Minimizing Charging Infrastructure for a High-Fraction-Electric Marguerite Bus System

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Background

With a growing interest in clean transportation, electric buses(EBs), particularly battery EBs, have become increasingly popular in public transit systems. EBs have the potential to reduce GHG and toxic air pollution emissions significantly and provide clean, low-cost, efficient transportation in urban areas as well as large university campuses.

As the nation's leading university in sustainability, Stanford introduced its first EB fleet in 2013 to its free Marguerite system. Since then, the number of operating EBs has increased from 3 to 23. In 2016, the percentage of vehicle miles by electric busses (EB's) reached 58%. Stanford Parking and Transportation Services (P&TS) plans to add 15 more EB's to the system in 2018, and is currently working toward the goal of making 80% of the bus miles in the Marguerite system electric by 2020. A few long distance and low-use routes make full electrification currently infeasible, but the long-term goal is likely 100% electrification.

The dominant charging infrastructure format which has emerged, especially in smaller centralized systems, is to have a 1-to-1 ratio between the number of EBs and charging stations. This is the case at Stanford. Keeping this ratio ensures reliability for EBs' operation and charging. However, as the number of EB's and the range of the bus routes expand, a 1-to-1 charging scheme may become infeasible or unreasonable given budget constraints and the capital required to expand transmission infrastructure for charging. There is likely a more optimal way to schedule charging so as to minimize capital expenditure and load on the grid.

Problem Basics

Key Bus Parameters:

- range: 125-145 miles
- approximately 270 kWh battery
- charge time to full: 6-8 hours

Key Marguerite System Facts:

- currently 1:1 charging ratio
- charging periods: 9AM-2AM, 9PM – 4PM
- central charging station
- currently 58% electric by bus-miles
- goal of 80% electric by 2020
- Stanford fixed rate of $0.10/ kWh – no Time Of Use rates
- Average route distance for the routes in our model: 12.92 miles
- No smart charging

Project Goals:

- **Model optimal run schedule for current 23 EB's and determine if current schedule is optimal**
- **Determine feasibility of operating 38 busses (future EB quantity) with 23 charging stations in 2018**
- **Run models with constraint on charging time to eliminate grid stress and lower GHG impacts.**

Modelling

Problem Formulation:

- Mixed Integer Linear Problem (MILP)
- Time Varying over one week
- 3 binary variables (Route Schedule, Charge Schedule, Idle Status); 1 integer variable(# of charging stations); 1 continuous variable (SOC starting %)
- Objective function: Minimize number of charging stations
- Program: AMPL , Solver: Cplex
- Progressively made model larger (Figure 1) until project goals were met.

Formulation of Time Variation:

$$\forall\,(t,b) \in (T_S - 1\,..\,T_E, BUSES)\!:\; \mathbf{S^C_{t,b}} = \mathbf{S^C_{(t-1),b}} - \sum_{r=1}^{n}\left(\mathbf{y^R_{t,b,r}} * \left(1 - \mathbf{C^R}\right) * C^L\right) + \mathbf{y^C_{t,b}} * \mathbf{T_{UNIT}}$$

"The SOC of each bus in each time step equals the SOC of that bus in the previous time step minus the sum of the SOC lost due to driving (incorporating the regenerative braking rate) plus the SOC gained from charging."

Key Constraint - Time Lag Due to Route Switching:

$$\forall\,(t,r,b) \in (TIME, ROUTES, BUSES)\!:\; \mathbf{y^R_{(t-1),b,r} = 1} \Rightarrow \sum_{i=1}^{n} \mathbf{y^R_{t,b,i}} \; - \; \mathbf{y^R_{t,b,r} = 0}$$

"If the bus was in service in the previous time period, it must either continue being in service on the same route (giving 1-1 = 0 in second half of constraint), or not be in service on any route (giving 0-0 = 0)." This gives our model a realistic lag time if a bus is switching routes and makes it less optimal to switch sporadically, making the model more implementable.

