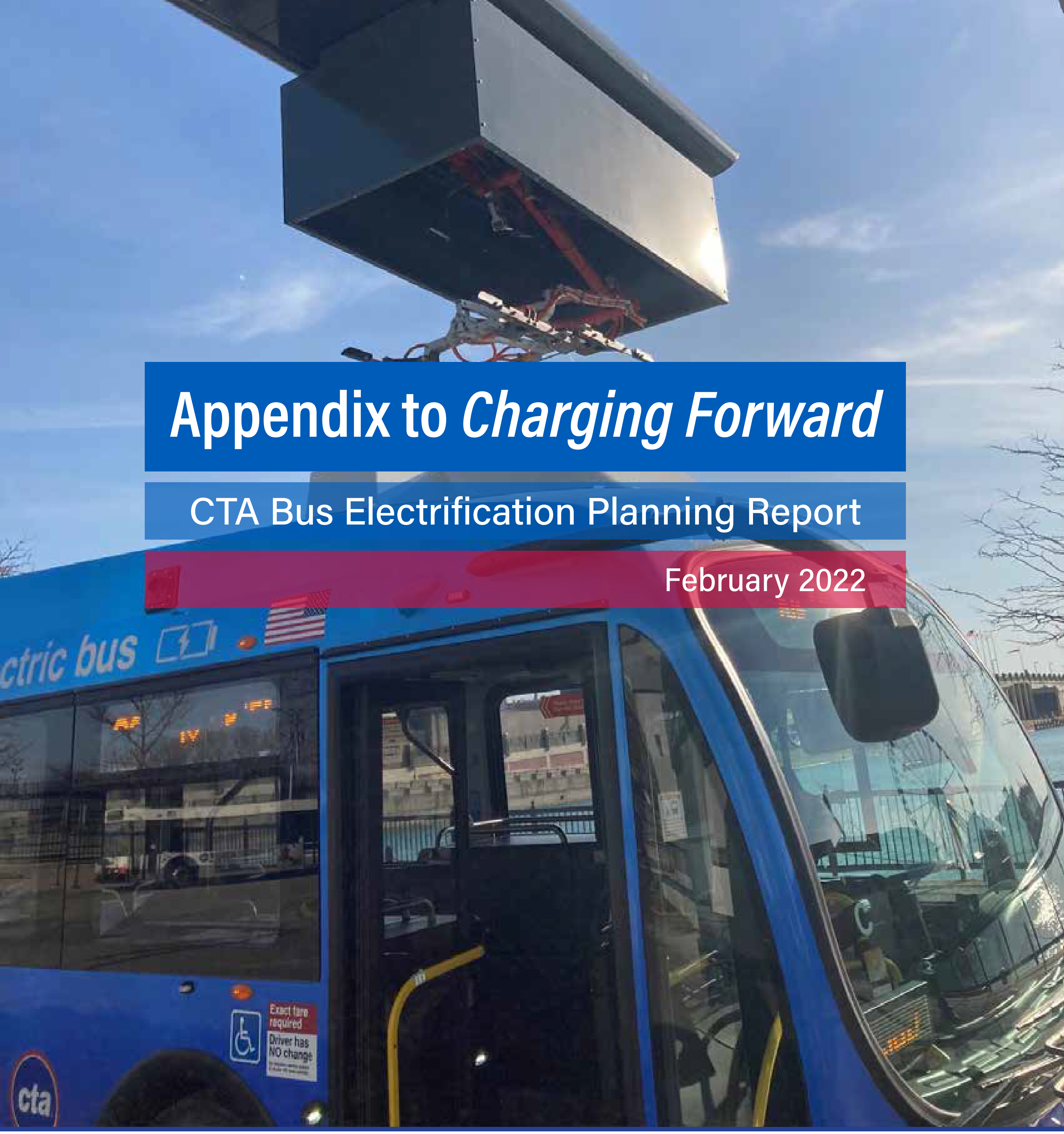

Appendix to *Charging Forward*

CTA Bus Electrification Planning Report

February 2022

Chicago Transit Authority

This appendix serves to provide additional information about the assumptions, methodology, modeling inputs, and results of the analyses used to develop this report as follows:

- Section A describes the equity analysis that supports Chapter 2b of the main report
- Section B describes the schedule modeling that supports Chapter 2c of the main report
- Section C describes the garage charging analysis that supports Chapter 2d of the main report.
- Section D describes the cost modeling inputs that support Chapter 4 of the main report.

