Overview of Battery-Electric Bus Technologies and Existing Conditions Review

Charleston Area Regional Transportation Authority Battery Electric Bus Master Plan

Final Report

January 2022

Stantec

Existing Conditions Report

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EXISTING CONDITIONS REPORT

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EXECUTIVE SUMMARY

As part of its Fleet Modernization Project and to support regional sustainability goals, the Charleston Area Regional Transportation Authority (CARTA) has committed to transition to a 100% battery-electric fleet for its fixed route services. This document, Overview of Battery-Electric Bus Technologies and Existing Conditions Review, is the first step in CARTA's electric bus master planning project process. This document provides a comprehensive overview of CARTA's current service, operations, maintenance facility, and finances. Specifically, this report includes:

- An overview of battery-electric bus (BEB) technologies that discusses different available bus types, purchase prices, manufacturers, maintenance and charging considerations, and conservations related to transitioning from conventional buses to BEBs
- A review of CARTA's current operations and service. This includes the current fleet composition and replacement schedule, operational characteristics that dictate the feasibility of a BEB transition (including an analysis of block mileages, deadheading, and current daily service schedule)
- An assessment of the existing conditions of CARTA's current operating base and maintenance facility
- A financial analysis of CARTA's current operations, including operating costs and well as capital funding sources.

Major findings from the report include:

- Overall, the majority of CARTA's service is within the mileage ranges of BEBs, though some blocks and vehicle assignments exceed current BEB range capacities. Nonetheless, it is likely that the majority of CARTA's BEB transition will be straightforward.
- While CARTA operates a variety of different vehicle sizes to fit the needs of its different service types and diverse service area, this can add complexity to the BEB transition as different vehicle types have different BEB equivalents with different operating ranges, and it will be important to ensure vehicles are scheduled on the correct block to avoid operational issues.
- CARTA already has BEBs in operation, which is helpful as operators and other staff are already familiar with the new technology and the agency has real-world data on fuel efficiency and estimated operating range, which will be a helpful tool to help compare the results of the predictive power and energy modeling.
- CARTA's operating base and maintenance facility are in good operating conditions and fit the needs of CARTA. There are currently six bus parking spaces with charging dispensers (125 kW per unit) for charging CARTA's six BEBs. CARTA is currently working with Proterra and Dominion

Energy to install an additional 40 charging dispensers that would be supplied by two 1.2MW charging stations. Future facility modifications and infrastructure improvements are unlikely to require changes to the current service cycle.

- Compared to peer agencies, CARTA's operating expenses increased at a much lower rate between 2014 and 2019. The vast majority of CARTA's operating expenses are allocated to contractor expenses as Transdev maintains and operates CARTA's services. It is the assumption that as agencies become more accustomed to operating BEBs and vehicle costs manifest, cost per mile and hour should drop. Thus, it will be important for CARTA to closely track these metrics.

Taken together, these steps lay the groundwork for CARTA's transition to a BEB fleet, and the major findings and takeaways presented here provide insights into the constraints and opportunities regarding CARTA's fleet composition, transition, and implementation strategies.

Abbreviations

APTA	American Public Transportation Association
AVTA	Antelope Valley Transit Authority
BBB	Big Blue Bus
BEB	Battery-electric bus
BRT	Bus rapid transit
BTM	Behind the Meter
CARTA	Charleston Area Regional Transportation Authority
CCS	Combined charging system
CTE	Center for Transportation and the Environment
DASH	Downtown Area Shuttle
EV	Electric vehicle
GHG	Greenhouse gas emissions
kW	Kilowatts
kWh	Kilowatt-hours
LCRT	Lowcountry Rapid Transit
LOTO	Lock-Out-Tag-Out
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
OCPP	Open Charge Point Protocol
OCTA	Orange County Transportation Authority
SCADA	Supervisory control and data acquisition
TAM	Transit Asset Management

TOU	Time of use
UCI	University of California, Irvine
ULB	Useful life benchmark
ZEB	Zero-emission bus

1.0 ABOUT CARTA

The Charleston Area Regional Transportation Authority (CARTA) provides public transportation services to the residents and visitors of Charleston County via a combination of local routes, express routes, and Downtown Area Shuttle (DASH) routes, as well as demand-response paratransit service. In 2014, CARTA identified a need for a large capital effort to replace its aging rolling stock, and as part of its Fleet Modernization Project, has decided to gradually transition to a battery-electric bus (BEB) fleet as part of this project. CARTA received its first BEB in 2019, and currently operates six BEBs in revenue service, with 27 more scheduled for delivery by the end of 2021. In addition, the region is planning its first bus rapid transit (BRT) line, called Lowcountry Rapid Transit (LCRT), to operate entirely with BEBs.

To help CARTA prepare for the future and accomplish goals related to greenhouse gas reductions and sustainability, Stantec has been retained by CARTA to help develop a comprehensive electric bus master plan, which includes determining the power, energy, and charging requirements at CARTA's maintenance facility to support the BEB fleet, charging strategy, and fleet management plan. This report is the first step in the master planning effort, developing a comprehensive understanding of CARTA's service and operations, which will lay the groundwork for future tasks such as modeling and determination of infrastructure needs.

