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Enabling Decision-Making in Battery Electric Bus Deployment through Interactive Visualization

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THE UNIVERSITY OF UTAH

Enabling Decision-Making in Battery Electric Bus Deployment Through Interactive Visualization

Final Report

NITC-TT-1519

by

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16. Abstract

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 the transit system and energy/power system in order to make informed deployment decisions. A recently completed NITC project, No. 1222 titled *An Electric Bus Deployment Framework for Improved Air Quality and Transit Operational Efficiency*, developed a bi-objective spatiotemporal optimization model for the strategic deployment of the Battery Electric Bus (BEB) to minimize the cost of purchasing BEBs, on-route and in-depot charging stations, and to maximize environmental equity for disadvantaged populations. As agencies such as the Utah Transit Authority (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 Translate Research to Practice grant will support the development of a visualization tool 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 tool will be built on the scenario-based optimization modeling effort in NITC Project No. 1222, and allow agencies to make phase-wise (short-, mid-, or long-term) decisions based on investment resources and strategic goals. This project will also develop a guidebook to provide step-by-step guidance on data compilation for BEB analysis, model input, model implementation, and results interpretation. It will further detail how the developed visualization tool is structured and designed to ensure results exploration across transit operation and energy consumption. Both the guidebook and the tool will be directly useful to practitioners to easily implement our optimization model for their own transit network, and allow them to build interactive visualizations to assist with decision-making.

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EXECUTIVE SUMMARY

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 a 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. To ensure the transferability of the pipeline of products, a guidebook detailing the step-by-step implementation, from data compilation to model running to results interpretation to visualization platform set-up, is developed in this *Translate Research to Practice* project, so that other agencies could replicate easily with their own customized data.

1.0   BACKGROUND

The previously funded NITC project No. 1222, titled *An Electric Bus Deployment Framework for Improved Air Quality and Transit Operational Efficiency*, was completed successfully in 2020. The project developed a bi-objective spatiotemporal optimization model for the strategic deployment of BEBs to minimize the cost of purchasing BEBs, on-route, and in-depot charging stations, and to maximize environmental equity for disadvantaged populations. The project produced scenario-based results, where for a specific budget plan the developed optimization model recommends the optimal BEB deployment strategy in terms of buses to replace and charging stations to site that could produce the maximum environmental equity (see Figure 1.1 for a deployment example) (Zhou et al., 2020). The project also developed a prototype visualization platform to showcase the overall results, where a user pinpoints to a budget plan, the embedded map will demonstrate the bus routes that BEBs will be operating on and the locations of charging stations, as well as the Traffic Analysis Zones (TAZs) those BEBs will be traversing.
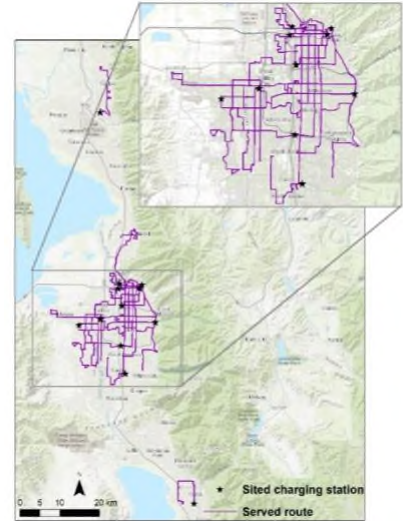
Figure 1.1 BEB deployment plan when budget is set at $120 million.

NITC project No. 1222's funding was extremely timely as UTA received the federal grant from the Low-No (Low or No Emissions) program to support BEB deployment. The results from NITC project No. 1222 guided the launch of the three currently operating BEBs as well as the siting of charging infrastructures. As UTA prepared to add more BEBs starting in 2021 to reduce emissions further and improve air quality, the partnership with Rocky Mountain Power (utility company) is an essential aspect of the milestone. With the BEB expansion and associated charging needs, the operation of the interdependent transit and power systems becomes a critical component to consider. For example, BEB charging might impose a significant load to the power grid and the emergent peak may result in congestion in power lines and violation of voltage limits. The charging events need to be closely monitored in high resolution to ensure that the power system could accommodate the BEB energy needs. A detailed exploration for assessing BEBs' operation, charging events, and energy consumption in spatiotemporal dimension is much needed. For this reason, UTA desires a robust visualization tool that is able to ingest and process high-resolution spatiotemporal data to help planners and decision-makers trace trends and patterns to make timely decisions.

NITC project No. 1222 reached Technology Readiness Level (TRL) scale 3 (proven concept), and UTA found the research very useful in guiding their future BEB deployment. In this *Translate Research to Practice* project, **UTA hopes to further expand the functionality of the visualization tool to assess detailed spatiotemporal operations of the BEB system and its interdependency with the power/energy system**. To this end, we attempt to reach TRL scale 4 (deployment) in

this project to further target UTA's transit network, and advance the visualization tool to enable high-resolution spatiotemporal analytic functionality. To ensure the transferability of the pipeline of products, a guidebook detailing the step-by-step implementation, from data compilation to model running to results interpretation to visualization platform set-up, is also developed so that other agencies could replicate easily with their own customized data.

2.0   PROBLEM STATEMENT

In this technology transfer effort, we present 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 (Zhou et al., 2020), 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. 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.

Besides the visualization tool, we also developed a guidebook to provide step-by-step guidance on data compilation for BEB analysis, model input, model implementation, and results interpretation. Both the visualization tool and the guidebook can be directly useful to practitioners to easily implement our optimization model for their own transit network, and allow them to build interactive visualizations to assist with decision-making.

