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Resilience Estimation for On-route and Depot Battery Electric Bus Charging: Methodology and Insights

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Executive Summary

As Battery Electric Buses (BEBs) become one of the main drivers to reduce transit GHG emissions, transit agencies seek to understand how resilient the service should be in face to failures of the charging system. This paper presents a methodology to estimate the resilience of the service provided by a fleet of BEBs when the charging system fails, or the charging efficiency drops for both on-route and in-depot charging. The methodology utilizes BOLT (Battery Optimization Lifecycle Tool), WSP's proprietary modelling tool, to simulate the operation of BEBs given specifications on the service design (bus blocks) and the BEB charging technology response to failures. BOLT has been used internationally to validate service design for BEB operations and determine preliminary design requirements for on-route and depot chargers. The methodology compares a baseline scenario to stress-test scenarios, covering multiple on-route and depot charger failures. Preliminary results show that a complete whole-day failure of all chargers at one of the on-route locations may lead to a failure to deliver the service 30% of the blocks selected for electrification.

Keywords: BEV, Infrastructure, Reliability, On-route Charging, Depot Charging.

1 Introduction

Public transportation operations play a key role in the decarbonization and improvement of air-quality within the transportation sector. In this context, Battery Electric Buses (BEBs) are one of the main technologies paving the way towards zero-emission operations. There are numerous deployments of BEB around the world, many of which are testing their adaption capabilities to the everyday service [1]. The resilience of a BEB charging system refers to its ability to withstand and recover from disruptions caused by various factors, such as power outages, equipment failures, traffic congestion, and weather conditions. A resilient charging system can ensure that the buses are charged on time and can operate as planned, even under adverse conditions. Therefore, estimating the resilience of on-route and depot BEB charging systems is critical for ensuring their reliable and efficient operation.

While on-route and depot charging infrastructure has been operational for BEBs, many unknowns exist surrounding the resilience of this equipment and practical risks that may arise while delivering transit operations. In the context of this study, based on Dehghani et al. [3], resilience is defined as the number of failing chargers up to which the fleet of BEB can maintain the normal delivery of the service. The synchronized operation of the on-route and depot charging infrastructure should be resilient to scenarios where the normal execution of the schedule may be affected by the failure of one or multiple chargers, and where the interruption of the charging capacity may last from a couple of hours to a full day.

This paper focuses on the case of Vancouver, Canada, and the transit electrification efforts lead by TransLink, the regional transportation authority. TransLink's 2022 investment plan includes adding more than 500 BEBs to their fleet by 2030 [2]. TransLink is in the process of procuring 57 BEBs which will operate a variety of routes in Metro Vancouver and will be supported by a combination of on-route-charging and depot charging.

The contribution of this paper is the methodology to assess the resilience of the planned BEB charging infrastructure and its subsequent impact to daily operations when facing major failures affecting one or multiple on-route and depot chargers. The methodology compares a baseline scenario with several stress-test scenarios, using WSP's proprietary tool BOLT, to simulate the operation of the 57 BEBs over their assigned blocks. The following three sections include a brief description of the methodology and insights as to operational risk.

2 Methodology Set-up

The methodology proposed in this paper requires inputs on various aspects including the on-route charger locations, the number of chargers, the operating conditions, the schedule assigned to the fleet, among others.

2.1 On-Route Charger Locations and Number

The potential on-route charger locations and the maximum number of chargers per location are provided by TransLink based on results of internal planning studies. These studies considered various factors such as bus route, traffic flow, passenger demand, and energy supply. The number of chargers per location is assumed to be determined based on the estimated charging demand and the available power capacity at each location.

The number of chargers per location are critical factors that can significantly affect the resilience of the BEB charging system. If the number of chargers at a given location is insufficient to meet the charging demand, the buses may experience delays or disruptions in their operation, which can reduce the overall system performance. On the other hand, if the chargers are located at suboptimal locations, the buses may have to deviate from their planned routes, which can increase the travel time, energy consumption, and the number of buses required to keep the given transit service frequency.

TransLink has considered 5 locations for the On-Route chargers. Table 1 shows the counts of fast chargers by location. Further details related to the considerations behind the location and number of on-route chargers are beyond the scope of this paper.

