

A Position Allocation Approach to the Scheduling of Battery Electric Bus Charging

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Abstract—Dependable charging schedules for an increasing interest of battery electric bus (BEB) fleets is a critical component to a successful adoption. In this paper, a BEB charging scheduling framework that considers spatiotemporal schedule constraints, route schedules, fast and slow charging, and battery charging dynamics is modeled as a mixed integer linear program (MILP). The MILP is modeled after the berth allocation problem (BAP) in a modified form known as the position allocation problem (PAP). Linear battery dynamics are included to model the charging and discharging of buses while at the station and during their routes, respectively. The optimization coordinates BEB charging to ensure each BEB has sufficient charge while using slow chargers where possible for sake of battery health. The model validity is demonstrated with a randomly generated set of routes for 40 buses and 220 visits to the charging station. The results show that the slow chargers are more readily selected and the charging and spatiotemporal constraints are met while considering the battery dynamics.

Index Terms—Berth Allocation Problem (BAP), Position Allocation Problem (PAP), Mixed Integer Linear Program (MILP), Battery Electric Bus (BEB), Scheduling

I. INTRODUCTION

The public transportation system is crucial in any urban area; however, the increased awareness and concern of environmental impacts of petroleum based public transportation has driven an effort to reduce the pollutant footprint [1]–[4]. Particularly, the electrification of public bus transportation via battery power, i.e., battery electric buses (BEBs), has received significant attention [4]. Although the technology provides benefits beyond reduction in emissions, such as lower driving costs, lower maintenance costs, and reduced vehicle noise, battery powered systems introduce new challenges such as larger upfront costs, and potentially several hours long “refueling” periods [2], [4]. Furthermore, the problem is exacerbated by the constraints of the transit schedule to which the fleet must adhere, the limited amount of chargers available, as well as the adverse affects in the health of the battery due to fast charging [5]. This paper presents a continuous scheduling framework for a BEB fleet that shares limited fast and slow chargers. This framework takes into consideration linear charging dynamics and a fixed bus schedule while meeting a certain battery percentage threshold for intermediate and final charges.

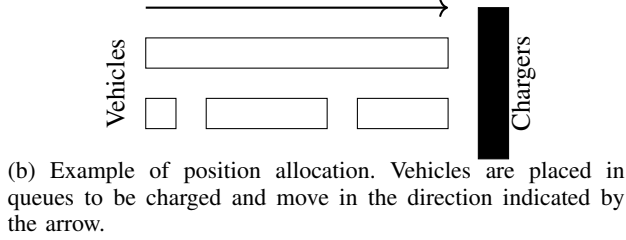
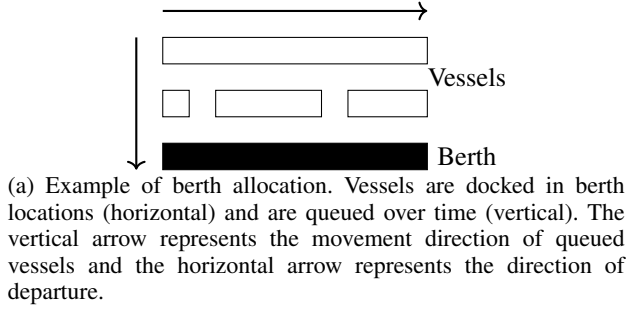
Recent research efforts have been made into solving the problem of scheduling and charging fleets as well as deter-

mining the infrastructure that they rely upon. Much attention has been given to solving both problems simultaneously [6]–[9]. The added complexity of considering both the BEB charge scheduling and the infrastructure problems necessitates simplifications for sake of computation. First, only fast chargers are utilized in planning [6], [7], [9]–[14]. Second, significant simplifications to the charging models are made. Some approaches assume full charge [6], [9], [10], [13]. Others have assumed that the charge received is proportional to the time spent on the charger [11], [12], which can be a valid assumption when the battery state-of-charge (SOC) is below 80% charge [11].

To do: Wordsmith Furthermore, the above described research shows a need for in determining a system that outputs an optimal charging schedule. In [6], [7], [9], initial interest is demonstrated in this topic. [7] uses simulation alongside an optimization strategy to identify charging station locations and average stop times to supply enough charge for BEBs to complete their routes. [6] utilizes a network flow approach to optimize the deployment strategy of BEBs; however, the focus is primarily on replacing diesel or CNG buses. In [8], the focus is on developing a strategy to optimally charge batteries for electric vehicles considering different sources of battery degradation. [9], who also touches on the need for further research in the recharging problem, addresses a similar problem as this paper where the overall objective is to minimize the annual total electric bus recharging system operating costs. Similarly to other works, such as [6], discrete network flow approaches are utilized. Although effective, having to discretize the system introduces variables scaled proportionally to the fidelity of the discretization of the model. This work attempts to remedy this by utilizing the Position Allocation Problem (PAP) which utilizes a continuous model to describe the system.

This work builds upon the Position Allocation Problem, a modification of the Berth Allocation Problem (BAP), as a means to schedule the charging of electric vehicles [15]. The BAP solves the problem of allocating space for incoming vessels to be berthed. Each arriving vessel requires both time and space to be serviced and is assigned a berthing location [16]. Vessels are lined up parallel to the berth to be serviced and are horizontally queued as shown in Fig 1a. The PAP utilizes this notion of queuing for scheduling vehicles to be

Fig. 1: Comparison between BAP and PAP



charged, as shown in Fig 1b. The PAP is formulated as a rectangle packing problem by assuming that vehicle charging will take a fixed amount of time, the amount of vehicles that can charge is limited by the physical width of the vehicles, and each vehicle visits the charger a single time [15].

