32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

Optimization of opportunity charged bus operation - a case study

Mikaela Ranta, Joel Anttila, Mikko Pihlatie, Ari Hentunen, Marko Paakkinen

VTT Technical Research Centre of Finland, Tietotie 4C, 02150 Espoo, Finland, mikaela.ranta@vtt.fi

Summary

Optimization and proper planning of electric vehicle systems becomes even more important as the number of electric vehicles grow, and the vehicles interact when sharing the same charging infrastructure. Different aspects related both to the vehicles themselves and the charging has to be considered in order to achieve a system that is economically competitive to conventional systems while providing a higher level of comfort. In this paper, detailed system simulations are performed in order to demonstrate various aspects related to opportunity charged systems and the economical impact is analysed.

Keywords: cost, fleet, public transport, reliability, simulation

1 Introduction

Electrification of transport has gained a lot of interest during the last years. Electric vehicles have many benefits as compared to conventional vehicles – such as high energy efficiency, no local pollution and low noise levels. The major obstacles in electrification of transport are related to the limited range of the vehicles and the high costs. When it comes to heavy duty vehicles, such as electric buses or trucks, opportunity charging has been offered as a solution. With frequent fast charging, the range of the vehicle is no longer an issue, and with a down-sized battery, the costs can be kept at an competitive level [1]. Pilot studies with electric buses have been going on around Europe for several years already, and the technology has been proven to work in practise. In order to roll out in full-scale commercial operation, the electric bus system needs to be planned with care. The charging infrastructure has to be able to serve all buses without being oversized causing additional costs. The buses and fleets have to be correctly dimensioned to be able to provide the required service the whole day without interruptions.

The problem has been approached in multiple ways in the literature. Various methods for selecting the suitable routes, the battery size and charging locations have been proposed in the literature. In [2], a model is proposed to select routes for electric buses while optimizing either the energy consumption or the costs, and in [3], a method for optimization of the charging locations is proposed. Neither of these methods address the schedules. In [4], a mixed integer linear optimization problem is used to describe the optimal placement of charging stations and their sizes. A genetic algorithm is used for scheduling and determination of the the fleet size for two types of electric buses when charging is available only at the depot in [5]. In [6], the locations of chargers and the battery capacities of the buses is optimized for a whole route network, assuming that chargers located at larger transport hubs are dedicated to specific lines. Simulations are used for evaluating the energy consumption for various bus types and conditions in [6, 7, 8, 9]. [7] proposes a method to optimize the speed profile while [8] concentrates on the selection of batteries for the buses. [9] uses the output of the simulation to optimize placement of chargers and to minimize the charging time. In this paper, different issues related to opportunity charged vehicles systems are discussed and the influence of different parameters are demonstrated by means of simulations. The approach is practical in the sense that data and experiences from real operation of electric buses are included in the simulation model. A cost analysis is presented, and the costs of electric buses are compared to the costs of conventional diesel buses. The outcome of the analysis can be used to optimize the operation.

2 Electric bus system

The bus schedule is the corner stone of the bus operation regardless of what kind of vehicles are used. A properly designed vehicle rotation enables cost-efficient use of the vehicles while offering a good service level for the passengers. Typically, the number of vehicles in operation vary throughout the day. During rush hours in the morning and afternoon, the amount of passengers is high and a short departure interval is desired. At the same time, buses are more prone to delays due to congestion. As a result, the required number of vehicles is usually higher during these peak hours and part of the vehicle fleet is not in use during other times of the day.

A system of electric buses sets additional requirements to the vehicle rotation. In a system of conventional buses, the range of the bus does not need to be considered as any bus available at the market can operate the whole day and refuelling is very quick. In the case of electric buses, the situation is different as these aspects set limitations to the operation of the buses. Depot charged buses might need extra breaks at the depot for charging in the middle of the day. Opportunity charged buses can operate practically non-stop, but time necessary for charging has to be taken into account in the schedule. Opportunity charged buses have been on the market for only a few years, and the bus manufacturers provide different kinds of technical solutions regarding the driveline and charging. Hence, to find the optimal solution, the process should include both the scheduling and the vehicle design.

The system of opportunity charged buses becomes even more interesting when several lines are electrified. When buses operating on different lines share the same charging infrastructure at large transportation hubs, there is a potential of lowering the costs related to the charging infrastructure when the utilisation of the chargers becomes higher. On the other hand, there is also a risk of queues to the charging stations if the number of charging stations is minimized and some disturbance occurs. In other words, analysing only one line at a time is not sufficient, but the whole system including both fleet and chargers needs to be considered in order to ensure a reliable operation of the buses without raising the costs. As electrification of other sectors, such as service vehicles and logistics, proceed in the future, also these sectors might have an influence on public transport through shared charging infrastructure.