Table 1: Location and count of the maximum number of on-route chargers per location

Location	Number of on-route chargers
1.	*3*
2.	*2*
3.	*3*
4.	*1*
5.	*1*

2.2 Operating Conditions

The operating conditions described in the paper correspond to a typical weekday operation of a BEB fleet under relatively high energy demand conditions. Specifically, the following criteria are considered:

- Temperature of 0 ºC: This represents a relatively cold weather condition, which increases the energy consumption of the bus due to the need for heating the passenger compartment and the battery [4].

- Diesel auxiliary heating system aboard the bus: This is a common feature of many BEBs, which uses a diesel-fuelled heater to provide additional heat to the passenger compartment and the battery during cold weather conditions. This system can consume additional energy and emit pollutants, which can affect the overall energy efficiency and environmental performance of the bus [5].
- Buffer state-of-charge (SOC) of 20%: This refers to the minimum SOC level required to ensure safe and reliable operation of the battery. The buffer SOC is typically set above the minimum SOC level to provide a margin of safety against unexpected events such as energy losses or system failures. In this case, the buffer SOC is set at 20%, which is relatively conservative but can help ensure the longevity and performance of the battery [6].

These conditions can affect the charging demand, energy consumption, and system performance, which can in turn affect the optimal charging strategies and the system resilience. Therefore, it is important to carefully consider the operating conditions during the design and planning of the BEB charging system.

2.3 BEB Service Simulation

The schedule selected for simulation corresponds to a weekday schedule of Translink's GTFS data [7]. In this paper WSP's proprietary BEB simulation software kit, Battery Optimization Lifecycle Tool (BOLT), is utilized [8]. BOLT is used to predict the performance of the 57 BEB operating over the service assigned, and estimates the daily electrical energy usage. The simulation software estimates the impact of factors such as the battery chemistry, passenger loading, route topography, scheduled speeds, air conditioning and heating load, and charging scenarios (on-route vs. in-depot).

BOLT predicts the changes of battery SOC depending on charging modes (on-route and depot) throughout the course of a day of operation. BOLT modelling results indicate operational impacts of BEBs, and energy requirements including peak power demand and total daily energy demand.

2.4 Charging Rates

For all scenarios, the nominal power for on-route charging is set-up at 450 kW. The docking and connection time has been assumed 1.5 minutes, based on the previous experiences of the agency. Additionally, charging events are scheduled to take place when the bus's schedule provides idling time (also called recovery time) at the location for more than 4 min. Furthermore, it has been assumed that only 70% of the recovery time is utilized for charging.

For depot charging, the nominal power considered for each charging station is 180kW, with the option of parallel charging. Parallel charging is the capability of a charging station to split the charging rate in equal values over the dispensers connected to the charger and is controlled by charging management software. The dispensers to charging station ratio considered is 3:1. This means that one charging station feeds 3 dispensers. Under the parallel charging mode, if there are more than one bus connected, or more than one dispenser is being utilized, the charging rates splits 60 kW equally for all three dispensers. If there is only one dispenser in use, the charging rate is reset at 180 kW.

2.5 Battery Capacity and Charging Constraints

The battery capacity for the BEBs is set at 550 kWh. A discharge efficiency of 0.95 is assumed for the battery to account for battery loses. Therefore, the effective battery capacity considered is 517 kWh.

To account for constant current and constant voltage charging modes, two different charging rates are assumed depending on if the SOC is below or above 0.85. When the dispensers are operating at 60 kW, it is assumed that the charging rate for a SOC ≤ 0.85 is equal to 0.90 kWh/min. For SOC > 0.85, the charging rate drops to 0.46 kWh/min. When the only one dispenser per charger is connected and charging (Charging power per dispenser is 180 kW), it is assumed that the charging rate for an SOC ≤ 0.85 is equal to 2.70 kWh/min. For SOC > 0.85, the charging rate drops to 1.39 kWh/min. These charging rates include efficiencies of the charger and the upstream distribution system.

3 Methodology

The objective of the tool developed is to conclude on the impact of charger infrastructure failure and charging efficiency on transit service delivery. The tool analyses two scenarios: a baseline scenario and a stress-testing scenario. The baseline scenario is representative of the normal operations of battery Electric Buses over a transit schedule. The stress-testing scenario is configured to evaluate the resilience of the charging system when experiencing a charging failure.

