ENABLE DECISION MAKING FOR BATTERY ELECTRIC BUS DEPLOYMENT USING ROBUST HIGH-RESOLUTION INTERDEPENDENT VISUALIZATION

Gabrielius A. Kudirka
School of Computing
University of Utah, Salt Lake City, Utah, 84112
Email: u1216377@utah.edu

Xinyuan Yan
School of Computing
University of Utah, Salt Lake City, Utah, 84112
Email: u1320974@utah.edu

Sarah Kunzler
School of Computing
University of Utah, Salt Lake City, Utah, 84112
Email: u1396293@utah.edu

Yirong Zhou
Department of Civil & Environmental Engineering
University of Utah, Salt Lake City, Utah, 84112
Email: yirong.zhou@utah.edu

Bei Wang, Ph.D.
School of Computing
University of Utah, Salt Lake City, Utah, 84112
Email: beiwang@sci.utah.edu

Xiaoyue Cathy Liu, Ph.D., P.E., Corresponding Author
Department of Civil & Environmental Engineering
University of Utah, Salt Lake City, Utah, 84112
Email: cathy.liu@utah.edu

Word Count: 3360 words
Submission Date: January 20, 2023

ABSTRACT

Encouraged by the advancement of battery technology, the transition from diesel or Compressed-Natural-Gas to fully zero-emission bus fleets has been the trend in the United States. Policymakers and transit agencies have set up goals to accelerate such transition yet various challenges that are by nature, institutional, technological and/or financial still present themselves. For example, in terms of institutional challenges, cities without a proper fleet management framework will have a hard time transiting directly to battery electric buses (BEBs). Also, BEBs will require a significantly larger upfront financial investment which could hinder the chance of deploying BEBs. From the technological perspective, successfully deploying BEBs requires a combined knowledge of transportation system, energy/power system, optimization, and risk assessment. To address the aforementioned challenges, we design a bi-objective optimization framework that takes cost and environmental equity into consideration. The flexible framework can also be applied to optimize any transit-related objectives. Built upon this framework, we develop a prototype of visualization tool, referred to as the **BEBExplorer**. Users are able to test, visualize, and explore deployment scenarios given all combinations of constraints on budget, bus schedule, bus routing, locations of charging stations, etc.

Keywords: Battery-Electric Bus, Visualization, Charging Station, Smart City

INTRODUCTION

The transit industry is rapidly transitioning to battery-electric fleets because of the direct environmental and financial benefits they could offer such as zero emissions, less noise, and lower maintenance costs. Yet the unique spatiotemporal characteristics associated with transit system, charging requirements, as well as various objectives when prioritizing the fleet electrification, requires the system operators and/or decision-makers to fully understand the status of transit system and energy/power system, in order to make informed deployment decisions. In an effort to assist with such decision-making process, a bi-objective spatiotemporal optimization model was developed (*1*) for the strategic deployment of Battery Electric Bus (BEB) to minimize the cost of purchasing BEBs, on-route and in-depot charging stations, and to maximize the environmental equity for disadvantaged populations. The model was implemented onto the transit network operated by the Utah Transit Authority (UTA) to offer insights on the benefits gained as a result of BEB deployment. Optimal deployment plans under different budgets are provided to illustrate the effectiveness of the model. This research set the foundation for transit agencies to develop optimal deployment strategies for BEB systems when multiple goals need to be considered, allowing planners and decision-makers to create a transportation ecosystem that better serves livable and sustainable communities.

As agencies such as UTA adopt the model and results, they desire to have a tool that could enable detailed spatiotemporal monitoring of components for the BEB system (e.g. locations of BEBs, the state-of-charge of batteries, charging station energy consumption at each specific timestamp), so that the integration of BEBs into the power/grid system as well as its operating condition could be better understood.

To this end, this paper presents the development of an innovative visualization framework that allows transit operators/planners as well as decision-makers to explore the interdependency of the BEB transit system and energy infrastructure in both spatial and temporal dimensions with high resolution. The visualization framework is built upon the scenario-based optimization modeling effort in our previous research (*1*), and allows agencies to make phase-wise (short-, mid-, or long-term) decisions based on investment resources and strategic goals. The strong transferability of the visualization framework is directly useful to practitioners to easily implement our optimization model for their own transit networks and allow them to build interactive visualizations to assist with decision making.