2.1 Battery

The choice of battery has a great influence on the energy consumption and range of the vehicle. Different types of batteries exist with various characteristics. Ideally, the battery has both a high energy density and high power rating on charging. A high energy density allows a quite high capacity without adding too much weight on the bus. High charging powers allow for rapid charging sessions whenever necessary without having to alter the bus schedule. Currently, the most attractive batteries for opportunity charging electric buses are Li-ion batteries with either LTO (lithium titanate oxide) or graphite (G) anode and a NMC (nickel manganese cobalt) type. The LTO-NMC battery can withstand relatively high charging powers, i.e. high C-rates, but the energy density is low. G-NMC batteries have a much higher energy density, but on the other hand, the maximum C-rate on charging is much lower than for LTO batteries. Hence, there is a trade-off between energy density and power rating.

Another important factor is the battery aging. Vehicle depreciation times are often around 15 years, and the battery has most probably to be replaced at least once during that time. The Li-ion battery aging is a complex combination of electrochemical and mechanical processes causing capacity decrease and power fading. These aging processes can be divided into two groups: aging during use and aging during storage. In other words: aging related to cycle life (driving) and aging related to calendar life (idling).

The degradation processes take place in the battery's electrolyte, especially at the interfaces with the anode and the cathode. Thus, the aging mechanisms strongly depend on electrodes composition. The key factor in Li-ion battery aging is the formation of the solid electrolyte interphase (SEI) layer on graphite anode. The SEI layer is naturally created during the first charge and it works as a protective barrier between the anode and the electrolyte. However, the SEI layer is not stable, but it develops over time, which induces loss of lithium ions. The wide range of degradation mechanisms can be clustered into three degradation modes: loss of lithium inventory, loss of active anode material and loss of active cathode material.

Li-ion battery degradation rate is greatly affected by the battery operation practices and the conditions where the battery is operated and stored. The factors that affect the degradation rate are called degradation stress factors. The most important degradation stress factors related to cycle aging are high cycle depth, high average SOC, high C-rate and high or low operating temperature. For calendar aging the main stress factors are high storage temperature and high storage SOC.

Furthermore, the battery losses need to be considered. Ideally, all stored chemical energy would be converted to electrical energy. However, polarization losses occur when a load current passes through the electrodes. Because of internal impedance, a voltage drop is present during discharging. This voltage drop is typically called ohmic polarization or *IR* drop, and it follows the Ohm's law, i.e., it is proportional to the magnitude of the load current. The total internal impedance of a cell is the sum of the ionic resistance of the electrolyte, the electronic resistances of the active mass and interfaces, the current collectors and electrical tabs of the electrodes, and the contact resistance between the active mass and the current collector. Polarization effects consume part of the total energy as heat losses and thus reduce the efficiency of the conversion.

The efficiency grades of lithium-ion batteries depend on the battery technology, discharge rate, and temperature. Typically the roundtrip energy efficiency of a full discharge–charge cycle of a large Li-ion battery at room temperature is higher than 97% for low rates less than or equal to C/3 and higher than 90% at a rate of 1C.

2.2 Charger

The conceptual design of the charging management and its optimisation is at the heart of implementing opportunity charged electric bus systems. As already stated, the charging power as well as the charging locations and number of chargers at each location need to be determined carefully. The charging power determines the time needed for charging, but it is also directly proportional to the costs of the charging infrastructure. Higher powers mean shorter charging times and lower operational costs, but the capital costs might outweigh the savings.

When selecting the type of charger, there are multiple aspects to consider. Charging interfaces can be either conductive or inductive. The most common solution is a pantograph, either roof-mounted or inverted. Other solutions include connections to the bus from the side or from the bottom. Conductive charging can provide very high power levels, whereas the maximum power of inductive solutions is currently 200 kW. The limited power level compared to the contact interfaces means that inductive charging requires longer charging times, or more charging points along the line.

When pantographs roof-mounted on the bus are being used, each vehicle must be equipped with a pantograph, and the cost and weight of each vehicle is slightly increased. The impact on service and maintenance might be more important. In case a roof-mounted pantograph is out of order, only one vehicle has to be taken out of service for maintenance. However, if the infrastructure-mounted ('inverted') pantographs are used, and the pantograph for some reason stops working, the whole bus line is affected, as the charging node cannot be used. As the probability of malfunction of the different solutions have not been analysed, it cannot be said whether one solution is better than the other.