3.1 Baseline Scenario

The baseline scenario includes three stages: the service selection, the baseline on-route charging schedule modelling, and the depot charging schedule modelling.

3.1.1 Service Selection

The service selection is a procedure conceived to select service for the 57 BEBs. The service is defined by the number of blocks the BEBs will be completing during a full day of operation. A block is a sequence of revenue/non-revenue vehicle trips within working duty. For the purpose of this paper, Each BEB is assigned one block. Therefore, the selection of the service consists in choosing 57 blocks for the 57 BEBs. The blocks chosen correspond to the weekday service. The procedure includes several steps:

1. Selecting only the service that is based at the garage of interest.
2. Discarding the service assigned to buses other that the 40-foot type.
3. Selecting the service that could be necessarily electrified with both on-route and depot charging
4. Completing the service for the 57 buses with blocks that could work without the need of on-route charging.

3.1.2 On-Route Charging Schedule

The procedure employed to determine the charging schedule includes the following steps:

1. Exclude instances with recovery time of less than 4 minutes.
2. Subtracts 1.5 minutes to selected layover to account for docking and departure
3. Calculate the charge time based on SOC of BEBs when arriving to charging locations and the charging rate that varies depending on the SOC.
4. The buses connect on a first-come first serve (FIFS) basis. This assumption helps avoiding unrealistic complex operations in sites with limited visibility for fleet management.

3.1.3 Depot Charging Schedule

At the depot, it is assumed that all BEBs have access to a dispenser. During the evening hours, when most of the buses arrive, the nominal power at the dispensers is set to 60 kW, following the parallel charging mode. When a portion of the fleet achieves full charge in the early morning hours, the power supplied by BEB may increase to 180 kW, depending on the distribution of the dispensers to buses. For the purpose of the simulation, it has been assumed that all buses throughout the charging window are dispensed 60 kW. Finally, it is assumed that a bus starts charging one hour after its arrival (service and maintenance) and that a charger is available at that time.

3.2 Stress Testing Scenario

The stress testing scenario design includes three stages: depot charging stress test, on-route charging stress test, and charging efficiency drop test. The intent is to stress test the charging system at each site as well as the garage charging system to simulate different systemic risks.

3.2.1 Depot Charging Stress Test

Under this stress test scenario all the chargers at the depot are down. The buses skip a night charge entirely and partially. The purpose of this test is to find the minimum SOC that the buses require to start their day at and still be able to complete their runs.

3.2.2 On-route Charging Stress Test

Under this stress test, two test cases are considered:

1. Stress-test per location. To limit the number of tests to run at each on-route location, the test procedure follows the steps listed below.
    a. One charger is down all day long. If none of the blocks are affected, continue to the next step; if at least one block is affected, jump to test number 2.
    b. Two chargers are down during all day.
    c. All chargers are down: during the morning peak, during the afternoon peak and the whole day.
2. All the on-route chargers at the 5 terminal locations are down

For the purpose of the study, the morning service peak is assumed to happen between 6 am and 9 am. The afternoon service peak happens between 3 pm and 6 pm.

3.2.3 Charging Efficiency Drop

This test is intended to simulate a reduced charging efficiency due to equipment failure, poor alignment or caused by weather conditions. A reduced charging efficiency will result in lowered SOC at the depart. In this test the charger efficiency considered are nominal efficiency (some manufacturers place this efficiency at ±95%), 80%, and 50% for all chargers at on-route terminals and all events during a day of operation.

4 Insights Baseline Scenario

The insights on the baseline model are summarized in the paragraphs below.

4.1 Service Selection

The distances travelled per block of selected service for the simulation are shown in Figure 1. The average distance for the blocks selected is 277.5 km.