Graphical Results

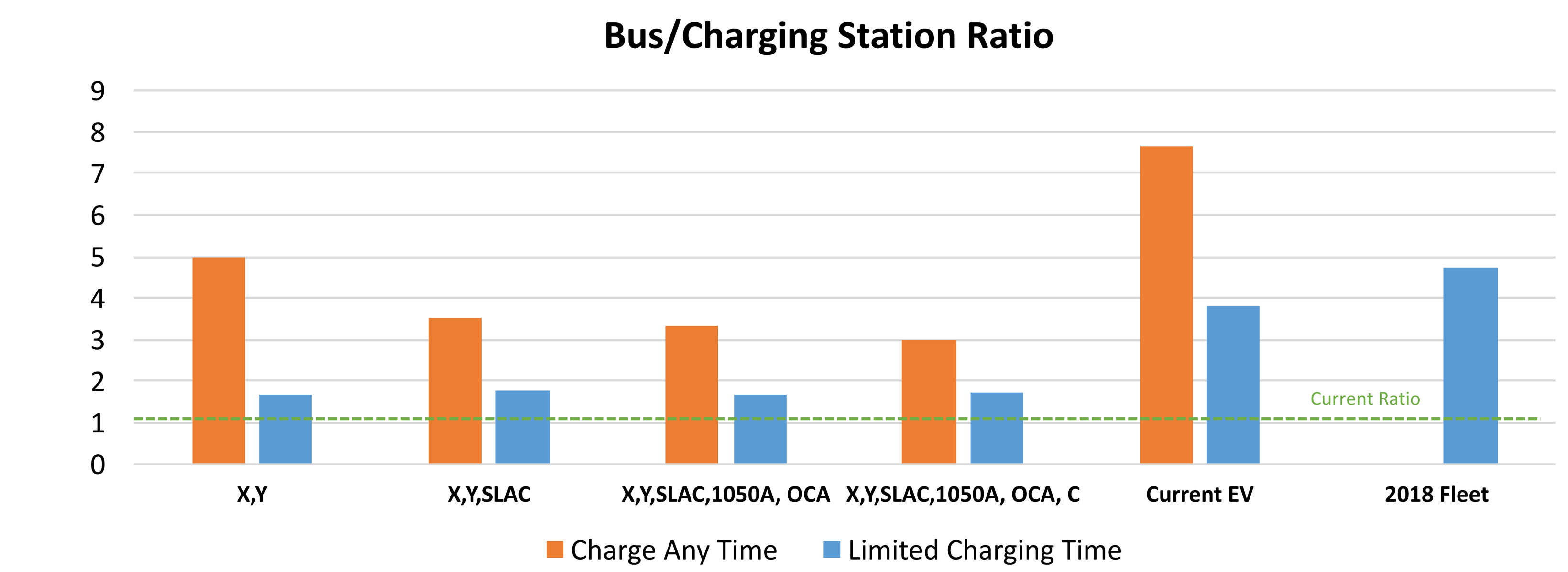

Figure 1. Ratio between the number of buses and the minimum charging stations with models containing 4,6,10,12,26,and 35 routes respectively on the bottom axis. Ratio is reported under both limited charging time (9pm-4am, 9am-2pm) and flexible charging time scenarios.

