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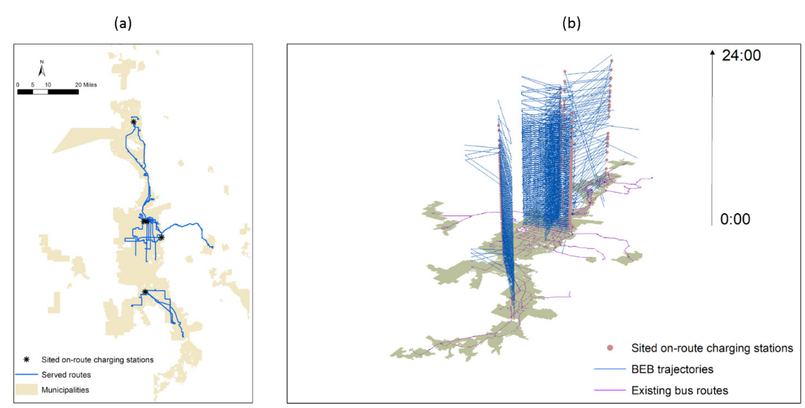
Strategic Planning and Design for Electric Bus Systems



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Strategic Planning and Design for Electric Bus Systems

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ABSTRACT

Environmental concerns due to fossil fuel consumption and emissions drive transportation industry to shift towards low-impact and sustainable energy sources. Public transit system, as an integral part of multimodal transportation ecosystem, has been supporting such a shift by exploring the adoption of electric vehicles. In recent years, the advancement in Battery Electric Buses (BEBs) and their supporting infrastructure technology made them a viable replacement for diesel and Compressed Natural Gas (CNG) buses. Yet, it remains a challenge on how to optimally deploy the BEB system due to its unique spatio-temporal characteristics. To fill this gap, this research introduces a spatio-temporal optimization model to identify the optimal deployment strategies for BEB system. The identified spatio-temporal deployment of BEB system can minimize the cost associated with vehicle procurement and charging station allocation, while satisfying transit operation constraints such as maintaining existing bus operation routes and schedules. The proposed method is implemented onto the transit network operated by the Utah Transit Authority (UTA) to showcase its effectiveness. As many transit agencies are testing electric buses and considering the integration of electric buses into future fleet, this research will help transit agencies make informed decisions regarding strategic planning and design of BEB systems.

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EXECUTIVE SUMMARY

BEBs with zero-emission has been recognized as a promising alternative to diesel and compressed natural gas (CNG) bus to advance air quality and save fuel costs. The adoption of BEBs requires significant investment and needs strategic and comprehensive planning on how to deploy electric buses and associated infrastructure (e.g., charging stations). Important decisions in deploying electric buses and charging stations will include, among others, identifying appropriate driving range (battery specification) for BEBs, allocating BEBs to appropriate transit routes, and determining locations of charging stations and their corresponding capacities that can charge the BEBs in a cost and time-effective way.

While previous research has investigated the system design of public infrastructure for private electric vehicles, no research currently exists that investigates the system design for electric buses and associated infrastructure. This research fills this gap by developing and using a combination of geographic information system (GIS) and optimization methods to identify optimal deployment strategies for BEB systems to achieve specified planning goals. As many transit agencies are testing electric buses and considering the integration of electric buses into future fleet, this research will help the transit agency evaluate the capital and operational cost, greenhouse-gas emission reduction and fuel cost saving associated with the integration of BEBs and make informed decisions regarding strategic planning and design for BEB systems.

The optimization model developed can be used to determine the following specific items:

1. What is the driving range of BEB for each route?
2. How many BEBs should be introduced into each bus route?
3. Where and how many charging stations should be deployed to serve all BEBs?

The application results using UTA’s network demonstrate that the optimization model is effective in selecting the retrofitted buses, routes and charging stations in a transit network for BEB deployment. The method can identify the optimal spatio-temporal deployment for BEBs and charging stations that can minimize the deployment cost of replacing a certain number of diesel or CNG buses with BEBs, while satisfying transit operation constraints such as maintaining existing bus operation routes and schedules. The deployment framework is implemented in a standalone software application, allowing transit planners to modify the input parameters and to examine the output scenarios.

1. INTRODUCTION

1.1 Problem Statement

Public transit system, as a critical component of the multimodal transportation ecosystem, plays a key role in the environmental profile of cities (Glotz-Richter and Koch, 2016). Public transit agencies have been slowly embracing the electric vehicle technology as the technology itself advances to offer carbon footprint reduction, improved reliability, and maintenance benefits (De Filippo et al., 2014). The Battery Electric Bus (BEB) is receiving an increasing amount of attention from transit vehicle industry and transit agencies due to recent advances in battery technologies and its unique zero-emission production. The progressive development and deployment of BEB has been mainly led by China, Europe and the United States (BYD, 2014; Jervey, 2017; ZeEUS, 2017).

While BEB and its supporting infrastructure have been commercialized and gradually adopted, a challenge remains on how to optimally deploy the BEB system, due to several unique spatio-temporal characteristics associated with the system. First, to support long daily operation time and high daily mileage, some BEBs would require periodic on-route charging at bus terminals and overnight charging at bus garages. Careful planning for the optimal locations of on-route charging stations and overnight in-depot charging stations is necessary to efficiently serve the BEBs and keep the cost minimal. Second, the space-time trajectories of BEBs should fit into current transit vehicle operation routes and schedules as much as possible, to enable smooth transition from traditional diesel or Compressed Natural Gas (CNG) buses to BEBs. The concern for potential interference with current operation routes and schedule would impede the acquisition of BEBs. It thus requires a sophisticated spatio-temporal analytical method to determine how to spatially and temporally integrate BEBs into current public transit system without interference with current operation routes and schedules.

1.2 Objectives

The strategic planning and design for BEB systems is essential for transit agencies to implement the electrification of the public transportation. This research will help transit agencies make informed decisions regarding strategic planning and design for BEB systems by achieving the following specific objectives:

1. Develop a systematic approach to identify optimal deployment strategies for BEB systems to achieve specified planning goals.
2. Create a software tool to assist transit agencies in conducting the BEB deployment.

Specifically, a spatio-temporal optimization model is developed to minimize the cost of replacing a certain number of diesel or CNG buses (part of the fleet) with BEBs, while in compliance with existing bus operation routes and schedules. The proposed model can be used to determine the optimal spatio-temporal allocation of the BEBs, and the associated on-route and in-depot charging stations.

1.3 Outline of Report

The rest of the report is structured as follows. Section 2 summarizes literature on BEBs and charging station allocation to demonstrate research gap. Then the spatio-temporal optimization model for the BEB deployment is explained in great detail in Section 3. Section 4 demonstrates the application of our model using existing bus network operated by the Utah Transit Authority (UTA). Conclusions and implications are discussed in Section 5.

2. LITERATURE REVIEWS

2.1 Review on BEB Charging Infrastructure

BEB, also known as pure electric bus, uses electricity stored in an on-board battery to power the electric engine (Kumar and Jain, 2014; Živanović and Nikolic, 2012). While its great potential to reduce emission has been acknowledged for years, the large-scale commercialization of BEB was not available until the mid-2000s due to developments in battery technology (Lajunen, 2014; Li, 2016). A growing number of literature has since examined the BEB system. Most of the research has been focused on energy management strategy (Hu et al., 2013; Li et al., 2015; Xu et al., 2012), technological specifications (Haggis and Beback, 2010; Li, 2016), and cost-benefit analysis (Lajunen, 2014; McKenzie and Durango-Cohen, 2012; Perrotta et al., 2014). A detailed review on the development and operation of the BEB can be found in Li (2016).