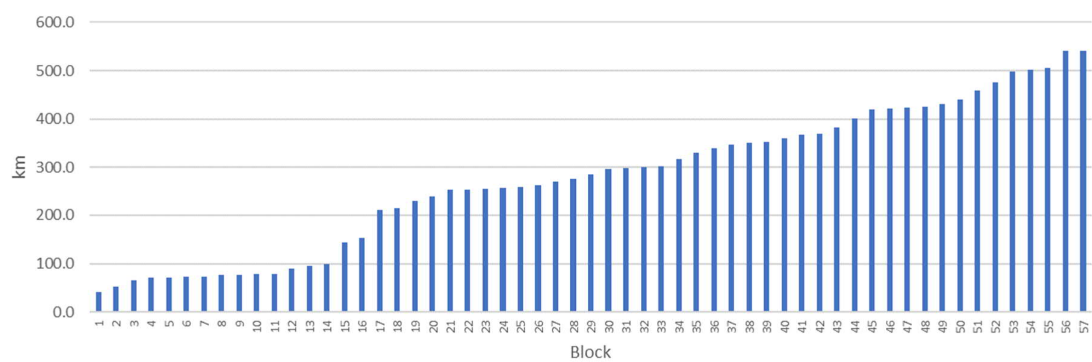

Figure 1 Distance Travelled per block

Some insights into the baseline model are:

- Considering the BOLT simulation, the range of the 550-kWh given the constraints described in section 2, is 258km. this means that the on-route charging is extending the number of blocks that can be completed from 28 to 57. Or extending the range supported to 541 km.
- Figure 1 demonstrates the importance of on-route charging for the delivery of the service configured by the 57 blocks

4.2 On-Route Charging

The recovery time used for charging purposes is illustrated in Figure 2. Figure 3 shows the total time dedicated to charging at on-route locations for each one of the blocks selected. Some of the key takeaways from the baseline on-route charging model are:

- Based on Figure 2, BEBs will need to utilize on average 54% of the recovery time per day to charge and be able to successfully complete their daily runs without running out of battery.
- According to Figure 3, the average total time dedicated for charging in a day is 64.15 minutes.
- This is approximately 8% of the average operation time of the bus estimated from the simulation at 13 hours per day.
- At least 9 out of the 57 blocks, the 9 right-most blocks in Figure 2, utilize more than 80 % of their recovery time per day for charging purposes.
- Therefore, these 9 blocks (15% of the total service selected) are the ones that would be the most impacted by failures on the charging infrastructure or service delays.

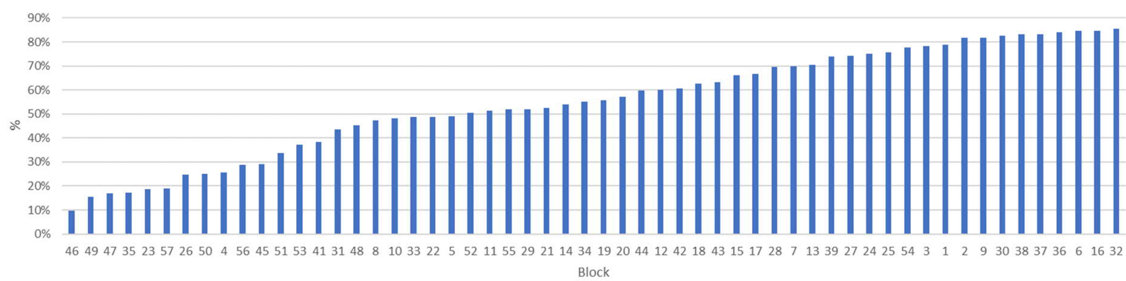

Figure 2 Percentage of recovery time used for charging events for each block

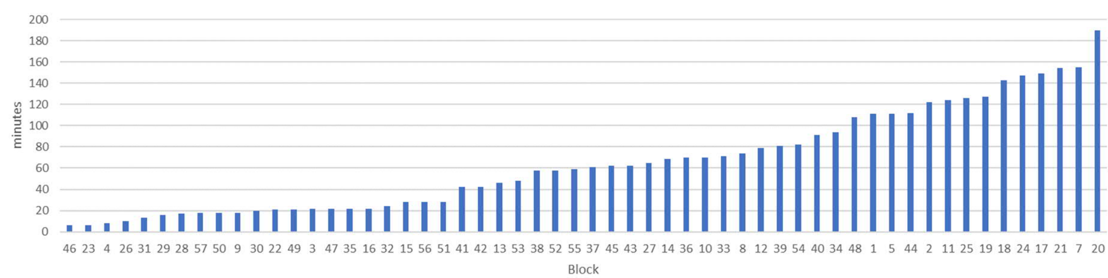

Figure 3 Total time dedicated to charging events in on-route locations per block

4.3 Depot Charging

The total power demand as a function of buses connected and charging at the depot is shown in Figure 4. Some key findings are:

- The daily energy requirement is 25 MWh with a peak demand at 1.98 MW.
- The average SOC after a day of operation when arriving to depot is 58%.
- The buses parked in Figure 4 (blue line), shows that after 2am the number of buses parked increases, but in comparison, the peak load stays levelled. This represents the situation where early in the morning next day BEBs park, connect, and start charging while the BEBs that have already a full charge stay connected but not charging.
- Moreover, it's important to note that the charge rate of the chargers depend on the vehicle SOC, as such the peak load doesn't necessarily correspond to the moment when all chargers work simultaneously.

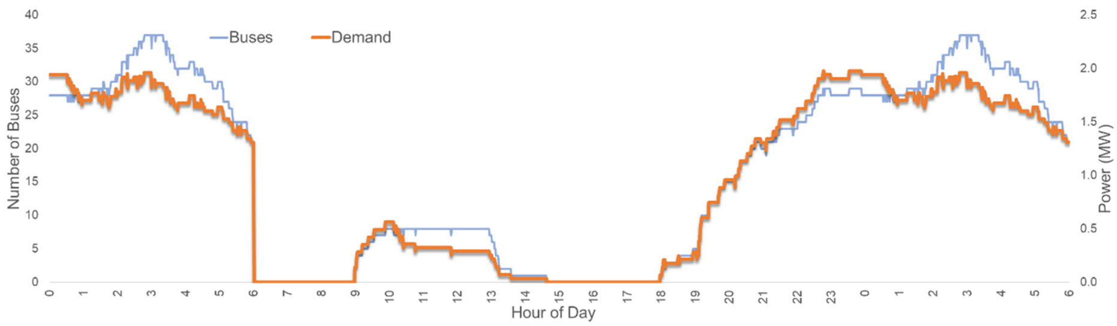

Figure 4 Power demand and count of buses connected at the garage

5 Stress-Testing Results

The results from the stress-tests are summarized in the paragraphs below.

5.1 Depot Charging Stress Test

5.1.1 All chargers are down

To simulate all the chargers down, it is assumed that the average SOC to start their service is 58%. This corresponds to the average SOC when the BEBs arrive to the Depot at the end of the weekday service. Consequentially, this would be the average SOC for the next day at the depart if none of the BEB at Depot had access to charge due to a blackout. The following are key observations from this test:

- At least 45 out of 57 blocks can still work (the service delivered fails for 12 blocks). As shown in Table 2, compared to the baseline, the distance travelled, kWh consumed and time of operation for the blocks in this scenario are lower because less energy is stored onboard the batteries at the beginning of the day and more blocks are unable to run their scheduled service.
- The blocks that finish the day with a SOC lower than 58% are at risk of failing during the day. At least 26 blocks fall below this average at the end of the day. A resilient system with planned redundancies could be put in place in case of full overnight blackout. Such system should be able to supply at least 6 MWh under the charging constraints assumed in this paper.
- If the blackout persists for 2 consecutive nights, preliminary analysis shows that none of the blocks will be completed during the second day of operation

Table 2 : Comparison of average key performance values between the Baseline and the Depot Charging Stress Test when all chargers are down

Parameters	Depot Charging Stress Test	Baseline
	Avg. daily value (over all blocks)	Avg. daily value (over all blocks)
Distance travelled (km)	255	277
kWh consumed	404	426
Hours of operation	12.2	13.2

5.1.2 BEBs with partial Depot charge

To simulate partial Depot, it is assumed that the average SOC to start their service is 80%. The following are key observations from this test:

- None of the blocks failed to deliver the service.
- This implies that on the one hand, a battery size reduction is possible. On the other hand, the 20% safety buffer for operation increases the resilience over partial failure of the charging infrastructure at the Depot.

- If the average SOC to start operation the next day is set at 79.5 %, some of the BEBs start to fail to complete some of the blocks.

5.2 On-route Charging Stress Test

Following the methodology presented in section 3.2.2, the sections below illustrate the results of the charging infrastructure stress-tests.

5.2.1 Stress-test per location

To illustrate the effects of the failure at each location, the stress-test for location No. 1 is analysed in detail below. The analysis for each of the locations is then summarize in the section 5.2.1.2.