Another aspect of the charging interface is the communication between the charger and the bus. With roof-mounted pantographs, wired Power Line Communication (PLC) is utilised while wireless communication, such as Wi-Fi, is needed in the case of inverted pantographs. The utilization of wireless communication between the bus and the charger increases the requirements for cybersecurity and system robustness, as the system becomes more vulnerable against external interference.

The charging power is directly linked to the energy that can be obtained from a charging event within a limited time. Hence, the power is closely interlinked with the bus schedules. It should be noted, though, that the charging power is not constant throughout the entire charging session, but the power decreases as the battery state of charge increases above a certain level, given the operational limits of the battery management system. Furthermore, the time needed for connection and disconnection of the charger depends on the selected solution.

3 Evaluation of electric bus system

3.1 Simulation method

In this paper, a simulation method based on [10] and [11] is used. Routes are based on data obtained from open data sources. Each route includes information on the length, curvature, elevation, speed limits and locations of bus stops and stoplights. A dynamic model of each vehicle is utilized, where the total force acting on the vehicles depend on the slope of the road, the rolling resistance and aerodynamic drag as well as the acceleration. The speed set point is created dynamically as in [11], and it is determined based on the speed limit and traffic conditions. The speed is also somewhat affected by the road curvature. The acceleration and deceleration is limited in order to avoid too harsh speed variations and to mimic the behaviour of real drivers. The simulations are based on actual duty cycles, and statistical variation is introduced in the simulation through variation of the stopping frequency, passenger amount, and stopping time. The driveline is modelled in a rather simple way in order not to slow down the simulation too much. An efficiency map dependent on the speed and torque is used to present the electric machine. The inverter has a constant efficiency. The battery is modelled as a constant voltage source with an internal resistance in order to include the influence of losses depending on the discharging and charging power.

In the simulation, chargers are located at selected bus stops. Each charger is defined by a maximum power that can be drawn from the grid and a maximum number of buses that can charge simultaneously. When a bus comes to a bus stop with a charger, it starts to charge in case there is a free charging node. As the battery state of charge is reaching a predefined maximum value, the charging stops and the charging node is free for the next bus to use. In this manner, the interaction between vehicles at the charging station is taken into account, and the simulation can easily be extended to any number of vehicles and routes. The charging power is determined by the battery capacity and state of charge. The maximum power is used only in the beginning of the charging session, and the power decreases as the battery state of charge increases.

3.2 Total cost of ownership

The total cost of ownership (TCO) analysis combines most of the technical aspects regarding the electric bus solutions, but also operational and energy management aspects play a key role. For example, the productivity of the electric bus system collapses if the traction battery is empty before reaching the next charging station. A TCO analysis comprises relevant capital costs arising from owning a bus fleet: purchase of the bus, battery and charging infrastructure. The operational costs arise from energy as well as service and maintenance. Furthermore, each of the components (vehicle, battery, chargers) have their own service life (depreciation time) that has to be taken into account.

The basis of the methodology and approach on techno-economics and TCO is described in [1]. In addition to that approach, the present analysis adds several aspects relevant to the implementation of electric buses at system level, including the charging and energy management, operability and availability of the buses and the charging infrastructure, as well as aspects related to the service level and operational scenarios in the public transport system. Labour costs have not, at this point, been taken into consideration in the TCO.

In the analysis, the concept of service level is introduced. The service level here is understood as the fleet's capacity of transporting passengers over time. While diesel buses are proven technology with commercial availabilities at 98-99%, this is currently not the case with electric bus systems; real system availabilities of recent electric bus system implementations have been reported very scarcely. The PTA's and PTO's need reliance on the new technologies and solutions before large roll-out tenders can commence. Key aspects are availability, reliability and operability of the system. These need to be addressed in the TCO.

When replacing a fixed number of conventional diesel buses with fully electric buses, the number of electric buses needed to ensure the same service levels is assessed. There are several parameters that affect the number of electric buses and charging devices or charging points needed for the same service. These include the available driving range of the bus in between charging events and the subsequent time and place needed for charging during the day, availability of the electric buses for operation from vehicular technology perspective, and availability of the charging equipment for the buses. The characteristics of the bus line analysed also play an important role, especially the length of the line, topography, duty cycle, energy consumption per km, the load (number of passengers) and stopping frequency in each section of the line. The operational scenarios of the vehicles in terms of rotations, time schedules and available charging times can have a major impact on the fleet TCO. Each of the factors mentioned affect the number of vehicles and chargers needed for the service, and thus the total capital cost of the system in comparison with the diesel bus fleet.

