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Evaluation of a Battery Electric Bus System Through Computational Simulations

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Summary

Battery electric buses are emerging in public transport operations. In addition to environmental benefits, battery electric buses have also been identified as economically competitive with conventional diesel buses. Although, battery electric bus systems require careful planning due to the novelty and set of restrictions entailed in the technology. The charging system particularly has to be designed and refined with great care, as the charging forms the backbone of battery electric bus operation. Under-sized charging system will render bus operations unreliable, especially in the case of unexpected disturbances. In contrast, over-sized systems lead to increased costs and cripple the economic potential of electric bus systems. An optimal system operates in a sweet spot, somewhere between the extremes. The technological novelty of electric buses means that the real-life references are scarce. Moreover, operational properties of bus systems can vary significantly making transferability difficult. Thus, computational simulations are one of the key utilities in the system planning. In this paper, a bus rapid transit (BRT) system with opportunity-charged double-articulated battery electric buses is simulated and evaluated with two different charging system options.

Keywords: BEV (battery electric vehicle), charging, mobility system, simulation

1 Introduction

Sustainability and environmental issues are key challenges for the modern societies in both global and local domain. One of the major contributors to CO_2 emissions is transport, which is mainly formed by road transport. For example in 2015 in the EU, road transport constituted about 73% of transport originated greenhouse gas emissions [1]. Electric powertrains are one of the most prominent solutions to reduce emissions as they offer considerably higher energy efficiency, less noise and no tail-pipe pollution. Electric vehicles are especially promising in fixed schedule heavy-duty applications such as city bus systems, where the limitations of single charge range can be eliminated by integrating charging to the duty cycle, for example through opportunity charging. Opportunity charging refers to charging the main traction battery of the vehicle with high power for a short time at the terminal or intermediary stops of the bus route. Furthermore, electric vehicle systems have already found out to be economically equal or better than conventional diesel bus systems when daily mileage is high but one round-trip is relatively short [2].

However, battery electric bus systems have limitations, which sets challenges for system planning and operation. As the single charge range of an electric vehicle is notably shorter than the range of a comparable conventional internal combustion engine powered vehicle, the charging becomes critical in the system. In order to match the service level of conventional bus systems, the charging system has to be able to dish out necessary amount of energy in short time and to be robust enough against unexpected disturbances and disruptions. System optimisation is required as an over-sized charging system leads to redundant costs and decreases the economic attractiveness of the whole system.

Battery electric bus technology is novel and even though the number of electric buses has increased worldwide, the operations have only been commenced for a relatively short time; mostly less than five years. In addition, there is variation in operational characteristics of bus systems, which can make transferability difficult. As an example, bus routes vary in length, elevation, commercial speed and passenger loads. Conducting practical experiments is expensive and it can be difficult to address the different operational fluctuations thoroughly. On the contrary, computational simulations can be used to experiment practically any type of vehicle with any type of conditions in any type of route. Thus, simulations can be used to agilely examine different scenarios, and hence, be used in the planning phase of a bus system.

The population in the city of Turku is expected to increase from about 190 000 to 250 000 residents over the next 30 years. Turku is planning [3] to introduce an electric mass-transit system to meet with the increased transportation demand in an environmentally conscious manner. A BRT-operated double-articulated battery electric system is regarded as one potential solution. However, due to the technological novelty, system specifications are not clear. Moreover, the system is currently in planning phase and the routes only exist on paper. This study analyses two opportunity-charged battery electric bus systems with simulation approach and introduces issues that should be considered in the planning of an electric bus system. The viability of the systems are examined from operational point of view and sensitivity to charging malfunctions is demonstrated by turning of respective charger power units.