1.1 ABOUT THIS DOCUMENT

As mentioned above, this report is the first step in the electric bus master planning process and helps to establish baseline conditions for all steps moving forward. This report includes an overview and market scan of different BEB technologies currently available, an analysis of current service and operations, an assessment of CARTA's maintenance facility and operating base, and financial analysis.

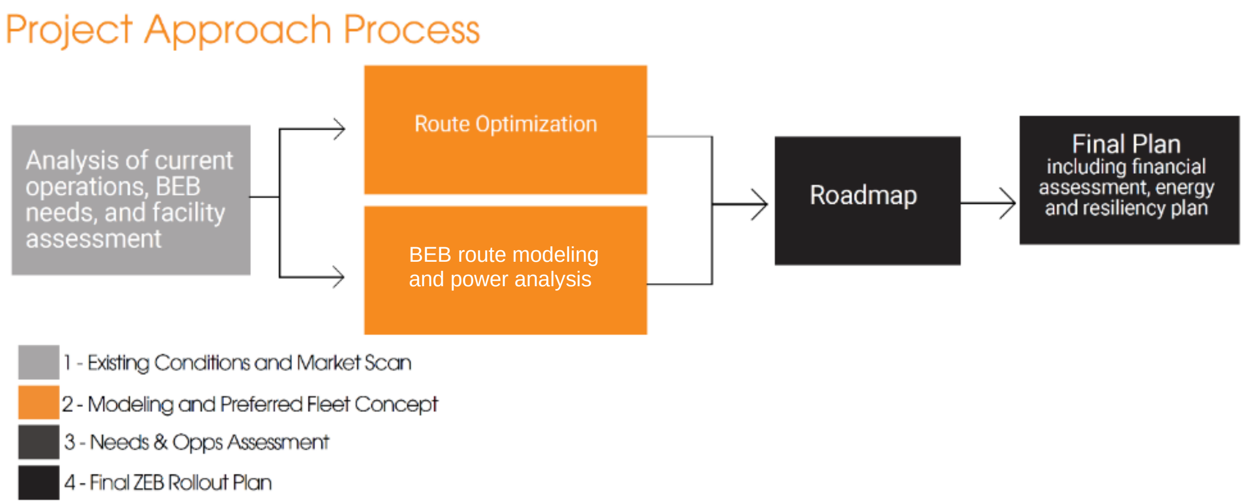

Figure 1: Electric Bus Master Plan project approach process

2.0 OVERVIEW OF BATTERY-ELECTRIC BUS TECHNOLOGIES

CARTA has determined that their zero-emission bus (ZEB) future will be implemented with BEBs, and currently has six BEBs in service with 27 more scheduled for delivery in 2021 (summarized in Table 1). While this is evidence that CARTA is familiar with BEB technology, it is still important to provide a high-level overview of BEB technology, including different vehicle types available, the differences between in-depot and on-route charging, and required infrastructure. This section also addresses technical, operational, and scheduling considerations when transitioning to a BEB fleet.

Table 1: Summary of CARTA's current BEB fleet

Bus type	Battery pack size	Bus size	Quantity	Schedule
Proterra E2 Catalyst	440 kWh	40’	3	In service since December 2019
Proterra ZX5	440 kWh	40’	3	In service since March 2021
New Flyer Xcelsior CHARGE	466 kWh	40’	7	Delivery commenced in August 2021 with final delivery anticipated in October 2021.
Proterra ZX5	440 kWh	35’	20	Delivery anticipated in December 2021

2.1 OVERVIEW OF DIFFERENT BATTERY-ELECTRIC BUS TECHNOLOGIES

Different configurations of BEBs are being considered today by transit agencies as a solution to replace fossil-based fuels with the goal to reduce criteria pollutant and greenhouse gas emissions (GHGs), improve air quality, provide a more pleasant riding experience, and reduce operating expenses. Because each BEB technology has different strengths and weaknesses, as well as unique operational requirements, the following sections present a brief overview of the commonly deployed BEBs and supporting infrastructures.

BEBs have battery packs with total energy-storage capacities currently ranging from about 100 kWh to 660 kWh. Buses with smaller batteries are typically used in applications that feature on-route or opportunity charging, while buses with larger batteries rely on in-depot charging. All BEBs are equipped with at least one combined charging system (CCS) charging port for 1,000V DC charging (for plugin dispensers), while on-route buses also have two roof-mounted contact bars that are used to interface with inverted pantographs. Depot-charged buses may also be equipped with contact bars, since in-depot charging may use either CCS plugin or pantographs. Both in-depot and on-route charging are discussed in further detail below.

2.1.1 Depot-Charging BEBs

Depot-charging BEBs (also referred to as plug-in BEBs) have batteries with large energy storage capacity and only charge while in the bus depot. Some examples of current models range between 444 kWh (Gillig)[1], 160 to 524 kWh (New Flyer)[2] to 660 kWh (Proterra)[3]. These battery capacities provide driving ranges between 150-240 miles, depending on average fuel efficiency, which is influenced by ambient temperature, auxiliary-HVAC loads, route topography, average speed, passenger loads, and other route characteristics. These types of buses must return to the depot to charge—a process that can take 4+ hours to achieve a full charge and range potential.

There is a wide range of charging equipment that can be used for in-depot charging, with two general architectures being available as follows:

- Individual chargers – 50 kW to 200 kW power rating, each supporting 1 to 4 dispenser cables (or pantographs) each[4]
- Centralized charger – 1 MW to 3 MW power rating, each supporting 20 to 60 dispenser cables (or pantographs) each.