4 Results

4.1 Simulation results

In this paper, simulations were performed to demonstrate the influence of different vehicle fleets. An electric bus pilot project has been going on in Helsinki for a few years [12], with fully electric buses operating on four different lines. Two of these lines were chosen for this analysis. Line 23 is about 9 km long, and it runs in the very city centre. Line 51 is also an urban line, but it is almost twice as long as line 23. Both lines have charging stations at both ends.

Statistical variation of the passenger amount, stopping frequency, stopping times, traffic flow and charging times was implemented based on data obtained from real bus operation. For instance, the stopping frequency depends on the time of the day, and in the simulations it was described by a normal distribution defined by mean values and standard deviations that varied throughout the day. Up to 50 days of operation was simulated on each line. Hence, the simulations represent the expected results of operating the lines exclusively with fully electric buses.

Two different types of vehicles were implemented. First, vehicles equipped with a down-sized LTO battery was analysed, and secondly, vehicles with a medium-sized NMC battery was used. The main parameters of the vehicles are shown in Table 1. The weights of the buses were slightly different, but except the batteries, the powertrains were identical. The maximum charging power also differed as the LTO battery can withstand higher charging powers than NMC. Different charging scenarios were analysed; charging at both ends of the line, and simulations with either of the chargers out of use.

The main results from the simulations are shown in Table 2. The average consumption of the two vehicle types are almost the same. The consumption of the bus equipped with LTO batteries is somewhat higher than the bus with NMC batteries, but the difference is rather small reflecting the fact that the buses have almost the same weight. In the simulations, the bus was required to have a battery state of charge level of at least 30% before every departure. The disturbance risk indicates the frequency at which disturbances occur having this requirement. On line 23, a total number of 7 buses are used, and as 50 days of operation were simulated, a total number of 350 bus days were analysed. Out of these, disturbances occurred only once in the simulations with charging only at the railway station, otherwise, there were no disturbances at all. In other words, the battery capacity is in both cases large enough to withstand an unsuccessful charging event or charger malfunction at either end of the bus line, and the bus has enough time to charge. Examples of the battery state of charge for one of the buses is shown in Figure 1. It can be seen that the bus occassionally arrives so late to the end bus stop that the charging time is too short for a full charge up to 80%. However, the safety margins are large enough, and the bus never runs out of energy.

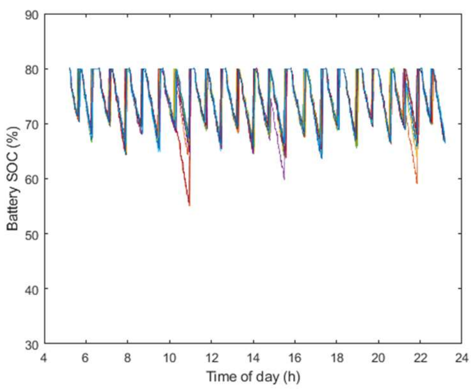
When electrifying entire bus fleets, queues to the charging station might occur. In the simulations, the charging queues were handled on a first come first served basis. With only seven vehicles on this bus line, the probability of queues to the charger were relatively low, and no intelligent optimization strategy is needed. For instance, when charging is available at both ends, a bus is expected to have to wait for the charging with a probability of 3%, and in these cases, the average queueing time has been only 14 s. Short queues like this has practically no influence at all on the bus operation. What is interesting to see, is that the queueing probability is even lower in case charging is available only at the railway station. The risk of queues are

Table 1. Main parameters of simulated vehicles

Battery chemistry	LTO	NMC
Battery capacity (kWh)	70	140
Vehicle mass (kg)	10 553	10 241
Nominal motor power (kW)	130	130
Nominal motor speed (rpm)	1 600	1 600
Maximum charging power (kW)	350	280

Table 2. Main simulation results on line 23.