2 Simulation method

A geographical information system (GIS) based simulation tool was used to produce data for the electric bus system analysis. The simulation method used in this study has been used previously in [4] and is validated in [5]. The base tool is comprised of two modules, one for route design and one for vehicle simulations. The route design module is used to create routes from a set of coordinates, while, the vehicle simulation module is used to perform energy flow simulations on the route with a vehicle model. In addition to the energy flow simulations, different simulation parameters can be set for the simulation in the vehicle simulation module, for example, traffic volume(s), location and number of bus stops, charging stations and traffic light stops.

In the energy flow calculations, speed profile for driving is created dynamically by utilising a control loop feedback mechanism to match vehicle speed to the reference set speed at each simulation frame. In essence, the driver model is a proportional-integral-derivative (PID) controller that adjusts the motor torque in order to match the speeds. The set speed is calculated based on the route characteristics, bus schedule and pre-set driving tasks, such as stopping to bus stops. The simulations are calculated on longitudinal axis, thus, the effect of curves in the route are taken into account by scaling the set speed accordingly. Moreover, the set speed has a time derivate (acceleration) limitation as an additional limitation that prevents too harsh accelerations or decelerations.

2.1 Route models and operation

The analysis was conducted on the main planned route of the four routes presented in the electric mass-transit plans [3] of the city of Turku. The route runs from Varissuo to Raisio and back. The outline of the bus route shape (shown in Fig. 1) was created on a map layer based on preliminary plans of the city of Turku. Route curvature, segmentation and segment lengths were obtained from the route shape. Moreover, elevations used to calculate slope for each segment of the route was fetched through Google Maps Elevation application programming interface (API). Some sections were manually tweaked, for example, to include bridges or bus stops that do not currently exist.

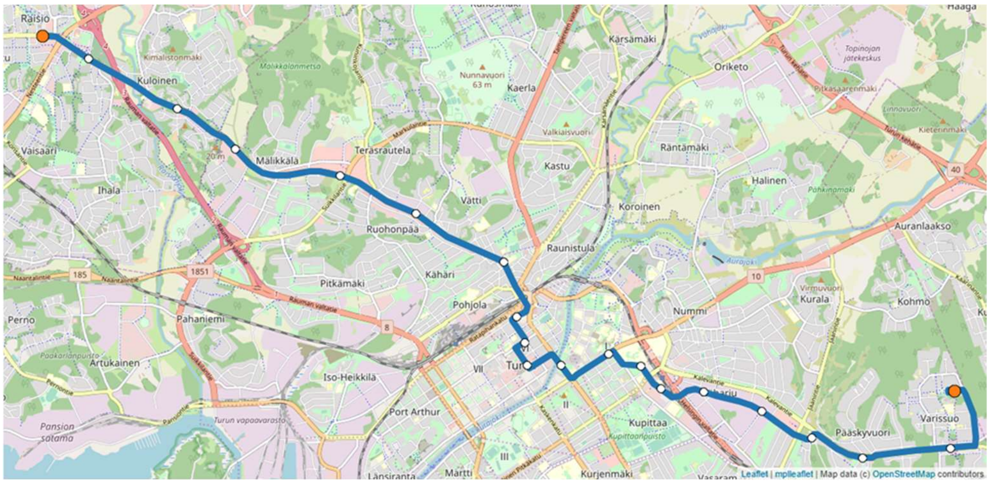

Figure 1: Route shape of Varissuo-Raisio on OpenStreetMap layer. End stops are marked with orange markers and intermediary stops with white markers.

Varissuo-Raisio route is 14.7km long in one direction and has 20 bus stops. Stopping times at each bus stop were set according to Ramboll in [6], which estimated the stop times based on assumed passenger flows at the bus stops. The stopping times are presented Table 1. Higher passenger count is expected at the bus stops located central area of the city, while less passengers enter and exit the buses at outskirts of the city. The route was operated in a fast-BRT method, in which, the buses have own two-way corridor separated from other traffic. Thus, the buses are completely unaffected by surrounding traffic. Moreover, the buses are expected to have priority at stoplights, thus, the effect of stoplights was neglected. The speed limits for the buses varied between 20 and 30 km/h in narrow inner-city parts to 40 km/h in outer-city and 60 km/h outside the residential areas. The planned driving time from one end to another is expected to be about 35 minutes. Turku has set a target for operational headway to seven and half minutes [3]. The operation was simulated with twelve buses, which results in 6 minutes of turnaround time at Raisio and 14 minutes at Varissuo.