A. Detailed Results of the Equity Analysis

Analysis considering minority populations and low-income populations

We first considered two indicators that CTA already utilizes for other evaluations: presence of minority populations, and presence of low-income populations. Analyses of these populations were developed using two approaches: one using the population residing **near each bus garage** (within ½ mile), and one using CTA's classification of each garage's **bus routes** that serve minority and low-income populations.

First, Table 1 shows the share of the population that is minority or low-income within ½ mile of CTA bus garages. This was determined using data from the Census Bureau's 2017 American Community Survey five-year estimates at the block group geographic level. Minority is defined as non-white, and low-income is defined as earning less than the poverty level. The results show that some garages are in areas with quite high minority and low-income population percentages.

Table 1 - Results based on the population residing in the area within ½ mile of ***each garage.***

Garage	Percent Minority	Percent Low-Income
103rd	86%	41%
74th	98%	27%
77th	98%	40%
Chicago	93%	37%
Forest Glen	19%	6%
Kedzie	95%	45%
North Park	41%	19%

Table 2 shows the analysis based on the classification of each garage's bus routes. For federal reporting, CTA classifies a bus route as serving minority and/or low-income populations if one-third of its total revenue mileage is in census blocks that have a minority or below-poverty-level population percentage that exceeds the minority or below-poverty-level population percentage for CTA's service area. Findings are generally similar to the analysis of the area surrounding each bus garage (illustrated in Table 1 above). Some garages have as many as 93% of routes classified as minority or as many as 88% of routes classified as low-income.

Table 2 - Results based on CTA classification of the ***bus routes*** *operated by each garage.*

Garage	Percent Minority Routes	Percent Low-Income Routes
103rd	92%	88%
74th	84%	68%
77th	76%	76%
Chicago	93%	86%
Forest Glen	26%	11%
Kedzie	56%	56%
North Park	16%	37%

Analysis considering the Chicago Air Quality and Health Index

Our analysis used the CAQHI, developed by the Chicago Department of Public Health, as a supplemental metric to the federal indicators of minority and low-income populations.

The CAQHI results are summarized in a similar manner to the minority and low-income results discussed in the previous section. Table 4 shows results for the areas **near each bus garage** (within ½ mile), while Table 5 shows results for the area **near the bus routes** operated by each garage (within ¼ mile). The results are also broken down for the four subcategories that make up the index: Sensitive Populations, Vulnerable Populations, Environmental Exposures, and Environmental Effects. These subcategories are defined in Table 3.

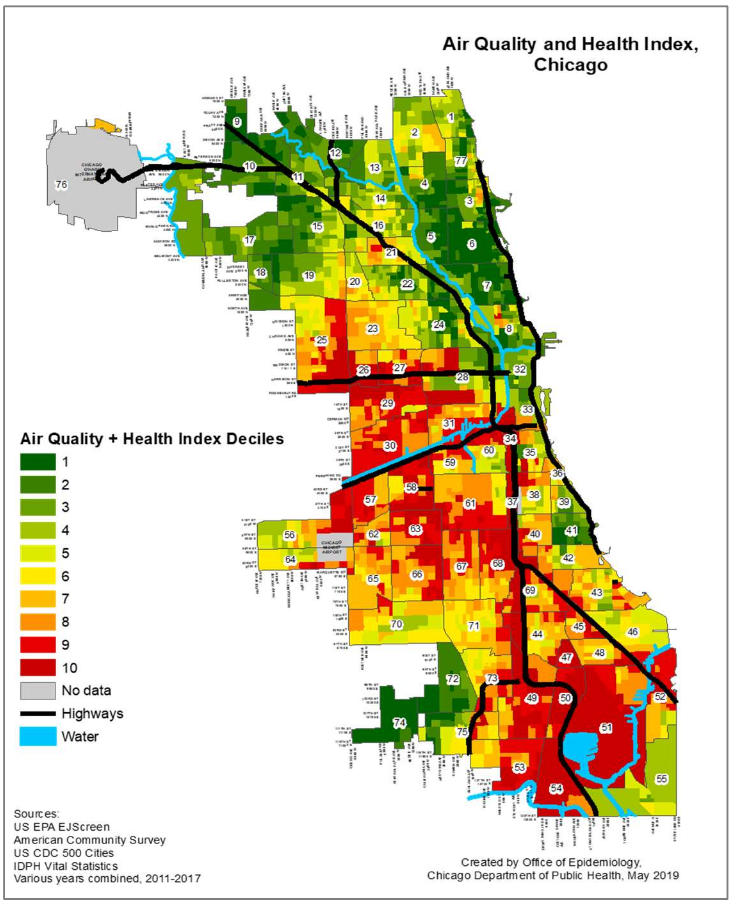

Figure 1 – Map of overall Chicago Air Quality and Health Index

Table 3 – Definition of the specific variables that make up the CAQHI. The variables fall within four subcategories of Sensitive Populations, Vulnerable Populations, Environmental Exposures, and Environmental Effects.