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[1] https://www.gillig.com/post/metro-gillig-electric-bus
[2] https://www.newflyer.com/buses/xcelsior-charge/
[3] https://www.proterra.com/vehicles/catalyst-electric-bus/range/
[4] ChargePoint Power Blocks can support up to 8 dispensers or cables per charger but require added equipment and results in diluted per-bus power rating.

The individual or centralized chargers are connected to dispensers that can have different configurations, as shown in Figure 2. Figure 3 shows an example of depot-charging BEBs operating at the University of California, Irvine (UCI) and at Santa Monica Big Blue Bus (BBB).

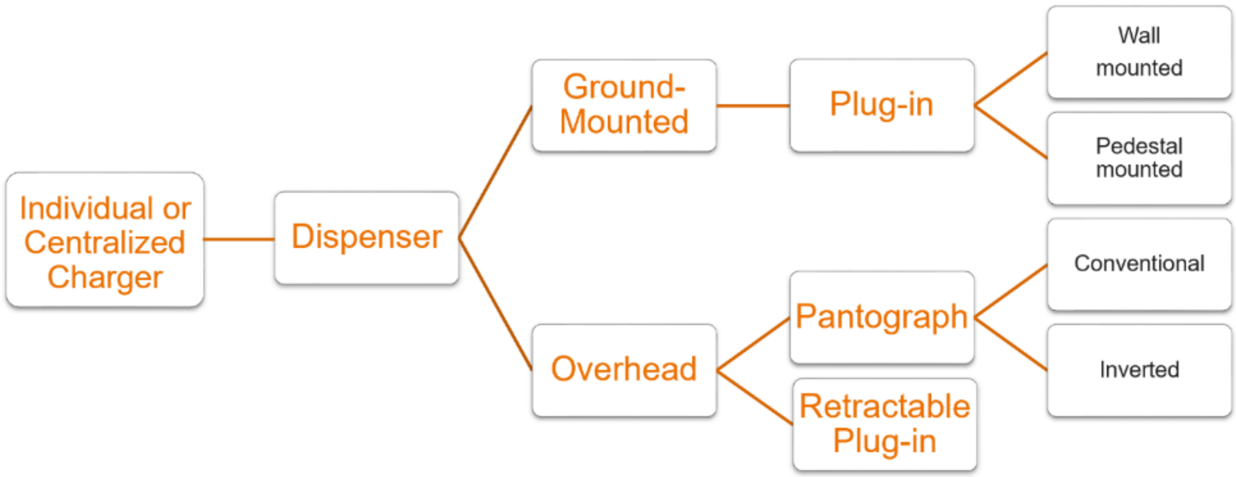

Figure 2: Dispenser configuration for depot charging BEBs.

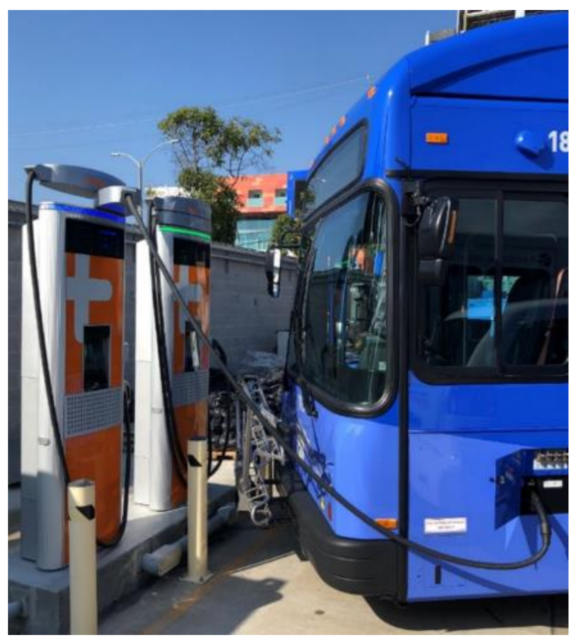

Figure 3: BEBs with pedestal-mounted plug-in chargers at UCI[5] (left) and Santa Monica BBB (right)

Table 2 presents an overview of depot-charging BEBs with advantages and disadvantages, while Table 3 presents an overview of individual vs. aggregated charger technologies.

[5] "Anteater Express Live Route Tracking." [Online]. Available: https://www.shuttle.uci.edu/. [Accessed: 30-Jan-2019].

Table 2: Overview of plug-in BEBs

In-Depot Charging Advantages	In-Depot Charging Disadvantages
• No road/traffic disruptions due to construction when installing on-route charging equipment • Control over charging schedules to minimize peak power demand to mitigate grid connection upgrades, and to reduce demand charges during peak-hours • Buses can be deployed on any route/block within 180-240 miles range of a garage • Control over infrastructure deployment since equipment will be on transit property (no easements or added security needed) • Easier to integrate with facility renewable energy supply and energy-storage systems	• More than one bus might be needed to provide the service one diesel or CNG bus can provide, depending on the block-distance requirements • Limitations on daily travel distance • Higher replacement cost at bus midlife for larger battery packs • Footprint constraints for charging equipment in garage and significant retrofit requirements at garage, including likely occupation of some parking to accommodate power cabinets, pedestals, or base for overhead infrastructure. • Need to implement a smart charging management software to reduce and optimize power requirements • Utility coordination to facilitate grid connection may take 1-2 years to complete • Heavier and larger batteries to maximize range may impact axle weight limitations and increase bus costs • Requires coordination with utility company