Table 1. Stopping times at bus stops

	Stop time (s)
Varissuo Pelttarinkatu	15
Varissuon liikekeskus	15
Hurttivuori	15
Laukkavuori	15
Itäharju Tierankatu	15
Itäharju Karjakatu	15
Kupittaan kampus	25
Sairaala	20
Yliopisto	20
Tuomiokirkko	20
Kauppatori	25
Puutori	20
Matkakeskus	25
Raunistulan koulu	15
Ruohonpää	20
Länsikeskus	15
Raisio Mälikkälä	15
Raisio Kuloinen	15
Raisio kaupungintalo	15
Raisio keskusta	15

2.2 Vehicle model

The vehicle model used in the study was based on a base model validated in [5]. Vehicle specifications of the base model were adjusted to correspond an opportunity-charged double articulated battery electric bus. The vehicle model specifications are listed in Table 2.

Table 2. Vehicle model specifications

	Value
Length	24 m
Gross weight	35 t
Battery type	LTO
Battery capacity	120 kWh
Nominal motor power	230 kW
Nominal motor speed	1 600 RPM
Frontal area	6.2 m^2
Drag coefficient	0.4365

2.3 Charging systems

The simulations were conducted with two different high-power charging systems (see Fig. 2). Both systems had same total power output of 600 kW at both end stops. However, system #1 had four power units with 300 kW charging power each, while, system #2 had two power units with 600 kW output each. In system #2, two buses can charge at a time with full 600 kW, whereas in system #1 four buses can charge at same time but with lower power of 300 kW. In case there are more buses at a charger than there are free nodes, the buses start forming a queue to the charger. The buses take on charging in the arriving order, no additional charging management was implemented.

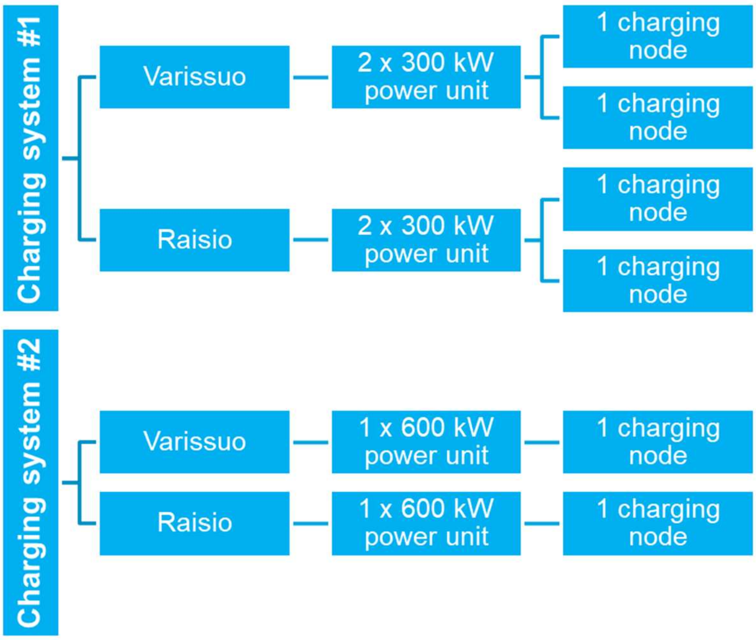

Figure 2. Charging systems utilised in the simulations

The vehicles were charged to 80% battery state of charge (SOC) as high-power charging is not suitable for a full-charge. Moreover, it must be noted that the total charging power over the whole charging event is less than the maximum charging power of the charger unit. The transient charging power is tied to SOC of the battery as the internal resistances of the battery increase with high SOCs. In the simulations, the effective charging power was set to ramp down linearly after 60% SOC was reached. Fig. 3 illustrates the change of effective charging power at the battery against battery SOC with 300 kW power unit.