We refer to our prototype visualization tool as the **BEBExplorer** in this paper. With **BEBExplorer**, users are able to interactively perform visual analysis and comparison of different deployment strategies of BEBs, which are generated by our previous optimization model. Specifically, our tool facilitates the analysis of each strategy from two aspects. First, four seamlessly linked views, represented by maps, tables, and charts, work together through interactions and animations for spatiotemporal exploration of each BEB plan. This includes accessing the detailed information of BEBs, routes, and charging stations at a specific timestamp. Second, we apply the design rationale from (*2*) throughout this tool, where users have an overview of each plan first, then conduct zooming and filtering for high-level analysis, and finally investigate details of data of interest such as a specific BEB. In addition, **BEBExplorer** is capable of comparing different plans in terms of cost, environmental equity, daily miles electrified, etc.

BI-OBJECTIVE OPTIMIZATION MODEL FOR BEB DEPLOYMENT

For completeness, we present the optimization framework of our previous study here (*1*), which is capable of maximizing environmental equity and minimizing cost for BEB deployment. The optimization problem is formulated as follows:

Objective:

$$\max \sum_i E_i Z_i \tag{1}$$

$$\max \sum_i C^B Z_i + \sum_m C^O_m Y^O_m + \sum_n C^I_n Y^I_n \tag{2}$$

Subject to:

$$\begin{aligned}
D_{i,s-1} + l_{i,s-1,s} &\leq R + (1 - Z_i) TD_i, \ \ \forall i, s \geq 2 && (3)\\
D_{i,1} &= 0, \ \ \forall i && (4)\\
D_{i,s} &\leq D_{i,s-1} + l_{i,s-1,s}, \ \ \forall i, s \geq 2 && (5)\\
D_{i,s} &\geq D_{i,s-1} + l_{i,s-1,s} - TD_i X_{is}, \ \ \forall i, s \geq 2 && (6)\\
D_{i,s} &\leq (1 - X_{is}) TD_i, \ \ \forall i, s \geq 1 && (7)\\
X_{is} &\leq Y^O_m, \ \ \forall m, (i,s) \in \alpha_m && (8)\\
X_{is} &\leq Z_i, \ \ \forall i, s && (9)\\
\sum_{(i,s) \in \beta_{mt}} X_{is} &\leq p^O Y^O_m, \ \ \forall m, t && (10)\\
\sum_{i \in \gamma_n} Z_i &\leq p^I Y^I_n, \ \ \forall n && (11)\\
X_{is} &\in \{0, 1\}, \ \ \forall i, s && (12)\\
Z_i &\in \{0, 1\}, \ \ \forall i && (13)\\
Y^O_m, Y^I_n &\in N^+, \ \ \forall m, n && (14)\\
D_{i,s} &\geq 0, \ \ \forall i, s && (15)
\end{aligned}$$

Indices:

i = index of buses

m = index of on-route charging stations

n = index of in-depot charging stations

s = index of bus terminal sequence

t = index of time sequence

Parameters:

E_i = environmental equity gained by replacing bus i

C^O_m = cost of building one on-route charging stations at m

C^I_n = cost of building one in-depot charging stations at n

C^B = cost of purchasing one BEB

p^O = number of BEBs that on-route charging station can charge simultaneously

p^I = number of BEBs that on-route charging station can charge simultaneously

$l_{i,s-1,s}$ = route distance between terminals s and $s-1$ for bus i

R = driving range for BEB without charging

TD_i = total driving distance for bus i in one day

α_m = set of bus terminal sequence at m

β_{mt} = set of sequences for bus arriving at m and time t

γ_n = set of buses charged at n overnight

Decision Variables:

Y_m^O = number of on-route charging stations built at m

Y_n^I = number of in-depot charging stations built at n

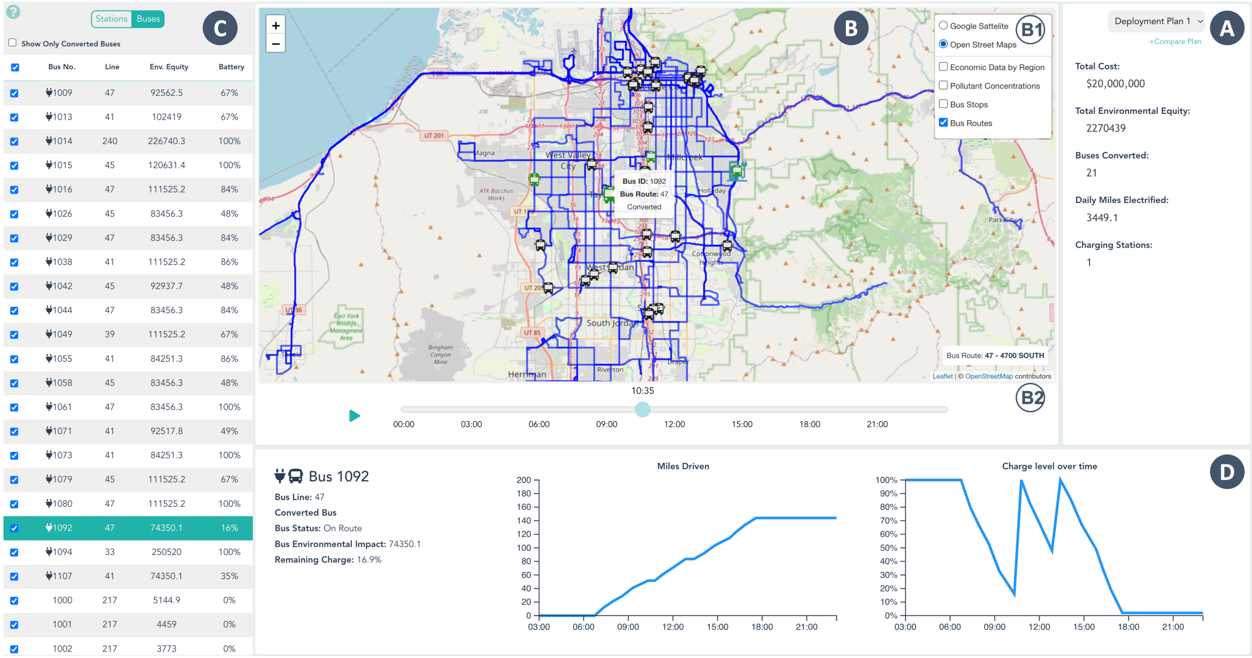
D_{is} = distance traveled by bus i at sequence s

$$X_{is} = \begin{cases} 1, & \text{bus } i \text{ is charged at } s \\ 0, & \text{otherwise} \end{cases}$$

$$Z_i = \begin{cases} 1, & \text{bus } i \text{ is replaced with BEB} \\ 0, & \text{otherwise} \end{cases}$$

Constraint (3) makes sure that BEB will not run out of battery on route. Constraint (4) sets accumulated mileage of BEB to 0 at Stop 1. Constraints (5) and (6) correctly accumulate the mileage of BEB. Constraint (7) resets accumulated mileage to 0 after charging (partially charging is not allowed in the current framework). Constraint (8) enforces that BEB can only be charged at one terminal unless there are built on-route charging stations. Constraint (9) excludes diesel buses from the constraints. Constraints (10) and (11) ensure there will be enough on-route and in-depot charging stations in the terminals. All constraints jointly makes sure that only buses that are feasible for replacement are considered and the current bus routes and schedules are not disturbed after deploying BEBs. In the rest of the paper, all visualization implementation is based upon this optimization framework.