3.0 VISUALIZATION TOOL DEVELOPMENT

3.1 VISUALIZATION FRAMEWORK
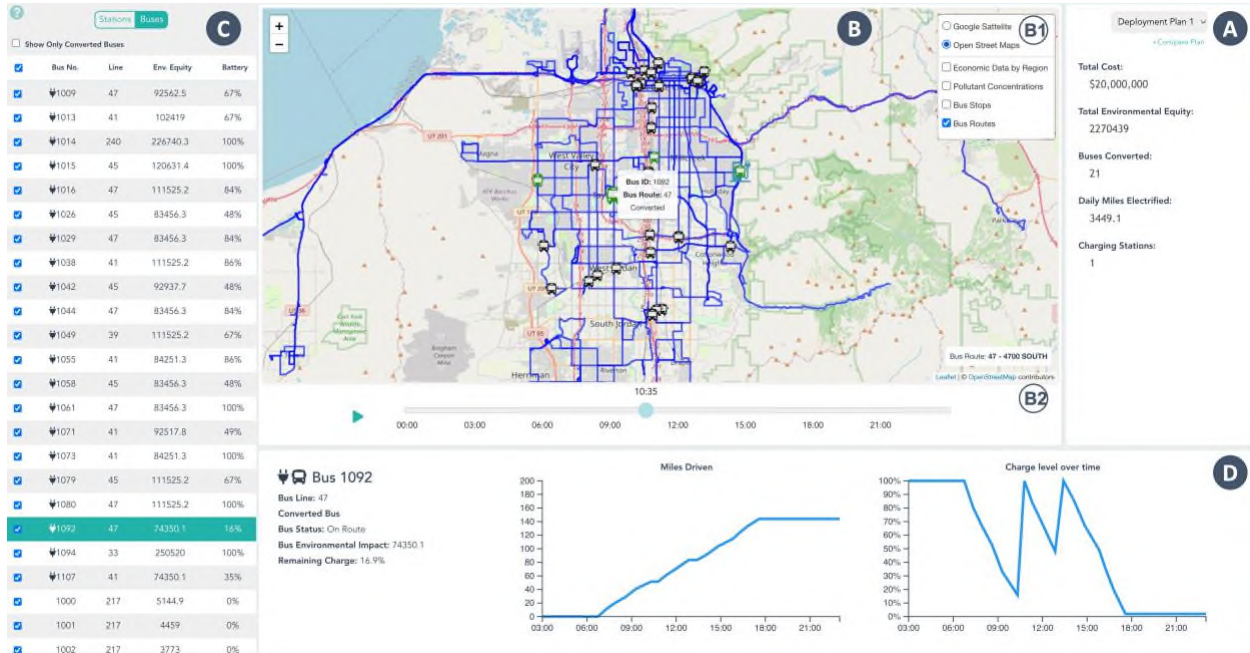
Figure 3.1: With BEBExplorer, users can interactively explore the interdependency of the BEB transit system and energy infrastructure spatially and temporally with high resolution.

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 3.1, 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.

A prototype of our framework can be found at: https://gracious-heisenberg-a8a687.netlify.app/. And the source code and readme file for customizing the platform for new dataset can be found at: https://github.com/gabekudirka/bus-vis-dynamic.

In our framework, we adopt the design principles of "overview first, zoom and filter, and details on demand" (Shneiderman, 1996) 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.

3.1.1 Statistics View (A)
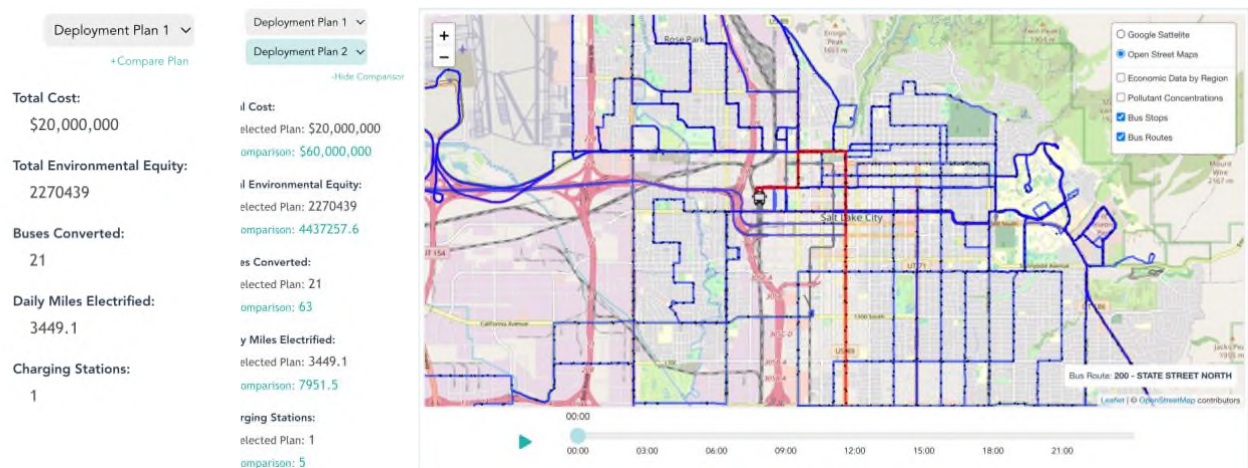
Figure 3.2: Left shows statistics of Plan 1, while middle shows a comparison between the selected Plan 1 and Plan 2. Right gives a zoomed-in view after the selection of a bus route.

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 3.2 (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 3.2 (middle).