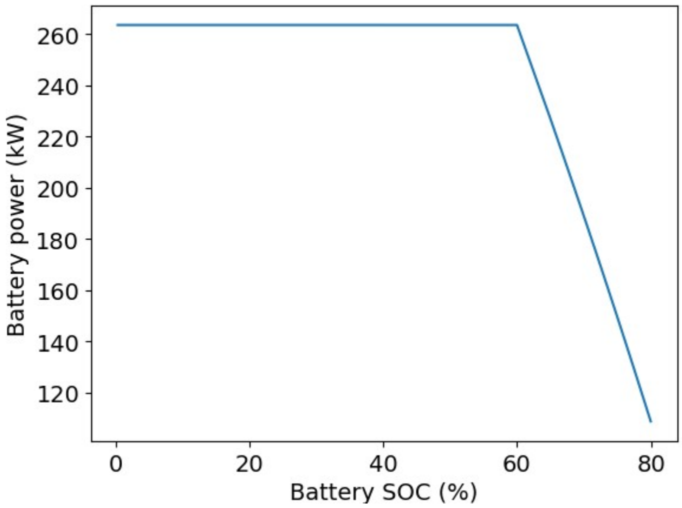

Figure 3. Simulated charging power against battery SOC with 300 kW power unit

3 Simulations and results

The simulation cases are listed in Table 3. In total, six simulation cases were executed. Bus fleet of twelve vehicles was simulated with two different charging systems. Additionally, the sensitivity and robustness of the system was tested by disabling one power unit at a time. The bus system validity was evaluated by monitoring the battery state of charge (SOC) levels of the simulated buses and charging time requirements at the end stops.

Table 3. Description of simulation cases

CASE	Charging system	Total charging nodes	Available charging nodes	Power unit malfunction
1.1	#1	4 x 300 kW	4 x 300 kW	-
1.2	#1	4 x 300 kW	3 x 300 kW	Raisio
1.3	#1	4 x 300 kW	3 x 300 kW	Varissuo
2.1	#2	2 x 600 kW	2 x 600 kW	-
2.2	#2	2 x 600 kW	1 x 600 kW	Raisio
2.3	#2	2 x 600 kW	1 x 600 kW	Varissuo

3.1 Simulation results with charging system #1

Simulation results for charging system #1 are presented in Fig. 4. Based on the results, the charging system #1 is capable to sustain the twelve-bus system for extended time when there is no disruptions in the charging system. However, the slight decrease of battery SOC implies the system may be rather sensitive to operational delays, which is not advisable in operational point of view. Bus operation tends to have unexpected delays, which could endanger operational reliability in this case.

