Daniel's Super Cool and overly long title

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***Abstract*—TODO: add abstract**

***Index Terms*—TODO: Add Keywords**

I. Introduction

The goal of public transportation is to provide transit services using cost effective and environmentally sound methods. To better meet these needs, electric buses are becoming more common. Benefits include the use of renewable energy, reduced emissions, and fewer maintenance costs [14]. However, there are also extended charge times, electrical expenses, increased loads on power infrastructure [16], [6], [3], and limited battery lifespans [9].

Because charging requires time, buses have limited availability, and there are limited charging resources, charge times must be scheduled with care. This work addresses the problem of charge scheduling and proposes a methodology with the following considerations: bus availabilty, external loads, fiscal expenses, day/night charging, and variable charge rates. To the best of our knowledge, this is the first time these methods have been included in the same framework.

The remainder of this paper is organized as follows... ===insert stuff here===

II. Literature Review

We acknowledge the existance of additional contributions, such as minimizing costs for startup infrastructure [17], and preserving battery lifespan [9]. However, as these are not relevent to this work, we consider them outside the scope of this review. We further acknowledge that some works cited herein contain solutions to several of these problems, such as in [20], but for sake of organization, we list them in the most relevent context.

A. Battery Charging

Here we consider solutions to empty batteries and focus our attention on either battery replacement or charging methods. We also refer to charging methods as either static (at rest) or dynamic (in motion).

Because charge times can significantly complicate logistics, [19] and [11] give methods for exchanging spent with charged batteries. The benefits include minimal down time as refueling can occur in a matter of minutes. Unfortunately, batteries can be cumbersome, and their exchange can be difficult. It also requires specialized tools, and could require automation.

Another alternative is to inductively charge buses while they traverse their routes [2], [11], [12], [5]. Unfortunately, this requires significant infrastructure which may not be available and is cost prohibitive for large systems.

Alternative solutions tend towards optimal planning. This allows for buses to charge in the traditional sense, minimizes additional infrastructure, and avoids the complexities of exchanging batteries. These approaches generally fall into one of three categories; reactive, hybrid, and global.

Reactive planning focuses strictly on presential circumstances. Methods of this type are computationally efficient, run in real-time, and are adaptable. These techniques generally stem from control theory and minipulate a current state to minimize cost. One such example includes the work done by [4], who uses comparable methodology to reduce demand on the power grid. This methodology however, does not account for global phenomena that require broader planning schemes and for the most part this class of technqiues remain unused for bus charging.

Another class of algorithms encompasses a limited number of projected events to improve decision making. This allows for a middle ground between simplicity and global planning and has proven useful in previous work [10], [1].

Global planning algorithms assume comlplete foreknowledge of future events and provide globally optimal plans [18],[7]. This class of algorithm requires more computation and is less flexible then reactive or hybrid approaches. However, the solutios are globally optimal and derive from insight unavailable to other algorithm classes.

B. Cost Management

The final set of constraints aim to decrease load on the grid. Previous work has shown that the use of electric buses can significantly complicate local power management [3] [6]. Additinally, power demand generally increases the fiscal cost from a billing perspective. [8] has provided methodology for forcasing the load on the grid. These types of models often form the basis for power distribution algorithms. For example, [15] gives an approach to minimize grid demand, but requires foreknowledge of uncontrolled loads. [4] takes a different approach and observes real-time data to control the charge rates of connected buses. [13] also operates in the real-time sense but uses on-board batteries to mitigate the effects of rapid charging.

III. Graph Info

This solution uses a graph to formulate constraints and describe bus availability. The graph represents a flow of chargers as they traverse a time-sequence of available buses. By activating graph edges, we imply a certain state associated with a number of chargers. Edges leading to active layers of the graph indicate that this charger is charging a bus where an active 'rest' layer gives an unused charger. The graph contains n + 1 layers, where n is the number of buses in the fleet.