3.1.2 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 3.1(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 3.2 (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 3.1(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 3.1(A). Figure 3.3 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 3.1(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.
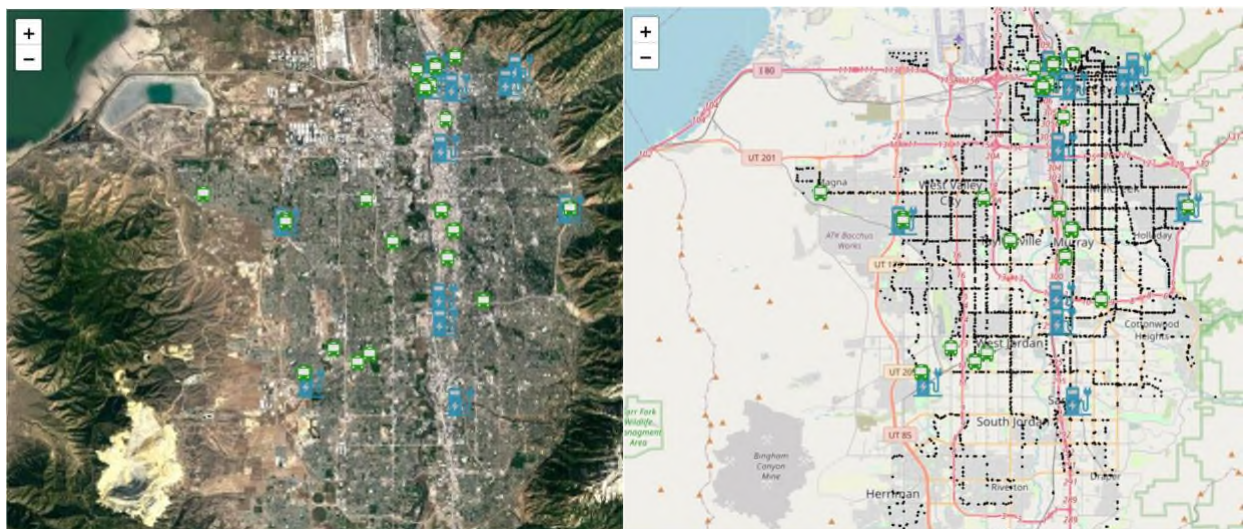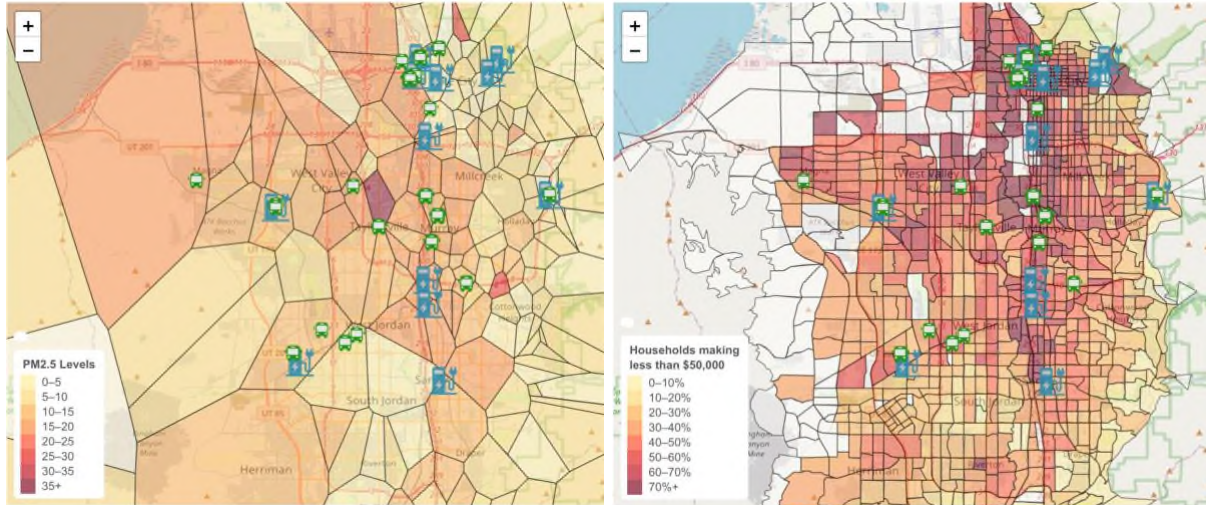
Figure 3.3: Different overlay options for the map, from left to right, from top to bottom: Google satellite, bus stops, pollutant concentrations, and economic data by region.

3.1.3 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 its ID (i.e., bus number), 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 3.1(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 3.1(D).

3.1.4 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 3.1(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.

3.2   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.

4.0 GUIDE TO IMPLEMENT THE BI-OBJECTIVE OPTIMIZATION MODEL

4.1 PREREQUISITE TO IMPLEMENTING THE MODEL

4.1.1 Code

The source code can be found at:
https://github.com/Duskdeep1/BEB_Visualization_Final_Report.git

This tool is based on Windows OS. Please download and unzip the entire folder "*BEB_Optimization_Model_User_Guideline*" to your local directory (please remember this path as it will be used).

4.1.2 Gurobi Optimizer

Gurobi optimizer is a tool to solve mathematical programming problems (e.g., linear programming (LP) problems, quadratic programming (QP), etc.). In this guideline, the BEB deployment problem is a single objective mixed integer programming problem with the objective to maximize the environmental equity outcomes under the budget restrictions. Therefore, we employ Gurobi optimizer to help solve this problem.

You need to install and obtain a license from Gurobi optimizer:
https://www.gurobi.com/products/gurobi-optimizer/

4.1.3 ArcGIS Desktop

In the following environmental equity calculation, the sites of air quality monitoring sensors are not the same as the TAZ. Therefore, ArcGIS is needed to interpolate the air quality data to each TAZ for environmental equity calculation.

ArcGIS can be downloaded at https://pro.arcgis.com/en/pro-app/2.8/get-started/download-arcgis-pro.htm. Please download and install it.

4.1.4 Python 2.7 + Interpreter Installation

4.1.4.1 Python 2.7 Installation

The code is based on Python 2.0.

(1) Download python 2.7.18 at https://www.python.org/downloads/release/python-2718/. Please make sure to select a suitable version (e.g., Windows x86-64 MSI installer).

(2) Run the installer package to install Python 2.7.18 following its steps.

4.1.4.2   PyCharm Installation

We recommend PyCharm as the Python IDE.