5.2.1.1 Stress-test at location No. 1.

As presented in section 2.1, this location assumes that there are 3 fast chargers available. The items below illustrate the stress-test analysis steps:

Baseline utilization: The baseline charger utilization of the on-route charger at location No. 1 is shown in Figure 5. The daily usage of energy at this location is 2 640 kWh.

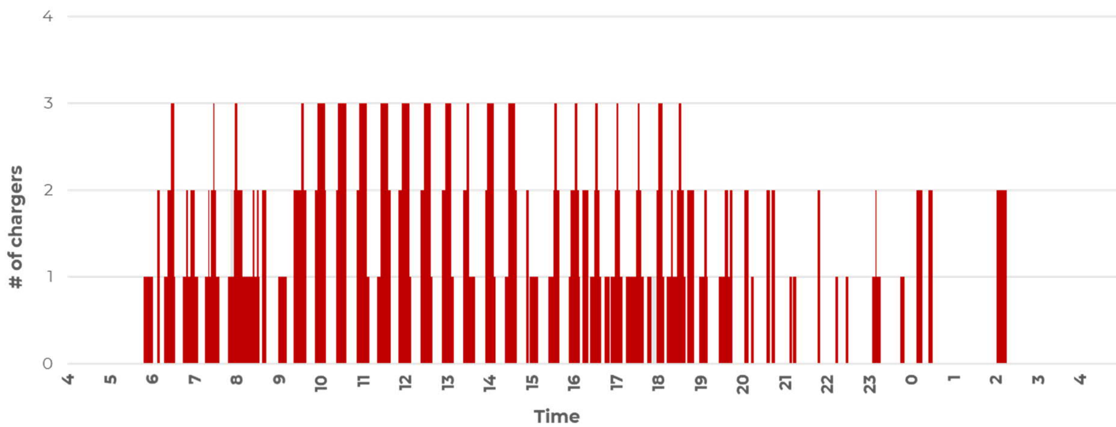

Figure 5. Baseline Charger utilization at location No. 1. In red, the total number of BEBs charging

One charger down all day long: the charger utilization for stress-test scenario consisting of one charger down is illustrated in Figure 6. Key take aways are:

- The daily energy use is reduced to 2 446 kWh. This is 93% of the baseline energy use.
- There are no blocks affected by this fault.
- As seen in the Figure 6, the number of BEBs charging is reduced, with two single events (in grey) of BEBs arriving on site and missing a charging opportunity because the two chargers left are occupied.

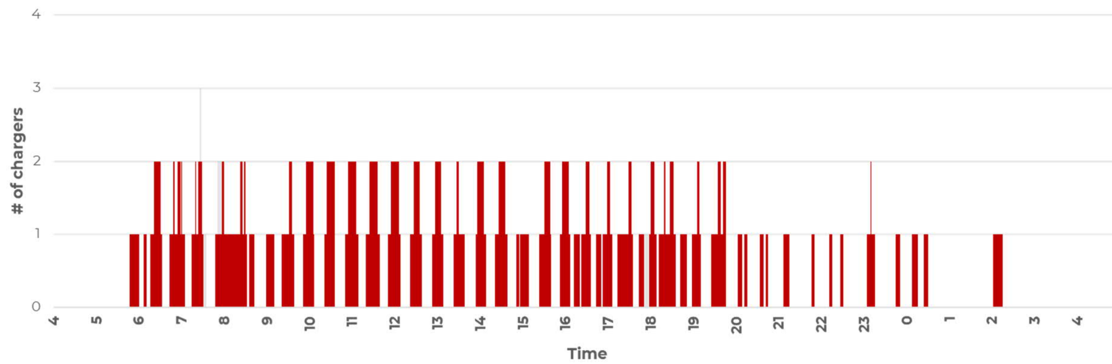

Figure 6. Charger utilization for one charger down test at location No. 1. In grey the total number of BEBs park at the location; in red, the total number of BEBs charging

Two chargers down during all day: the charger utilization for stress-test scenario consisting of two chargers down is illustrated in Figure 7. Key take aways are:

- The daily energy use is reduced to 1 604 kWh. This is 61% of the baseline energy use.
- There are no blocks affected by this fault.
- As seen in Figure 7, the number of BEBs charging is reduced, with several events (in grey) of BEBs arriving on site and missing a charging opportunity because the only available charger is occupied, or because it did not require to charge.