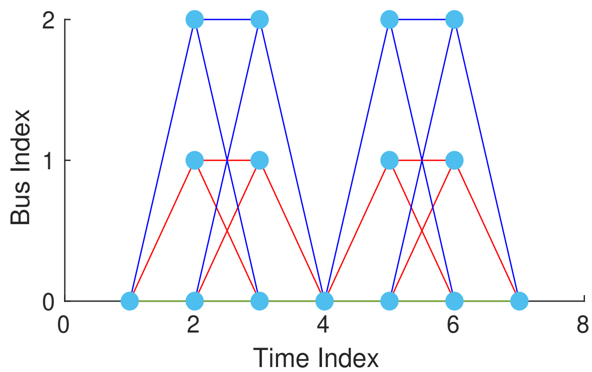

Fig. 1: A simple graph with two buses and six time intervals

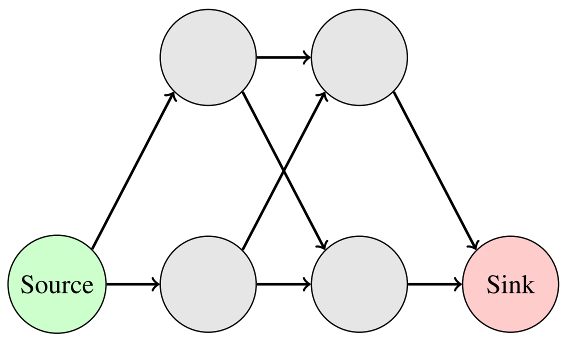

Fig. 2: Network flow illustrating sources and sinks

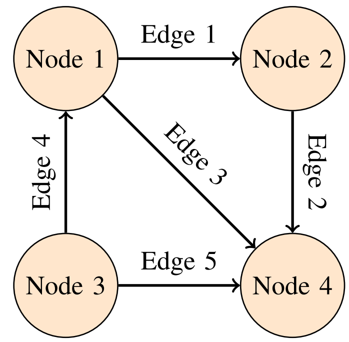

Fig. 3: A generic directed graph consisting of nodes and edges

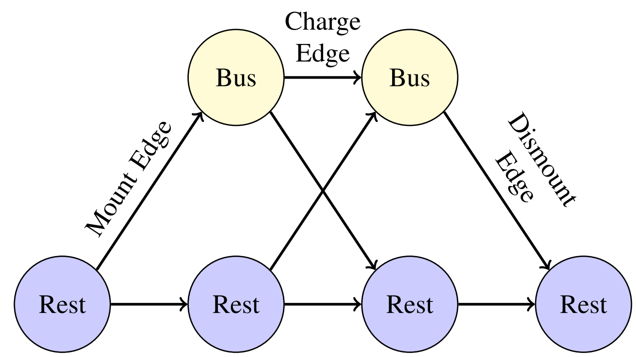

Fig. 4: Mount, Dismount, and Charge Edges

There is one layer for each bus as well as a 'rest' layer for non-charging elements.

nodes represent bus availability. A node for bus i at time j indicates bus i's availability for charging at time j. In Figure 1, for example, both buses one and two are available at times two, three, five, and six, and unavailable otherwise. Note how the zeroeth element always has nodes. This is consistent with an ever-present no-charge option.

Edges represent potential actions to be done between time indices and represent one of three actons: mount, charge, or dismount (see figure 4). A mount acton signals a bus to connect to a charger. A charge action causes a bus to charge, and a dismount to disconnect. A charge command must always be lead by a mount, and followed be either an additional charge or dismount command.

This type of directed graph can be represented using an incidence matrix, where the i,jth element refers to a connection between node i and edge j. This value is either positive or negative 1. A positive 1 implies an incoming edge whereas negative one indicates an outgoing edge. For example, the graph given in figure 3 would be described as:

$$\begin{bmatrix} -1 & 0 & -1 & 1 & 0 \\ 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 \\ 0 & 1 & 1 & 0 & 1 \end{bmatrix} \tag{1}$$

If we let x be a vector representing the number of chargers occupying any one edge and A be an adjacency matrix, then the total 'flow' for each node can be expressed as

$$\text{flow} = Ax. \tag{2}$$

Because chargers are not consumed or produced during the day, the total flow for each node must be zero with the exception of *sources* and *sinks*. Sources are single nodes from which the first edges originate as shown in figure 2, and give a negative flow value equal to the number of chargers. A sink is converse, where the final edges terminate and maintains a corresponding positive flow value.