(1) Download PyCharm at
https://www.jetbrains.com/pycharm/download/#section=windows. The
Community vision should be sufficient.

(2) Open the application package to install PyCharm.

You can refer to this video needed:
https://www.youtube.com/watch?v=lM5Y7BnP56k

4.1.5 Python Interpreter Setting

4.1.5.1   Open PyCharm

From Windows Start, find PyCharm and open it. You also can use the PyCharm
shortcut on your desktop if you have one.

4.1.5.2   Open Project

On the PyCharm interface (see **Figure 4.1**), click "File" →"Open" →find the folder
of codes you just downloaded→and click "OK". Then, you may see a pop-up
window asking you to select the window. Either "New Window" or "This Window"
is acceptable.
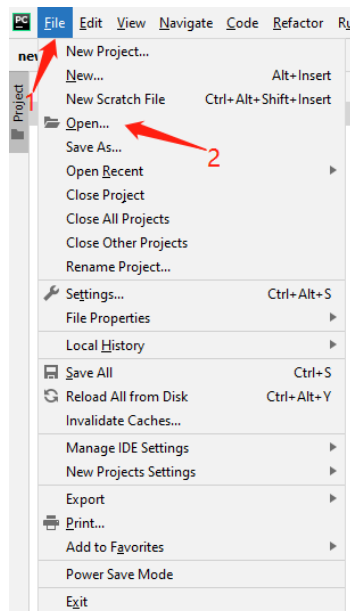
Figure 4.1: Open the project.

4.1.5.3   Select Python Interpreter

Select Python 2.7 as the project's Python Interpreter in the lower right corner (see Figure **4.2**).
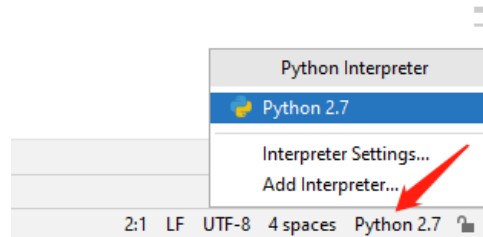
Figure 4.2: Select python interpreter.

4.1.5.4   Set Python Interpreter

There is a TAB named "Terminal" in the lower left corner. Click it. Copy and paste the command below (see Figure **4.3**) and hit Enter.

---

pip install -r requirements.txt
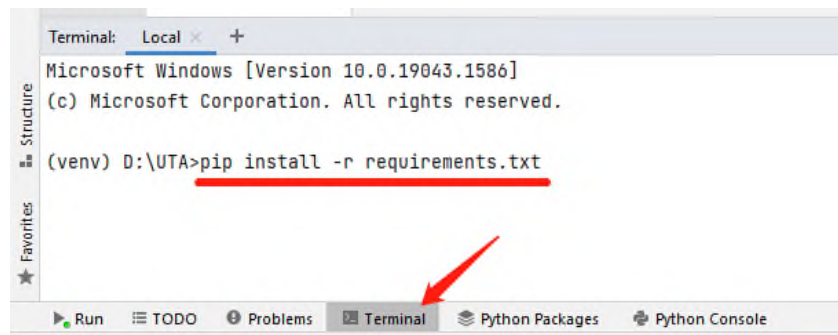
Figure 4.3: Set python interpreter.

Wait for about one minute. Then, you will see "Successfully installed certifi-2021.10.8 chardet-4.0.0 docopt-0.6.2 idna-2.10 numpy-1.12.0 pandas-0.20.0 pipreqs-0.4.11 pyshp-1.2.12 python-dateutil-2.8.2 pytz-2021.3 requests-2.27.1 six-1.16.0 urllib3-1.26.8 xlrd-0.9.4 xlwt-1.3.0 yarg-0.1.9". (See Figure **4.4**)
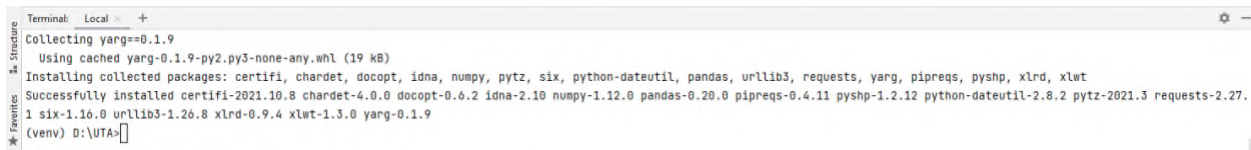
Figure 4.4 Example of setting interpreter successfully.

Till now, the Python Interpreter has been set up successfully!

4.2 DATA PREPARATION

Two parts of data are required to create the optimization model for BEB deployment (i.e., bus network data and the environmental equity in the analyzed area).

4.2.1 Network Data

The shpfiles of bus routes and bus stops are required to analyze this problem.

A runcut file is also needed, which must include the following columns/features, and all features should be included in the corresponding shapefiles. You can refer to the template (see Figure **4.5**) in the folder you just downloaded, named "Runcut. xslx".