The main contribution of this work is the extension of the PAP to BEB charger scheduling. This includes modeling and incorporation of a proportional charging model into the MILP framework, consideration of multiple charger types, and inclusion of the route schedule for each bus. The result is a MILP formulation that coordinates charging times and charger type for every visit that each bus makes to the station while considering a dynamic charge model and scheduling constraints.

The remainder of the paper proceeds as follows: In Section II, the PAP is introduced with a formulation of the resulting MILP. Section III constructs the MILP for BEB scheduling, including modifications to the PAP queuing constraints and development of a dynamic charging model. Section IV demonstrates an example of using the formulation to coordinate 40 buses over 220 total visits to the station. The paper ends in Section V with concluding remarks.

II. THE POSITION ALLOCATION PROBLEM

The BEB charge schedule formulation in this work builds upon the PA, which, in turn, builds upon the BAP. This section provides a brief overview of the BAP and a detailed formulation of PAP as presented in [15].

A. Overview of BAP

The BAP is a rectangle packing problem where a set of rectangles (\odot) are attempted to be optimally placed in a larger rectangle (O) as shown in Fig 2. The rectangle packing problem is an NP-hard problem that can be used to describe many real life problems [17], [18]. In some of these problems,

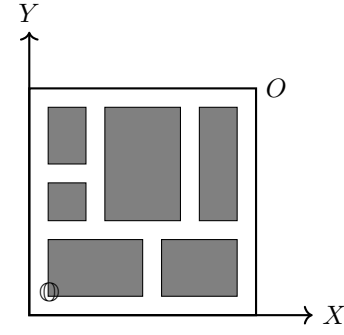


Fig. 2: Example of rectangle packing problem

the dimensions of \odot are held constant such as in the problem of packing modules on a chip, where the widths and height of the rectangles represent the physical width and heights of the modules [18]. Other problems, such as the BAP, in some formulations, allow one side of the rectangle to vary depending on its assigned position (i.e. the handling time is dependent on the berth) [19].

the BAP solves the problem of optimally assigning incoming vessels to berth positions to be serviced (Fig 1a). The width and height of O represent the berth length S and time horizon T , respectively. Similarly, the width and height for \odot represent the time spent to service vessel i and the space taken by docking vessel i , respectively. The vessel characteristics (length of the vessel, arrival time, handling time, desired departure time) are assumed to be known for all N vessels to be serviced. A representation of a BAP solution is shown in Fig 3.

The BAP objective is generally represented as minimizing some operational time for a given vessel i . The operational time may be chosen to minimize the difference between arrival and departure times, time spent being serviced, or overall waiting time [19]–[21]. The model must then constrain the vessel placement as to not allow overlap spatially or temporally.

B. The PAP Formulation

The BAP formulation forms the basis of the PAP; however, there are some differences in the way the variables are perceived. For the i^{th} visit, starting service time, u_i , is now the starting charge time, the berth location, v_i , is now the charger queue for assignment, and the service time, p_i , is now the time to charge. The PAP utilizes a number of parameters. The following parameters are constants.

- S : charger length
- T : time horizon
- N : number of incoming vehicles
- p_i : charging time for vehicle i ; $1 \leq i \leq N$
- s_i : width of vehicle i ; $1 \leq i \leq N$
- a_i : arrival time of vehicle i ; $1 \leq i \leq N$

These constants define the problem bounds. The following list provides a series of decision variables used in the formulation.

TABLE I: Notation used throughout the paper

Variable	Description	Variable	Description
Input values			
A	Number of buses in use	M	An arbitrary very large upper bound value
N	Number of total visits	O	Bounding box for rectangle packing
\mathbb{O}	Set of rectangles to be packed in O	Q	Number of chargers
S	Length of charger	T	Time horizon
Input variables			
Γ_i	Array of ID's for each visit i	α_i	Initial charge percentage time for visit i
β_i	Final charge percentage for bus i at the end of the time horizon	ϵ_q	Cost of using charger q per unit time
γ_i	Array of values indicating the next index visit i will arrive	κ_i	Battery capacity for bus i
λ_i	Discharge of visit over route i	ν	Minimum charge allowed on departure of visit i
τ_i	Time visit i must depart the station	ζ_i	Discharge rate for vehicle i
a_i	Arrival time of visit i	i_0	Indices associated with the initial arrival for every bus in A
i_f	Indices associated with the final arrival for every bus in A	m_q	Cost of a visit being assigned to charger q
r_q	Charge rate of charger q per unit time	s_q	Length of vehicle i
Decision Variables			
δ_{ij}	If $v_i + s_i \leq v_j$ ($\delta = 1$) otherwise $\delta = 0$	η_i	Initial charge for visit i
σ_{ij}	If $u_i + p_i \leq u_j$ ($\sigma = 1$) otherwise $\sigma = 0$	c_i	Detach time from charger for visit i
g_i	Linearization term for bilinear terms $g_i := p_i w_{iq}$	p_i	Amount of time spent on charger for visit i
u_i	Initial charge time of visit i	v_i	Assigned queue for visit i
w_{iq}	$w_{iq} = 1$ if bus visit i is assigned to charger q		

- u_i : starting time of service for vehicle i ; $1 \leq i \leq N$
- v_i : charge location i ; $1 \leq i \leq N$
- c_i : departure time for vehicle i ; $1 \leq i \leq N$
- σ_{ij} : binary variable that determines ordering of vehicles i and j in time
- δ_{ij} : binary variable that determines relative position of vehicles i and j when charging simultaneously