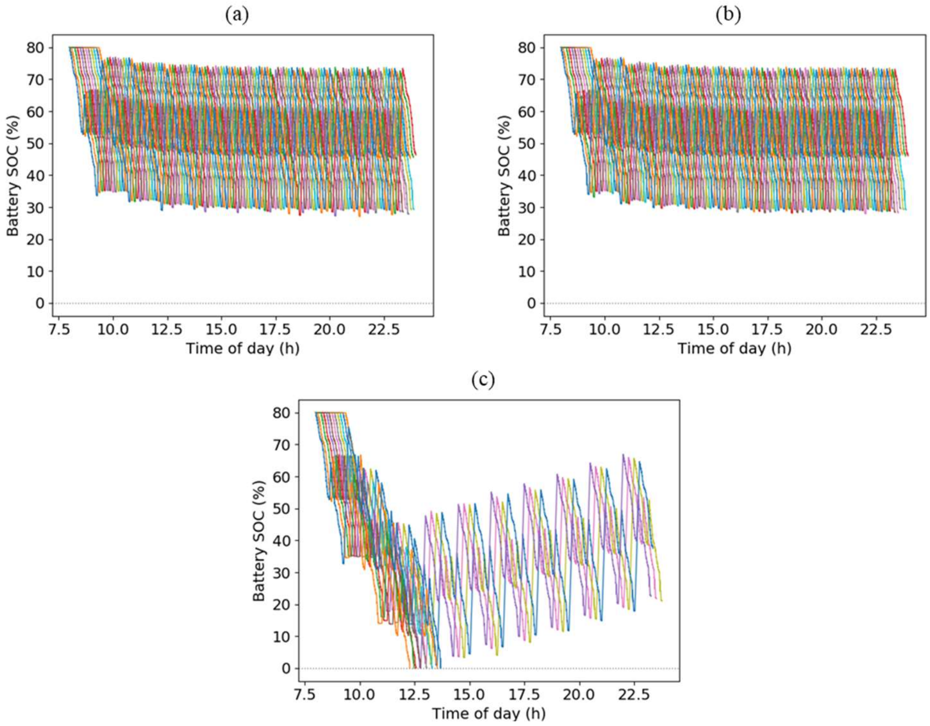

Figure 4. Charging system #1, where (a) refers to case 1.1 with fully operational charging system, (b) to case 1.2 with power unit malfunction at Raisio and (c) to case 1.3 with power unit malfunction at Varissuo

On the contrary, the system is some-what resistant to power unit malfunctions. In case a power unit malfunctions at Raisio, normal operation is still possible to be maintained. As the operation in case 1.2 was nearly identical to 1.1, it indicates the end stop has surplus in charging capabilities. However, the surplus becomes advantageous in case power unit malfunction occurs at Varissuo. In case 1.3, normal operation is not feasible for extended time. There appears to be about four hours of time before the operation is interrupted. After the four hours, however, partial operation it is still plausible. The system was still able to maintain operation for four buses in the simulations.

3.2 Simulation results with charging system #2

Simulation results for charging system #2 are illustrated in Fig. 5. When the system is fully functional, it appears to be more resilient against operational delays compared to the system #1. Battery SOCs of the buses are kept on constant high level, above 40%, for the whole day. The more powerful charger is almost able to charge the buses to operational target charge of 80% at both ends. Only at Raisio, where turnaround time is less, the buses were charged to about 75% SOC.

However, system #2 was very sensitive to power unit malfunctions. A power unit malfunction at either end will lead to complete halt of operation. The system was slightly more resilient when the malfunction occurs at Raisio. There was about four hours of time before the first bus stopped operating. In case of Varissuo power unit malfunction, the first bus was out of order in about three hours. None of the buses was able to continue operation and full stop of service resulted in.