Battery	LTO	LTO	LTO	NMC	NMC	NMC
Charging scenario	Both ends	Invalidi-säätiö	Railway station	Both ends	Invalidi-säätiö	Railway station
Average consumption (kWh/km)	0.97	1.00	0.99	0.95	0.95	0.94
Disturbance risk (%)	0	0	0	0	0	0.3
Charging queue formation (per bus per day)	0.03	0.02	0.003	0.10	0.13	0.065
Average queueing time (s)	14	16	5	31	49	47
Charger utilization, railway station (%)	17.4	0	28.0	14.6	0	37.7
Charger utilization, Invalidisäätiö (%)	20.7	28.6	0	32.1	40.6	0



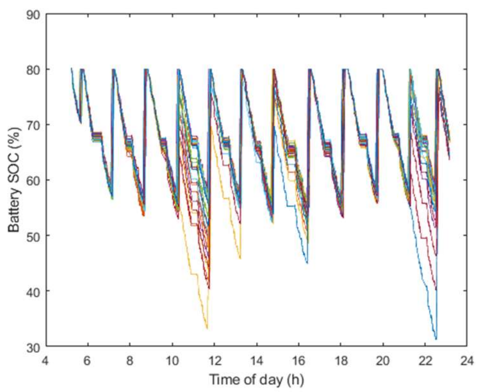


Figure 1. Battery state of charge on line 23 for mid-sized NMC-battery (left) and down-sized LTO-battery (right).

slightly higher for the NMC battery, simply because the charging time is longer. On the other hand, the NMC battery has larger capacity and therefore offers a better operational flexibility in case some charging is skipped. The more time a vehicle needs for charging, the higher is the risk that the next vehicle arrives before

Table 3. Main simulation results on line 51.

Battery	LTO	LTO	LTO	NMC	NMC	NMC
Charging scenario	Both ends	Malmin-kartano	Haka-niemi	Both ends	Malmin-kartano	Haka-niemi
Average consumption (kWh/km)	0.88	0.90	0.87	0.84	0.85	0.84
Disturbance risk (%)	0	21.5	29.2	0	0.8	1.3
Queue formation (per bus per day)	0.64	0.49	0.67	1.32	1.47	1.28
Average queueing time (s)	109	131	178	177	168	266
Charger utilization, Hakaniemi (%)	30.7	0	39.3	42.4	0	55.1
Charger utilization, Malminkartano (%)	29.5	38.0	0	41.3	55.2	0

the charging has ended. On average, the queueing time was less than a minute, and as the line is fairly easy with long turnaround times, the charging queues did not cause any disturbances.

The charger utilisation is another important aspect of the operation. The charger utilisation was calculated as the time the charger is occupied compared to the entire bus operation time, i.e. the night hours when there is no bus traffic were left out of the analysis. On bus line 23, the charger utilisation was notably higher at the Ruskeasuo end than at the railway station. This is because of the elevation profile of the line, travelling from the railway station to Ruskeasuo requires more energy than travelling in the reverse direction, and the bus will spend more time charging at Ruskeasuo.

The results on bus line 51 are shown in Table 3. This bus line is characterized by a slightly lower average consumption than bus line 23, but the line is much more demanding due to its length. As a consequence, the risk of disturbances is much higher. With both chargers functioning, no disturbances occurred, but when one of the chargers is out of use, the risk of disturbances with a small battery is very high. For instance, when charging only at Malminkartano, the average risk that a vehicle is not able to fulfill the given schedule is 21.5%. It should be noted, that this risk is highly dependent on the vehicle rotation and what departures a specific vehicle is planned for, and some of the vehicles were more prone to disturbances than others.

Bus line 51 is operated by 15 vehicles, hence, the risks for queues to the charging stations are higher than on bus line 23. On average, the bus equipped with an LTO battery queues for the charging station 0.64 times per day, while the bus equipped with an NMC battery queues 1.32 times per day in the case both charging stations are working. The average queueing time varies from a couple of minutes up to over four minutes. Some quite long queueing times were observed, and the bus equipped with an NMC battery was sometimes not able to charge at all when only one charger at each end of the line was available. However, the battery capacity is high enough for the bus to complete several rounds without charging, and the system disturbance risk was much lower than for the bus with the smaller LTO battery.

As compared to line 23, the chargers are more evenly used, and no significant difference can be observed. In the case of an LTO-battery bus, the chargers are used approximately 30% of the time, and up to 40% if one of the chargers are out of use. The corresponding numbers for the NMC-battery bus are 42% and 55% as these buses require slightly longer charging times. Based on the simulations, queues occur on a daily basis even though the charger is used less than half of the time. This is due to the fact that at maximum 15 buses are in operation simultaneously and the driving time from one end to the other is sometimes over one hour. The variation in driving time on this long line can be up to 20 minutes, so that if one bus is late, there is a rather high risk that the next bus arrives before the previous has finalised the charging. This holds particularly for the NMC-battery buses. In the simulations, no intelligent charging strategy is applied, instead, every bus charges until the battery state of charge reaches 80% if the schedule of that particular bus allows. As the NMC battery has a large capacity, it could be wiser not to charge the battery up to this level every time, but to allow the next bus to charge in case that bus has a lower state of charge. Intelligent fleet optimisation strategies could, thus, be very useful for this line.

