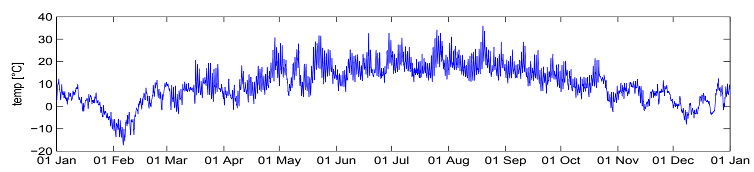

Figure 4: Ambient temperature, Berlin 2012 [13].

Referring to Figure 4 the minimum temperature was in February with -17°C and the maximum temperature was in August with 35°C. Hence, the VDI recommendation seems reasonable.

A guideline for climate control of low floor buses can be found in [14]. Therein, it is described that the cabin temperature should be held at 18°C in urban areas. In winter with ambient temperature down to -10°C the HVAC system must be capable to regulate a cabin temperature of 18°C ± 2 K. If the ambient temperature is less than -10°C, the maximum tolerance amounts to 18°C ± 5 K. In summer the HVAC system has to attain a cabin temperature of 3 K less than ambient temperature. Thus, heating is more critical than cooling because of the temperature delta.

Exemplarily, in this paper electric heating using positive temperature coefficient (PTC) heater has been modeled. It was assumed that all doors were open as long as the bus paused at a bus stop. This represents a worst case scenario. For the calculation of the needed energy the following assumptions have been made:

1) Total mass is 18,000 kg
2) Power train efficiency is 88% [15]
3) Occupants release an average heat of 115 W [16]
4a) Ambient temperature is 18°C (as a base scenario)
4b) Ambient temperature is -17°C (as worst case scenario)
5) Desired interior temperature in urban buses is 18°C ± 2 K according to [14]
6) Energy consumption of other auxiliaries 6 kW
7) Rolling resistance 0.013 [17]

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3.3 TCO model

The TCO model is composed of vehicle cost (CAPEX and OPEX), the infrastructure cost (CAPEX and OPEX) and capital financing cost. The input parameters of the TCO model are listed in Table 3. The final TCO value is given as the sum of all mentioned costs and is expressed as EUR per km based on the total mileage over the operation period of twelve years. The energy cost, as a portion of the operational vehicle cost, are calculated by multiplying the average energy consumption (derived from the energetic simulation) for each bus system taking the charging efficiency into account, the distance traveled, and the average expected electricity price (German industrial price for transport companies) over a period of twelve years paid by a German transit operator. The maintenance costs for the vehicle and the charging station encompass the expenses for spare parts as well as for labor. The vehicle investment cost covers a battery replacement after six years of operation to estimated future battery prices referring to the mentioned source [2]. All other investment cost for the vehicle and infrastructure are stated from the year 2013.

Table 3: Input parameters of the TCO model.

Vehicle cost	CAPEX	E-bus incl. battery system and charging equipment
	OPEX	Energy cost
		Maintenance
Infrastructure cost	CAPEX	Charging station incl. installation
	OPEX	Maintenance
Financing cost	Interest expenditures	

The operational bus cost does not include regular driver cost. It is assumed that the labor cost for bus drivers is independent from the deployed technology. Though, additional labor cost for charging services is captured by the applied model. Furthermore, the operating lifetime is equal to the depreciation period and stated with twelve years for the bus as well as for the infrastructure equipment. After this period it is assumed that the salvage value is equal to zero.

The input data for the TCO model are obtained from a series of demonstration studies on alternative fuel buses [18–20] and interviews with project stakeholders such as transport authorities and manufacturers. However, due to a lack of cost data for infrastructure, maintenance expenses are estimated.

4 Results

4.1 Energy consumption

Figure 6 shows the result of the simulation at 18°C and -17°C. The electric bus with its specifications as shown in Table 2 has 1.9 kWh/km driving consumption and 0.5 kWh/km energy saving from recuperation. Other auxiliaries have an energy consumption of 0.5 kWh/km. At 18°C 0.1 kWh/km is needed for ventilation due to the heat release of humans to maintain the set temperature. With respect to 0.3 kWh/km energy consumption caused by electrical losses the total needed energy to operate the bus line is 2.3 kWh/km.