Several recent studies investigated the siting of charging infrastructure for the BEB. Xylia et al. (2017) presented an optimization model to identify the distribution of fast-charging stations for fueling the bus network of Stockholm. Kunith et al. (2017) developed an optimization model to identify the tradeoff between charging infrastructure and battery size. Wang et al. (2017a) developed an optimization charging scheduling framework for BEBs in an urban transit network, with the aim of minimizing the total cost of operating a BEB system. However, each of these approaches made simplifying assumptions and could not capture the unique spatio-temporal characteristics associated with the BEB system. For example, Xylia et al. (2017) did not take into account bus operation schedule. Kunith et al. (2017) assumed charging stations are exclusively assigned to one bus route. These three studies only considered fast-charging stations on the route and did not include the overnight in-depot charging stations at bus garages. In addition, all these studies assume replacement of the entire fleet with the BEB, while transit agencies often want to replace partial fleet due to budget constraint or organizational reasons.

Another thread of related work is charging station allocation for private electric or alternative fuel vehicles. Several mathematical approaches have been proposed including flow-refueling (Kuby et al., 2009; Kuby and Lim, 2005; Mirhassani and Ebrazi, 2012), p-median (Lin et al., 2008; Nicholas et al., 2004), set covering (Frade et al., 2011; Kang and Recker, 2014; Wang and Lin, 2009), activity-based (Dong et al., 2014), agent-based (Sweda and Klabjan, 2011), and mixed-interactive models (Chung and Kwon, 2015; He et al., 2013; Jiang et al., 2012; Jung et al., 2014; Kameda and Mukai, 2011; Wang et al., 2010). All these methods strive to minimize the distance between charging stations and spatial distributions of activities throughout the day. Nevertheless, these studies are not applicable to BEB system due to the unique characteristics associated with public transit service and network. First, BEB is required to run up to 16 hours per day, whereas an average passenger car runs less than an hour per day (Glotz-Richter and Koch, 2016). As a result, the available charging time for BEBs is much less compared to private vehicles. Second, charging stations often have limited capacity (e.g. six vehicles at a time), which might cause queueing delay and consequently interfere with transit schedules. The queuing issue at charging stations has been neglected in past literature (Jung et al., 2014). Third, private electric or alternative fuel vehicle charging station allocation studies have focused on covering majority of the trips to accommodate demand. However, electric buses are mainly operating on fixed route with fixed schedule. As a result, any battery charging activity that violates vehicle schedule and/or path can be costly (Wang et al., 2017b), from an operational perspective. Last, private electric or alternative fuel vehicle charging station allocation aims at minimizing cost while fulfilling as much refueling demand as possible (Xi et al., 2013). Yet transit agencies require that charging stations satisfy all refueling demand exactly at the scheduled time and location, while minimizing cost.

2.2 Summary

As presented above, although a few studies have investigated the placement of charging infrastructure for BEB and much research has been devoted to charging station allocation for private electric vehicles, there is still a lack of method that can optimize the deployment of BEB and associated charging infrastructure while explicitly accounting for spatial and temporal constraints imposed by vehicle configuration, charging station capacity (both on-route and in-depot), and transit vehicle schedules. This research aims to fill this research gap by developing a new spatio-temporal optimization model for the strategic deployment of BEB system.

3. RESEARCH METHOD

Given the unique spatio-temporal characteristics of BEB and its supporting infrastructure, we will develop a spatio-temporal optimization model. It will identify the optimal deployment for BEBs and charging stations that can minimize the deployment cost of replacing a certain number of diesel or CNG buses with BEBs while maintaining compliance with existing bus operation routes and schedules. Consider the following notation:

Indices:
i = index of buses (entire set I)
j = index of on-route charging stations (entire set J)
g = index of in-depot charging garages (entire set G)
k = index of bus terminal sequences
t = index of temporal periods
Parameters:
c_j^R = cost associated with building one on-route charging station at j
c_g^G = cost associated with building one in-depot charging station at g
f = cost of purchasing BEB
$d_{i,k-1,k}$ = route distance between terminal sequence $k-1$ and k for bus i
l = driving range for BEB
v^R = number of BEBs that an on-route charging station can charge simultaneously
v^G = number of BEBs that an in-depot charging station can charge overnight
p = number of buses to be replaced with electric buses
M_i = daily mileage of bus i
Ω_j = set of bus terminal sequences at j
Ψ_{jt} = set of conflict bus terminal sequences at location j at time t
Φ_g = set of buses parking at garage g
Decision variables:
m_{ik} = accumulative mileage of bus i at sequence k
$$X_{ik} = \begin{cases} 1, & \text{if bus } i \text{ get charged at an on-route charging station around } k \\ 0, & \text{otherwise} \end{cases}$$
Y_j^R = number of on-route charging stations sited at j
Y_g^G = number of in-depot charging stations sited at g
$$Z_i = \begin{cases} 1, & \text{if bus } i \text{ is replaced with electric bus} \\ 0, & \text{otherwise} \end{cases}$$

Each bus, i, is running through a sequence of terminals, which are indexed by k. Each terminal indexed by j is considered as a potential location for siting on-route charging stations. Each garage indexed by g is considered as a potential location for siting in-depot charging stations. The temporal period indexed by t is defined by bus arrival and departure time at each terminal. An example is shown in Figure 3.1, where bus $i = 1$ departs terminal j_3 at time t_1, arrives at terminal j_1 at time t_2, then goes back to terminal j_3 at time t_3, and finally switches to another route arriving at terminal j_2 at time t_4. The sequence of terminals bus i passes through during a day is $j_3 \rightarrow j_1 \rightarrow j_3 \rightarrow j_2$, which will be indexed by k. The set of bus terminal sequences at j is denoted by Ω_j. For instance, $\Omega_3 = \{(i = 1, k = 1), (i = 1, k = 3)\}$ in Figure 3.1. A subset of Ω_j, Ψ_{jt}, is used to represent the set of bus terminal sequences that are at terminal j around the same time. The distance between those terminals is represented by $d_{i,k-1,k}$, which is calculated as the actual route distance. The driving range, l, represents the mileage that a BEB can drive on one electric charge. A popular goal of transit agencies in the adoption of BEBs is to replace a certain number of existing diesel or CNG buses with BEBs. Another parameter, p, is used to indicate the number of BEBs to be introduced into the bus fleet.

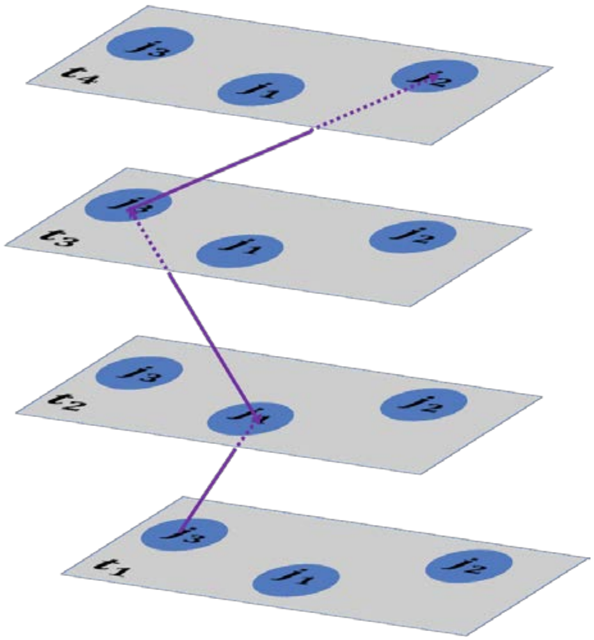

Figure 3.1 A Sample BEB Trajectory

The continuous positive decision variable, m_{ik} refers to the accumulative daily mileage of bus i at sequence k. If the bus is selected to be replaced with BEB, m_{ik} represents the accumulative mileage of the bus after charging. In other words, if a BEB gets charged, the accumulative mileage is reset to zero. X_{ik} is a binary decision variable indicating whether bus i gets charged at terminal sequence k. Z_i is a binary decision variable suggesting whether bus i is replaced with BEB. Y_j^R is an integer decision variable representing the number of on-route charging stations sited at j, since the model allows more than one charging station at each terminal. Y_g^G is an integer decision variable representing the number of in-depot charging stations sited at g.