4.2 TCO input

The main input parameters used in the TCO analysis are shown in Table 4. Current technological maturity level of electric buses (vehicular technology, including the battery systems) and the charging systems is not yet at the same level compared to conventional diesel buses, which are proven technology. This means that the availability of the system as a whole is somewhat lower for the electric buses and some extra vehicles are needed in the fleet to secure the same level of service. Secondly, electric buses are always dependent on the charging systems. What is more, the opportunity charging buses are more susceptible to disturbances in operation and availability than depot charging buses, because the number of charging events is larger and they are charged all through the operative day.

Diesel buses are assumed to have an availability of 98%, whereas the opportunity charging buses are at 90%. The opportunity charged e-bus concept is dependent on the automatic charging interface of the e-bus, the pantograph, which in this case was assumed to be roof-mounted on the bus. The charger availabilities are estimated to be 75%. This number comprises all reasons for which the electric bus cannot charge at a given time, for example, the charging point is occupied, the interface is not working, bus is badly positioned, the charger is down or doing self-diagnostics.

Additional input parameters included the following: diesel consumption 40 l/100 km, price of diesel 1 €/l, price of electricity including transmission 0.1 €/kWh. It should be noted that current electricity tariffs depend on both energy and power. Information on the exact tariffs were not available and will vary from city to city. Service and maintenance costs for electric bus systems was 0.13 – 0.18 €/km, depending on vehicle and charger availability. In other words the service and maintenance includes for electric buses both the vehicle and the charging system. Real data on the actual S&M costs on electric bus systems is scarce or unavailable. For the service and maintenance costs of the chargers, the following is assumed for annual S&M cost: small depot charger 200 €/year, large depot charger 500 €/year, opportunity charger 5000 €/year. Additionally, the estimated S&M costs are assumed here to depend linearly on the availability of the vehicles and the chargers. In other words, the more the systems are unavailable for use, they need to be serviced and repaired, therefore, their S&M costs are increasing. For diesel buses the service and maintenance cost was assumed to be 0.18 €/km.

4.3 Results of TCO

The results from the TCO of the fleets are shown in Table 5 and Table 6 for line 23 and 51, respectively. The approach of the analysis is that a service level in continuous operation is required. Therefore, in actual fact, more than nominal number buses are needed in the fleet. This is due to two factors. First, to get the number of buses needed for the service, the minimum fleet size for the service is divided by the availabilities of both the buses and chargers. Secondly, because the opportunity charging buses may have a range limitation in case charging is not available or the charging time is too short, more buses may be needed in the fleet since part of the buses need to be back at the intermediate parking or depot charging while the service is active. This gives the multiplier for fleet size due to limited range.

Lifetime cost of the traction battery is another important parameter in the TCO calculation as already highlighted in earlier sections. The cycle life of Li-ion batteries depends on the materials/chemistry used and the duty cycle and conditions in operation. Typical battery lifetime for each line and bus concept was estimated from the line and operation data and the energy consumption from simulations. The delta of state of charge (SoC) during operation on the line was obtained and, based on that, the cycle life and lifetime of the traction battery in years resulted in. Typical lifetimes of the batteries in the study were in the order of 5 to 12 years. There is significant uncertainty in the battery lifetimes used in the analysis, therefore, this part, although relevant as a methodical approach, is not accurate in terms of specific numbers. Therefore, the battery lifetimes reported here should be taken with care and indicative.

Table 4. Summary of the main input parameters to the TCO calculation.

	Electric bus - LTO battery	Electric bus - NMC battery	Diesel bus
Charger availability (average, %)	75	75	-
Vehicle availability (average, %)	90	90	98
Vehicle depreciation time (years)	14	14	10
Charging efficiency (including battery, %)	91	92	-
Charger depreciation time (years)	14	14	-
Battery capacity (kWh)	70	140	-
Battery maximum charging power (kW)	350	280	-
Battery price (€/kWh)	1200	400	-
Vehicle price (without battery, €)	360.000	360.000	220.000
Charger power (kW)	350 (opp.) 10 (depot)	280 (opp.) 20 (depot)	-
Charger unit price (€)	300.000 (opp.) 4000 (depot)	300.000 (opp.) 8000 (depot)	-

Table 5. TCO of opportunity charging electric bus fleet in comparison with diesel bus on Helsinki line 23, a fleet providing the service level equivalent to 7 diesel buses.