- 'LineAbbr': Route number of the trip

- 'ServiceName': WEEKDAY, "SATURDAY", or "SUNDAY". We only need the data of "WEEKDAY"

- 'DirectionName': The direction of the bus

- 'block_num': a service pattern used for route dispatch. Oftentimes, transit agencies have more than one route per block (bus number)

- 'trip_id': id for a specific bus trip

- 'from_stop': the departure station of the trip

- 'FromTime': departure time from the origin terminal

- 'to_stop': the destination of the trip

- 'ToTime': arrival time to the destination terminal

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
217	WEEKDAY	TO ROSE PARK	1000	2795402	REDWOOD RD @ 8021 S	10:43	1300 N @ 1710 W	11:45
217	WEEKDAY	TO 7800 S TRAX	1000	2795341	1300 N @ 1710 W	11:54	REDWOOD RD @ 8021 S	13:05
217	WEEKDAY	TO ROSE PARK	1000	2795401	REDWOOD RD @ 8021 S	13:13	REDWOOD RD @ 1351 N	14:21
217	WEEKDAY	TO 7800 S TRAX	1000	2795340	REDWOOD RD @ 1351 N	14:30	REDWOOD RD @ 8021 S	15:35
217	WEEKDAY	TO ROSE PARK	1000	2795399	REDWOOD RD @ 8021 S	15:37	REDWOOD RD @ 1351 N	16:51
217	WEEKDAY	TO 7800 S TRAX	1000	2795339	REDWOOD RD @ 1351 N	16:58	REDWOOD RD @ 8021 S	18:10
217	WEEKDAY	TO ROSE PARK	1000	2795405	REDWOOD RD @ 8021 S	18:28	REDWOOD RD @ 1351 N	19:36
217	WEEKDAY	TO 7800 S TRAX	1000	2795338	REDWOOD RD @ 1351 N	19:45	REDWOOD RD @ 8021 S	20:50
217	WEEKDAY	TO ROSE PARK	1000	2795400	REDWOOD RD @ 8021 S	20:58	REDWOOD RD @ 1351 N	22:06
217	WEEKDAY	TO 7800 S TRAX	1000	2795337	REDWOOD RD @ 1351 N	22:45	REDWOOD RD @ 8021 S	23:50
217	WEEKDAY	TO ROSE PARK	1001	2795397	REDWOOD RD @ 8021 S	4:43	1300 N @ 1710 W	5:45
217	WEEKDAY	TO 7800 S TRAX	1001	2795336	1300 N @ 1710 W	5:54	REDWOOD RD @ 8021 S	7:05
217	WEEKDAY	TO ROSE PARK	1001	2795396	REDWOOD RD @ 8021 S	7:11	1300 N @ 1710 W	8:13

Figure 4.5: Example of runcut file.

4.2.2 Environmental Equity

4.2.2.1   Socioeconomic Data

From your city or state census (e.g., metropolitan planning organizations in Utah), obtain the information of the distribution of the low-income populations (e.g., $0-34,999 was treated as the low-income group for Utah) at the TAZ level. There should be different criteria for classifying low-income households and different sources to obtain the distribution information in your city or state. Similar data should be acceptable, but you need to convert the distributions to the TAZ level.

4.2.2.2   Air Quality Data

Air quality data is needed as the input to calculate environmental equity. For UTA's network, we retrieved such information from Purple Air (https://map.purpleair.com/), which is an air quality monitoring network built on a new generation of laser particle counters to provide real-time measurement of PM1.0, PM2.5, and PM 10. The concentration of PM2.5 during a period was used in this model.

Choose a period of the concentration of PM2.5 (e.g., 14 days) and calculate the average for each site. Then, we need to convert the concentration of each site to the pollutant level at the unit of TAZ. Kriging method can be used for interpolation in ArcGIS.

Pollutant Level at Each Sensor Site

To obtain the pollutant level at each sensor site, first, we need to locate your research area. Find the latitude of your research areas (e.g., by Google Maps) and update the latitude values to the below link:
www.purpleair.com/json?nwlat=<nwlat>&selat=<selat>&nwlng=<nwlng>&selng=<selng>

- nwlat is the Northwest latitude of the area of interest

- nwlng is the Northwest longitude of the area of interest

- selat is the Southeast latitude of the area of interest

- selng is the Southeast longitude of the area of interest

Pollutant Level Calculation at Each TAZ

The data obtained above is the average concentration of PM2.5 at each sensor site. We need to convert them to the pollutant level at the unit of the TAZ. Using kriging in ArcGIS, we will be able to interpolate the point values of PM2.5 concentration into raster values (Zhou et al., 2020).

4.3 LINEAR PROGRAMMING (LP) FILE GENERATION

4.3.1 Parameter Settings

4.3.1.1 Cost Budget

In the source code, for the cost we assume that the cost of one on-route charging station is $1 million; the cost of purchasing one BEB is $0.749 million; and the cost of building one in-depot charging station is $0.35 million. If you would like to configure these parameters, follow the steps below:

First, follow "section 4.1.5.2" to open the project. On the project navigation bar, double click "ele_bus.py" to open the file (See Figure **4.6**).
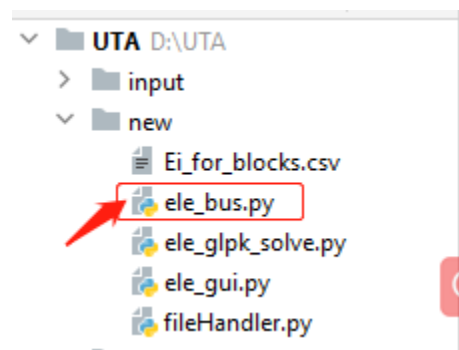

Figure 4.6: Way to open source code.

Some parameters need to be updated for building the optimization model (see Figure **4.7**).

- Go to line 755, "df = pd.read_csv("Ei_for_blocks.csv"). "Ei_for_blocks.csv" is the file name of the environmental equity we just calculated for each TAZ. If the name of your environmental equity data file is not the same, please update your file name accordingly.

- Go to line 763, " stopsStr += '1 ' + 'Y' + str(stop_item['stop_id']) + ' + '". The number '1' is the cost of one on-route charging station ($1 million). Change as you see fit.

- Go to line 771, "busStr += '0.749 Z' + str(int(bus_item['block_num'])) + ' + '". The number "0.749" is the cost of purchasing one BEB ($0.749 million). Change as you see fit.