This relationship can be described in terms of a *flow constraint*:

$$Ax = \begin{bmatrix} 0 \\ \vdots \\ -\text{nCharger} \\ \vdots \\ 0 \\ \text{nCharger} \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

We also assume that a bus will only charge once before departing for the next route, and that one charger can only service one bus at a time. This constraint is described as a *group* constraint, where groups are collections of nodes for a single bus that describe continuous time at the hub (see figure 5) This behavior is described in terms of an inequality

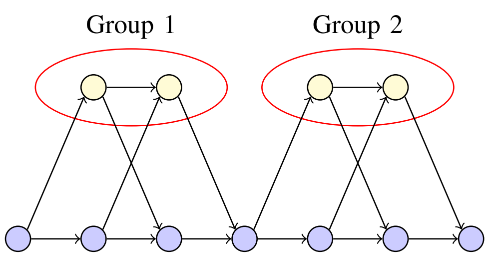

Fig. 5: Example of groups in a network flow graph

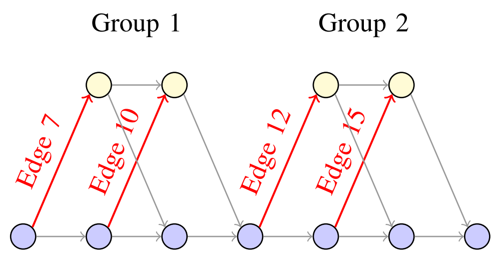

Fig. 6: Mount edge example for groups

constraint

$$Bx \leq \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}, \tag{4}$$

where x is a matrix giving the number of chargers traversing an edge, and B describes all mount edges (see figure 4) corresponding to the same group. In B, the i,jth value is one if the jth edge mounts to the ith group. For example, the graph given in figure 6 would have the following group constraints:

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{5}$$

IV. Multi-Graph Additions

An additional contribution this work offers is the expansion to night vs day charging. During the night, there is one charger for each bus; each with a single charge rate. During this time, buses are also available to charge at any time. These differences in operations introduce changes to the original graph formation and warrent a separate graph.

Night graphs consider a situation where both the number of buses reflecte the number of chargers and buses are readily available. Note how there are several source and sink nodes in figure 7. When a bus deploys for the day, the available number of charges changes and are reflected in the underlying source and sink constraints.

Changes in the first graph are reflected in the second through use of state of charge variables.

V. Battery State of Charge

The state of charge (SOC) is influenced in three ways; initial conditions, discharge events, and traversing charge nodes (as shown in figure 4). There are SOC variables for each node representing an available bus, where the SOC value for the ith bus at SOC index j is denoted as $d_{i,j}$ as shown in figure 8. Note, there only needs be SOC variables for time indices where buses are available to charge and $d_{i,j}$ does not generally correspond to the charge at *time interval* j. All other timesteps are deterministic and need not be computed.

When charging, the change in SOC associated with the ith bus at the jth charge edge is denoted $g_{i,j}$. Again, note that j is *not* indicative of a time interval, rather it gives the *index* of the *charge edge* in use as shown in figure 9.

An additional contribution this paper gives is the addition of multi-rate charging. This adapts the basic methodology to incorporate additional charge edges and $g_{i,j}$ variables. Under this methodology, the graph given in figure 5 would be modified to reflect figure 10, where $g_{i,j,k}$ represents the ith bus at charge instance j and charge rate k.

To model the effect of charging on a battery state of charge, we adopt the Constant Current Constant Voltage (CCCV) model as derived in [18] which gives

$$s_{k+1} = \bar{a}_l s_k - \bar{b}_l M \tag{6}$$

Where s_k is the charge of a battery at time k, $\bar{a}_l$ is a charge rate dependent, experimentally determined value, $\bar{b}_l = \bar{a}_l - 1$, and M is the maximum capacity of the battery in kWh.

Recall how g represented the change in state of charge of the battery in kWh. This allows us to express s_{k+1} in terms of

$$s_{k+1} = s_k + g_{\pi_g(m,k,l)} \tag{7}$$

where $\pi_g(m,k,l)$ represents the index of g for bus m at time index k for charge rate l. These two equations imply that

$$\begin{aligned} s_k + g_{\pi_g(m,k,l)} &= \bar{a}_l s_k - \bar{b}_l M \\ \Rightarrow g_{\pi_g(m,k,l)} &= \bar{a}_l s_k - s_k - \bar{b}_l M \\ \Rightarrow g_{\pi_g(m,k,l)} &= s_k(\bar{a}_l - 1) - \bar{b}_l M. \end{aligned} \tag{8}$$

But the state of charges for bus m are given in terms of $d_{i,j}$. If we let $d_{i,j} = \pi_d(i,k,l)$, then the final expression for g becomes

$$g_{\pi_g(m,k,l)} = d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M. \tag{9}$$

Note, 9 is only valid when the bus is charging and must be tempered with additional constraints to account for the non-charging case.