Table 3: Overview of alternative low-power in-depot charging architectures

Individual Chargers[6] Advantages	Centralized Charger Advantages
• Scalability and expansion is more granular • Easier to upgrade or replace most components • Power directed to a given bus can be higher for systems that otherwise have similar average kW-per bus metric • Many competing manufacturers (ABB, Chargepoint, Heliox, Power Solutions/Proterra, Siemens) • Multiple chargers may be aggregated and located remotely from the dispensers, or may be collocated near its dispensers • Individual charger units can be added as required to meet the total energy needs of any depot	• Fewer components to install for a given number of BEBs at a given average per-BEB power level • Less space required • New manufacturer (Hitachi) recently announced market entry, in addition to Proterra • Centralized charger units can be added as required to meet the total energy needs of any depot • Very flexible packaging, where power levels of 37.25 kW to 450 kW per bus (at various quantities of each) can be configured

[6] Each charger can support 1 to 4 dispenser cables.

Typical depot chargers that use plug-in dispensers include commercial products available from Siemens, Chargepoint (Figure 4), ABB, and Hitachi (Figure 5). Other BEB manufacturers, like Proterra, provide their own in-depot chargers ranging from 60 kW to 150 kW.

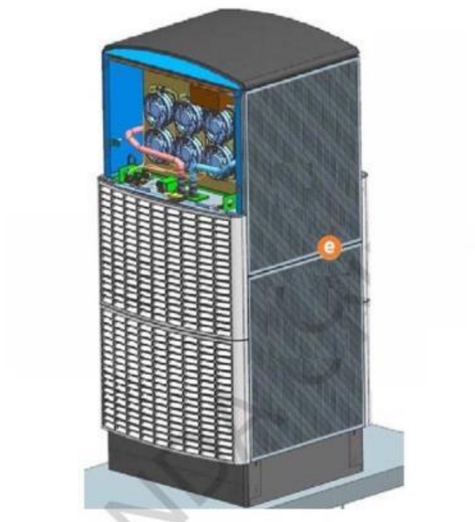

Figure 4: Individual Chargepoint 200 kW 'Power Block' Depot Charger – Can Power CCS plugins or Pantograph Dispensers

Figure 5: Centralized Hitachi 2.25 MW Depot Charger – Can Power CCS plugins or Pantograph Dispensers

It is important to note that bus depots will require multiple chargers and that depending on their use, this could significantly impact the facility power service. Furthermore, the average charger capacity (e.g., 37.5 kW vs. 150 or 200 kW) will dictate the charging time for each bus (10 hrs vs 5 hrs for a 450-kWh battery size), and the power peak of the charging cycle. Conversely, if available average power per bus is inadequate to complete a charge in the available time, average power must be increased accordingly. For example, if a 150-kW charger is powering four plug dispensers that charge simultaneously, the average power would be 37.5 kW per bus. If each of the four buses require 225 kWh to recharge, the 37.5 kW average rate would allow all four buses to be charged in 6 hours.[7] However, if the recharge must be completed in 5 hours, a higher power ratio of at least 45 kW[8] per bus would be needed. Based on available power ratings for chargers, the configuration would be rounded up to 50 kW per bus.

The average power rating that is required per bus also drives the total system power requirement. For example, expanding on the two models described in the above paragraph, 100 buses at 37.5 kW each (and 6 hours to charge) would require a facility-power rating of 3.75 MW[9], while the scenario with 50 kW chargers and 5 hours would require 5 MW of power. Note that these power values are at the charger-

[7] 4 buses * 225 kWh per bus = 900 kWh charge needed / 37.5 kWh per connector / 4 buses = 6 hours.
[8] 4 buses * 225 kWh per bus = 900 kWh charge needed / 5 hours / 4 buses = 45 kW power per bus.
[9] 100 buses * 37.5 kW charger capacity = 3,750 kW or 3.75 MW

system output, and do not include efficiency loses for inverting AC power to DC. When a typical efficiency factor of 93% is applied, the actual AC input power required would be 4.0 MW and 5.4 MW respectively.

Power requirements for a charging system are also impacted by how charging is organized. In Figure 6, 60 kW chargers are arranged in a 1:1 dispenser to bus configuration for 100 buses that are used simultaneously, this requires a high-power demand capacity (~6 MW) over five hours and would require a large upgrade to the grid utility connection. Alternately, in Figure 7, a 150 kW charger is used for up to three buses during an extended charging window of eight hours, resulting in a reduced power capacity of ~3.75 MW, but would require dispensers with multiple CCS connectors and automatic-sequential switching.[10] The second scenario has a lower power demand, and a lower investment cost in equipment and grid upgrades, but requires a new operational system and additional staff to coordinate and supervise the charging schedule. Alternate configurations that have three or more dispensers per charger are feasible and use smart-charging systems that automatically switch the bus (or buses) being charged. These systems require added planning and design.