- Go to line 778, "budget = stopsStr + busStr[:-3] + ' + 0.35 I'". The number "0.35" is the cost of building one in-depot charging station ($0.35 million). Change as you see fit.

```
757    # 1 is the price of one on-route charging station
758    # 0.749 is the price of purchasing a BEB  #BIAO 0.79 was used in the paper
759    # 0.35 is the price of building one in-depot charging station,
760    # the number of buses replaced determines the number of in-depot charging stations entirely
761    # We only need a variable that shows the number of in-depot charging stations.
762    for stop_item in self.potential_bus_stops:
763        stopsStr += '1 ' + 'Y' + str(stop_item['stop_id']) + ' + '
764        Y_str += 'Y' + str(stop_item['stop_id']) + ' '
765    print(stopsStr)
766    busStr = ''
767    ei_str = ''
768    budget = ''
769    for bus_item in busList:
770        Z_str += 'Z' + str(int(bus_item['block_num'])) + ' '
771        busStr += '0.749 Z' + str(int(bus_item['block_num'])) + ' + '
772        ei_str += str(df.loc[df["block_num"] == int(bus_item['block_num'])].iloc[0, 1]) + ' ' + 'Z' + str(int(bus_item['block_num'])) + ' + ' #BIAO objective (1)
773    # print ('stop_count:', len(self.potential_bus_stops))
774
775    lp_file_str += ei_str[:-3]
776    # I is the number of in-depot charging stations
777
778    budget = stopsStr + busStr[:-3] + ' + 0.35 I'        #BIAO objective (2)
```

Figure 4.7: Parameter setting for cost budget.

4.3.1.2   On-route Charging Duration

We assume the changing time for a BEB using on-route charging time is 10 minutes. Only the bus dwells more than 10 minutes will be deemed as potential sites for building on-route charging stations. You can change it per your project requirements. In line 23 (see Figure **4.8**), the time gap is charging duration.

```
21    METER_TO_MILE = 0.000621371192
22
23    TIMEGAP = 10
24
25    sys_windows = "Windows"
26
```

Figure 4.8: Parameter setting for on-route charging time.

4.3.1.3   BEB Driving Range with Fully Charged

In our case, 62 miles are viewed as the driving range for a BEB that is fully charged. If you would like to revise it according to your project, go to line 727 (see Figure **4.9**) and revise the "max_length".

```
727    def write_gurobi_lp(self, output_dir, max_bus=1, max_length=62, time_type='WEEKDAY'):
728
729        # All strings.
730        # Initiate
731        lp_file_str = ''
732
733        outputStr = 'Maximize\n'
734        lp_file_str += outputStr
735        # write object.
```

Figure 4.9: Parameter setting for driving range of BEB when fully charged.

4.3.2 Generate lp File

4.3.2.1   Run the "ele_gui.py" file.

On the project navigation bar, double click "ele_gui.py" to open the file→ Right click the file and select "Run 'ele_gui'" (see Figure **4.10**).
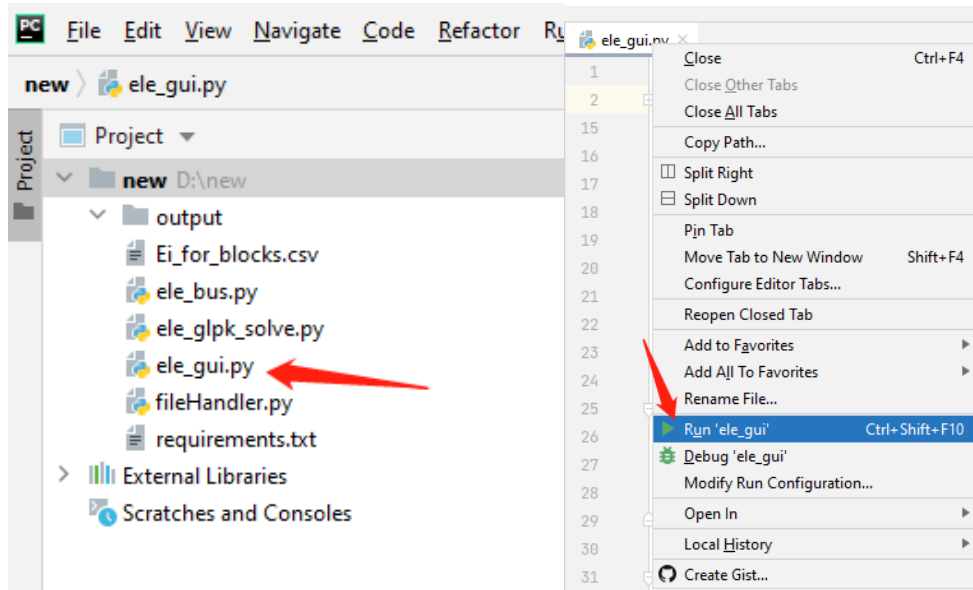

Figure 4.10: Open "ele_gui.py" file.

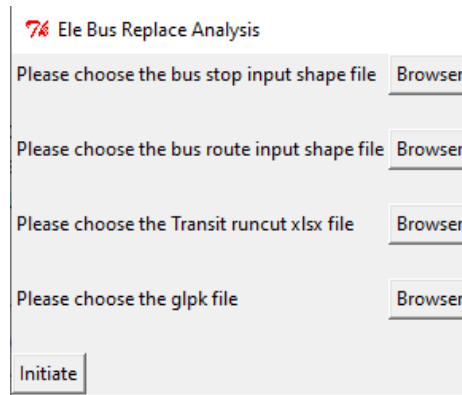A window will pop up, which should be similar to Figure **4.11**:

Figure 4.11: A pop-up window of BEB replacement analysis.

4.3.2.2   Input Data File

In this window:

- Click the first and second "Browser" buttons and choose the bus stop and bus route input shapefile separately (e.g., BusStops_UTA.shp and BusRoutes_UTA.shp).

- Click the third "Browser" button and choose runcut xlsx file (e.g., UTARuncut.xlsx).

- Click the fourth "Browser" button and select the "glpsol.exe" file in the folder "winglpk-4.61/w64". You can find it in the folder which you just downloaded from GitHub.