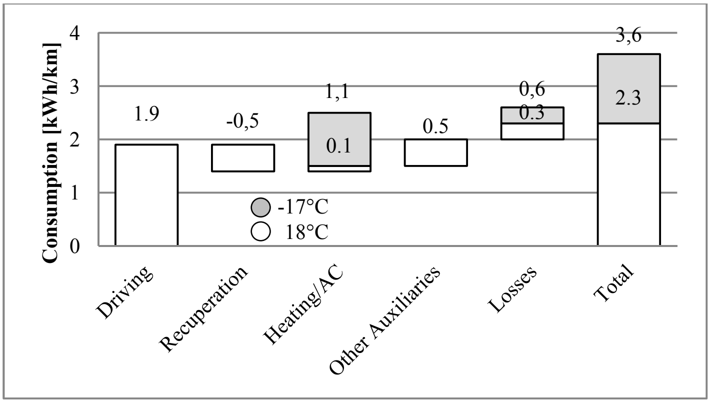

Figure 5: Energy consumption at 18°C and -17°C.

For the extreme temperature case in Berlin (-17°C) the total energy consumption adds up to 3.6 kWh/km. In case of PTC-heating the needed energy for heating is 1.1 kWh/km. This is more than half of the driving consumption. Thus, the needed energy for a single ride of 8 km is 18.4 kWh or 28.8 kWh, respectively.

4.2 Qualitative pre-selection

Overnight charging, battery changing and opportunity charging are possible options. These charging technologies can be observed in ongoing projects in several countries, e.g., Germany, USA and China. Which strategy is most applicable for Berlin according to required battery capacity, range, cost, flexibility etc. is qualitatively shown in Table 4.

For overnight charging of the buses on the chosen line a battery capacity of more than 660 kWh would be necessary (2.3 kwh/km*8 km*36 schedules). Considering a Li-Ion battery with 110 Wh/kg specific power [15] a battery weight of 6,000 kg would be necessary. Since the maximum payload is set to 5,350 kg the battery size of the overnight charging technology is excluded.

This comparison indicates that the opportunity charging battery-system strategy seems to be most advantageous for Berlin since the relatively small and light battery modules allow a high passenger capacity and the integration of the charging stations at final stops result in no excessive additional infrastructure. Moreover, with suitable infrastructure and fast charging an unlimited range can be achieved. The demanded energy can be recharged at final stop and assuming a charging system with 200 kW charging power the amount of 18.4 kWh is equivalent to 6 min charging time (28.8 kWh = > 9 min).

Table 4: Comparison of battery-system-strategies.

Criteria		Overnight charging	Battery changing	Opportunity charging
Required battery capacity		- > 660 kWh	+ ca. 300 kWh	+ ca. 60 kWh
Range	Company specification	ca. 100–300 km	ca. 100–150 km	ca. 10–20 km
	Realistic operation	- significantly lower	+ unlimited; by battery changing	+ unlimited by fast-charging
Battery wearing characteristics		o deep discharge	o deep discharge	o low discharge, many cycles
Battery costs		+ large, but relatively low priced batteries	- many redundant batteries	+ few, but relatively expensive batteries
Required space for infrastructure		o one charging station for each bus in depot required	- changing station incl.. storage	+ charging stations at final stops and depots
Infrastructure costs		+ charging station in depots	- changing station with chargers	o charging stations at final stops and depots
Route management flexibility		+ range dependent	o within the operation area of changing station only	- between charging stations only
Additional Expenditures		- possibly more buses required due to limited range	- very few battery changing stations	o interruption possibly required for charging

4.3 Additional TCO assessment

Opportunity charging can be operational deployed with conductive (manual or automated) or inductive charging (automated). To determine the most appropriate charging technology, criteria such as influence on cityscape and additional labor cost have been included in the model. In Table 5 the opportunity charging alternatives have been compared.

Due to additional labor cost the manual charging has been excluded by the Berlin Transportation Authority. The additional labor cost caused by the needed charging service is estimated with EUR 185.000 per year for the bus operation based on the cumulative charging time and labor wage (25€/h) which is equivalent to a TCO premium of EUR 0.36 per kilometer. These costs are not stemmed by other cost beneficial aspects in comparison to the inductive and

Table 5: Comparison of charging-system-strategies.

Criteria	conductive manual	conductive automated	inductive
Required infrastructure complexity	+ converter, 200kW charging station	o converter, charging station, known technology	- converter, inductive charging system
Cityscape	- charging posts or stations	- charging stations with contact wire	+ Invisible roadside integration of charging stations
Additional labor cost	-	+	+
Maintenance	o	- maintenance of contact wire	+
Total charging efficiency	+ ca. 95%	+ ca. 95%	- ca. 90%
Vandalism	o few accessible components	- accessible infrastructure	+ no accessible components
Pilot Projects	[21]	[22, 23]	[24, 25]

automated conductive charging system. Hence, the manual conductive charging concept has been excluded from consideration.