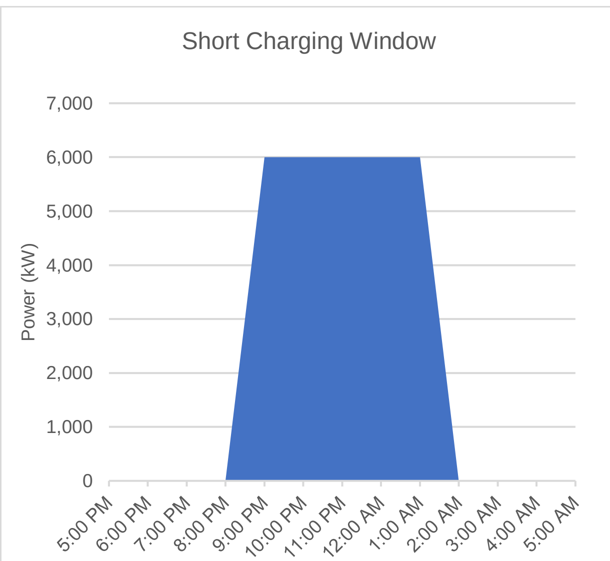

Figure 6: Power profile for a short charging window

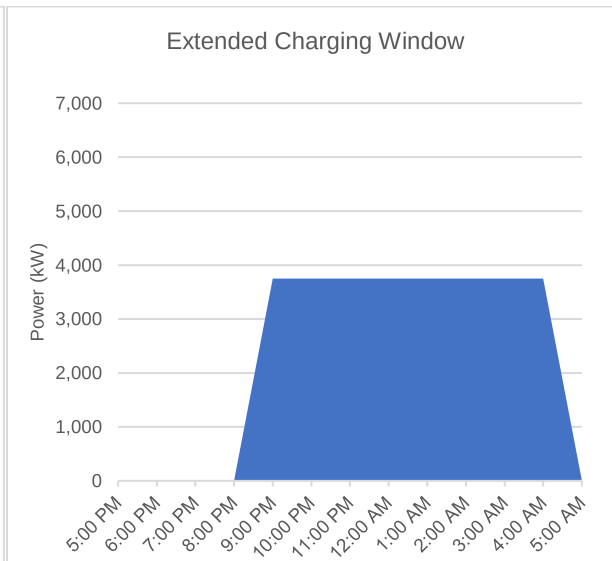

Figure 7: Power profile for an extended charging window

Depot-charging equipment includes the configuration of a modular charging system that provides charge power via multiple connectors. Such connectors can be CCS plug-in, or they can be pantographs. Most companies package standard pantograph assemblies from companies like Schunk (Figure 8 and Figure 9) and Stemmann-Technik.

[10] All charger manufacturers support automatic and sequential switching of dispensers and connectors from a charger, and some (Chargepoint and Heliox) also support simultaneous flows from a charger.

Figure 8: Schunk Pantograph

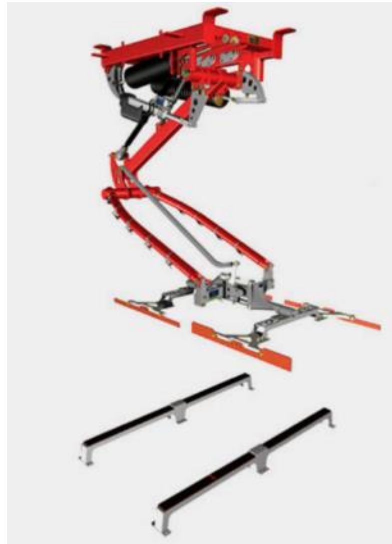

Figure 9: Schunk Inverted Pantograph (most common in North America)

Although these pantographs were originally intended for on-route opportunity charging, they can also be used in the depot for ‘low power' overnight charging (in lieu of CCS plugin) or for high-power fast charging. This might be useful to coordinate preventative maintenance activities on a returning bus where maintenance needs to occur immediately. Furthermore, pantographs are usually adopted where footprint restrictions justify the extra investment in charging/dispensing equipment and supporting infrastructure.

Note: A BEB can have plug-in charging capabilities and equipment to use overhead pantographs. However, throughout this report, we term a BEB that can only charge in-depot as “depot BEB”.

2.1.2 On-Route Charging BEBs

On-route charging BEBs typically have a smaller battery pack, between 106-320 kWh, that can translate to a reduction in purchase cost. However, with that battery size the expected range with full charge is between 50 and 130 miles. Therefore, these types of buses need to recharge while on route to expand the range of service. The overhead chargers are typically allocated along the route, usually at a bus stop that has a long layover such as a terminal, where the battery is charged, and the bus continues its service. The on-route charging of the battery can take between five and ten minutes to extend operating range between 30 and 60 miles (using at least a 450-kW charger capacity). If the BEBs are exclusively on-route charging, then each bus would require between 15 and 40 minutes (depending on the battery size) to completely recharge the batteries at the end of its service before returning to base.

Furthermore, current manufacturers are upgrading the battery packs in on-route charging BEBs, between 450 and 660 kWh, to resemble depot-charging BEBs, with the added benefit (and complexity) of on-route charging. These BEBs have the capability to charge on-route, but they will also require equipment to charge at the depot (mostly occurring overnight). Therefore, the charging equipment for this type of BEB could include a combination of plug-in dispensers (for the depot charging), with fast-charging pantographs (for opportunity charging while on-route).