Figure **4.12** shows an example of how to input needed data.

Figure 4.12: Example of how to input data files.

Then, click the "Initiate" button. You will see a new window, as shown in Figure **4.13**. The meanings of the results generated are shown below:

- "Applicable bus" (e.g., 302 in this case) refers to the number of buses that can be potentially replaced with BEB, including the number of buses that do not need the in-route charge.

- "No needed charge in route" (e.g., 114 in this case) is the number of buses with daily mileage less than 62 miles (we assume 62 miles is the driving range for a BEB that is fully charged; you can change it as your fit according to Section 4.1).

- "Can't charged in routes" (e.g., 51 in this case) is the number of buses that cannot be charged in routes because they will run out of battery before charging due to the long distance between stops.
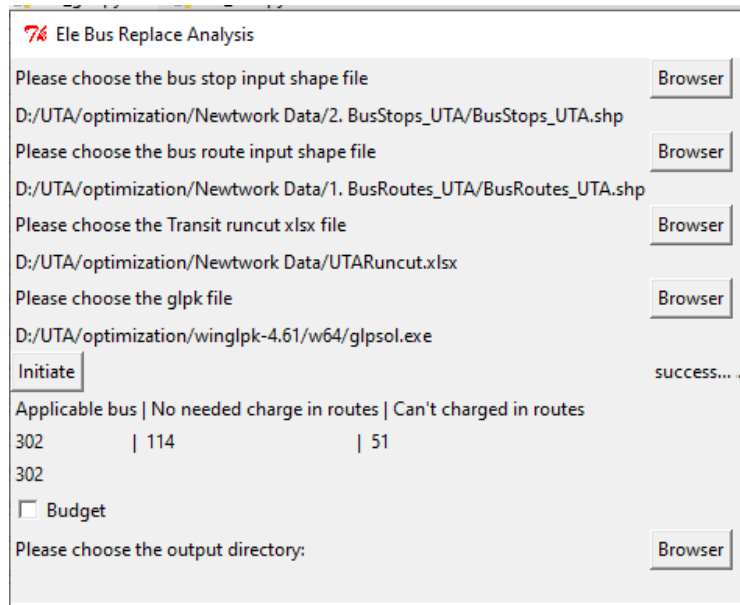
Figure 4.13: Example of a new window after initiating.

4.3.2.3 Generate lp File

In the new window, you can follow the steps below to generate an lp file (see Figure **4.14**). (1) check the "Budget" box (a new blank will appear)→(2) Input your budget for the entire system, including the cost of purchasing a BEB, on-route and in-depot charging station, in millions (e.g., 10)→ (3) Click the "Browser" button to choose your output directory, where you want to store the generated lp file →(4) Click "Calculate" Button→(5) You will see " success…g…" in the window. Or you can see "write succeed! stops write succeed write succeed!" in PyCharm console →(6) Click "output bus types xlsx" Button→(7) You will see " success…g…" in the window (see Figure **4.15**).

Till now, the lp file has been generated successfully!
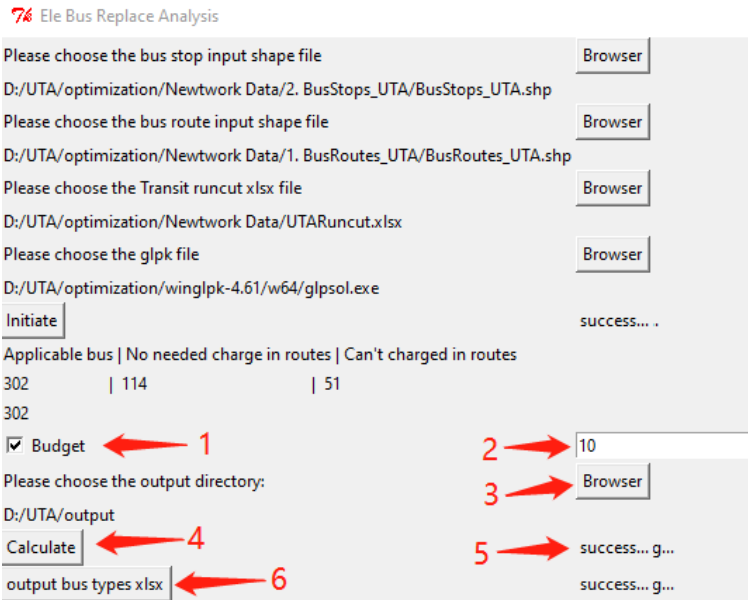
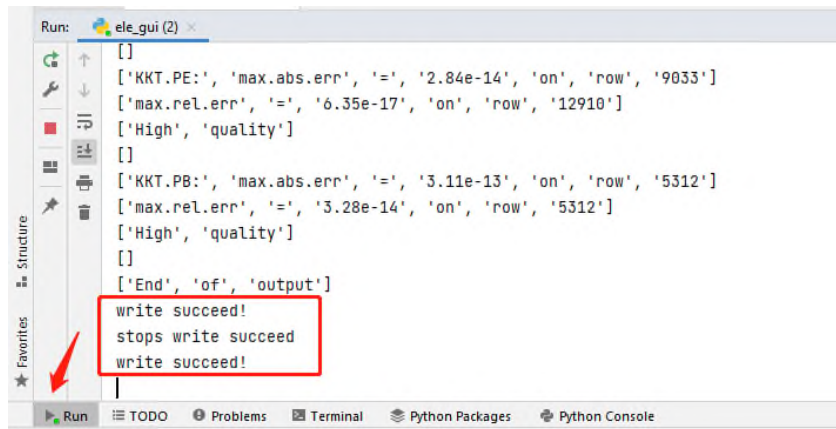**Figure 4.14: Steps to generate lp file.**

Figure 4.15: Example of lp file generated successfully.