VISUALIZATION FRAMEWORK



☐ Show Only Converted Buses

☑	Bus No.	Line	Env. Equity	Battery
☑	1009	47	92562.5	67%
☑	1013	41	102419	67%
☑	1014	240	226740.3	100%
☑	1015	45	120631.4	100%
☑	1016	47	111525.2	84%
☑	1026	45	83456.3	48%
☑	1029	47	83456.3	84%
☑	1038	41	111525.2	86%
☑	1042	45	92937.7	48%
☑	1044	47	83456.3	84%
☑	1049	39	111525.2	67%
☑	1055	41	84251.3	86%
☑	1058	45	83456.3	48%
☑	1061	47	83456.3	100%
☑	1071	41	92517.8	49%
☑	1073	41	84251.3	100%
☑	1079	45	111525.2	67%
☑	1080	47	111525.2	100%
☑	1092	47	74350.1	16%
☑	1094	33	250520	100%
☑	1107	41	74350.1	35%
☑	1000	217	5144.9	0%
☑	1001	217	4459	0%
☑	1002	217	3773	0%

○ Google Sattelite
● Open Street Maps
☐ Economic Data by Region
☐ Pollutant Concentrations
☐ Bus Stops
☑ Bus Routes

Bus Route: **47 - 4700 SOUTH**

Deployment Plan 1
+Compare Plan

Total Cost: $20,000,000

Total Environmental Equity: 2270439

Buses Converted: 21

Daily Miles Electrified: 3449.1

Charging Stations: 1

Bus 1092

Bus Line: 47

Converted Bus

Bus Status: On Route

Bus Environmental Impact: 74350.1

Remaining Charge: 16.9%

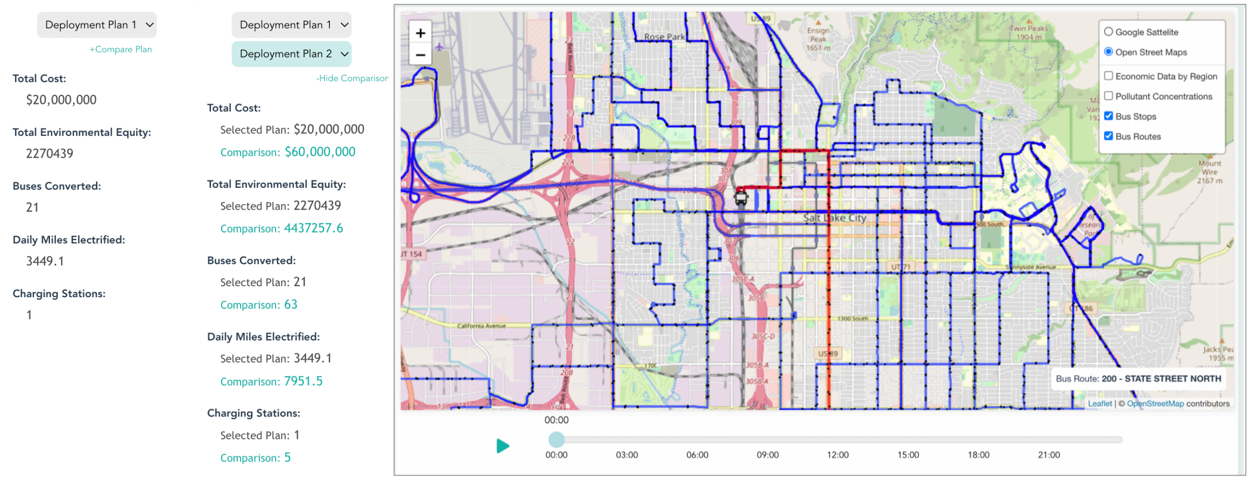
FIGURE 1 With BEBExplorer, users can interactively explore the interdependency of the BEB transit system and energy infrastructure spatially and temporally with high resolution.

The visualization system aims to enable the users — system operators and/or decision makers — to explore the condition of the interdependent BEB system and power system simultaneously, to ensure the reliable operation of both systems. It allows effective monitoring of BEB operation and its associated power consumption in high spatiotemporal resolution, such as the locations of BEBs, the state-of-charge of batteries, charging station energy consumption, etc. It also provides visual cues for insights discovery, and offers embedded chart viewing options that enable separate and focused visualizations of the two systems.