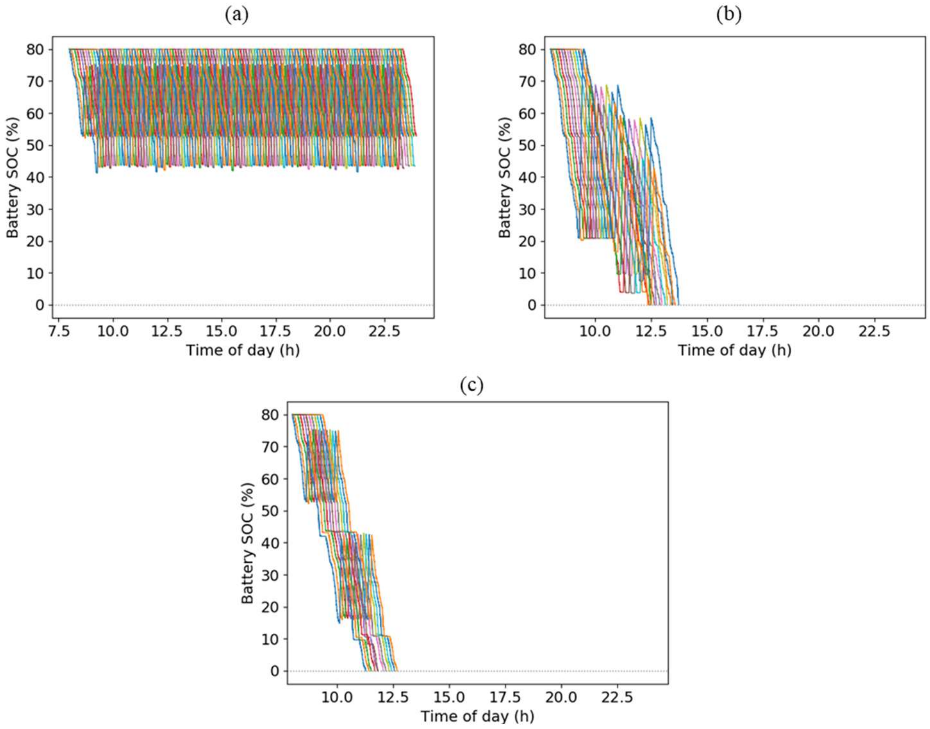

Figure 5. Charging system #2, where (a) refers to case 2.1 with fully operational charging system, (b) to case 2.2 with power unit malfunction at Raisio and (c) to case 2.3 with power unit malfunction at Varissuo

4 Conclusions

To meet with future demand for high volume public transportation, city of Turku is considering two options; either a traditional tramway system or a double-articulated battery electric bus system. This paper used a validated simulation method to analyse two system configurations of the hypothetical full electric bus system based on the mass transit plans of Turku.

The bus system consisted of one BRT-route operated with 7.5-minute headway, and thus, resulting in operating fleet of 12 battery electric buses. The analysis was conducted with two charging systems with same overall charging power but with different power unit setup. One charging system was divided into four power units that have lower maximum power output of 300 kW, while the other system had only two power units but with high power output of 600 kW. Hence, the first system is able to charge multiple buses at the same time in one location, while the second system can only charge one bus at a time.

Both charging systems were able to maintain normal operations when the systems were fully operational. Although, the system with higher node output gave buses more excess time at the end stop before next departure. As a result, the system with had more resilience against operational delays compared to the other system with lower power output at the charging nodes. Contrarily, the high node power system was much more sensitive to charging system malfunctions. The sensitivity to system malfunctions was addressed by shutting down power units at both ends of the route at a time. It turned out the lower power system was able to continue normal operation in case the power unit malfunction occurred at Raisio. If a power unit at Varissuo malfunctions, the system was able to maintain normal operation for slightly over four hours and partial operation with at least four buses afterwards. Power unit malfunctions with the high node power system resulted in faster operational interruptions in both cases and partial operation deemed infeasible. With both charging systems, Varissuo formed the most critical point for charging. Bulk of the charging happens in Varissuo due to the longer turnaround time. In Raisio, turnaround time for a fleet of twelve buses is too short for a full-charge, even for the 600 kW power unit.

This study points out the importance of the charging system in the design of opportunity charged battery electric bus systems. Even systems with same total power output but with different setups can have widely deviant characteristics. Charging systems with parallel power units prove to be more reliable against charging system related issues. However, high node power provides more flexibility against delays evident in city bus operations. In the end, an opportunity charged bus system should take into account both aspects.

This study focused on operational performance of the two fixed systems. Further analysis would be in place with more comprehensive view. For example, how would the operation differ with bigger fleets, which would permit more charging time for individual buses and how would the changes in the system affect economical aspects. Proper life cycle cost analysis should also take in account additional operational effects, such as battery degradation. In addition, the system could be tested with alternative powertrain options, for example with different battery options. Modular chargers, which permit dynamic power distribution to individual nodes, are emerging on the markets. This kind of technology could have potential of combining benefits of both systems analysed in this study.

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