To handle the two cases, we express the cases for charging (equation 9 and non-charging ($g = 0$) as

$$\begin{aligned} g_{\pi_g(m,k,l)} &= d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M \\ g_{\pi_g(m,k,l)} &= 0. \end{aligned} \tag{10}$$

which also implies that

$$\begin{aligned} g_{\pi_g(m,k,l)} &\leq d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M \\ g_{\pi_g(m,k,l)} &\geq d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M \\ g_{\pi_g(m,k,l)} &\leq 0 \\ g_{\pi_g(m,k,l)} &\geq 0. \end{aligned} \tag{11}$$

Next, let $x_{\pi_x(m,k,l)}$ be the index of the edge corresponding to $g_{\pi_g(m,k,l)}$. A switch between the two constarints expressed

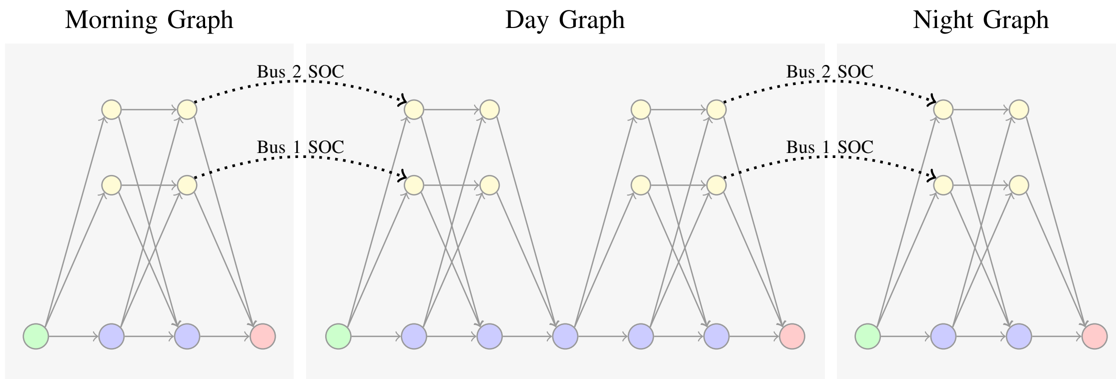

Fig. 7: Night vs Day Graphs

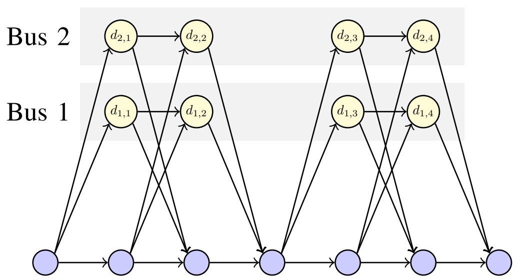

Fig. 8: SOC indicators

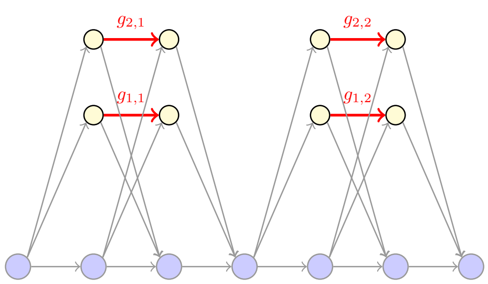

Fig. 9: Depiction of which edges increase SOC for the single rate case

in equation 11 can be constructed using the *big M* technique. This modifies equation 11 such that

$$\begin{aligned}
&g_{\pi_g(m,k,l)} \le d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M - M(1 - x_{\pi_x(m,k,l)}) \\
&g_{\pi_g(m,k,l)} \ge d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M \\
&g_{\pi_g(m,k,l)} \le 0 + M x_{\pi_x(m,k,l)}) \\
&g_{\pi_g(m,k,l)} \ge 0.
\end{aligned} \tag{12}$$

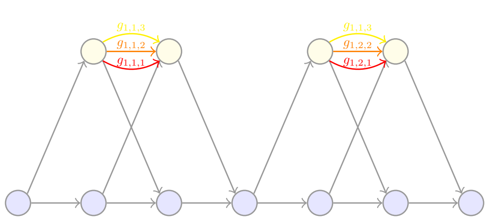

Fig. 10: Multi-Rate Charging

Note that as expressed, when the charge edge is active (i.e. $x_{\pi_x(m,k,l)} = 1$), then

$$\begin{aligned}
&g_{\pi_g(m,k,l)} \le d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M \\
&g_{\pi_g(m,k,l)} \ge d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M \\
&g_{\pi_g(m,k,l)} \le M \\
&g_{\pi_g(m,k,l)} \ge 0.
\end{aligned} \tag{13}$$