Note: For the remainder of this report, vehicles that use opportunity charging **and** in-depot charging are termed “on-route charging BEBs”.

Table 4 presents an overview of on-route charging BEBs with advantages and disadvantages of this bus configuration, and Figure 10 shows an example of on-route charging BEBs operated by Los Angeles Metro in Southern California.

Table 4: Overview of on-route charging BEBs

On-route charging BEB Advantages	On-route charging BEB Disadvantages
• Smaller batteries on buses have lower purchase price, reduced bus weight, and reduced battery replacement cost at the bus midlife compared to other ZEB technologies (for battery packs of 320 kWh and lower) • Potentially better power to weight ratio for performance	• Charging events of five to seven minutes after every roundtrip may exceed scheduled layover times • High infrastructure costs • Infrastructure along routes can disrupt traffic during and after construction • Demand charges for electricity during the day and at peak hours • Buses can only serve electrified routes where charging equipment is available or be assigned to other route/block where driving range will be limited • Additional buses assigned to the same routes during a service expansion might require additional chargers to avoid increasing layover times • If charging protocol requires bus operators to stay with the vehicle while charging is occurring, schedules may further be compromised to allow operators a “short personal relief” if such facilities are located at this point • Additional space requirements for adjacent charging infrastructure along the routes might require special city contracts, permits and rights of way • If charging infrastructure needs repairs, it can compromise service of routes until repairs are completed • Requires coordination with utility company

Figure 10: LA Metro's on-route/layover charging at the North Hollywood bus-rail station.

2.1.2.1 Conductive On-Route Charging Infrastructure

The most common type of on-route charging is the overhead inverted pantograph, where a charging head is lowered on to a set of DC charging rails on the top of the bus. Earlier iterations of this utilized a set of fixed overhead charge rails with a bus-mounted pantograph that raises to contact the overhead rails. This method evolved to the overhead inverted pantograph to reduce additional weight and cost required to accommodate a charging mechanism on each bus.

Many of the BEB providers have aligned with universal high-power opportunity chargers from companies such as Siemens (Figure 11) and ABB (Figure 12). Proterra offers their own high-power opportunity charger (Figure 13).

Figure 11: Siemens 300 kW Overhead Charger

Figure 12: ABB 300 kW and 450 kW Overhead Charger

Figure 13: Proterra 500 kW High-Power Charger

Many transit agencies and cities have expressed concerns over the impact these overhead chargers may have on the built urban environment. The foundations alone for the charge pedestal can be significant (Figure), not to mention the visual impact of the final unit.

Figure 14: Typical rebar structure for overhead charging pedestal

There are also concerns over right-of-way easements and permitting constraints, as well as the "permanence" of such infrastructure should the chargers ever need to be relocated. For this reason, several companies have investigated the use of non-contact inductive charging for opportunity charging.

2.1.2.2 Inductive On-Route Charging

Inductive or wireless chargers, in principle, work the same as the cell phone charging pads that many consumer electronics utilize. A capacitive coupling coil is installed at the bottom of the bus which close-couples to an inductive charging coil embedded in the pavement under a bus parking location. Inductive charger coils occupy a small footprint and can be used at layover or extended-stop locations on-route. While aesthetically more pleasing because no large external space is needed like for overhead chargers (as they are built into the roadway), charging efficiency varies greatly with bus alignment. Also, not all OEMs offer receiving coils needed for inductive charging, and there is no interoperability among wireless charger providers. And while the coil dispenser is effectively out of sight, a large rectifier cabinet near the charging location as needed to generate DC power is still required.

There are many current and future advantages to this type of technology, including:

- Cleaner urban design integration (except for the related cabinetry, Figure 17)
- Possible substitution for pedestal or overhead charging infrastructure, saving space at a maintenance facility
- No connector standards required, though BEBs equipped with inductive charging systems would still have a conventional CCS receptacle
- Future integration with autonomous vehicle operation

The trade-offs to such benefits include slower charging rates, increased capital cost, increased energy consumption[11], traffic disruption during installation within public roadways, and lower charging efficiencies which results in higher total energy costs. Additional driver training is necessary for operators of buses fitted with inductive charging technology, so they understand how to line up the bus's receiver pad with the transmitter pad embedded in the roadway or bus depot.

Two companies, WAVE and Momentum Dynamics, have made significant headway with this technology and have successfully installed trials at several cities throughout the country. The WAVE installation shown in Figure 15, Figure 16, and Figure 17 are for the Antelope Valley Transit Authority (AVTA), which utilizes 250 kW inductive chargers. The company is currently working on a pilot for a 500-kW inductive charger in conjunction with Volvo.

[11] Momentum quotes a 93% energy-transmission efficiency, vs. 95% efficiency for a typical CCS charger. A daily 300 kWh consumption rate per bus x 300 days per year = added consumption of 1800 kWh per bus x 40 buses = total added energy consumption of 72,000 kWh per year.

Figure 15: BYD bus fitted with WAVE charger in position to receive a charge

Figure 16: WAVE Inductive Pad at transit terminal

Figure 17: Adjacent charging infrastructure at terminal

Inductive charging is not exclusive of other charging modes. Buses fitted with receiver pads for inductive charging will still retain their plug-in ports for in-depot charging from dispenser cables. Inductive charging is also compatible with the installation of equipment to allow charging from overhead pantographs – in theory, a BEB could be fitted to receive all three charging modes. The combined weight of all equipment necessary to support multiple technologies may ultimately reduce the efficiency and range of the BEB, so a thorough analysis should be undertaken prior to committing to both inductive and overhead charging equipment.