With this notation, a new optimization model that can identify the optimal deployment strategies for BEBs and charging stations, referred to as Battery Electric Bus System Deployment problem (BEBSD), is structured as follows:

Battery Electric Bus System Deployment Problem (BEBSD)

$$\min \sum_j c_j^R Y_j^R + \sum_g c_g^G Y_g^G + \sum_i f Z_i \tag{1}$$

Subject to:

$$m_{i,k-1} + d_{i,k-1,k} \leq l + (1 - Z_i) M_i, \forall i, k \tag{2}$$

$$m_{ik} = 0, \forall i, k = 1 \tag{3}$$

$$m_{ik} \leq m_{i,k-1} + d_{i,k-1,k}, \forall i, k \geq 2 \tag{4}$$

$$m_{ik} \geq m_{i,k-1} + d_{i,k-1,k} - M_i X_{ik}, \forall i, k \geq 2 \tag{5}$$

$$m_{ik} \leq (1 - X_{ik}) M_i, \forall i, k \geq 1 \tag{6}$$

$$X_{ik} \leq Y_j^R, \forall j, (i, k) \in \Omega_j \tag{7}$$

$$X_{ik} \leq Z_i, \forall i, k \tag{8}$$

$$\sum_{(i,k)\in\Psi_{jt}} X_{ik} \leq v^R * Y_j^R, \forall j, t \quad (9)$$

$$\sum_{i\in\Phi_g} Z_i \leq v^G * Y_g^G, \forall g \quad (10)$$

$$\sum_i Z_i = p \quad (11)$$

$$X_{ik} = \{0,1\}, \forall i, k \quad (12)$$

$$Y_j^R \in integer\ \forall j$$

$$Y_g^G \in integer\ \forall g$$

$$Z_i = \{0,1\}, \forall i$$

$$m_{ik} \geq 0, \forall i, k$$

The objective (1), is to minimize the total cost of purchasing BEBs and building their required charging stations. Constraints (2) ensure that the accumulative mileage of a bus before charging cannot exceed the driving range of a BEB, if that bus is replaced with a BEB. Constraints (3) specify that the accumulative mileage of a bus at the first terminal is zero. Constraints (4)-(5) define m_{ik} to be accumulative mileage of a bus by requiring that m_{ik} equal to the total of accumulative mileage at previous terminal ($m_{i,k-1}$) and the route distance between the previous terminal and current terminal ($d_{i,k-1,k}$), if no on-route charging occurs at current terminal. Constraints (6) require m_{ik} to be reset to zero if bus i gets charged at terminal sequence k. Constraints (7) prohibit charging at terminal j unless one or more on-route charging stations are built at terminal j. Constraints (8) ensure that a bus get charged only if this bus is replaced with a BEB. Constraints (9) mandate that the number of on-route charging stations built at terminal j can satisfy the simultaneous charging needs of BEBs arriving at terminal j. It is assumed that each BEB is fully charged in the garage at night, so constraints (10) require that the number of in-depot charging stations installed at terminal g can satisfy charging needs of BEBs parked at garage g overnight. Constraint (11) stipulates that p buses are to be replaced with BEBs. Finally, integer restrictions are stipulated in constraints (12).

This model formulation mathematically addresses the unique spatio-temporal challenges associated with the deployment of the BEB system. Specifically, constraints (2)-(9) combined to ensure that on-route charging stations are sited at selected terminals so deployed p BEBs can get charged appropriately before running out of battery. This works in the following manner. Without loss of generality, suppose that a bus $i = 1$ in Figure 3.1 is selected to be replaced with a BEB. This would mean that $Z_1 = 1$. Consider constraints (2)-(6) for the case of $i = 1$ and $k = 3$:

$$m_{13} \leq l - d_{1,3,4}$$

$$m_{13} \leq m_{12} + d_{1,2,3}$$

$$m_{13} \geq m_{12} + d_{1,2,3} - M_1 X_{13}$$

$$m_{13} \leq (1 - X_{13}) M_1$$

Clearly, this bus is in not feasible for BEB replacement if $d_{1,3,4}$ is larger than l. In fact, any bus running a route whose distance is larger than the driving range is infeasible for BEB replacement as it will run out of battery before reaching a terminal charging station. Otherwise, these constraints will ensure that this bus gets charged at $k = 3$ when the remaining battery is not enough to finish the next route $3 \rightarrow 4$. For example, assume that $l = 60$ miles, $m_{12} = d_{1,1,2} = 20$ miles, $d_{1,2,3} = 30$ miles, and $d_{1,3,4} = 20$ miles, the only feasible result for decision variable m_{13} is zero ($m_{13} = 0$) with binary decision variable X_{13} equals to 1 ($X_{13} = 1$), implying that this bus gets charged at $k = 3$. Combined with known decision variable values to this point, constraint (7) associated with $i = 1$ and $k = 3$ now becomes:

$$1 \leq Y_3^R$$

This will guarantee that at least one charging station is built at terminal $j = 3$. Plugging in the known value of Z_1, constraint (8) becomes:

$$X_{13} \leq 1$$

This will allow for charging at $k = 3$. Alternatively, if this bus is not selected for BEB replacement, meaning $Z_1 = 0$, constraint (8) becomes:

$$X_{13} \leq 0$$

This will ensure that no charging occurs for unselected buses. Constraints (9) play a role when multiple BEBs require simultaneous charging at a terminal. For example, assume another bus $i = 2$ is also selected for BEB replacement and requires charging at $k = 2$, corresponding to terminal $j = 3$, around the same time ($X_{22} = 1$), constraint (9) would become:

$$2 \leq v^R * Y_3^R$$

If one charging station can only charge one bus at a time ($v^R = 1$), then at least two charging stations will be built at terminal $j = 3$. Constraints (2)−(9) also address the challenge of maintaining current bus operation schedule as they are formulated strictly based on planned space-time trajectory of each bus and any feasible solution ensures the current operation schedule to be maintained.

This BEBSD explicitly takes into account on-route charging at bus terminals and in-depot charging at garages while ensuring the replacement with BEBs does not interfere with current bus operation schedules. The BEBSD is a mixed integer programming (MIP) model and can be solved directly using commercial or open-source MIP solvers that commonly employ linear programming with branch and bound techniques, such as Gurobi, GLPK, etc. After optimally solving the BEBSD, we can identify which buses are replaced with BEBs, how many on-route charging stations are built at each terminal, how many in-depot charging stations are built at each garage, as well as when and where each BEB gets charged, so that the deployment cost is minimal for varying BEB adoption levels.

4. APPLICATION

4.1 Study Area and Data

The proposed method is used to examine potential adoption of BEB system into the bus fleet operated by the Utah Transit Authority (UTA). UTA is the primary transit provider throughout the Wasatch Front of Utah, in the United States, which includes the metropolitan areas of Salt Lake City, Park City, Provo, Ogden, and Tooele. With an annual budget of $275 million, UTA's service area covers almost 2.2 million people, accounting for 79 percent of the state's total population. UTA is operating 467 diesel or CNG buses that serve 121 fixed and flexible bus routes on a typical weekday, as of August 2016 (see Figure 2). Many of these buses are running across multiple bus routes as UTA employs vehicle interlining to reduce operating cost. The BEBSD is applied to identify optimal deployment strategies for BEB system if a certain number of diesel or CNG buses are to be replaced with BEBs. The bus fleet operation schedule, bus routes, and bus terminals are provided by UTA and based on the August 2016 operation.