Bus as g can never exceed the charge capacity of the battery, the bottom two constraints are inactive and g is both less than or greater than equation 9, making it equal. When the edge is inactive, or $x_{\pi_x(m,k,l)} = 0$, equation 12 becomes

$$\begin{aligned}
&g_{\pi_g(m,k,l)} \le d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M - M \\
&g_{\pi_g(m,k,l)} \ge d_{\pi_d(m,k,l)}(\bar{a}_l - 1) - \bar{b}_l M \\
&g_{\pi_g(m,k,l)} \le 0 \\
&g_{\pi_g(m,k,l)} \ge 0.
\end{aligned} \tag{14}$$

where the top two constraints become inactive and g is both less than and greater than 0, making it equal. Hence, these constraints can be expressed in linear form as

$$\begin{aligned}
-g_{m,k,l} + d_{m,k,l}(\bar{a}_l - 1) + x_{m,k,l} &\le M(\bar{b}_l + 1) \\
g_{m,k,l} - d_{m,k,l}(\bar{a}_l - 1) &\le -\bar{b}_l M \\
g_{m,k,l} - M x_{m,k,l} &\le 0 \\
-g_{m,k,l} &\le 0.
\end{aligned} \tag{15}$$

The constraints for state of charge are circumstantially dependent. Each $d_{m,k,l}$ must be defined by a set of constraints which are defined by either initial conditions, previous graphs, route discharge, or $g_{m,k,l}$ variables.

Initial conditions and previous graphs are straight forward. Initial conditions are given as an equality constraint. For example, if d_0 was initialized to 80 kWh, the constraint would be $d_0 = 80$. To initialize to the value of a previous graph, use an equality constraint.

Suppose we modeled early morning and day-time operations and had two corresponding graphs. The final node of graph one would be equivalent to the first node of graph two in the temporal sense and the corresponding $d_{m,l,k}$ values would also be equated as $d_{\text{Graph 1}} - d_{\text{Graph 2}} = 0$.

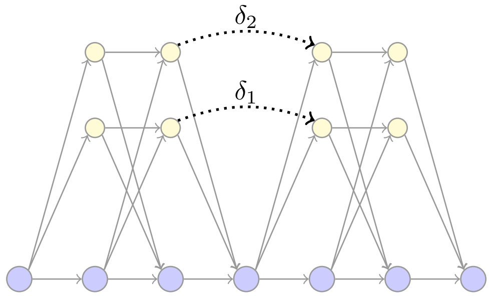

Fig. 11: δ values for routes

$d_{m,l,k}$ values corresponding to available charge times are expressed as a sum of $g_{m,k,l}$ values given in equation 15 such that

$$d_{m,k+1} = d_{m,k} + \sum_{l} g_{m,k,l}$$

or as given in linear form,

$$d_{m,k+1} - d_{m,k} - \sum_{l} g_{m,k,l} = 0. \tag{16}$$

The final case deals with battery discharge over a route. As seen in figure 11, discharge values, also refered to as δ represent the power expenditure overa route. This expenditure is modeled as a withdrawel from the resevour in a battery and was calibrated from data received from the Utah Transit Authority. In figure 11, the SOC constraints corresponding to δ_1 would be as follow:

$$d_{1,3} = d_{1,2} - \delta_1$$

or in linear form,

$$d_{1,2} - d_{1,3} = \delta_1. \tag{17}$$

VI. Fiscal Rate Schedule

general introduction with details for demand and consumption charge and how these relate to the end-of-the-month billing. a. external loads (contribution) b. consumption charge i. total energy in Kwh ii. on-peak vs off-peak iii. constraints for consumption charge c. demand charge i. average power in 15 minute window ii. on-peak vs facilities iii. constraints for on-peak and facilities charges d. total cost breakdown i. Show how Rocky Mountain Power uses these and what the cost weighting is.

VII. Bus Fleet Operations

Overview of bus operations during the day vs the night a. night environment i. one charger per bus ii. slow chargers iii. single rate chargers iv. buses always available b. day environment i. limited number of chargers ii. fast/variable rates iii. limited charging availability c. multiple graphs to incorporate day vs night charging i. show picture to illustrate this ii. show SOC constraints to implement these relationships

VIII. Objective Function

IX. Gurobi & Usage

X. Results

XI. Future Work

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