Pollution Burden	Population Characteristics
Environmental Exposures • Particulate matter • Ozone • Diesel particulate • Air toxics cancer risk • Air toxics respiratory hazard index • Traffic proximity and volume	**Vulnerable Populations** • Poverty/income • Race/ethnicity • Education • Linguistic isolation • Unemployment • Housing-burdened low-income population
Environmental Effects • Proximity to risk management plan sites • Proximity to hazardous waste facilities • Proximity to National Priorities List sites	**Sensitive Populations** • Young/old age • Chronic obstructive pulmonary disease • Coronary heart disease • Asthma • Low birth weight

*Table 4 - **CAQHI Results** based on the population residing in the area within ½ mile of **each garage**. Note that higher scores indicate higher burden or vulnerability.*

Garage	Overall Index Score	Sensitive Populations	Vulnerable Populations	Environmental Exposures	Environmental Effects
103rd	94	76	66	50	76
74th	65	76	68	40	47
77th	84	75	68	54	48
Chicago	74	78	76	35	59
Forest Glen	23	50	33	43	35
Kedzie	85	76	71	44	65
North Park	31	40	45	47	37

*Table 5 - **CAQHI Results** based on the population residing in the area within ¼ mile of the **bus routes** operated by each garage. Note that higher scores indicate higher burden or vulnerability.*

Garage	Overall Index Score	Sensitive Populations	Vulnerable Populations	Environmental Exposures	Environmental Effects
103rd	58	61	55	48	54
74th	57	52	55	51	58
77th	58	55	55	51	56
Chicago	48	46	50	54	57
Forest Glen	26	38	39	52	36
Kedzie	50	44	50	56	55
North Park	32	36	38	58	44

B. Detailed Assumptions for Schedule Modeling

Schedule modeling was completed to test the compatibility of CTA bus schedules with various electric bus technologies. This analysis was completed for weekdays and Saturdays using schedules from CTA's Fall 2018 service, which represents the maximum service in that year.

First, the **technology options** to be analyzed were selected. These technologies included 40 ft and 60 ft buses under current technology, moderate technology improvement, and significant technology improvement. Each technology option was given attributes including a usable battery capacity, a battery consumption rate per mile, and a charging power level. These assumptions were selected to represent reasonably adverse conditions, based on CTA experience during winter conditions and including battery degradation over time. (Note that different battery consumption rate inputs are used elsewhere when seeking to represent average annual conditions for cost modeling.) The details of the technology options for schedule modeling are shown in the tables below.

Table 6 – Technology assumptions for 40 ft electric buses. Sources: CTA Bus Engineering and various OEMs.

	Current technology (matches CTA experience and reliable performance in adverse conditions)	**Moderate technology improvement**	**Significant technology improvement**
Buses and chargers	Battery capacity: – Nominal 440 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 282 kWh Battery consumption rate: 3.18 kWh/mi Fast charging power level: 450 kW Slow charging power level: 125 kW	Battery capacity: – Nominal 660 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 422 kWh Battery consumption rate: 3.18 kWh/mi Fast charging power level: 600 kW Slow charging power level: 188 kW	Battery capacity: – Nominal 880 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 563 kWh Battery consumption rate: 3.18 kWh/mi Fast charging power level: 750 kW Slow charging power level: 250 kW

Table 7 – Technology assumptions for 60 ft electric buses. Sources: CTA Bus Engineering and various OEMs.