For the two remaining technologies a comprehensive TCO model has been additionally applied in order to economically assess and to determine the most suitable technology choice for the bus line. The comparison shows that the vehicle costs appear lower for the conductive automotive than for the inductive charging. This cost advantage is explained by the lower complexity of the bus-side charging equipment. Contrarily, the inductive technology feature cost benefits in operational expenses. Thus, the vehicle OPEX as well as the infrastructure OPEX indicate lower TCO values. An increasing annual mileage would therefore advantage the inductive bus system.

However, the total TCO values do not prove a prevailing technology under the described assumptions. The values of both technologies are within a range of ± 3 percent referring to an underlying value of EUR 1.49 per km.

Nevertheless, the evaluation shown in Table 5 attributes two crucial criteria in favor of the inductive charging technology. The invisible integration of the charging infrastructure within the cityscape and the protection against vandalism are outstanding advantages of this technology.

Overall, it can be inferred that the similar TCO values of the two technologies and the evident advantages due to the structural integration of the roadside charging components lead to the preference of the inductive charging system for the Berlin case.

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5 Conclusion

Prior work has primarily documented assessment models focusing on different drive trains. However, this study provides an evaluation approach for electric buses featuring different charging concepts. The approach is aiming to support the decision-making process of public transport stakeholders in context of the deployment of innovative electric bus systems.

A comprehensive analysis has been conducted in order to identify the most appropriate system solution for an electric bus line in Berlin. By determining the needed energy for the respective bus line and by defining evaluation criteria in scope of the pre-selection, the technology variety could be limited to the opportunity charging concept. Finally, the qualitative analysis was complemented by a financial performance assessment. The investigation reveals that similar TCO results were achieved. Nevertheless, the technology assessment under the Berlin conditions favors the opportunity inductive charging system due to technical design characteristics.

The assessment approach can be applied without any difficulty to a wide range of application scenarios. The underlying bus line specifications and the derived technical data are typical for urban areas. Therefore, the presented results are reasonable from an operational perspective, though variations of certain input parameters such as annual mileage have significant influence on the TCO results.

As shown in the simulation heating requires a significant part of energy. The daily operation of the bus covers 36 scheduled rides amounting to a total distance of 288 km. Thus, with a PTC heater one particular bus has an energy consumption of up to 1000 kWh per day under extreme but realistic ambient conditions. Future work should take other HVAC into account, e.g. the deployment of a heat pump. Heat pumps have been observed in conventional buses [26] and seem to have promising potential to lower the total energy consumption significantly.

However, some limitations are worth noting. Although, a multi-criteria approach was conducted, the results are limited to one certain bus line. Future work should therefore broaden the scope of the analysis; in particular the TCO assessment offers potential for improvements by taking into account a wider variety of technologies and the characteristics of fleet operation.

6 Outlook

The Berlin E-Bus project will implement a fully electric operation in the framework of a consortium of five partners. Besides the Berlin Public Transport Authority (BVG) [27], in charge of the project management, operation and infrastructure, and the Technical University Berlin, entrusted with the feasibility study, conceptual system design and the overall system evaluation, three industrial companies are involved: Bombardier Transportation providing the PRIMOVE charging technology [28] and battery system, Vossloh-Kiepe developing the electric drive train and power electronics and finally the bus original equipment manufacturer Solaris.