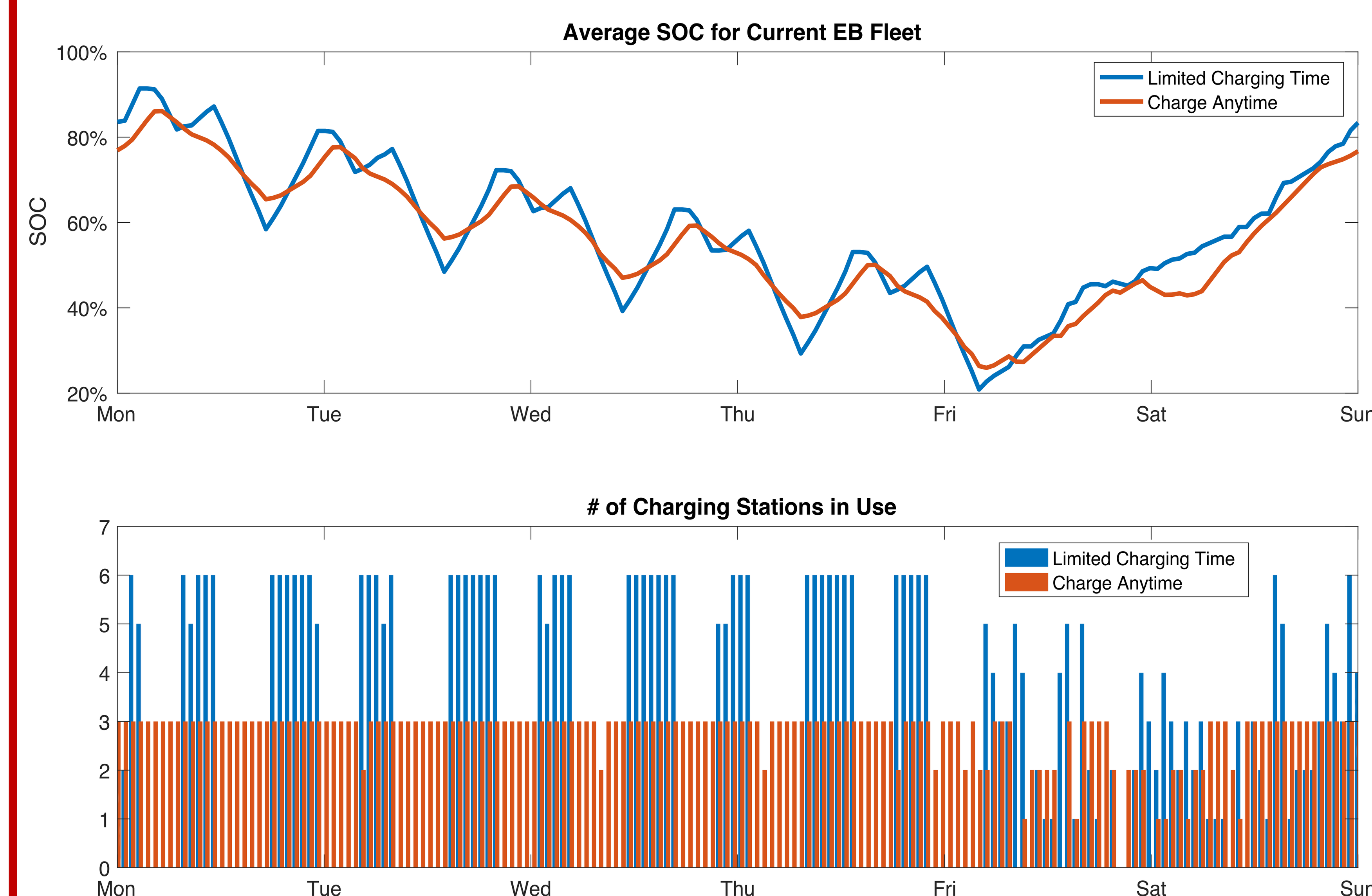

Figure 2. Upper: Averaged hourly state of Charge(SOC, %) status for the current EB fleet (23 buses) under limited and flexible charging scenarios. Lower: number of charging stations in use at each hour

0:00	0	+	+	0	0	+	+
1:00	0	+	+	0	0	0	+
2:00	+	+	0	+	0	0	+
3:00	0	+	+	0	+	0	0
4:00	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0
7:00	Y2	SLAC1	0	Y1	X2	0	X1
8:00	Y2	SLAC1	SLAC2	Y1	X2	X1	0
9:00	Y2	SLAC1	0	Y1	X2	X1	SLAC2
10:00	Y2	SLAC1	Y1	0	X2	X1	SLAC2
11:00	Y2	0	Y1	SLAC1	X2	X1	SLAC2
12:00	Y2	X1	Y1	SLAC1	X2	0	SLAC2
13:00	Y2	0	Y1	SLAC1	X2	X1	SLAC2
14:00	Y2	X2	Y1	SLAC1	0	X1	SLAC2
15:00	Y2	X2	0	SLAC1	Y1	X1	SLAC2
16:00	0	X2	Y2	SLAC1	Y1	X1	SLAC2
17:00	SLAC2	X2	Y2	SLAC1	Y1	X1	0
18:00	SLAC2	X2	Y2	0	Y1	X1	SLAC1
19:00	SLAC2	X2	Y2	X1	Y1	0	SLAC1
20:00	SLAC2	0	Y2	X1	Y1	X2	SLAC1
21:00	SLAC2	SLAC1	Y2	X1	Y1	X2	+
22:00	0	+	+	0	+	0	+
23:00	+	0	+	+	0	+	0