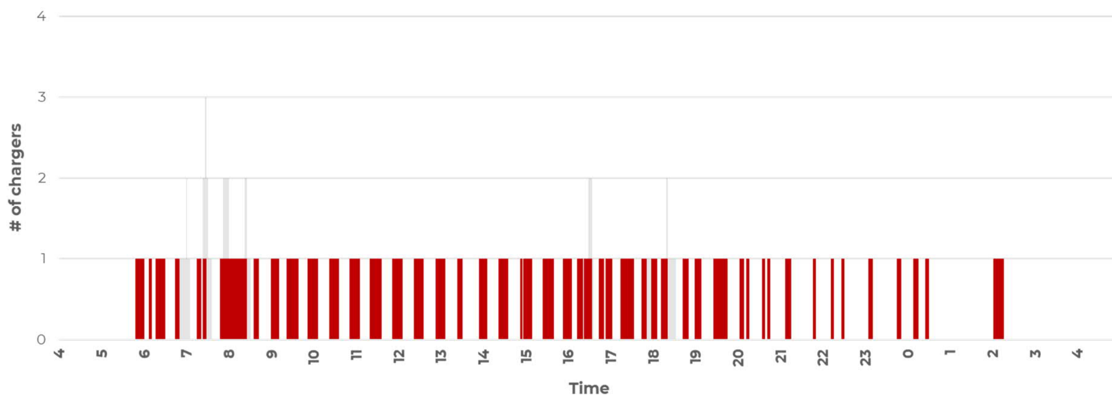

Figure 7. Charger utilization for the two chargers down test at location No. 1. In grey the total number of BEBs parked at the location; in red, the total number of BEBs charging.

5.2.1.2 Summary of the stress-test for one to two chargers down at each location

Table 3 shows the results on the number of blocks failed to be delivered under one to two chargers fails for a whole day. Locations 1 and 3 are the most resilient because they have three chargers on-site. A failure of the chargers in locations 4 and 5 can be considered critical, given that these only count with one charger and its failure can lead to the BEBs failing to deliver 9 and 6 blocks, respectively.

The most critical failure can be expected on location No. 2. At this location the failure of both chargers may lead to the BEBs failing to deliver more than 17 blocks or approximately 30% of the service assigned to the BEBs at this garage, or in total 57 blocks.

Table 3: Number of blocks failing to be delivered from stress-test on one to two chargers failing. Highlighted in orange, the locations for which the number of blocks failing is bigger than 0.

Location	Baseline		One-charger down		Two-Chargers down	
	No. Chargers available	No. blocks failing	No. Chargers available	No. blocks failing	No. Chargers available	No. blocks failing
1	3	*0*	2	*0*	1	*0*
2	2	*0*	1	*4*	0	*17*
3	3	*0*	2	*0*	1	*1*
4	1	*0*	0	*9*	0	*9*
5	1	*0*	0	*6*	0	*6*

5.2.1.3 Summary of stress-test on all chargers down at different hours during the day

Table 4 shows a summary of the stress test on all-chargers failing at each location during different schedules during the day. As expected, total failure of chargers at location No. 4 will have a higher impact on the service for the timeframes considered. In total a complete failure of all on-route chargers at all locations would cause at least 41 blocks to be not successfully completed.

Table 4: Number of blocks failing to be delivered from stress-test on all charges failing at each location at different schedules during the day. Highlighted in orange, the locations for which the number of blocks failing is bigger than 0.