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References

[1] European Commission – Climate Action. European Commission, Roadmap for moving to a low-carbon economy in 2050, Online. http://ec.europa.eu/clima/policies/roadmap, 2012.
[2] Boston Consulting Group (BCG), Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020, 2010.
[3] Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Urban buses: alternative powertrains for Europe, 2012.
[4] Goehlich, D., Spangenberg, F., Kunith, A., Stochastic Total Cost of Ownership Forecasting for innovative Urban Transport Systems. Proc. of the 7th IEEE Int. Conf. On Industrial Engineering and Engineering Management, IEEE: New York, print, 2013.
[5] McKenzie, E., Durango-Cohen, P., Environmental life-cycle assessment of transit buses with alternative fuel technology. Transportation Research Part D: Transport and Environment, 17(1), pp. 39-47, 2012.
[6] Lajunen, A., Energy consumption and cost-benefit analysis of hybrid and electric city buses. Transportation Research Part C: Emerging Technologies, 38, pp. 1-15, 2014.
[7] Hellgren, J., Life cycle cost analysis of a car, a city bus and an intercity bus powertrain for year 2005 and 2020. Energy Policy, 35(1), pp. 39-49, 2007.
[8] Tzeng, G.H., Lin, C.-W.i., Opricovic, S., Multi-criteria analysis of alternative-fuel buses for public transportation. Energy Policy, 33(11), pp. 1373-1383, 2005.
[9] Goetz M., Verbrauchssimulation eines elektrischen Busses mit induktiver Ladetechnologie auf Basis einer Systemstrukturanalyse (Consumption simulation of an electric bus with inductive charging technology, based on a structural system analysis), diploma thesis, Technical University of Berlin, 2013.
[10] Lam L., Bauer P., Kelder E., A practical circuit-based model for Li-ion battery cells in electric vehicle applications. Proc. of the 33rd IEEE Int. Conf. on Telecommunications Energy Conference (INTELEC), IEEE: New York, pp. 1-9, 2011.
[11] Lam L., Bauer P., Practical Capacity Fading Model for Li-ion Battery Cells in Electric Vehicles, IEEE Transactions on Power Electronics, 28(12), pp. 5910-5918, 2013.
[12] Deutsches Institut für Normung (DIN), DIN EN 14750-1, Bahnanwendungen – Luftbehandlung in Schienenfahrzeugen des

innerstädtischen und regionalen Nahverkehrs – Teil 1: Behaglichkeitsparameter (Railway applications – Air conditioning for urban and suburban rolling stock –Part 1: Comfort parameters), 2012.
[13] Freie Universität Berlin. Daten und Gutachten Webseite (Data and Evaluation Website), Berlin, http://www.geo.fu-berlin.de/met/service/wetterdaten/, 2013.
[14] Wallentowitz, H., Freialdenhoven, A., Olschewsk,i I.. Strategien zur Elekrifizierung des Antriebsstranges (Strategies for the electrification of the drive train). Vieweg + Teubner: Wiesbaden, 2010.
[15] Verein Deutscher Ingenieure (VDI), VDI 2078, Berechnung von Kühllast und Raumtemperaturen von Räumen und Gebäuden (VDI-Kühllastregeln) (Calculation of cooling load and room temperatures of rooms and buildings (VDI Cooling Load Code of Practice)), 2012.
[16] Verband Deutscher Verkehrsunternehmen (VDV), VDV-Schriften 236, Klimatisierung von Linienbussen (Climate control of public buses), Köln, 1996.
[17] Appel, W., Nutzfahrzeugtechnik: Grundlagen, Systeme, Komponenten (Utility Vehicle Technology), Springer :Dordrecht, 2012.
[18] Bedell, R., A Practical, 70-90% Electric Bus without Overhead Wires. EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, pp. 1-7, 2009.
[19] Taborelli, S., Case Study: Gruppo Torinese Trasporti uses electric minibuses in Turin charged within 7 minutes (Italy). ELTIS - The Urban Mobility Portal, Online. http://www.eltis.org/index.php?id=13&study_id=2726, 2012.
[20] Živanović, Z., Nikolić, Z., The application of electric drive technology in city buses (Chapter 6). New Generation of Electric Vehicles, ed. Z. Stevic, InTech, Online. http://www.intechopen.com/download/get/type/pdfs/id/41487, pp. 165-197, 2012.
[21] Chongqing Currents, China's 1st electric bus fast charging station debuts in Chongqing Online. http://www.chongqingcurrents.com/?p=57434, 2012.
[22] Proterra, Online. www.proterra.com, 2013.
[23] Opbrid, Online. http://www.opbrid.com, 2013.
[24] Conductix, Online. www.conductix.de/de/maerkte/e-mobility#, 2013.
[25] Bombardier Transportation, Online.primove.bombardier.com/de/, 2013.
[26] Sonnekalb, M., Tegethoff, W., Foersterling, S., CO2 basierte Air-Condition und Heizung fuer Stadtbusse (CO_2 based Air-Condition and heating for urban buses), final report on a research project, Braunschweig, Germany, 2008.
[27] Olszewska, M., Solaris Urbino electric – First operational experiences, VDV Conference 2013, Germany, 2013.
[28] Koebel, C., Bombardier Zero Emission Bus Systems with PRIMOVE Wireless eMobility, VDV Conference 2013, Germany, 2013.

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