To determine the values for each of these decision variables, a MILP is formulated in [15] and shown here for sake of completeness.

$$\min \sum_{i=1}^N (c_i - a_i) \quad (1)$$

Subject to:

$$u_j - u_i - p_i - (\sigma_{ij} - 1)T \geq 0 \quad (2a)$$

$$v_j - v_i - s_i - (\delta_{ij} - 1)S \geq 0 \quad (2b)$$

$$\sigma_{ij} + \sigma_{ji} + \delta_{ij} + \delta_{ji} \geq 1 \quad (2c)$$

$$\sigma_{ij} + \sigma_{ji} \leq 1 \quad (2d)$$

$$\delta_{ij} + \delta_{ji} \leq 1 \quad (2e)$$

$$p_i + u_i = c_i \quad (2f)$$

$$a_i \leq u_i \leq (T - p_i) \quad (2g)$$

$$\sigma_{ij} \in \{0, 1\}, \delta_{ij} \in \{0, 1\} \quad (2h)$$

$$v_i \in [0, S] \quad (2i)$$

The objective function (1) minimizes the time spent to service each vehicle by minimizing over the sum of differences between the departure time, c_i , and arrival time, a_i . i.e., It seeks to get each vehicle charged and on its way as quickly as possible.

Constraints 2a-2e are used to ensure that individual rectangles do not overlap. For the PAP, they ensure that two vehicles charging simultaneously are at different positions and, similarly, two vehicles that have overlapping positions do not overlap

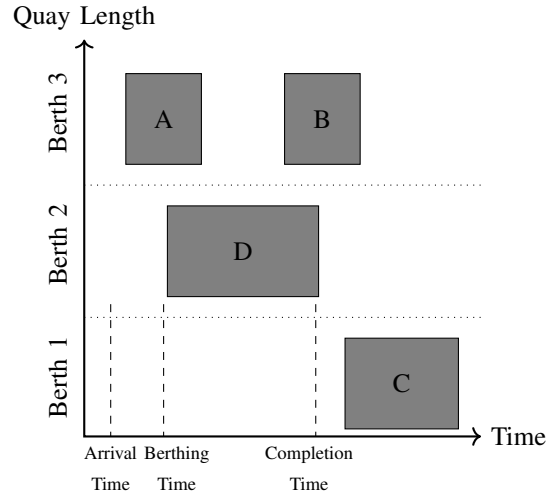


Fig. 3: The representation of the berth-time space

temporally. Constraint (2a) establishes temporal ordering when active ($\sigma_{ij} = 1$). Similarly, when $\delta_{ij} = 1$ in (2b) then spatial ordering is established. Constraints 2c-2e enforce that spatial and/or temporal ordering is established between each possible vehicle pair. Constraints (2d) and (2e) enforce consistency. For example, (2d) enforces that vehicle i cannot come before vehicle j and vehicle j simultaneously come before vehicle i .

The last constraints force relationships between arrival time, charge start time, and departure time. Constraint (2f) states that the service start time, u_i , plus the time to service vehicle i , p_i , must equal the departure time, c_i . Constraint (2g) enforces the arrival time, a_i , to be less than or equal to the service start time, u_i , which in turn must be less than or equal to the latest time the vehicle may begin to be serviced to stay within the time horizon. Constraint (2h) ensures that σ_{ij} and δ_{ij} are binary. Constraint (2i) ensures that the assigned value of v_i is a valid charging position.

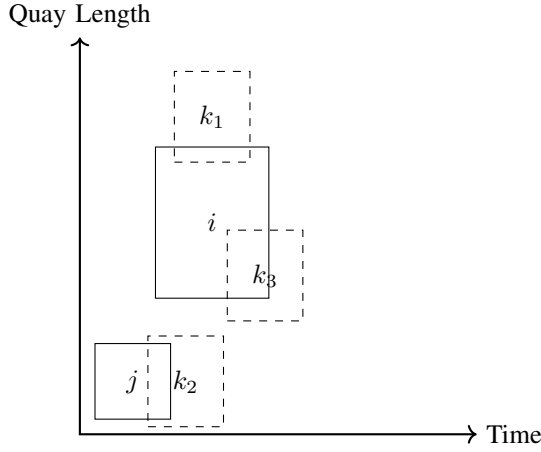


Fig. 4: Examples of different methods of overlapping. Space overlap: $v_{k_1} < v_i + s_i \therefore \delta_{k_1 i} = 0$. Time overlap $u_{k_1} < u_j + p_j \therefore \sigma_{k_2 j} = 0$. Both space and time overlap $\sigma_{k_3 i} = 0$ and $\delta_{k_3 j} = 0$.

III. PROBLEM FORMULATION

Applying the PAP to BEB charging requires four fundamental, but significant changes. The first is that the time that a BEB spends charging is allowed to vary. Thus, p_i becomes a variable of optimization. Second, in the PAP each visit, i , is assumed to be a different vehicle. For the BEB charging problem, each bus may make multiple visits to the station throughout the day and the resulting charge for a bus at a given time is dependent upon each of the prior visits made. The third change is formulaically simple, but fundamentally essential. In the PAP, the charger is one continuous bar with vehicle width effectively restricting the number of vehicles charging simultaneously. For the BEB, it is assumed that a specific number of chargers exist and these chargers can charge the vehicle at a different rate. The fourth fundamental change is related to the first three. The charge of each bus must be tracked in the optimization to ensure that charging across multiple visits is sufficient to allow each bus to execute its route throughout the day.