Fleet cost over lifetime	Electric bus - LTO	Electric bus - NMC	Diesel bus
Number of buses needed for service	7.8	7.8	7.1
Bus fleet cost	2 800 000	2 800 000	2 200 000
Number of batteries	10	19	
Total battery cost	811 493	1 081 648	
Charger costs	631 111	662 222	
Energy costs	729 249	692 178	2 681 280
Maintenance costs	1 037 339	1 037 339	1 231 2000
Total cost	6 009 193	6 273 388	6 112 480
Cost per bus in service per year	61 318	64 014	62 372

Table 6. TCO of opportunity charging electric bus fleet in comparison with diesel bus on Helsinki line 51, a fleet providing the service level equivalent to 15 diesel buses.

Fleet cost over lifetime	Electric bus - LTO	Electric bus - NMC	Diesel bus
Number of buses needed for service	17.9	16.7	15.3
Bus fleet cost	6 459 749	6 000 000	4 714 286
Number of batteries	18	21	
Total battery cost	1 507 275	1 165 686	
Charger costs	671 775	733 333	
Energy costs	1 478 769	1 380 522	6 048 000
Maintenance costs	2 070 017	2 070 017	2 777 143
Total cost	12 187 584	11 349 558	13 539 429
Cost per bus in service per year	58 036	54 046	64 473

5 Conclusions

The energy consumption and performance of a bus fleet was evaluated by means of simulations. The simulations were based on actual duty cycles, and measured data from buses in operation was used as an input. Statistical variation of several parameters was implemented in order to mimic the real behaviour of a bus system, and the performance during charger malfunction was evaluated. TCO analysis was performed based on the simulation results. Both bus fleets perform well on a short line, while the buses are prone to disturbances on the longer line particularly in the case where smaller batteries are utilized. Intelligent charging management strategies could help up the situation. Based on the TCO analysis, both bus types are competitive as compared to conventional diesel buses even though the number of buses have to be slightly increased due to the lower availability. As the reliability of electric bus systems reach the level of conventional systems, the total costs are expected to further decrease. Future work will concentrate on a seamless integration of the simulations and cost analysis in order to automatically optimize the fleet and its performance under realistic conditions. Data on the battery lifetimes and maintenance costs of electric bus systems will also contribute to a more accurate evalution.

Acknowledgements

This work was carried out within the EU-funded H2020 ZeEUS-project. The authors acknowledge the support by Helsinki Region Traffic.

References

[1] M. Pihlatie, S. Kukkonen, T. Halmeaho, V. Karvonen and N.-O. Nylund, "Fully electric city buses - the viable option," in *IEVC*, Florence, Italy, 2014. doi: 10.1109/IEVC.2014.7056145

[2] M. Xylia, S. Leduc, P. Patrizio, F. Kraxner and S. Silveira, “Locating charging infrastructure for electric buses in Stockholm,” *Transportation Research,* pp. 183-200, 2017. doi: 10.1016/j.trc.2017.03.005

[3] X. Wang, C. Yuen, N. Ul Hassan, N. An and W. Wu, “Electric Vehicle Charging Station Placement in Urban Public Bus Systems,” *Trans. on Intelligent Transportation Systems,* vol. 18, no. 1, pp. 128-140, January 2017. doi: 10.1109/TITS.2016.2563166

[4] N. A. El-Taweel, M. Mohamed and H. E. Farag, “Optimal Design of Charging Stations for Electrified Transit Networks,” in *ITEC*, Chicago, Illinois, 2017.

[5] M. Rogge, E. van der Hurk, A. Larsen and D. U. Sauer, “Electric bus fleet size and mix problems with optimization of charging infrastructure,” *Applied Energy,* pp. 282-295, 2018. doi: 10.1016/j.apenergy.2017.11.051

[6] A. Kunith, R. Mendelevitch and D. Goehlich, “Electrification of a city bus network - And optimization model for cost-effective placing of charging infrastructure and battery sizing of fast-charging elecctric bus systems,” *Int. Journal of Sustainable Transportation,* vol. 11, no. 10, pp. 707-720, 2017. doi: 10.1080/15568318.2017.1310962

[7] M. A. Gormez, A. Topcu and Y. Sozer, “Cost Optimization of and Opportunity Charging Bus Network,” in *ECCE*, Portland, Oregon, 2018.