	Current technology (peer agency experience and reliable performance in adverse conditions)	**Moderate technology improvement**	**Significant technology improvement**
Buses and chargers	Battery capacity: – Nominal 440 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 282 kWh Battery consumption rate: 4.17 kWh/mi Fast charging power level: 450 kW Slow charging power level: 125 kW	Battery capacity: – Nominal 660 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 422 kWh Battery consumption rate: 4.17 kWh/mi Fast charging power level: 600 kW Slow charging power level: 188 kW	Battery capacity: – Nominal 880 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 563 kWh Battery consumption rate: 4.17 kWh/mi Fast charging power level: 750 kW Slow charging power level: 250 kW

The core of our schedule analysis is a **simulation of each vehicle block**[1] to test whether a particular technology option would be suitable to complete the scheduled service miles. The state of charge (SOC) of the vehicle's battery is modeled to decline based on distance traveled and to increase when on-route charging occurs. If the battery SOC falls below a minimum threshold, the vehicle block is determined to be incompatible with that technology. Below is a summary of the steps in this process:

1. Vehicles are assumed to start their service blocks with battery SOC at 90% of adjusted capacity. Our modeling is neutral with regard to the specific types of charging (fast or slow) that occur at garages to achieve this starting SOC.
2. Battery SOC declines based on distance traveled and the battery consumption rate.
3. If on-route charging is used, the battery's resulting SOC increase is calculated based on several factors:
    a. On-route charging may occur at the 13 locations selected to represent a "limited on-route charger network." These locations were selected to maximize potential charger utilization, especially by buses that would otherwise have a low SOC, without requiring excessive infrastructure investment. However, further analysis will be required to finalize the network of on-route charging locations and to identify the optimal number of chargers at each location.

[1] A vehicle block is an assignment of work for a single (non-specific) bus, outlining all trips, both revenue and non-revenue, and any recovery time between those trips. A vehicle block typically starts and ends at a garage, but some have alternate start/end locations.

b. Estimated layover time is determined by adjusting scheduled layover time according to the average percent of scheduled layover time buses experienced during actual operation at the end of the appropriate route, in the appropriate direction, at the appropriate time of day. This uses on-time performance data from eight weeks at various times in 2018.
c. Time with access to a charger is determined by adjusting estimated layover time based on the number of buses scheduled to be present at the charging location. If there are more buses than chargers, the charging access is assumed to be distributed equally.
d. Time spent charging is determined from the time with access to a charger by subtracting two minutes total for charger connection and disconnection.
e. The power level that a bus will accept from an on-route fast charger depends on the battery SOC. When the SOC is relatively high or low, the battery will accept a reduced portion of the charger's rated power level. Figure 2 shows the relationship between the power accepted from a charger and battery SOC. This graph was provided by CTA Bus Engineering based on observed performance of CTA's installed 450kW overhead pantograph fast-chargers.

4. At every scheduled timepoint, battery SOC is compared with the minimum reserve SOC (which is 20% of adjusted capacity) to confirm the SOC is acceptable.

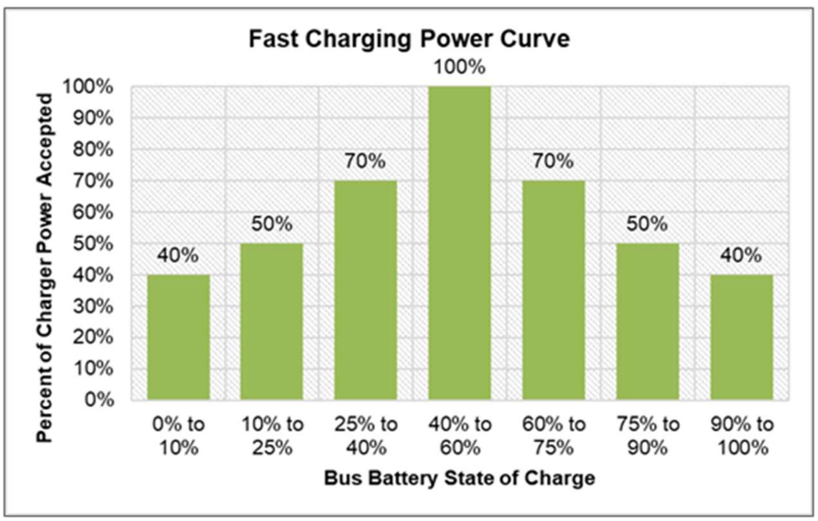

Figure 2 – Fast charger power accepted by a bus battery varies based on battery SOC.
Source: CTA Bus Engineering

A summary of the schedule modeling results is provided in the two tables below. This illustrates how schedule compatibility increases as technology improves. It also demonstrates the impacts of the different schedule characteristics between weekdays and Saturdays. Note that on Saturdays, vehicles tend to be assigned to operate significantly longer distances than on weekdays.