The discussion of the four changes are separated into two sections. Section III-A discusses the changes in the spatial-temporal constraint formulation to form a queuing constraint. Section III-B then discusses the addition of the bus charge management. This section ends with a statement of the objective in Section III-C and the statement of the full problem in Section III-D. The notation is explained throughout and summarized in Table I.

A. Queuing Constraints

Instead of referring to a vehicle or a bus arriving at a station, most variables are defined in terms of a visit. Two separate visits could correspond to different buses or visits by the same bus. Instead of each vehicle having a width, the spatial variable s_i is removed and v_i is made to be an integer corresponding to which queue visit i will be using. Thus, when $\delta_{ij} = 1$,

the visits must be at different chargers, i.e., $v_i - v_j \geq 1$. The variable S is likewise replaced with Q , where Q corresponds to the number of available queues. Note that $Q = A + C$ where A is the number of vehicles and C is the number of chargers. The rationale for having extra queues is to allow buses to sit idle instead of charging. The modified queuing constraints can be written as follows.

$$u_i - u_j - p_j - (\sigma_{ij} - 1)T \geq 0 \quad (3a)$$

$$v_i - v_j - (\delta_{ij} - 1)Q \geq 1 \quad (3b)$$

$$\sigma_{ij} + \sigma_{ji} + \delta_{ij} + \delta_{ji} \geq 1 \quad (3c)$$

$$\sigma_{ij} + \sigma_{ji} \leq 1 \quad (3d)$$

$$\delta_{ij} + \delta_{ji} \leq 1 \quad (3e)$$

$$p_i + u_i = c_i \quad (3f)$$

$$a_i \leq u_i \leq (T - p_i) \quad (3g)$$

$$c_i \leq \tau_i \quad (3h)$$

$$p_i \geq 0 \quad (3i)$$

$$\sigma_{ij} \in \{0, 1\}, \delta_{ij} \in \{0, 1\} \quad (3j)$$

$$v_i \in [1, 2, \dots, Q] \quad (3k)$$

Constraints (3a)-(3g) and (3j) are nearly identical to those described in Section II with the sole change in (3b) being described above to conform to a queue. Constraint (3h) is added to ensure that the ending charge time, c_i , must be less than or equal to the required departure time from the station, τ_i . This enables the bus schedules to be considered during optimization. Finally, (3k) enforces v_i to be an integer.

B. Battery Charge Dynamic Constraints

Using purely the constraints in (3) with the objective in (1) would result in c_i being chosen as small as possible by employing $p_i = 0$, $u_i = c_i$. Thus, the vehicles would not charge. Furthermore, it does not encode any revisiting of the BEB to the charging station. To remedy this, battery dynamic constraints are introduced.

The battery dynamic constraints are used to drive time spent on the charger, p_i , as well as define initial, final, and intermediate bus charges for each visit i . The initial and final bus charges are predefined and are represented by the equations $\eta_{i_0} = \alpha_{i_0} \kappa_{i_0}$ and $\eta_{i_f} = \beta_{i_f} \kappa_{i_f}$, respectively, where α_{i_0} and β_{i_f} are percentages of the battery capacity for the first and final visits for each bus, b , respectively. The intermediate charges must be determined at solve time.

To accomplish such a task, each arrival i must be associated with an initial charge, η_i , which represents the charge received from the previous visit minus the discharge observed while on route. However, because the PAP assumes each arrival is unique, bus visits must be associated with a unique bus ID to appropriately initialize charges for each visit. This visit/ID pair is represented as vector denoted by Γ , where the index represents visit i and the value is the bus ID. To propagate charges forward, another term γ is introduced to represent the next index bus i arrives. For example, assume $A = 3$ buses, $N = 5$ visits, and $\Gamma = [0, 1, 2, 0, 1]$. Γ informs us that the first

and fourth visits correspond to bus 1 and the second and fifth visits correspond to bus 2. As γ maps from one visit to the next, it would take the value $\gamma = [3, 4, -1, -1, -1]$, where 0-indexing is assumed and -1 represents no further visits for bus Γ_i .

It is assumed that the charge received is proportional to the time spent charging. The charge rate for charger q is denoted as r_q , the charge at visit i is η_i , and the amount of discharge between visit i and the next visit of the same bus, λ_{γ_i} . If visit i occurred at charger q , the charge of the bus coming into visit γ_i would be

$$\eta_{\gamma_i} = \eta_i + p_i r_q - \lambda_{\gamma_i}. \quad (4)$$

The binary decision variable w_{iq} is introduced to determine whether visit i uses charger q . This allows the charge of the bus coming into visit γ_i to be written in summation form as

$$\eta_{\gamma_i} = \eta_i + \sum_{q=1}^Q p_i w_{iq} r_q - \lambda_i \quad (5a)$$

$$w_{iq} \in \{0, 1\} \quad (5b)$$

Maximum and minimum values for the charges are to be placed to ensure the battery is not overcharged and to guarantee sufficient charge for subsequent visits. Assuming each bus has its own upper bound, the upper bound for the bus corresponding to visit i is κ_{Γ_i} . The lower bound is assumed to be a percentage of the upper bound, and is written as $\nu\kappa_{\Gamma_i}$. The upper and lower bound constraints are written using the charge as

$$\eta_i + \sum_{q=1}^Q p_i w_{iq} r_q \leq \kappa_{\Gamma_i} \quad (6a)$$

$$\eta_i + \sum_{q=1}^Q p_i w_{iq} r_q - \lambda_i \geq \nu\kappa_{\Gamma_i} \quad (6b)$$