4.4 SOLVE LP FILE

4.4.1 Check lp File

Go to the output directory you specified in Section 4.2.3. The file named "ele_bus_v61.lp" lists the linear problem, including the objective and constraints. This is the lp file we need to analyze further.

4.4.2 Solve lp

In the output folder, input "cmd" into the path and press Enter (see **Figure 4.16**). Then you will see a cmd window
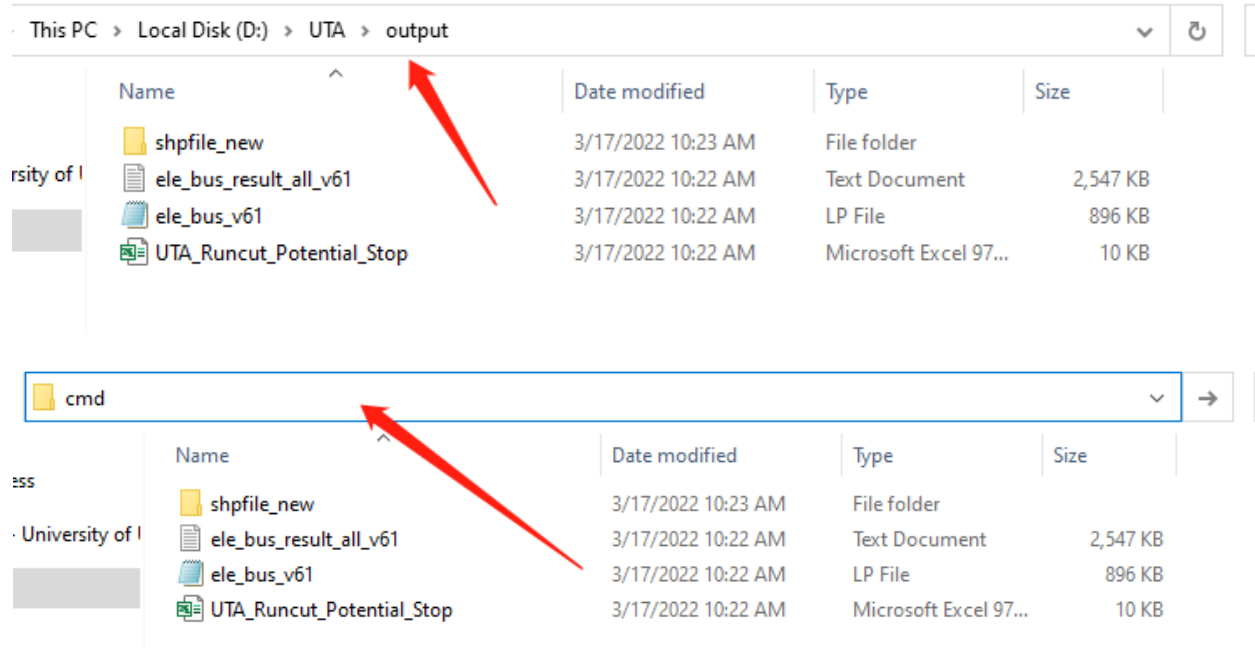
Figure 4.16: Way to use the cmd command.

Copy and paste the command below in the cmd window and hit Enter (see **Figure 4.17**).

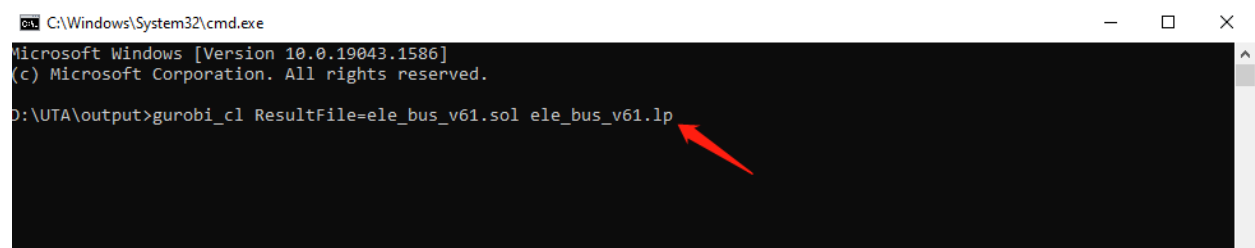gurobi_cl ResultFile=ele_bus_v61.sol ele_bus_v61.lp

Figure 4.17: Example of solving lp problem in cmd window.

A new file will be generated named "ele_bus_v61.sol" in the output directory. It is the solution to the optimization problems (see **Error! Reference source not found.**).

Figure 4.18: New file for solution.

4.4.3 Results Interpretation

Open the "ele_bus_v61.sol" file, and you will see the optimization results.

Index Z:

- Z_bus id: if Z_bus id=0, the bus id should be replaced with BEB. Otherwise, it should not. For example, "Z4030 0" and "Z1013 1" mean that bus 4030 should not be replaced with BEB, while bus 1013 should be replaced.

Index X:

- X_bus id_ terminal id: if X_bus id_ terminal id=1, bus id is charged at terminal id. Otherwise, it is not. For example, "X1013_1 0" and "X1013_2 1" mean that bus 1013 is not charged at terminal 1 but charged at terminal 1.

Index m:

- m_bus id_terminal id: m_bus id_terminal id = total driving distance for bus id in one day. For example, "m1065_1 7.25" means bus 1065 has driven 7.25 miles when reaching terminal 1.

Index Y:

- Y+ depot id: if Y + depot id = 1, depot id should add an in-depot charging station. Otherwise, it should not. For example, "Y0 0" means that depot 0 should be set charging station.

25

5.0   CONCLUSIONS AND RECOMMENDATIONS

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. We further detail the step-by-step procedure to implement the bi-objective optimization model for analyzing BEB deployment plans using a guidebook, which allows for replication and transferability to any transit network of interests.

6.0   REFERENCES

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