As shown in Figure 1, our system, **BEBExplorer**, consists of four views in the interface that work collectively towards the spatiotemporal analysis of BEB deployment plans. The *Statistics View* (**A**) displays the statistical information from a selected deployment plan, and enables comparisons between a pair of plans. The *Map View* (**B**) visualizes the spatial locations of buses, routes, and charging stations over time. The *Table View* (**C**) shows a list of buses and charging stations under the selected plan. The *Chart View* (**D**) presents detailed information about a bus or a charging station selected in the *Map View* or the *Table View*. In addition, it provides rich interactions for linking the four views together. In the current prototype, **BEBExplorer** includes three deployment plans generated by our optimization model, each with varying levels of BEB deployment.

In our framework, we adopt the design principles of "overview first, zoom and filter, and details on demand" (*2*) to design effective visualizations and interactions. Using **BEBExplorer**, users can first select a deployment plan and get an overview that includes statistical information from (**A**), spatial distribution from (**B**), and its associated buses and charging stations from (**C**). Then, users can apply multiple interactions on the map in (**B**) for a global analysis, such as zooming, style customization, and route filtering. Finally, users can select a bus or a charging station of interest for detailed information shown in (**D**). We now introduce the four views separately and describe how they are seamlessly linked together through interactions.

Statistics View (A)


Deployment Plan 1

Total Cost:
$20,000,000

Total Environmental Equity:
2270439

Buses Converted:
21

Daily Miles Electrified:
3449.1

Charging Stations:
1

Deployment Plan 1
Deployment Plan 2

Total Cost:
Selected Plan: $20,000,000
Comparison: $60,000,000

Total Environmental Equity:
Selected Plan: 2270439
Comparison: 4437257.6

Buses Converted:
Selected Plan: 21
Comparison: 63

Daily Miles Electrified:
Selected Plan: 3449.1
Comparison: 7951.5

Charging Stations:
Selected Plan: 1
Comparison: 5

○ Google Sattelite
● Open Street Maps
☐ Economic Data by Region
☐ Pollutant Concentrations
☑ Bus Stops
☑ Bus Routes

Bus Route: **200 - STATE STREET NORTH**

FIGURE 2 Left shows statistics of Plan 1, while middle shows a comparison between the selected Plan 1 and Plan 2. Right gives a zoomed-in view after the selection of a bus route.

As a starting point, the *Statistics View* allows users to select one of the three deployment plans and displays its statistical information. As shown in Figure 2 (left), the first deployment plan is selected by showing its total cost, total environmental equality, the number of converted buses, daily miles electrified, and the number of charging stations. This view also enables the comparison between a selected plan (Plan 1) and another plan (Plan 2), see Figure 2 (middle).

Map View (B)

After selecting a deployment plan from the *Statistics View* (**A**), all buses in the transit system and charging stations from this plan are displayed at their locations for a given time of the day. Meanwhile, the *Map View* (**B**) provides the users with a *Map Customization* (**B1**) for customizing the style of the map and a *Time Slider* (**B2**) for displaying the movements of buses at a specific time of the day or across a time interval.

As shown in Figure 1(**B**), a background map (from OpenStreetMap) is centered at Salt Lake City and supports zooming and dragging. The bus routes are shown in blue. A bus route becomes red when it is hovered over, and the route name is displayed at the lower right-hand corner of the map. Upon clicking on a route, buses not on the selected route are hidden to allow for a route-specific visualization, see Figure 2 (right). The opacity of a route on a given section of the map corresponds to the number of overlapping routes in that section. By right-clicking a section where routes overlap, users can change which overlapping route they wish to select at that segment.

We use icons to represent buses and charging stations on the map, in which converted (BEB) and non-converted buses (non-BEB) are shown in green and black, respectively. A tooltip appears by hovering over a bus or a charging station to display information such as IDs and route names. After clicking on a bus or a charging station, the selected item becomes enlarged, the corresponding row in the *Table View* (**C**) is highlighted, and its detailed information is shown in the *Chart View* (**D**).

As shown in Figure 1(**B1**), the *Map View* displays the selectable overlay options for the map, and we use “Open Street Maps” and “Bus Routes” by default as shown in Figure 1(**A**). Figure 3 illustrates cases where we apply differing overlays, including a Google satellite view, bus stops, the pollutant concentrations, and the economic data by region. In this view, users can also hide or view the bus routes and bus stops on the map. For the pollutant and economic data, each region on the map is clickable for accessing the specific measurements. These four overlays can be combined selectively to enable advanced analysis of the deployment data.