Note that the term $p_i w_{iq}$ is a bilinear term (two decision variables being multiplied together) which is nonlinear [22]. A standard way of linearizing a bilinear term that contains a continuous and integer term is by introducing a new term, an either/or constraint, and utilizing big-M notation [22], [23]. Introducing the slack variable g_{iq} to be equal to $p_i w_{iq}$, g_{iq} can be defined using the following constraints

$$p_i + (1 - w_{iq})M \geq g_{iq} \quad (7a)$$

$$p_i \leq g_{iq} \quad (7b)$$

$$Mw_{iq} \geq g_{iq} \quad (7c)$$

$$0 \leq g_{iq} \quad (7d)$$

where M is defined sufficiently large such that for constraints (7a) and (7b) if $w_{iq} = 1$ then the two equations will take the form of $p_i \leq g_{iq}$ and $p_i \geq g_{iq}$ effectively, stating $p_i = g_{iq}$. If $w_{iq} = 0$ then the two equations will take the form of $p_i \leq g_{eq}$

and $p_i \geq g_{iq} - M$ which deactivates the constraint. Similarly, (7c) and (7d) state if $w_{iq} = 0$ then the constraints take the form $0 \geq g_{iq}$ and $0 \leq g_{iq}$ directly implying $0 = g_{iq}$. If $w_{iq} = 1$ then the constraints take the form $M \leq g_{iq}$ and $0 \geq g_{iq}$ deactivating the constraint. Putting the two sets of constraints together defines the linear representation of the bilinear term $w_{iq}p_i$.

C. The Objective Function

The last consideration is the objective function. The goal of the MILP is to utilize slow chargers as much as possible. Thus, an assignment cost m_q and usage cost ϵ_q are associated with each charger, q . The cost for both the assignment and utilization of slow chargers is less than that of the fast chargers. The objective function has an assignment term, $w_{iq}m_q$, which is non-zero if charger q is used for visit i . Similarly, a usage term $g_{iq}\epsilon_q$ is non-zero only if charge is received for visit i at charger q . The resulting objective is defined in Eq 8. The assignment cost, $w_{iq}m_q$, and the usage cost, $g_{iq}\epsilon_q$, are summed over each visit, i , and charger, q .

$$\min \sum_{i=1}^N \sum_{q=1}^Q (w_{iq}m_q + g_{iq}\epsilon_q) \quad (8)$$

D. The BEB Charging Problem

The resulting problem to be optimized is outlined in Eq 9. Constraints (9a)-(9h) are reiterations of the queuing constraints in (3). Constraints (9i)-(9m) provide initialization and terminal conditions as well as intermediate constraints to provide continuity in vehicle charges. Constraint (9i) states the first arrival for each bus is initialized with a charge of $\alpha\kappa_{\Gamma_i}$. Constraint (9j) defines that the previous charge, η_i , plus the charging done by charger q minus the discharge amount due to completing route, λ_i . This constraint is only used with indices with valid next visit values (i.e. $\gamma_i \neq -1$). Constraint (9k) is similar to (9j), except it states that the initial charge, η_i , plus the charge from q and the discharge from route, λ_i , must be greater than some percentage of its capacity, κ_{Γ_i} , in order to guarantee sufficient charge to complete the next route. Constraint (9l) states that the charging done for visit i cannot be greater than the capacity of the battery, κ_{Γ_i} . Constraint (9m) states that the last visit for each vehicle must have a minimum charge of $\beta\kappa_{\Gamma_i}$. Constraint (9n) is included to guarantee a minimum initial charge for the next working day.

The constraints (9o)-(9q) represent the linear form of the bilinear term the $g_{iq} := p_i w_{iq}$. The set of constraints (9r)-(9s) define the linking constraint between the queuing constraint and w_{iq} (i.e. $1w_{i1} + 2w_{i2} + \dots + Qw_{iQ} = v_i$) and enforces that only a single w may be selected per visit, respectively. The last constraints (9t)-(9x) defines the sets of valid values for each.

$$\begin{aligned}
u_i - u_j - p_j - (\sigma_{ij} - 1)T &\geq 0 & (9a) \\
v_i - v_j - s_j - (\delta_{ij} - 1)Q &\geq 0 & (9b) \\
\sigma_{ij} + \sigma_{ji} + \delta_{ij} + \delta_{ji} &\geq 1 & (9c) \\
\sigma_{ij} + \sigma_{ji} &\leq 1 & (9d) \\
\delta_{ij} + \delta_{ji} &\leq 1 & (9e) \\
p_i + u_i &= c_i & (9f) \\
a_i \leq u_i &\leq (T - p_i) & (9g) \\
c_i &\leq \tau_i & (9h) \\
\eta_{i_0} &= \alpha_{i_0} \kappa \Gamma_{i_0} & (9i) \\
\eta_i + \sum_{q=1}^Q g_{iq} r_q - \lambda_i &= \eta_{\gamma_i} & (9j) \\
\eta_i + \sum_{q=1}^Q g_{iq} r_q - \lambda_i &\geq \nu \kappa \Gamma_i & (9k) \\
\eta_i + \sum_{q=1}^Q g_{iq} r_q &\leq \kappa \Gamma_i & (9l) \\
\eta_{i_f} &\geq \beta_{i_f} \kappa \Gamma_{i_f} & (9m) \\
p_i + (1 - w_{iq})M &\geq g_{iq} & (9n) \\
p_i &\leq g_{iq} & (9o) \\
M w_{iq} &\geq g_{iq} & (9p) \\
0 &\leq g_{iq} & (9q) \\
\sum_{q=1}^Q q w_{iq} &= v_i & (9r) \\
\sum_{q=1}^Q w_{iq} &= 1 & (9s) \\
w_{iq} &\in \{0, 1\} & (9t) \\
\sigma_{ij} \in \{0, 1\}, \delta_{ij} &\in \{0, 1\} & (9u) \\
v_i &\in [1, \dots, Q] & (9v) \\
i &\in [1, \dots, N] & (9w) \\
q &\in [1, \dots, Q] & (9x)
\end{aligned}$$

IV. EXAMPLE

An example will now be presented to demonstrate the utility of the developed MILP. A description of the scenario is first presented followed by results.