*Table 8 – Schedule compatibility results for **weekdays**, using the limited on-route charging network*

	Garage Charging is Sufficient	On-Route Charging is Required	Not Suitable to Electrify	Total Percent Compatible
Current Technology	51%	15%	34%	66%
Moderately Improved Technology	63%	14%	23%	77%
Significantly Improved Technology	78%	10%	12%	88%

*Table 9 – Schedule compatibility results for **Saturdays**, using the limited on-route charging network*

	Garage Charging is Sufficient	On-Route Charging is Required	Not Suitable to Electrify	Total Percent Compatible
Current Technology	7%	27%	66%	34%
Moderately Improved Technology	21%	30%	49%	51%
Significantly Improved Technology	43%	26%	30%	70%

C. Detailed Assumptions for Modeling of Garage Charging

A garage charging analysis was completed to compare the likely impacts of different potential charging strategies. The analysis considered how each bus in the system could be charged from its expected state of charge (SOC) at the end of its scheduled operations, to a target SOC that is required before starting its next assignment. Note that this analysis accounts for electrification of vehicle blocks that were shown to be incompatible with electric bus technologies,[2] and a small number of vehicle blocks do not require garage charging because on-route charging is sufficient, using results from the schedule modeling. Note also that this analysis focused on the "end state" of a fully electric fleet and did not explore the significant issues involved in the transition period during which garages would house both diesel and electric buses.

Table 10 – Bus SOC Assumptions for Garage Charging

Variable Description	Assumption	Source and Notes
Technology inputs	Moderate technology improvement	This was defined in Section B of this Appendix as part of schedule compatibility modeling.
On-route charger network	A limited on-route charger network with 13 locations	This was selected as the preferred on-route charger network.
Target battery state of charge (SOC) after garage charging	• 90% for most buses • 97% for buses at outdoor garages that are charged using fast charging only	The higher target SOC for outdoor buses that are charged using fast charging only serves to offset the 7% reduction in battery SOC that is anticipated in order to maintain battery temperature during outdoor storage in cold weather, while not connected to a charger.
Battery SOC of buses returning to the garage	Determined from schedule modeling for each vehicle block	The difference between this value and the target battery SOC represents the amount of charging that each vehicle block will require.

[2] The garage charging requirements of these vehicle blocks are unknown. There might be different amounts of charging needed depending on what changes are implemented to make the service compatible. Our solution to this is to assume similar characteristics to the service that was compatible for electrification with garage charging.

Our analysis tested several potential approaches to providing garage charging that achieves the target SOC. These approaches are summarized using the following three charging strategies with different mixtures of fast charging and slow charging. The assumptions regarding how these chargers would function are shown in Table 11.

- At one extreme, charging could be achieved with "**All Slow Charging**," defined as slow chargers available for all buses at a garage, in the locations where the buses are parked overnight. This would not require any fast chargers.[3]
- Next, a "**Moderate Fast Charging**" strategy would mean that existing fueling lanes are converted to offer one fast charger each; this allows every vehicle to fast-charge for a limited time during overnight servicing, similar to existing fueling operations. The vehicles that cannot reach their target SOC using fast charging during this time would be stored in parking lanes with slow chargers so they could charge sufficiently overnight.
- The third strategy, "**Mostly Fast Charging**," tested a greater amount of fast charging, with two more fast chargers installed at each garage in addition to the one fast charger per fueling lane included in the previous strategy. These additional fast chargers would prioritize buses that need a small amount of additional charging beyond what was possible using only existing servicing time. Note that our approach is agnostic to the specific configuration of additional fast chargers; they could be installed at locations aside from fueling lanes. A modest number of slow chargers would be provided to accommodate buses that cannot reach their target SOC using the fast chargers.

Table 11 – Charger Usage Assumptions for Garage Charging

Variable Description	Assumption	Notes
Operation of fast chargers matching existing fueling lanes	Each bus occupies a charger for 15 minutes	Source: CTA Bus Maintenance This approach mimics current fueling operations. One minute of the 15 would be spent connecting and disconnecting with the charger.
Operation of fast chargers in excess of existing fueling lanes	Prioritize buses closest to their target SOC	This approach maximizes charger utilization over an 8-hour charging period.
Power accepted from fast chargers	See Figure 2 in previous section.	Power accepted from fast chargers varies depending on the SOC of the bus charging.
Slow chargers required	Each slow charger has dispensers to serve three buses.	Buses that cannot sufficiently charge using fast chargers will use slow chargers.

[3] Note that in reality, at least one or two fast chargers would be desired as a failsafe, but these are excluded here for purposes of analysis.