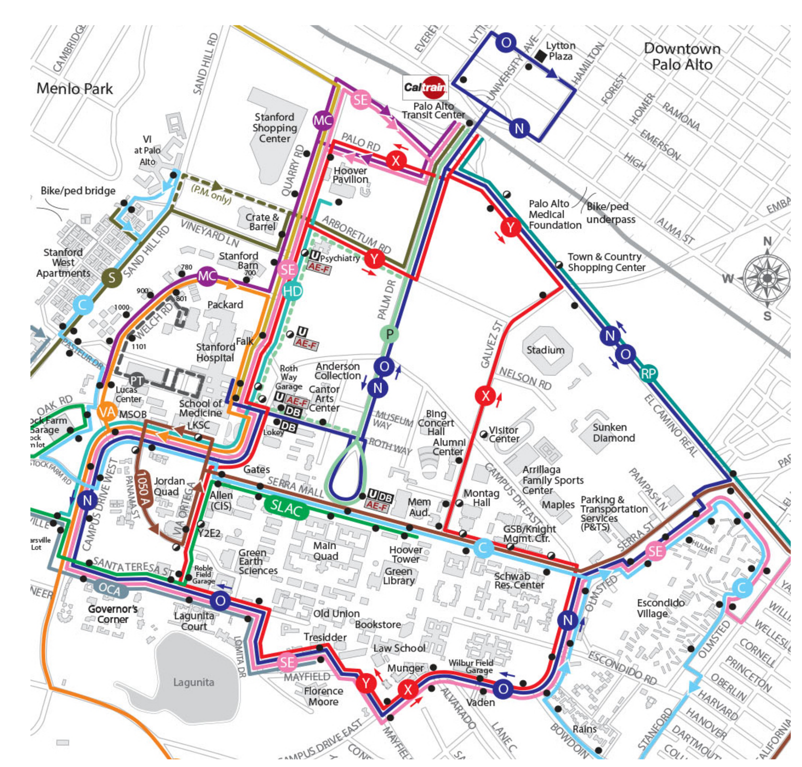

Figure 4. Marguerite Shuttle System Map

Figure 3. Sample daily Bus Assignment and charging Schedule for 6 Routes + 7 Buses (with limit on when to charge). Routes are colored differently and charging periods are marked as "+". Note that buses are consistently staying on the same route, with a required1-hr idle period before assigned to another route.

Discussion of Results

- ✓ The optimized charging ratio (4:1) under the limited charging time scenario is significantly higher than the 1:1 charging ratio of the current fleet, which suggests the current charging infrastructure is underutilized, and highly uneconomical.
- ✓ As the number of buses and routes increase, charging stations are operating more efficiently. Under the limited charging time scenario Charging ratio gradually increases, from 1.7 per station to 3.8 (Figure 1). To reach P&TS's 2018 goal, no more charging stations need to be built.
- ✓ Average SOC rates in both scenarios decrease over time during weekdays, and return to the initial SOC level during weekends as a result of low weekend bus demand and absence of charging time constraint.
- ✓ Charging schedule under the limited charging scenario exhibits a daily bimodal pattern. Charging activities are concentrated during designated time slots (noon and midnight), resulting in a higher bus/charging station ratio. (Figures 1,2).
- ✓ Under the flexible charging schedule, buses are charged continuously throughout the day. Charging demand are smoothed out, requiring a smaller number of charging stations, but are still centered around the two daily peaks.
- ✓ Relaxation of SOC constraint significantly improves the running time and feasibility of the model
- ✓ With some sporadic charging and route switching behavior, both charging and route schedule are fairly reasonable and implementable (Figure 3)

Project Goals:

- ✓ **Model optimal run schedule for current 23 EB's and determine if current schedule is optimal - COMPLETED**
- ✓ **Determine feasibility of operating 38 busses (future EB quantity) with 23 charging stations in 2018 - COMPLETED**
- ✓ **Run models with constraint on charging time to eliminate grid stress and lower GHG impacts - COMPLETED**

Sensitivity / Model Improvements

Sensitivity:

We found that final charging station value did not change significantly by varying set points of most variables or parameters , but whether or not the problem was considered "infeasible" by Cplex did.

In the hourly model, the biggest contributor to model sensitivity and feasibility was the starting and ending SOC level. We found that instead of operating the model with a fixed starting and ending SOC for every bus, better results were obtained faster by making this a variable that was unique to each bus and constraining the final value of SOC to be within 5% of the starting value. Doing this allowed us to extend our model to include all EB's currently in the system and get a reasonable result (6 charging stations for 23 buses running 26 routes) in a reasonable amount of time (1.5 hours). Previously we ran the model for eight hours with an infeasible result. This sensitivity is likely due to the finite and relatively high value used for hourly SOC gain while charging, and would be improved by increased model resolution.

Future Work/ Model Improvements:

- incorporate buses of different battery sizes
- higher time resolution (15 mins best)
- objective function on dollar costs
- include inductive charging
- Add constraints to limit route switching and
- Charge more continuously to make the model more implementable.
- Add mileage penalty for travel to and from the charging station and between routes if switching.

References

Matthew Brown – Deputy Director of Marguerite System.
Marguerite Shuttle Maps and Schedules. https://transportation.stanford.edu/marguerite
Electric buses at Stanford. California Higher Education Sustainability Conference (CHESC), 2015