A. Scenario

The given example utilizes $A = 40$ buses with $N = 220$ visits to the station divided between the A buses. Each bus has a 388 KWh battery that is required to stay above 25% charge (97 KWh) to maintain battery health, and the bus is assumed to begin the working day with 90% charge (349 KWh). Additionally, each bus is required to end the day with a minimum charge of 95% (368 KWh). Planning is done over a 24-hour time horizon. $Q = 9$ chargers are utilized where five of the chargers are slow charging (100 KWh) and four are fast

charging (400 KWh). As discussed in Section III-C, the slow chargers take longer, but are better for battery health than the fast chargers. Therefore, the slow chargers are modeled with a lower cost than the fast chargers for both assignment, $m_q = r_q$, and utilization, $\epsilon_q = r_q$, in the objective, (8).

The bus schedules are randomly generated. It is assumed that each bus has no more than 30 minutes between route departures. Bus routes are created by generating a random list of arrival times, assigning bus ID's to each visit, then generating route durations. They may vary anywhere from a minimum of the average time between the current and next arrival to a maximum of the next arrival time (i.e. $\frac{a_i + a_{\gamma_i}}{2}$ to a_{γ_i}). The discharge is assumed to be linear and is calculated via $\lambda_i = \text{rand}(\frac{a_i + a_{\gamma_i}}{2}, a_{\gamma_i}) \zeta_{\gamma_i}$ where $1 \leq i \leq N$ and ζ_i is the discharge rate for each bus.

The optimization was performed using the Gurobi MILP solver [24] on a machine running a quad-core Intel i7-9700 4.7 GHz processor. The optimizer ran for 5 seconds to completion to produce the optimal solution.

B. Results

The schedule generated by the MILP is shown in Fig 5. The top graph indicates the slow charger usage, and the bottom indicates the fast charger usage. Although $Q = 9$ chargers were used, Fig 5 shows that only five chargers were utilized.

Each color in Fig 5 is used to identify the bus ID assigned. It is noted that the overlaps in Fig 5 indicate the waiting time of vehicle j while vehicle i charges. This is recognized by viewing the vertical bars. These bars indicate the time bus i is set to charge. The area before indicate waiting time and the area after indicates the time spent on the charger. Note that, based upon vehicles needs, bus i may arrive before bus j , but wait until after bus j charges before starting its charge (Fig 6). This is an unintuitive schedule caused by the cost of assignment parameter in the objective function, m_q . This type of constraint would not be achieved through a greedy scheduling algorithm.

Fig 8 depicts the charge for every bus over the time horizon. Every vehicle begins at 90% charge, finishes at 95% charge, and never goes below 25% in the intermediate arrivals as stated in the constraints (9). Fig 7 represents the usage of each charger over the time horizon. The maximum amount of slow chargers used at any given time is three and only one fast charger is utilized at a time.

The pattern, for the most part, in Fig 5 is to populate the first charger and supply the other chargers as needed. Where this pattern primarily breaks down is around hour 15. Having moved each bus one charger down would have resulted in the same cost. This behavior is due to a lack of cost for the amount of total chargers being utilized. Adding a cost in the objective function to minimize the total amount of unique chargers would resolve this problem by effectively attempting to "pack" the chargers down reducing the peak of Fig 7.

Although this formulation effectively discourages the use of fast chargers to utilize the more cost-effective slow charges

more readily, there is no consideration for the cost consumption and demand cost. Consumption cost accounts for peak use of power in the system and demand cost accounts for the total energy used. These metrics are used to calculate the monetary cost of the system. Calculating the demand cost would create more bilinear terms as the objective function would have to sum over $\sum_{i=1}^N \sum_{q=1}^Q w_{iq} r_q(p_i)$, creating yet another linearization term. Furthermore, the demand cost would require discretization of the system. The demand utilizes the peak energy consumption over 15 minute intervals and uses the largest peak as the rate to charge. This would require tracking of when a charger is active and including another variable to enable and disable $w_{iq} r_q$. This example displays the limitation of the MILP solver as it adds effort and complexity to the system as a trade-off for calculating the optimal schedule. Other metaheuristic solvers, such as simulated annealing (SA), would allow the problem to be solved without having to linearize the system. **To do: get the citation for this**

V. CONCLUSION

This work developed a MILP scheduling framework that optimally assigns slow and fast chargers to a BEB bus fleet assuming a constant schedule. The BAP was introduced with an example formulation and was then compared to the PAP. The PAP constructed on the BAP to allow the time spent on the charger, p_i , to be a decision variable. Because the original PAP required service time, p_i , to be given, linear battery dynamics were introduced to drive charging times. Additional constraints were also introduced to provide limits for the battery dynamics.