The Time Slider in Figure 1(**B2**) controls the time of day at which the data is visualized. Manually sliding the slider to a specific time updates the bus locations and charging information in (**B**). Pressing the play button automatically changes the time of day at a rate of 10 minutes per second, and simultaneously updates the information visualized.

Table View (C)

The *Table View* lists all buses in the transit system and charging stations in a deployment plan, which can be selected and sorted via the column headers. For each bus, this table lists the its ID (i.e. Bus no.), line number, environmental equity measurement, and remaining battery charge at the given time (for buses that are converted to BEB under the selected plan). Specifically, buses with a charge icon by their ID have been converted under the current plan.

This view also supports several interactions linking to the *Map View* (**B**) and the *Chart View* (**D**). By checking/unchecking buses in the table, the associated buses are shown/hidden on the map in Figure 1(**B**). Users can hide or show all non-converted buses. By clicking on a bus or a charging station on the table, the map pans to an enlarged icon of the selected item with more details displayed in Figure 1(**D**).

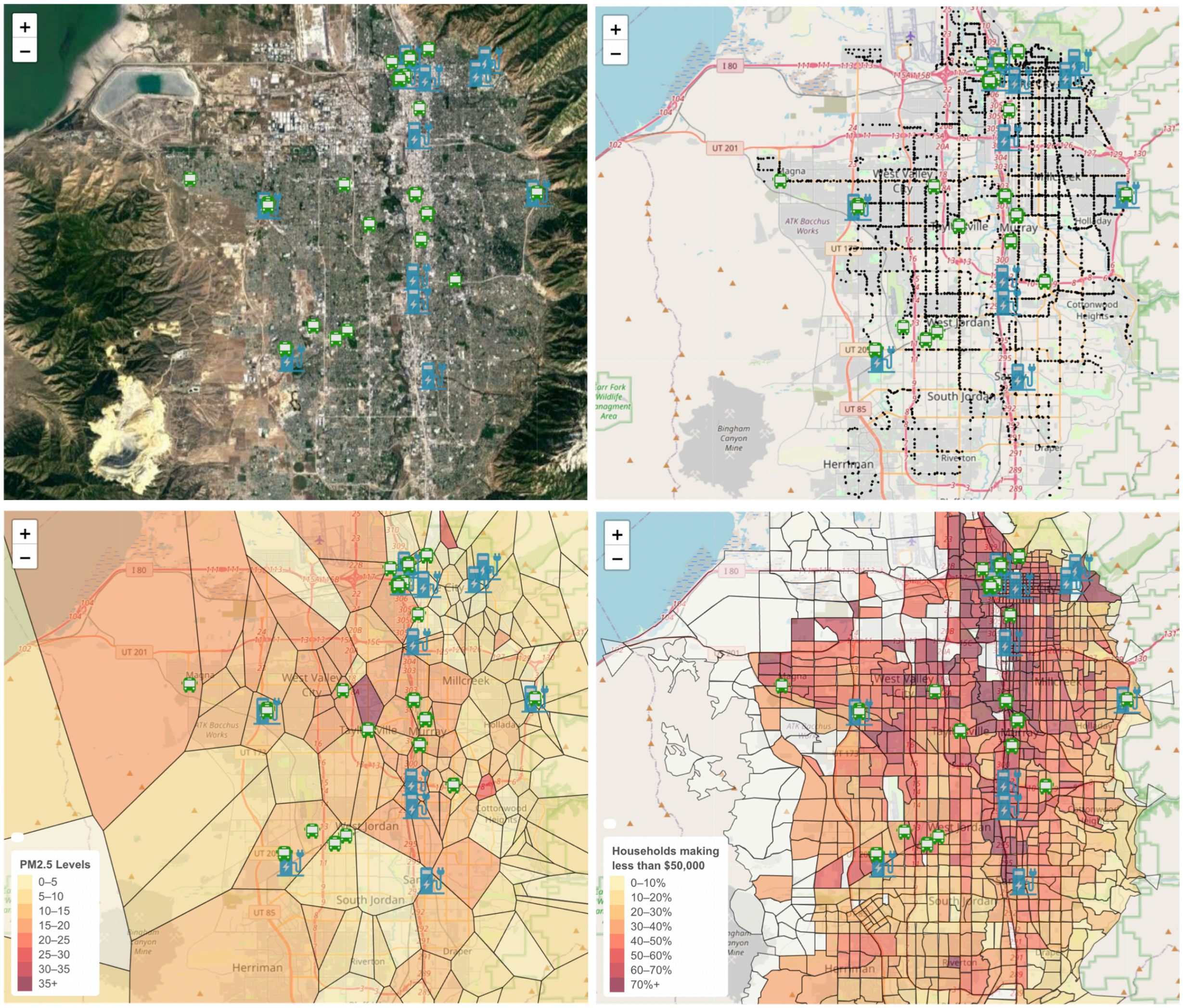


FIGURE 3 Different overlay options for the map, from left to right, from top to bottom: Google satellite, bus stops, pollutant concentrations, and economic data by region.

Chart View (D)

Data for a selected bus or a charging station is displayed in the *Chat View* (**D**), which is also linked with the *Map View* and *Table View* in Figure 1(**B**) and (**C**), respectively.

If a converted bus (under the selected deployment plan) is selected, this view displays its line, environmental impact, status (on route or charging), and the level of remaining charge at a given time of the day. This view also contains two charts displaying the number of miles the bus travels and its level of charge over the course of a day. If an unconverted bus is selected, this view displays the same information as above excluding the charging information. If a charging station is selected, this view displays the UTA stop ID at which the station is located, the bus IDs at the station, and a chart displaying the number of buses at the station over the course of a day.

Implementation Details

The system is implemented using the *Vue JavaScript* framework, with the *Map View* and *Table View* implemented using the *Leaflet* and *D3 JavaScript* libraries respectively. Background maps are provided by *OpenStreetMap* and *Google Maps*.