Our analysis compared various characteristics of the charging strategies, in addition to the numbers of chargers required. We estimated the cost of the charger infrastructure and potential servicing labor; these assumptions can be found in the Cost Modeling section of this appendix. We also estimated each garage's peak power draw, assuming charging can be managed so the peak utilization is one-third less than it would be if all chargers were simultaneously running at full power. Finally, the additional space needed for slow charging infrastructure was estimated based on the assumptions in Table 12; at a typical garage the space needed was estimated in the range of 1 to 3 SBE.

Table 12 – Space Impact Assumptions for Garage Charging[4]

Variable Description	Assumption	Notes
Storage space reduction from each slow-charging bus stored outdoors	7 square feet	Source: CTA Bus Engineering. Space is used by gantry footings and the rows of electrical cabinets that must be positioned near charging dispensers. At indoor garages, we assume that gantry footings can be aligned with structural columns and will not contribute to the spatial impact.
Storage space reduction from each slow-charging bus stored indoors	6 square feet	
Space for one standard bus equivalent (SBE)	791 square feet	Used to convert spatial impacts into storage capacity impacts. Includes space for travel lanes and walkways between buses.

[4] While these values suggest a relatively small footprint, it will not always be possible to place equipment in a compact consolidated way that minimizes storage impacts. As a result, bus storage capacity lost could be greater than our estimates if equipment needs are spread throughout the storage area. Note that many of CTA's garages may have some unused space that could be repurposed to house charger equipment, but to be conservative we are not considering that in our space estimates. We assume no storage space reduction with fast charging space on the basis that several fast chargers can fit within the garage space currently occupied by fueling islands.

D. Detailed Assumptions and Inputs for Fleet Electrification Cost Modeling

Table 13 – Overall Assumptions

Variable Description	Value	Source and Notes
Inflation rate	1.8% annually	Producer Price Index & CTA Finance
Annual miles operated	34,000 per bus	CTA Bus Engineering

Table 14 – Diesel Fuel Cost Inputs

Variable Description	Value	Source and Notes
Diesel bus fuel consumption	• 3.590 miles per gallon (mpg) for a 40 ft bus • 2.435 mpg for a 60 ft bus	CTA Transit Asset Management. Note that this does not account for potential improvement over time; we similarly do not account for electric bus energy consumption rates improving over time.
Hybrid bus fuel consumption	3.463 mpg for a 60 ft bus	
Diesel fuel price	$2.53 per gallon	CTA Finance. Future diesel prices will follow US Energy Information Administration (EIA) projections for Transportation Diesel Fuel (distillate fuel oil).
Annual cost of diesel auxiliary heating	• $44 per indoor-stored bus • $261 per outdoor-stored bus that is connected to a slow charger overnight • $523 per outdoor-stored bus that is *not* connected to a slow charger overnight	CTA Bus Engineering. Calculated based on CTA's existing diesel auxiliary heater specifications, including diesel consumption rates and temperature setpoints.

Table 15 - Electricity Cost Inputs

Variable Description	Value	Source and Notes
Electric bus electricity consumption rate	• 2.8 kWh/mi for a 40 ft bus • 3.5 kWh/mi for a 60 ft bus	Average of values observed for adverse conditions and ideal conditions. Note that different battery consumption rate inputs are used in the schedule modeling when seeking to represent adverse winter conditions to represent year-round reliably achievable performance.
Electricity pricing	Typically between 7 and 9 cents per kWh.	Calculated based on based on CTA's current electricity supply pricing and electric utility rates, including variable demand (kW) charges. Future pricing will apply growth based on EIA projections for Transportation Electricity.

Table 16 – Bus Maintenance Cost Inputs

Variable Description	Value	Source and Notes
Annual maintenance cost per mile operated	Inputs for diesel (including diesel hybrid) buses and electric buses are shown in the graph below.	Inputs vary based on bus age. The graph below shows a projection by CTA Bus Engineering.
Mid-life overhaul cost	• $150,000 for diesel/hybrid bus • $350,000 for electric bus	CTA Bus Engineering