Table 5: Advantages and disadvantages of inductive charging technology

Advantages	Disadvantages
Less invasive/smaller footprint for inductive charging equipment in transit stations or public rights-of-way versus overhead pantograph	Only two manufacturers (Wave and Momentum Dynamics) provide inductive charging infrastructure

Use as in-depot charging option can maximize bus parking efficiency versus ground-mounted plug-in charging dispensers and the additional space required within the bus yard	More expensive than ground-mounted plug-in charging dispensers on a per-unit basis due to higher equipment and installation costs.
Inductive charging can "piggyback" on the vehicle with other charging options (plug-in, overhead pantograph), allowing a bus multiple charging options depending on location.	The two manufacturers do not offer interoperability between their two technologies (i.e. bus with Wave receiver pads cannot charge from a Momentum Dynamics transmitter pad)
Charging capacity per charging (transmitter) pad now up to 300 kW, with higher capacity expected in the future as the technology advances	Gillig and BYD are the only bus manufacturers which offer inductive charging (to date). Proterra and New Flyer do not yet offer this option, but increased customer interest could sway them.
On-route inductive charging offers the opportunity to extend BEB block times to all-day operation, depending on the route length and ability to add extended stop durations needed for charging.	90% - 93% charging efficiency is lower than the 95% achieved by plug-in and pantograph dispensers and can result in increased electrical consumption and costs.

A summary of the two companies' inductive charging offerings is shown in Table 6, below. Although only BYD and Gillig buses have established relationship with the two inductive charger manufacturers and produce buses capable of receiving the technology, it is expected that New Flyer and Proterra will follow suit based on anticipated demand from their customers.

Table 6: Commercially available inductive charger manufacturers

Manufacturer	Present Charging Capacity	Bus Manufacturer Partners	Transit Partners
Wave	Up to 250 kW	BYD Gillig	PSTA, St. Petersburg, FL AVTA, Lancaster, CA Twin Transit, Centralia, WA
Momentum Dynamics	Up to 300 kW in 75 kW increments*	BYD	Link Transit, Wentachee, WA

*Momentum Dynamics advertises up to 450 kW charging capacity, but there has not been an example of this being deployed yet for transit buses.

Some recent transit agencies' initiatives to incorporate inductive charging include:

- **Link Transit**: In 2018, Momentum Dynamics installed a 200 kW inductive transmitter pad in Wentachee, WA for on-route charging of Link Transit buses. Located at the Wentachee transit center, this was the first installation of inductive on-route charging infrastructure in the United States. One bus, a BYD K9S model with a 266 kWh battery, was equipped with four 50 kW receiver pads totaling 200 kW capacity to match the output of the transmitter pad embedded in the pavement. The bus typically dwells for 7-10 minutes for recharging and one charging event can power the bus through an additional run of its route, increasing the effective range from 145 miles to over 300 miles. In July 2021, Link Transit increased their inductive charging capacity by installing two more Momentum pavement-embedded transmitter pads, now with a 300 kW capacity, and upgrading the original 200 kW transmitter to 300 kW. A $1.4 million state grant helped fund this capital project (but is not necessarily reflective of the total equipment and construction cost). The agency is in the midst of procuring five more 30-ft BYD vehicles to be equipped with receiver pads (four per bus for 300 kW charging - the company now offers receiver pads each with individual capacity of 75 kW).

- **Pinellas Suncoast Transit Authority**: PSTA in St. Petersburg, FL debuted a 250 kW Wave inductive transmitter pad at its 34th Street transfer hub in June 2020, which will provide on-route charging to six BYD battery-electric buses in the PSTA fleet. The inductive charging now allows PSTA's BEBs to remain in continuous service throughout the workday, after a 10-minute charging period at the transfer hub. Installation costs for the embedded charging pad (construction cost only – does not include equipment cost) totaled $192,000. This is the first application of inductive charging on the US East Coast. Like Charleston, St. Petersburg is a relatively flat coastal city subject to hurricanes and their associated storm surges and flooding. The inductive charging infrastructure is resistant to both standard heavy rainfall events, as well as seawater inundation from coastal flooding.

- **Antelope Valley Transit Authority**: AVTA in Lancaster, CA, announced in September 2021 a procurement of 28 Wave wireless charging systems, as part of their 2019 commitment to become the first fully electric fleet to be powered completely by wireless chargers in partnership with Wave. AVTA operates BYD electric buses, with which Wave has extensive experience in installing inductive receiver pads.

Efficiency

The manufacturers state their charging efficiency as between 90% to 93%, with Momentum Dynamics claiming the highest percentage. This compares with the 95% efficiency rating of plug-in chargers. The lower efficiency of inductive charging versus plug in charging could increase electrical costs by $160 or more annually per bus (depending on electrical cost per kWh, mixture of in-depot plug-in charging and on-route inductive charging, etc.)