The available data describes the time-of-day at which buses are at the beginning and the end of their respective routes. To provide temporal location updates, the position of a bus along its route at a given time is interpolated from its start and end locations. State variables that are shared across the different components of the system such as the time of day, selected bus, and selected deployment plan are kept in a system-wide *Vuex* store. Relevant components watch for changes in these shared variables and update the data being displayed when they are modified by a user. Because the pollutant concentration data is provided as readings from individual points, to create the regional pollutant concentration overlay, a Voronoi diagram from these points is calculated as a first-order approximation where the center of each region is the point at which the reading takes place.

CONCLUSION

To facilitate BEB deployment, we have developed a visualization tool referred to as the **BEBExplorer**, which allows users to interactively perform visual analysis and compare different layers of spatiotemporal information. The visualization is built on a bi-objective optimization framework to help UTA advance BEB deployment. The framework is flexible enough to accommodate any objective of interest to transit agencies, not limited to budget and environmental equity. **BEBExplorer** consists of four seamlessly linked views, represented by maps, tables, and charts, which allows dynamic updates and demonstration of different deployment plans and real-time bus locations. Also, users have full freedom to choose resolutions of the visualizations to create overviews, zoom-ins, and filters. Moreover, detailed statistics of deployment plans and bus status can be retrieved from the visualization.

Currently **BEBExplorer** can only be applied to BEB deployment plan visualization. However, given the current system design, **BEBExplorer** can be expanded to other spatial visualizations relevant to transportation easily, which we will leave as future work.

ACKNOWLEDGEMENT

This research is funded by NITC project No. 1519 "Enabling Decision-Making in Battery Electric Bus Deployment Through Interactive Visualization" and the Seed2Soil program at the University of Utah.

REFERENCES

1. Zhou, Y., X. C. Liu, R. Wei, and A. Golub, Bi-objective optimization for battery electric bus deployment considering cost and environmental equity. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 22, No. 4, 2020, pp. 2487–2497.
2. Shneiderman, B., The eyes have it: a task by data type taxonomy for information visualizations. *Proceedings of the IEEE Symposium on Visual Languages*, 1996, pp. 336–343.