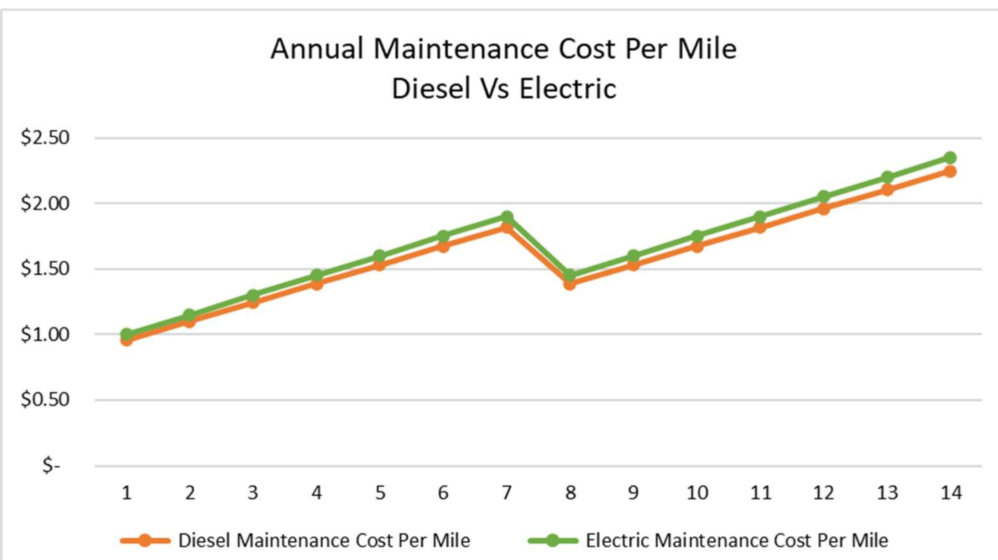

Figure 3 – Annual maintenance cost per mile inputs for diesel and electric buses

Table 17 - Electric Bus Charging Infrastructure Maintenance Cost Inputs

Variable Description	Value	Source and Notes
Slow charger annual maintenance	• 24 hrs labor per unit • $1,200 for material per unit	CTA Bus Engineering
Fast charger annual maintenance	• 72 hrs labor per unit • $11,500 for material per unit	CTA Bus Engineering
New substation annual maintenance	• 480 hrs labor per unit • $5,900 for material per unit	CTA Infrastructure, based on current substation annual material budget.
Fully-loaded cost per hour for electricians	$87.85 per hour	CTA Infrastructure
Note that this category has a 15% contingency included on material and a 20% contingency included on labor. This reflects industry best practice to cover an array of possible costs such as additional maintenance of fire life safety systems, heating, or HVAC systems.		

Table 18 – Bus Schedule Change Cost Inputs

Variable Description	Value	Source and Notes
Fully-loaded cost per hour for bus operations	$82.62 per hour	This rate is applied to the bus operator labor associated with splitting apart long vehicle blocks as needed to ensure compatibility with electrification. This added labor cost is incorporated into the cost modeling in the later years of the transition period as schedule changes become necessary to continue fleet electrification.

Table 19 – Charging Labor Cost Inputs

Variable Description	Value	Source and Notes
Fully-loaded cost per labor hour for Bus Servicers	$49.35 per hour	This rate is applied to the *added* time spent in a fueling lane for fast charging, beyond current servicing time.

Table 20 – Garage Facility Upgrade Cost Inputs

This category includes estimates of facility improvements that will be necessary to bring bus facilities into a state of good repair. Not all of these investments are necessary to support electrification, however; more detailed facility-specific studies will be required to clarify the specifics of required electrification-related facility upgrades. (The studies themselves should be considered part of these costs.) Some of the facility costs may be essential to address at the time of electrification, and others may be convenient/cost-effective to address at the time of electrification.

Variable Description	Value	Source and Notes
State of good repair improvements for Chicago, 103rd Street, 74th Street, and Kedzie	$100 million for each garage	CTA Infrastructure and Facilities. This may include roof repairs to prevent water damage to installed chargers, paving repairs concurrent with installation of gantry foundations, or other code compliance upgrades identified through construction permitting processes.
Full replacement of 77th Street & South Shops Bus Shops Heavy Maintenance	$630 million	CTA Infrastructure and Facilities
New garage facility, including land	$450 million	CTA Infrastructure and Facilities
Potential upgrades for Forest Glen	• Full replacement as outdoor garage for $335 million • Full replacement as outdoor garage with reconfiguration (adding 101 SBE) for $399 million • Full replacement as indoor garage for $450 million	CTA Infrastructure and Facilities
Potential upgrades for North Park	• Full replacement as outdoor garage for $335 million • Full replacement as outdoor garage with reconfiguration (adding 40 SBE) for $360 million • Full replacement as indoor garage for $450 million	CTA Infrastructure and Facilities