A specific type of BEBs considered by UTA is Proterra's 35-foot catalyst FC+ model that can achieve 62 miles range with a standard charging time of 10-13 minutes (Proterra Catalyst Vehicle Specs, 2017). A BEB is therefore assumed to be capable of getting charged at a terminal only if it dwells at that terminal for more than 10 minutes, based on the current transit operation schedule. Given this requirement, 135 existing buses will not be able to get charged before running out of battery if they are replaced with the FC+ BEBs. This leaves 332 existing buses feasible for the potential replacement. The cost of purchasing a FC+ BEB is approximately $749,000. A bus terminal is considered a potential site for on-route charging station if one or more buses stop there for more than 10 minutes. This results in 70 potential sites for on-route charging stations (see Figure 4.1). All four bus garages in the Wasatch Front are identified as potential sites for in-depot charging stations (Figure 4.1). Given the requirement of minimal 10-minute charging time, any buses that arrive at the same terminal within the same 10-minute charging window are considered to be potentially in conflict and might need simultaneous charging at that terminal. The on-route charging station by Proterra can provide simultaneous charging for up to six FC+ BEBs, and the in-depot charging station can provide full charging for up to 12 FC+ BEBs overnight. Here we assume the cost to build an on-route charging station is approximately $499,000 across all potential bus terminals and the cost to install an in-depot charging station is approximately $50,000 across all garages. All BEB related data are obtained from Proterra.

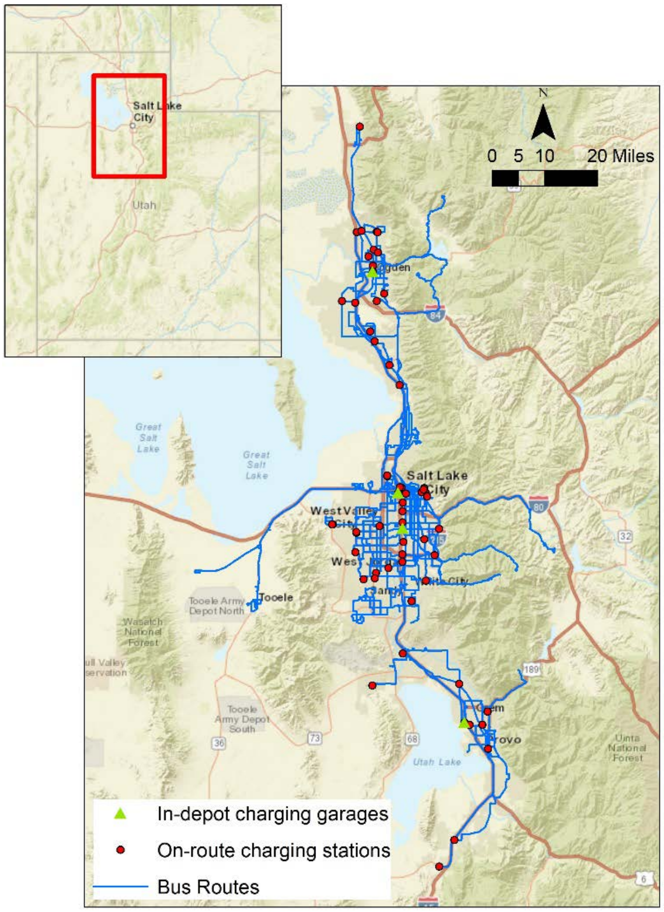

Figure 4.1 Study Area

4.2 Results

The data preprocessing to identify potential sites for charging stations (J), terminal sequences (K) for each bus, route distance between each terminal sequence for each bus ($d_{i,k-1,k}$), set of bus terminal sequences at each potential charging station (Ω_j), and a set of conflict bus terminal sequences at each potential charging station and each time period (Ψ_{jt}), is accomplished using Python. The BEBSD is structured using Python, and subsequently solved using a commercial MIP solver, Gurobi. Processing was conducted on an Intel Core i7-4770 (3.40 GHz) computer running Windows with 16 GB RAM.

The BEBSD is solved for various potential values of p—number of buses selected to be replaced with BEBs—to explore the implications of p at regional level in terms of total cost, and more locally in terms of the spatio-temporal patterns of BEB trajectories and charging stations. Every model is optimally solved with solution time ranging from 0.34 seconds to 73.22 seconds. Figure 4.2 gives the tradeoff curve associated with the cost of purchasing BEBs, cost of installing on-route charging stations, cost of installing in-depot charging stations, and total cost by each p. As more buses are replaced with BEBs (p increases), the cost of purchasing BEBs increases strictly linearly, while the cost to install charging stations shows a stepwise increase. The strict linear relationship between the number of adopted BEBs and purchasing cost is due to the consistent unit cost ($749,000), assuming no discount is associated with the size of order. The tradeoff curve associated with the costs of charging stations to serve adopted BEBs is more interesting. Specifically, there is no need for installing on-route charging stations till 111 buses are replaced with BEBs. This is because those 111 buses have a daily mileage of less than 62 miles, suggesting there is no need for on-route charging for those buses if they are replaced with BEBs. While no on-route charging station is needed, a total number of 10 in-depot charging stations will be installed at all four garages to satisfy the overnight charging demand of those 111 BEBs. When more than 111 buses are replaced with BEBs, on-route charging stations become necessary and the cost to build on-route charging stations starts to play a role in the total deployment cost of the BEB system. Given that there are 332 existing buses feasible for replacement, 221 of them will need on-route charging if they are replaced with the BEBs. Among those 221 buses, Figure 4.3 plots the maximum number of BEBs that can be served by each possible number of sited on-route charging stations. The first on-route charging station can serve up to 45 additional BEBs. However, as the growth rate of number of on-route charging stations outpaces the growth rate of number of BEBs served by them, 36 charging stations will be eventually enough to serve the entire 221 BEBs (an average of 6.13 BEBs served by one charging station).