An example was presented that demonstrated the ability of the formulation to optimally select slow and fast chargers to meet the requirements of the time schedule and the charge consumed during the bus routes. It was also observed that the formulation was able to successfully create a charging schedule without creating conflicts (Fig 5). The charge for each bus was tracked in Fig 8 and shows that the schedule maintained the charges between the maximum charge, 100%, and the minimum charge, 25%.

Limitations were demonstrated in the lack of objective to limit the total amount of chargers utilized and to calculate the demand and consumption costs. Further fields of interest are to utilize the formulation (Eq (8) and (9)) with nonlinear battery dynamics, calculation and utilization of the demand and consumption cost in the objective function, and utilizing this formulation in a metaheuristic solver.

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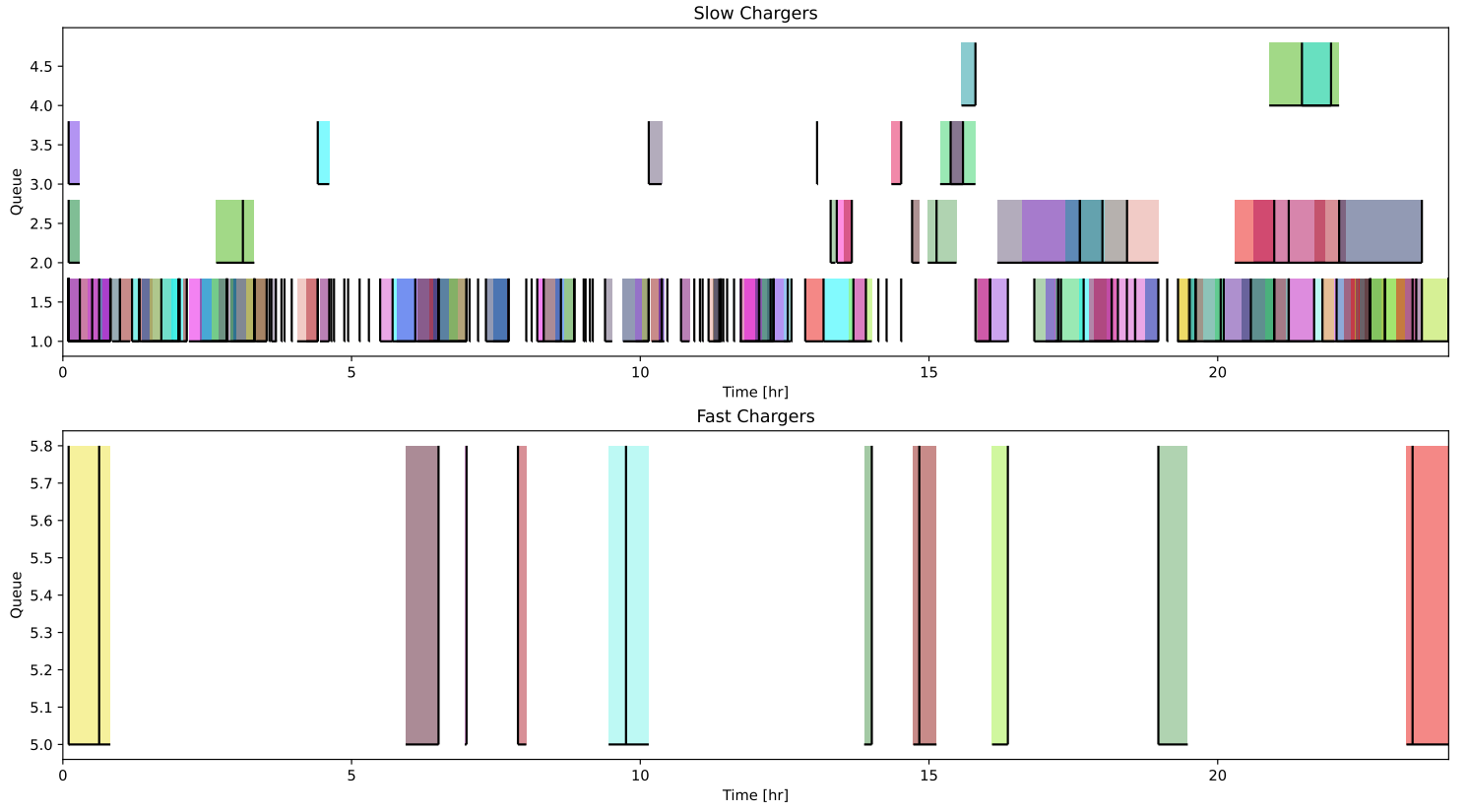


Fig. 5: Bus schedule generated with PAP MILP. Each color is assigned to a specific bus ID. The vertical bars indicate the time the vehicles are set to charge, the area before said bars indicate the waiting times for each visit $1 \leq i \leq N$. Similarly, the area after the bars indicate the time spent on the charger.

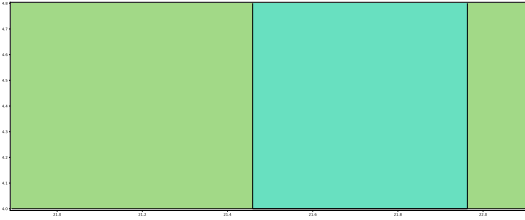


Fig. 6: An example, from Fig 5, of a bus i arriving before j , having i wait for j to arrive, and charge i after j is detached.