Table 21 – Bus Purchase Cost Inputs

Variable Description	Value	Source and Notes
Bus lifetime	14 years	Analysis Plan
Electric bus purchase prices	• $1 million for a 40 ft bus • $1.5 million for a 60 ft bus	CTA internal budgeting values from CTA Bus Engineering. Future electric bus purchase price trends are assumed to follow average California Air Resources Board (CARB) projections.
Diesel bus purchase prices	• $656,000 for a 40 ft bus • $1.018 million for a 60 ft bus	CTA internal budgeting values from CTA Bus Engineering. Future diesel and hybrid bus purchase price trends are assumed to increase $17,900 annually based on the average trend of new bus deliveries reported in the APTA Fact Book.
Hybrid bus purchase prices	• $906,000 for a 40 ft bus • $1.268 million for a 60 ft bus	
After-market features	$11,580 per bus that increases the fleet size	CTA Revenue and Fare Systems. Includes farebox and Ventra mobile validator.

Table 22 – Electric Bus Charger Infrastructure Cost Inputs

Variable Description	Value	Source and Notes
Fast chargers at garages	$1.75 million per charger	Based on CTA experience with chargers at Chicago Garage. Includes materials, design, labor, liabilities, and installation. Value also includes all infrastructure needed between the switchgear and the charger, including conduit, cabling, design, construction management, and CTA management costs. The same cost is used for fast charger replacements.
Slow chargers	$652,000 per slow-charging bus	Based on manufacturer quotes and estimates from CTA Bus Engineering. Includes charger, dispenser, gantry to support slow chargers, delivery, installation, conduit, foundations, ventilation, and other soft costs. We assume that, in both indoor and outdoor facilities, slow chargers are suspended by overhead gantry on dedicated supports.
Slow charger replacements	$126,000 per bus	Includes old equipment removal, new equipment installation, and soft costs, and excludes one-time investments such as gantry and conduit.
On-route fast charger installations	$3,472,000 per location plus $2,267,000 per charger	Extrapolated based on actual costs from CTA's on-route charger installations at Chicago/Austin and Navy Pier, including construction and electrical infrastructure.
Charger lifetime	14 years	Matches bus lifetime
Note that costs in this category have a 40% contingency included; this reflects industry best practice to cover an array of risks at an early phase of project development. For example, the contingency may cover items such as diesel fuel tank decommissioning and fire safety upgrades.		

Table 23 – Garage Electrical Upgrade Cost Inputs

Variable Description	Value	Source and Notes
ComEd electrical upgrade costs	Typical values range from $4 million to $8 million per garage	ComEd provided estimates for potential electrical capacity upgrades up to the 10 MW level; we include the Rider DE Deposit and On-Property Costs and scale to each facility's modeled total power demand.
Back-up power source	$2.8 million per garage	Based on CTA estimates for an on-site energy storage system. This serves to represent a range of resiliency solutions that could be considered at garages.
Switchgear	$504,000 per 2.5 MW of capacity	Based on past CTA charging station and substation projects.
Construction costs of garage electrical upgrades	$15.476 million per garage	Based on past CTA charging station and substation projects.
Note that costs in this category have a 40% contingency included; this reflects industry best practice to cover an array of risks at an early phase of project development. For example, the contingency may cover items such as code-required upgrades.		

Table 24 – Emissions Inputs

Variable Description	Value	Source and Notes
CO_2 emissions rate for diesel/hybrid buses	10.21 kg CO_2 per gallon diesel + 5.5929 g CO_2e per gallon diesel	2018 USEPA Emission Factors for Greenhouse Gas Inventories
NO_x emissions rate for diesel/hybrid buses	16.64 g NO_x per mile	California Air Resources Board
$PM_{2.5}$ emissions rate for diesel/hybrid buses	Declines over time from 0.089 g per mile in 2022 to 0.038 g per mile in 2030	EPA Estimated U.S. Average Vehicle Emissions Rates per Vehicle by Vehicle Type Using Gasoline and Diesel, 2020
CO_2e emissions rate from power generation	452.6 g CO_2e per kWh	This combines the 2020 generation fuel mix of PJM with emissions rates from Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model. We assume that PJM's trend of declining CO_2e emissions rates (2.6% annually) will continue per the 2020 PJM Emissions Rate Report.
NO_x emissions rate from power generation	0.21635 g NO_x per kWh	This combines the 2020 generation fuel mix of PJM with emissions rates from the GREET Model. We assume that PJM's trend of declining NO_x emissions rates (5.7% annually) will continue per the 2020 PJM Emissions Rate Report.
$PM_{2.5}$ emissions rate from power generation	0.01757 g $PM_{2.5}$ per kWh	This combines the 2020 generation fuel mix of PJM with emissions rates from the GREET Model.