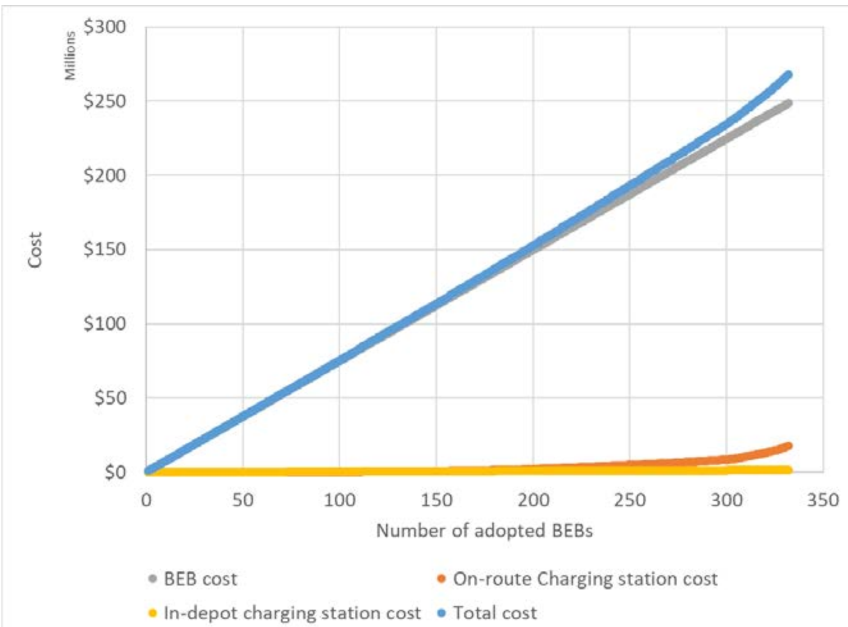

Figure 4.2 Tradeoff between Number of Adopted BEBs and Deployment Cost

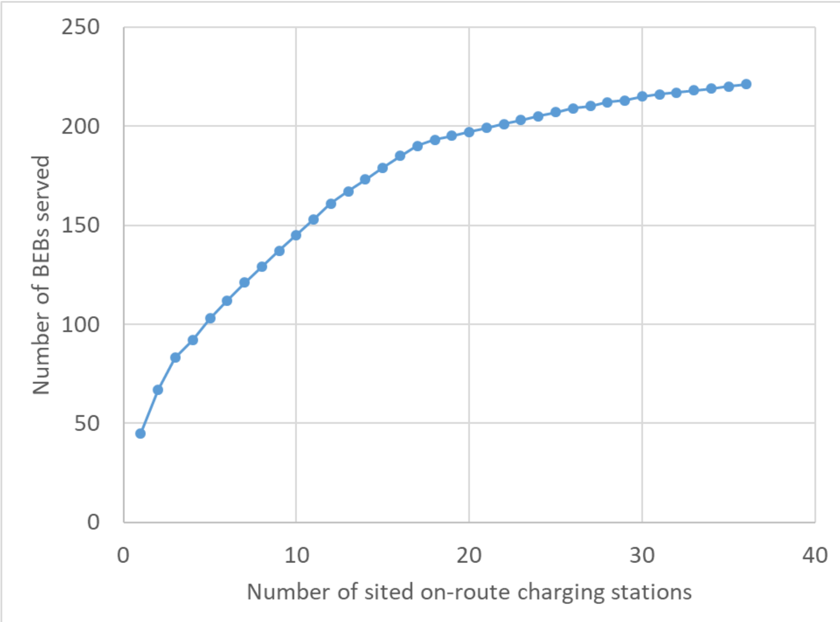

Figure 4.3 Maximum Number of BEBs That Can Be Served By The Number of Sited On-route Charging Stations

Beyond implications for the total cost and number of charging stations, each p reflects a different spatio-temporal pattern. The served routes and space-time trajectories of the 111 buses that can be replaced with BEBs without requiring on-route charging are shown in Figure 4.4. The daily mileage of those buses varies from 9.19 miles to 60.18 miles, indicating that a full charging during the night at garage will be sufficient for their daily operation, thus on-route charging is not required. These 111 buses serve 51 bus routes with distances ranging from 4.16 miles to 57.84 miles and an average of 16.10 miles, as depicted in Figure 4.4a. The served bus routes are simplified as straight lines between origin and destination terminals in Figure 4.4b to better demonstrate daily trajectories of these BEBs. We can find that these buses either serve long-distance routes once or twice per day or serve short routes multiple times. Either way, their total daily mileage is still within 62 miles and daily operation time is relatively short.

Figure 4.5 shows the 2D space and 3D space-time on-route charging configuration when only one on-route charging station is sited. In this scenario, the on-route charging station is sited at Salt Lake Central Station, which is the main intermodal hub in Salt Lake City, Utah. Forty-five adopted BEBs can be served by this single station, on top of the aforementioned 111 BEBs. Those 45 BEBs serve 16 bus routes whose distance ranges from 4.48 miles to 58.17 miles with an average of 14.39 miles as depicted in Figure 4.5a. The daily mileage of these 45 BEBs varies from 88.77 miles to 251.27 miles and detailed daily trajectories are shown in Figure 4.5b. Clearly, the incorporation of one on-route charging station significantly increases the replaceable buses' daily mileage and operation time compared to those in Figure 4.4. The pink 3D points in Figure 4.5b describe when and where the BEBs get charged. While it is hard to identify all of them in Figure 4.5b due to the overlap of those points, the sited on-route charging station will provide charging for these BEBs for 318 times from 6:30 am to 21:50 pm. A total of 14 in-depot charging stations are installed at four garages to provide over-night charging for the entire 156 (111+45) BEBs.

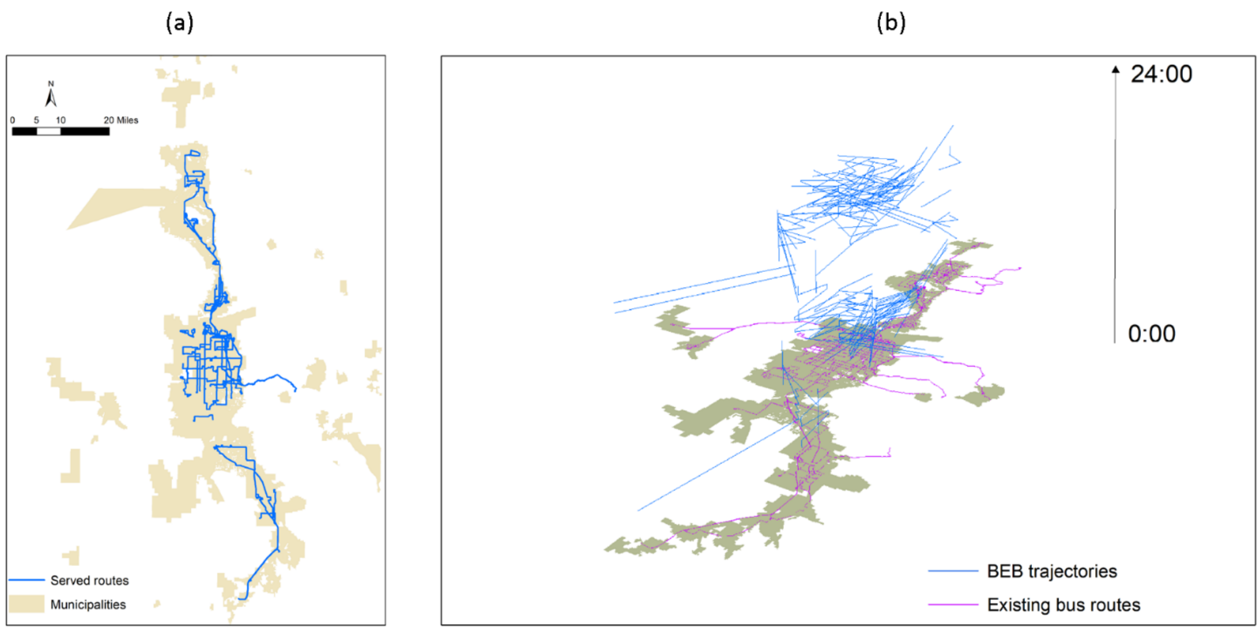

Figure 4.4 Served Routes and Space-time Trajectories of BEBs When No On-route Charging Station is Built