Location	Total Number of chargers	Morning service peak	Afternoon service peak	All-day
		6:00 – 9:00	15:00 – 18:00	
1	*3*	*No impact*	*No impact*	*3 blocks*
2	*2*	*3 blocks*	*5 blocks*	*17 blocks*
3	*3*	*No impact*	*No impact*	*6 blocks*
4	*1*	*1 block*	*1 block*	*9 blocks*
5	*1*	*No impact*	*No impact*	*6 blocks*

5.3 On-route Charging Efficiency Drop

This test is intended to show the impact of the loss of efficiency of the on-route chargers on the service delivered. Table 5 shows the average daily values for three different charger efficiencies applied to all chargers at on-route charging locations. The following are key takeaways from the results:

- The on-route charging infrastructure does not present major impacts on the service for a reduction in the efficiency of around 20% (80% scenario).
- A 50% reduction of the efficiency for all on-route chargers would only affect 4 blocks out of the 57 considered for the service. This is a 7% impact on the service due to a loss of efficiency of 50%.
- Consider that at least 41 blocks' successful completion depend on on-route charging. Therefore, the failure of on 4 blocks to be delivered due to a 50% loss of efficiency represents 10% of the service supported by on-route charging.
- The main effect of the 20% reduction in efficiency is the reduction in daily energy usage, which is approximately proportional to the reduction in the avg. SOC.
- The major impact of a 50% reduction on the charging efficiency is on the total daily energy usage and on the avg. SOC at the end of the service. These impacts add increase the stress over the depot charging infrastructure, as the energy not delivered will have to be compensated during depot charging.

Table 5: Average daily key metrics for three different charger efficiencies applied to all chargers at on-route charging locations.

Parameter	Average (over all blocks) daily values		
	Chargers at nominal efficiency	Chargers at 80% efficiency	Chargers at 50% efficiency
No. blocks successfully completed by BEBs	57 (all)	57 (all)	53
Distance Travelled per block (km)	356.4	356.4	345
Daily BEB usage (kWh)	12 744	11 963	8 668
Energy Consumption (kWh/km)	1.56	1.56	1.58
Hours of operation per block	16.9	16.9	16.6
Avg. SOC at the end of the service	52%	49%	37%

6 Conclusions

This paper presents a tool that assesses the resilience of a BEB service when subjected to a variety of system failures at the depot and on-route charging systems, or when the charging efficiency drops. Although the 57 buses will primarily rely on on-route charging to complete their daily run, depot-charging is essential to supplement charging and add resilience to the system. This is primarily shown by the hypothetical scenario of a complete power blackout at the depot. This scenario would affect the delivery of at least 12 blocks, or 20% of the service. Nevertheless, the system is resilient to partial failures of the depot electrical charging system resulting in an average departure SOC of 80% or more. A complete failure of the on-route charging infrastructure can lead to the fleet of BEBs to unsuccessfully deliver 41 blocks or 72% of the service assigned to the BEBs. Particularly, when looking at the resilience of each location, an all-day all-chargers failure at location No. 4 can lead to 17 uncompleted completed blocks, or around 30% of all service assigned to BEBs which speaks to the importance for TransLink to invest in measures to decrease the failure probability at this site (by adding battery energy storage systems, for instance). Finally, a 50% reduction of the charging efficiency for all on-route chargers would affect 7% of the service assigned to BEBs. This is equivalent to 10% of the service that depend on on-route charging for a successful completion (41 blocks).

The model and methodology can be utilized to identify on-route charging locations critical for the successful delivery of the service. In such application, given the blocks to deliver and the endpoints within each block, the model would evaluate the critical number of charging stations for each endpoint and its criticality among all the endpoints. A functionality like this would also inform on the most suitable and critical endpoints to locate the charging infrastructure and the relevance for the normal operation of the fleet of BEBs. Future work should consider the effects of charging modes on the overall service completion and peak demand. Charging modes to be considered include split and sequential charging. Additionally, a Monte-Carlo simulation should be carried out to consider all possible scenarios, ranging from the selection of the service to different combinations of on-route charging failure events for each on route location, to the study of added resilience by adding on-site generation or additional chargers and dispensers at each location.

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Presenter Biography

Julian Fernandez-Orjuela, PhD, is a Senior Consultant with the Sustainable Transportation Advisory Services at WSP Canada. Since joining the team, Julian has been actively contributing to projects related to Zero-Emissions Fleet feasibility analysis, planning and modelling. He specializes in electric vehicle charging requirements and fleet planning.

Before joining WSP, he worked as Project Manager with the University of British Columbia in projects ranging from to feasibility zero-emissions transportation in the province of BC to machine learning applications for modeling the charging infrastructure and battery electric drivetrains to communications protocols to integrate charging stations in energy management systems for Microgrids to reviewing the state-of-the-art of the shared-autonomous-electric technology.