[8] P. Sinhuber, W. Rohlfs and D. U. Sauer, “Study on Power and Energy Demand for Sizing the Energy Storage Systems for Electrified Local Public Transport Buses,” in *VPPC*, Seoul, Korea, 2012.

[9] M. T. Sebastiani, R. Lüders and K. V. Ono Fonseca, “Evaluating Electric Bus Operation for a Real-World BRT Public Transportation Using Simulation Optimization,” *Trans. on Intelligent Transportation Systems,* vol. 17, no. 10, pp. 2777-2787, October 2016. doi: 10.1109/TITS.2016.2525800

[10] T. Halmeaho, P. Rahkola, A.-P. Pellikka, K. Tammi and S. Ruotsalainen, “Electric City Bus Energy Flow Model and Its Validation by Dynamometer Test,” in *VPPC*, Montreal, Canada, 2015.

[11] M. Ranta, V. Karvonen, J. J. Potter, R. Pasonen, E. Pursiheimo, T. Halmeaho, P. Ponomarev and M. Pihlatie, “Method Including Power Grid Model and Route Simulation to Aid Planning and Operation of an Electric Bus Fleet,” in *IEEE VPPC*, Hangzhou, China, 2016.

[12] J. Laurikko, M. Pihlatie, N.-O. Nylund, T. Halmeaho, S. Kukkonen, A. Lehtinen, V. Karvonen and R. Mäkinen, “Electric city bus and infrastructure demonstration environment in Espoo, Finland,” in *EVS28*, Kintex, Korea, 2015.

[13] A. Agrawal, M. Kumar, D. K. Prajapati, M. Singh and P. Kumar, “Smart Public Transit System Using an energy Storage System and Its Coordination With a Distribution Grid,” *Trans. on Intelligent Transportation Systems,* vol. 15, no. 4, pp. 1622-1632, August 2014. doi: 10.1109/TITS.2014.2303501

[14] M. Jiang, Y. Zhang, Y. Zhang, C. Zhang, K. Zhang, G. Zhang and Z. Zhao, “Operation and Scheduling of Pure Electric Buses under Regular Charging Mode,” in *Int. Conf. on Intelligent Transportation Systems*, Maui, Hawaii, 2018.

[15] C. Yang, W. Lou, J. Yao and S. Xie, "On Charging Scheduling Optimization for a Wirelessly Charged Electric Bus System," *Trans. on Intelligent Transportation Systems,* vol. 19, no. 6, pp. 1814- 1827, June 2018. doi: 10.1109/TITS.2017.2740329

[16] A. Houbbadi, R. Trigui, S. Pelissier and T. Bouton, "Multi-objective optimization of the management of electric bus fleet charging," in *VPPC*, Belfort, France, 2017.

[17] D. Zhou, Z. Ren, K. Sun and H. Dai, "Optimization Method of Fast Charging Buses Charging Strategy for Complex Operating Environment," in *EI2*, Beijing, China, 2018.

Authors

Mikaela Ranta received the D. Sc. (Tech) degree in electrical engineering from the Aalto University in 2013. She is currently a research scientist at VTT Technical Research Centro of Finland, and her main research interests are related to simulations and optimization of electric vehicle systems.

Joel Anttila, M.Sc. (Tech) in automotive technology from Aalto University, Finland. Works as a research scientist in Digital Engineering team at VTT Technical Research Centre of Finland. Professional interest and proficiency in automotive electric powertrains, vehicle system simulations, analysis and software development.

Mikko Pihlatie, holds a D.Sc (Tech) from Aalto University. He works as a Research Team Leader, Electrical Powertrains and Storage at VTT Technical Research Centre of Finland. His current research interests include battery systems, electric vehicles and systems, and TCO analysis.

Ari Hentunen received the D.Sc. (Tech.) degree from Aalto University in 2016. He is currently a research scientist at VTT Technical Research Centre of Finland. His current research activities focus on the integration of battery storages into the distribution grids.

M.Sc. Marko Paakkinen is a Senior Scientist in the Electric Powertrains and Storage team at VTT Technical Research Centre of Finland. He holds a M.Sc. (Tech) degree from Tampere University of Technology, and has a career of over 20 years in the off-road vehicle industry. His experience includes control systems integration, electronics design and contracting and project management tasks. Mr. Paakkinen's current research activities includes project management and research tasks in various EU H2020 and Business Finland projects, related to electric vehicle charging, interoperability and standardisation.