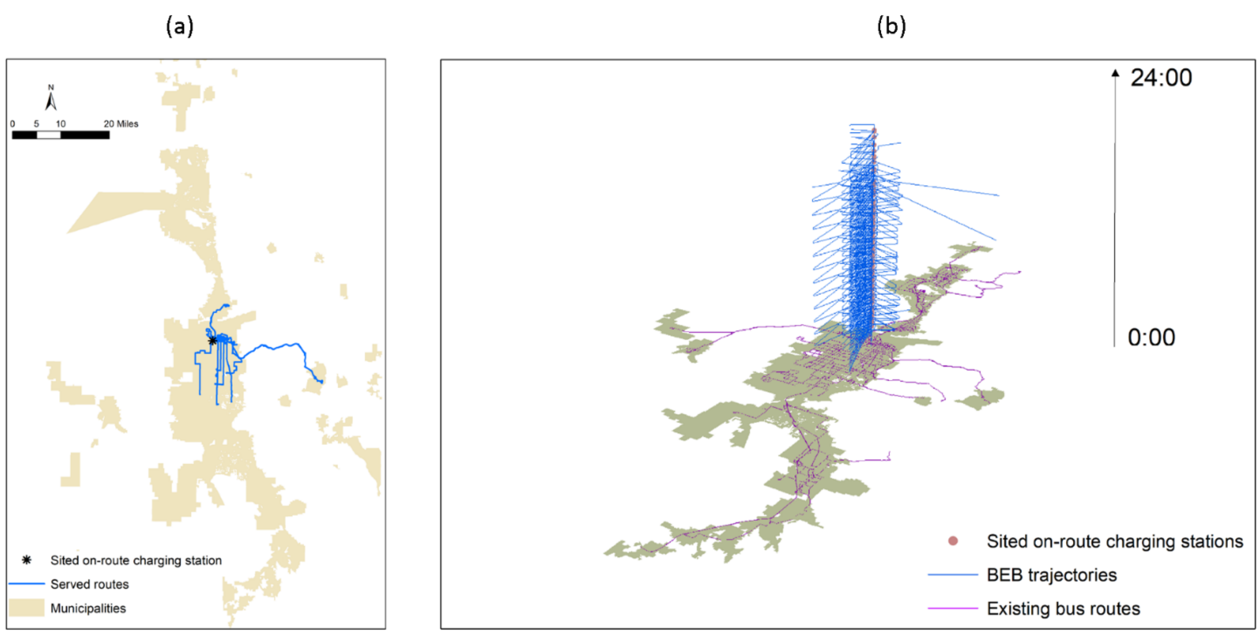

Figure 4.5 Served Routes and Space-time Trajectories of BEBs When One On-route Charging Station is Built

The 2D space and 3D space-time on-route charging configuration when five on-route charging stations are sited to serve 103 newly adopted BEBs are shown in Figure 4.6. In addition to Salt Lake Central Station, another terminal at Salt Lake City downtown (State Street @ 355 S) was also selected to accommodate one charging station to satisfy the busy operation schedule in the downtown area. The other three charging stations will be built in Ogden, Lehi, and Millcreek, which are north, south, and east of Salt Lake City, respectively, to extensively serve BEBs' operation in the metropolitan area. Those 103 BEBs serve 29 bus routes whose distance ranges from 1.81 miles to 58.17 miles with an average of 16.73 miles as depicted in Figure 4.6a. The daily mileage of these BEBs varies from 88.77 miles to 378.54

miles, which is larger than the previous two scenarios. The additional charging stations provide extra charging flexibility. The daily trajectories of these BEBs and their corresponding charging timestamps and locations are depicted in Figure 4.6b. Those five sited on-route stations will provide charging for the adopted BEBs for 672 times from 6:05 am to 23:45 pm. A total of 20 in-depot charging stations are installed at four garages to provide overnight charging for the entire 214 (111+103) BEBs.

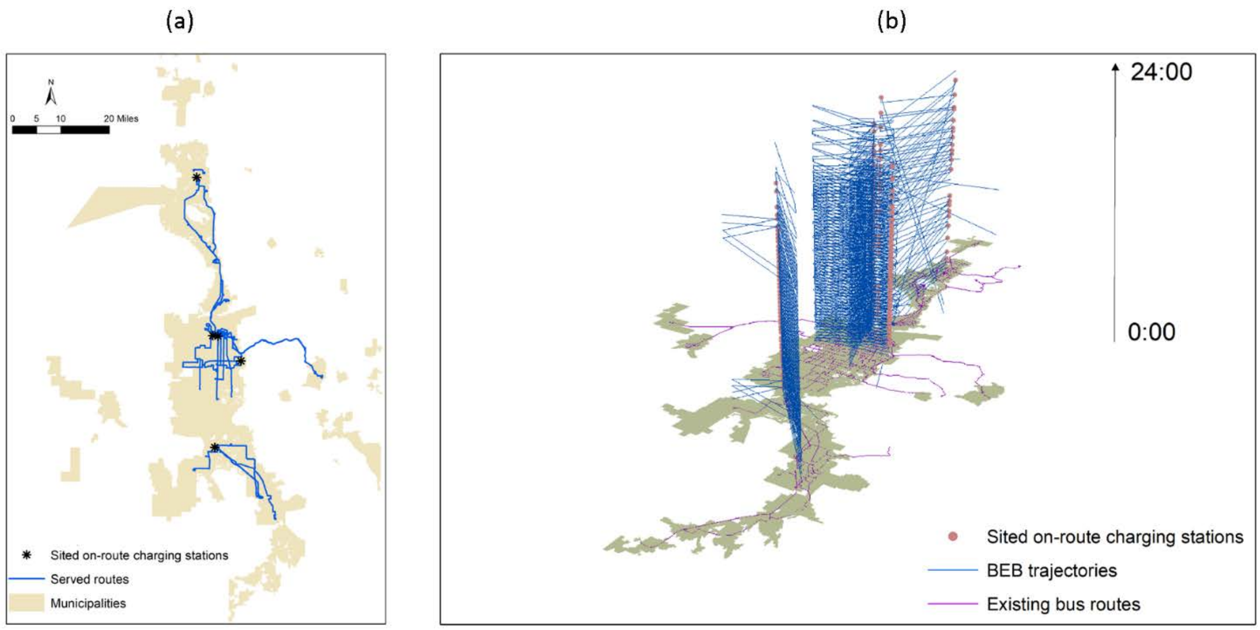

Figure 4.6 Served Routes and Space-time Trajectories of BEBs When Five On-route Charging Stations are Built

Finally, the 2D space and 3D space-time on-route charging configuration when all feasible buses are replaced with BEBs are shown in Figure 4.7. A total of 36 charging stations were sited throughout the entire metropolitan area to provide on-route charging for 221 BEBs. 67 bus routes will be serviced by these BEBs, with an average distance of 16.53 miles as depicted in Figure 4.7a. The daily mileage of these BEBs gets extended to 62.88-456.69 miles due to a much denser deployment of charging stations. The daily trajectories of these BEBs and their corresponding charging timestamps and locations are depicted in Figure 4.7b. Those 36 sited on-route stations will provide charging for the adopted BEBs 1,576 times from 5:30 am to 23:45 pm. Twenty-eight in-depot charging stations were installed at four garages to provide overnight charging for the entire 332 (111+221) BEBs.

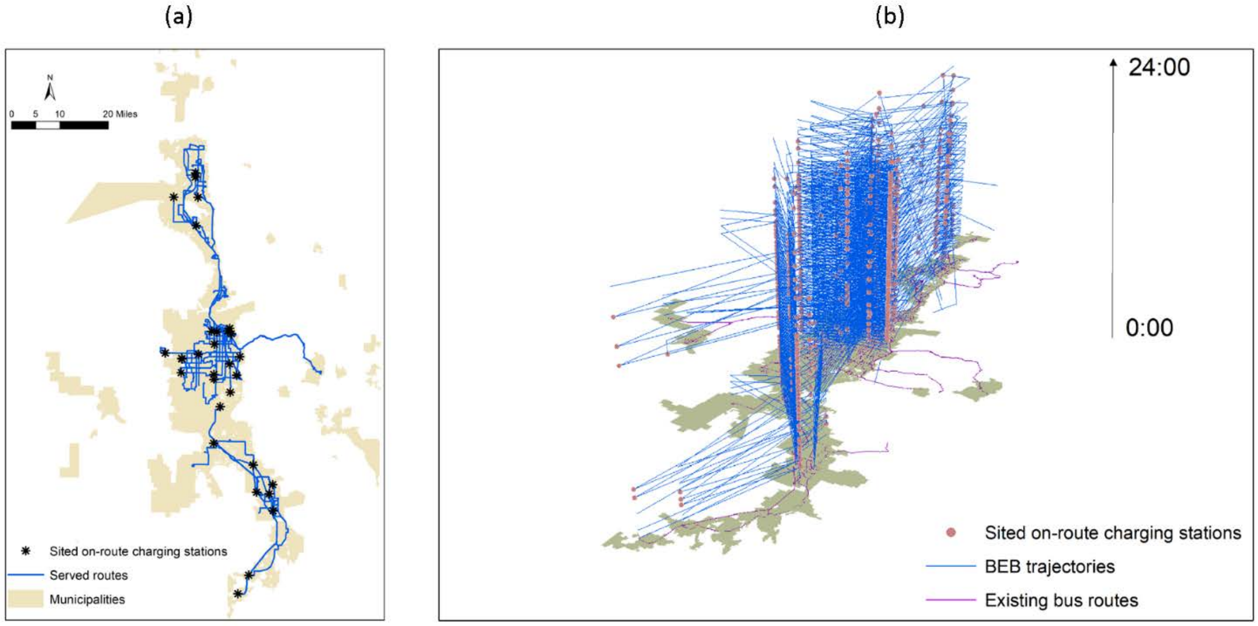

Figure 4.7 Served Routes and Space-time Trajectories of BEBs When 36 On-route Charging Stations are Built