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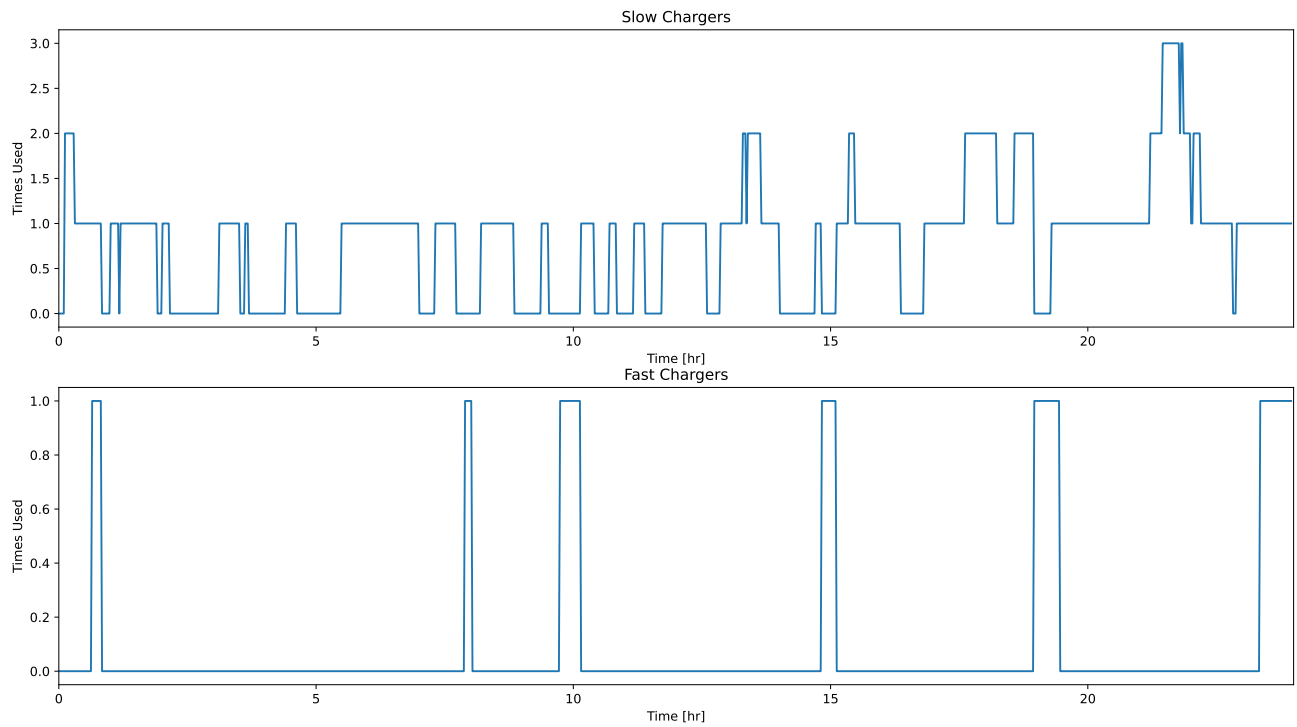


Fig. 7: Amount of slow and fast chargers used at any given time.

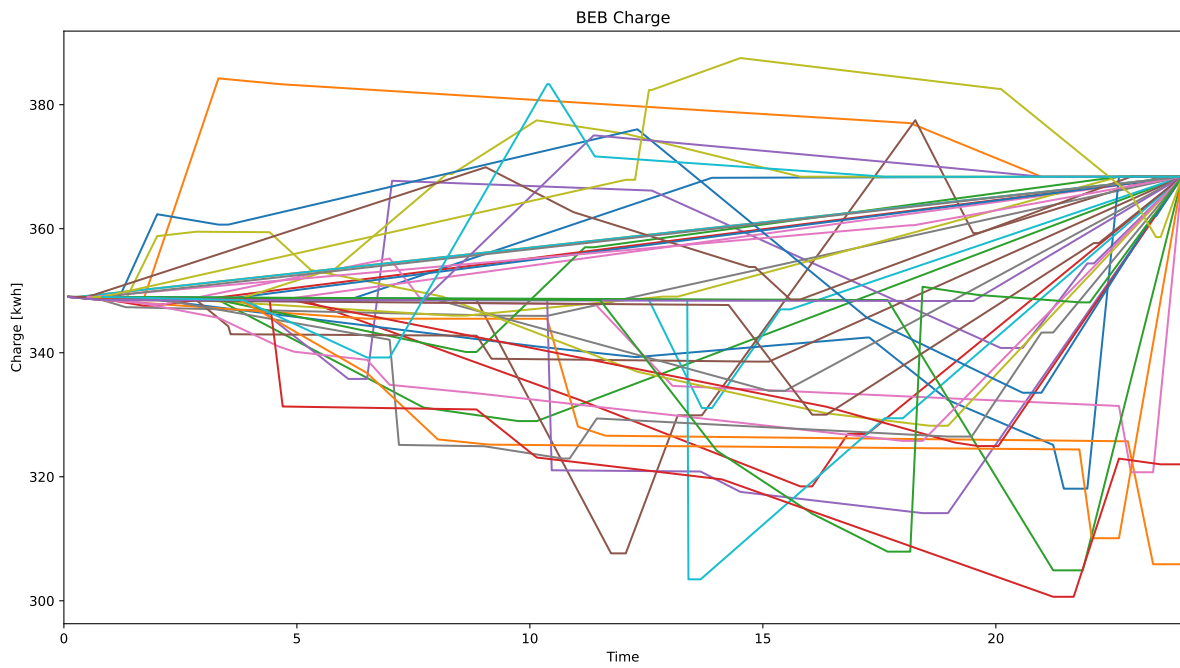


Fig. 8: Charge for each bus over the time horizon.