5. DISCUSSIONS AND CONCLUSIONS

There are several issues worth further discussion, based on the results presented. First, Figure 4.3 shows that the number of BEBs introduced to the existing network demonstrates a logarithmic-like pattern with the number of on-route charging stations required. This implies that at the initial BEB deployment phase, charging stations and BEBs can be selected at highly dense service locations, e.g. downtown or Central Business District, where several routes are operating to cover relatively smaller geographical areas and are passing a main transit hub multiple times a day. Figures 4.5b and 4.6b validate such implication. As *p* grows, the number of on-route charging stations also increases to serve those adopted BEBs. Note that such expansion results in a wider coverage of the network for both on-route charging stations and BEBs, particularly extending to outskirts. Those routes tend to have longer distances to serve low-density service areas with fewer number of buses. This forces installation of several on-route charging stations at locations that will only serve one or limited number of BEBs per day. The space-time trajectories presented in the three levels of BEB adoptions (shown in Figures 4.5 b through 4.7b) demonstrate such differences.

The BEB network expansion pattern also has important policy implication. At the initial stage, a significant portion (e.g. 20 percent) of diesel or CNG buses can be replaced with BEBs, and with limited number of on-route charging stations needed, if deployed properly. This represents a cost-effective strategy for BEB deployment. As demonstrated earlier, the number of on-route charging stations required for serving the same number of BEBs in denser areas of the transit network is significantly less than in low-density service region. The high-density service areas represent regions with higher demand, induced by higher level of population and/or job opportunities served by many transit routes. This makes BEBs a favorable choice for locations with larger population and job density that are serviced by high density transit network. The BEBSD also enables comparison of short-term (e.g. 15 percent of bus fleet is replaced with BEBs), mid-term (e.g. 50 percent of bus fleet is replaced with BEBs), and long-term (i.e. the entire bus fleet is replaced with BEBs) investment planning. Transit agencies would be able to make planning-level decisions based on their short- and long-term strategic goals (e.g. how many BEBs are needed in the next 5, 10, and 20 years) and resources (budget level in the next 5, 10, 20 years) to find the investment tipping point.

The BEBSD could be extended to incorporate other prioritized goals set forth by the transit agencies, such as maximizing fuel efficiency, environmental benefits, and air quality improvement. For example, while the 111 buses in Figure 4.4 could be replaced with BEBs without the need to build any on-route charging station, they might not be the best candidates if the goal is to maximize fuel saving and emission reduction as those retrofitted fleets have short daily mileage and operation time. Integrating various and competing goals into BEBSD will allow transit agencies to address their specific and prioritized needs, but this remains for future research. The BEBSD currently only accounts for the capital investment of the BEB system, due to data availability. The operation cost associated with the BEB system could also be included in the BEBSD by adding maintenance/labor cost and charging cost if those data become available in the future. Also, we currently consider bus terminal as a potential site for on-route charging station if one or more buses stop there for more than 10 minutes. Other factors, such as the possibility of connecting to the power grid, land ownership and space issues, could also impact whether it is feasible to build on-route charging stations at a bus terminal.

The adoption of the electric bus is a quite complex process that requires significant investment and cautious planning for the bus fleet and supporting infrastructures. While previous research has investigated the system design of public infrastructures to support private electric vehicles, very few studies to date have attempted such network design for electric bus due to the unique spatio-temporal features and challenges associated with transit operations. This research fills this gap by developing a spatio-temporal analytical method to assist agencies in identifying optimal deployment strategies for BEB system using a combination of Geographic Information System (GIS) and optimization techniques. The application results demonstrate that the BEBSD is effective in selecting the retrofitted buses, routes, and charging stations in a transit network for BEB deployment. The method can identify the optimal spatio-temporal deployment for BEBs and charging stations that can minimize the deployment cost of replacing a certain number of diesel or CNG buses with BEBs, while satisfying transit operation constraints such as maintaining existing bus operation routes and schedules. As many transit agencies are testing BEBs and considering the integration of BEBs into future fleet, this research sets the foundation for agencies to evaluate the capital and operational costs associated with deployment of various types of BEBs, and make informed decisions regarding strategic planning and design of BEB systems.

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APPENDIX: SOFTWARE TUTURIAL

Introduction

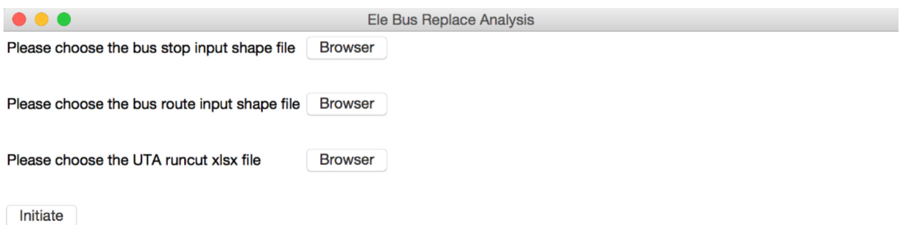
Electric bus Analysis program is for evaluating and finding the best plan to replace a certain number of current bus with electric bus. The optimization is based on linear programming by using glpk package.

Prerequisite

* Windows system
* launchEleAnalysis.exe
* glpk package which contains glpsol.exe.

How to use:

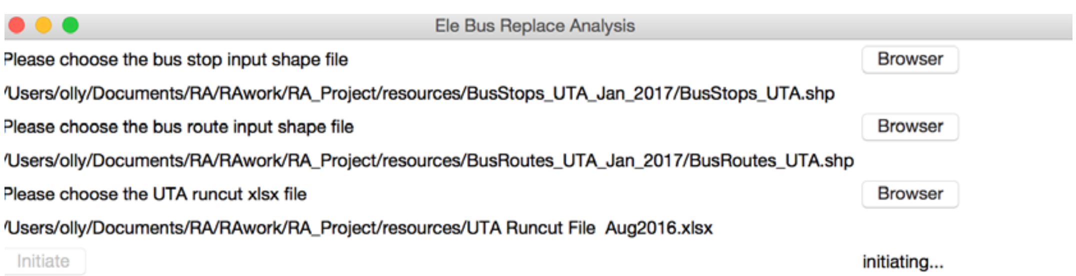
1.Files selection:



You can select the three input files by clicking the Browser buttons, from top to bottom are:
1. bus stops shapefile
2. bus routes shapefile
3. runcut excel file.

Notes: The file extensions of shapefiles should be .shp.

***
After selecting all the input files, click the initiate button.



Input format:
Excel file example:

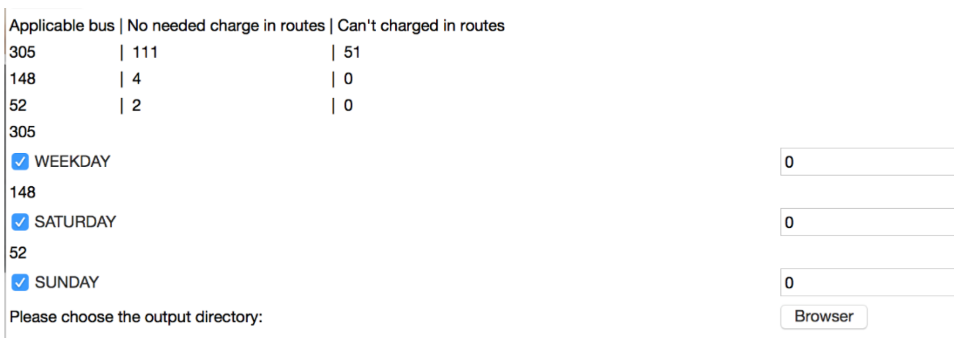
LineAbbr	ServiceName	DirectionName	block_num	trip_id	from_stop	FromTime	to_stop	ToTime
217	WEEKDAY	TO 7800 S TRAX	1000	2795344	1300 N @ 1710 W	4:09	REDWOOD RD @ 8021 S	5:20
217	WEEKDAY	TO ROSE PARK	1000	2795404	REDWOOD RD @ 8021 S	5:43	1300 N @ 1710 W	6:45
217	WEEKDAY	TO 7800 S TRAX	1000	2795343	1300 N @ 1710 W	6:54	REDWOOD RD @ 8021 S	8:05
217	WEEKDAY	TO ROSE PARK	1000	2795403	REDWOOD RD @ 8021 S	8:11	1300 N @ 1710 W	9:15
217	WEEKDAY	TO 7800 S TRAX	1000	2795342	1300 N @ 1710 W	9:24	REDWOOD RD @ 8021 S	10:35

***

2. Select the number and running day of buses needed to replace:

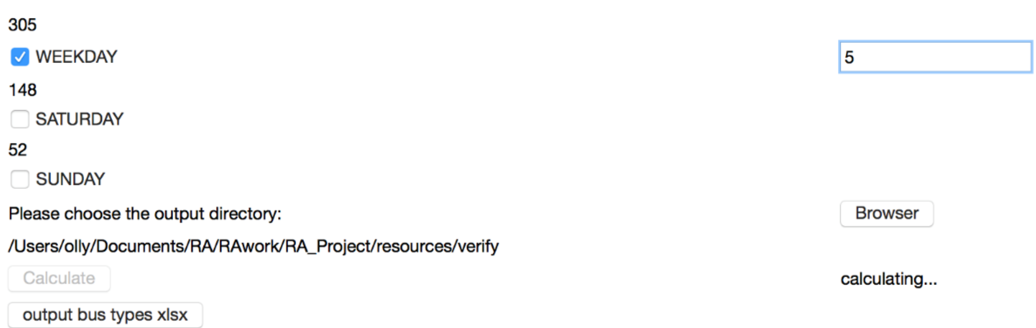
When the initiation is done, the interface will show a table which describes three types of buses.

The first one is applicable bus to be replaced, the second is the buses can run the routes without charging, the last kind of buses is impossible to be charged since it has at least one route whose distance is larger than the largest distance a bus can run without charging.

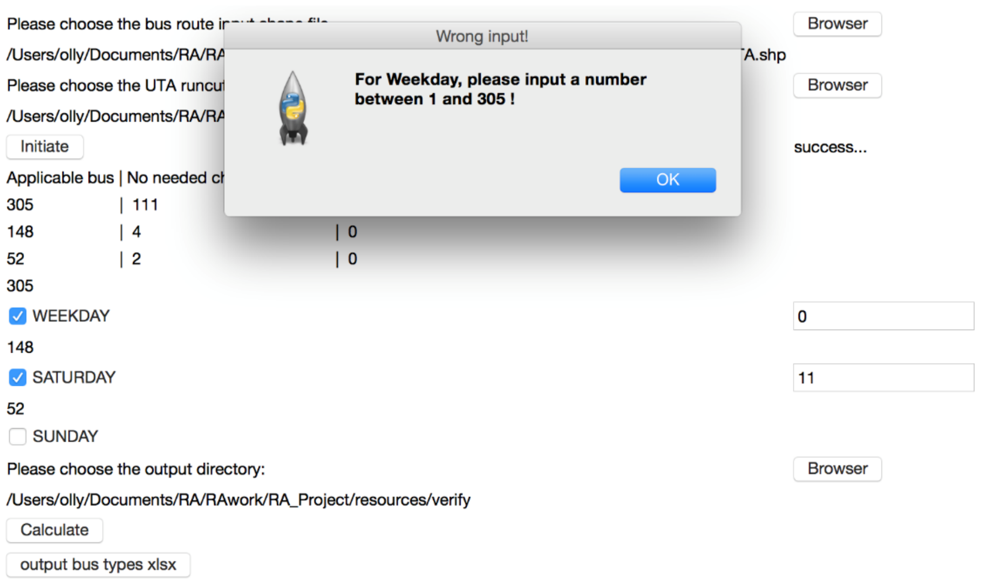


By putting a tick in front of the day label, and typing a valid number indicated above the day label, it means you want to replace how many buses run on weekday, Saturday or Sunday.

Then click the Browser button to choose your output folder.



Please select the number in a valid range which is from 1 to the maximum number of applicable buses, otherwise, it will show an error message.



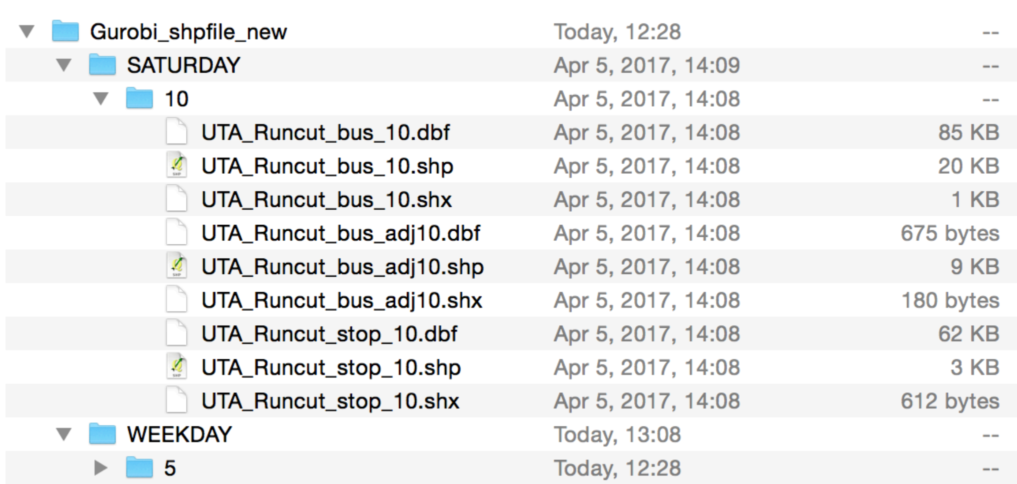
Also, you can calculate and output an excel file about bus types.

3.The results:

The files are under the folder you chose.

***

For example:



The Saturday folder means the number of buses you want to replace is run on Saturday, and '10' means the number of buses you want to replace with electric buses.

In the '5' folder, there are three different shapefiles.

UTA_Runcut_bus_10.shp:
3D normal bus route shapefile.

UTA_Runcut_bus_adj_10.shp:
3D adjacent bus route shapefile.

UTA_Runcut_stop_10.shp:
3D bus stop shapefile.

***

Output format:
For Weekday, Saturday, Sunday buses, each has 5 table, which are applicable buses, buses who has at least one route larger than the distance an electric bus can run without charging, the buses whose total route distance less than 62 miles, the buses whose total route distance less than 251 miles, the buses whose total route distance larger than 251 miles.

And for each table, it contains block_num(bus_num), total run time, and total route length:

block_num	total_time	total_length
2049	367	161.25
2050	274	91.97
2051	311	227.26