The air gap, the distance between the bottom surface of the bus-mounted charging coils and the embedded dispensing pad in the pavement, is a factor in the overall charging efficiency. Typically, charging efficiency is measured and reported with an air gap of 11 in (28 cm) or less. Any greater distance will cause the charging efficiency to drop off significantly. Reducing the air gap can be beneficial for charging purposes, but comes with the trade-off of reduced ground clearance and the risk of damage to the charging plates and bus undercarriage when passing over speed bumps, uneven terrain, etc.

2.1.2.3 On-Route Emergency Charging Options

If a BEB expends the power in its battery prematurely (perhaps in the event of a battery failure, prior to returning to a depot or on-route charger), there are few on-route emergency charging options. Lightning eMotors offers a mobile charging station (Lightning Mobile) that can provide up to 80 kW of DC fast-charge output, sufficient to get a stranded BEB mobile again. The charging station can be transported in a cargo van, or in a trailer towed by a pickup truck. The station's output connector is a SAE J1772 CCS Type 1 universal plug-in and has a battery capacity of 192 kWh.

2.2 BEB MANUFACTURERS

This section provides an overview of the commercially available BEBs and their manufacturers, including information about charging infrastructure.

Table 7 was obtained from a bus manufacturer review completed by the Center for Transportation and the Environment (CTE) in 2019[12] and presents a summary of different body styles, length, and energy storage options offered by different bus manufacturers. The table includes low-floor BEBs ranging in length from 30' to 40'.

Table 7: Commercially available ZEBs and their manufacturers

Body style	Length (ft)	Energy storage (kWh)	BYD	CCW	Gillig	Green Power	NovaBus	Proterra	New Flyer	Van Hool
BEB Low Floor	30	210-466	2	1		1				
	35	94-440	1	1		1		5	1	
	40	94-660	2	1	1	1	1	7	3	1

2.3 BEB CHARGER MANUFACTURERS

While a few vehicle OEMs construct their own BEB charger equipment, there are several charging infrastructure providers that do not manufacture vehicles. The variety of OEMs is facilitated by the interoperability of standards, such as SAE J-1772 for plug-in DC charging, J-3105 for overhead charging, CSS, CHAdeMO, and so on (Figure 18).

[12] Center for Transportation and the Environment, "Electric Bus Planning Workshop for the Colorado Department of Transportation"

Figure 18: Current SAE Standards for BEBs.

Table 8 shows the equipment specifications for plug-in chargers from different manufacturers. Currently, there are eleven manufacturers that provide charging equipment for BEBs.

Table 8: Equipment specifications of depot and on-route chargers by different manufacturers

Manufacturer	kW	Specs
Siemens	120, 150, 600	2.6 ft deep, large footprint. Both, overhead and ground mount
ABB	150	Remote dispenser pedestal (integrated)I[13]
Heliox	50, 300, 600	Remote dispenser pedestal
Proterra	60 or 125	Remote dispenser pedestal
ChargePoint CPE Depot	156	Remote dispenser pedestal
ChargePoint CPE 250	62.5 or 125	1.3 ft deep to fit between lanes
BYD	80	1.3 ft deep to fit between lanes
BTC Power	50 or 100-200	Ground integrated and modular
Delta	100	DC city charger ground mount
Efacec	20, 150, 350	Ground mount, integrated and modular
Signet	100, 350	Ground mount, integrated and modular
Tritium	50, 175	Ground mount, integrated and modular

[13] Footprint for remote dispenser pedestals is currently unavailable based on current literature review. The Stantec team has contacted several charger manufacturers and will provide further detail in subsequent task reports once more information has been obtained.

2.4 OTHER BEB VEHICLE TYPES

In addition to standard 40-ft and 35-ft buses, CARTA also operates smaller 30-ft buses and cutaways for a portion of its fixed route services, as well as a fleet of vans and SUVs for paratransit. While assessing the BEB transition of CARTA's paratransit fleet is not within the scope of this project, this section includes information on currently available smaller battery-electric vehicles to provide CARTA with high-level information on options for their paratransit and non-revenue fleet if CARTA is interested in transitioning these fleets to battery-electric in the future.

2.4.1 Battery-Electric Cutaways

The challenge for small buses to move to ZE propulsion is three-fold. The first issue is that since the cutaway propulsion is generated by the chassis makers, the start to a change may need to be generated there. There would be a significant time and cost factor if the bus body makers need to "gut" and replace the powertrain with a ZE unit. This would be passed onto customers. Because there are so many more cutaway bus vendors, economies of scale are not present as they are for the smaller number of heavy-duty bus OEMs. The second issue is the space requirement for the ZE apparatus (mainly the energy storage system). The envelope to work with is smaller and the passenger area may be affected if there is insufficient area on the roof. The third item is weight. Axle capacities are limited and the passenger load, which needs to make provision for battery/electric powered mobility aid devices, can be diminished by the weight of the ZE equipment, be it batteries of hydrogen cylinders, etc. If an insufficient amount of this equipment is installed, operating range will be proportionately less.

Despite these challenges detailed above, there have been some products that are suited for transit bus applications at this point; however, the current product and technology state in North America is very much still evolving. A few examples are as follows:

- A Quebec, Canada firm, Lion Bus, has developed a line of electric conventional type C school buses. Evolving from this is a purpose built small electric low floor bus offered in both school bus and transit bus versions. It resembles a flat front type D school bus and is approximately 26-ft. long with a capacity of up to 31 passengers. A 75-mile range is claimed with one battery but adding an optional second battery doubles the range[14].
- A partnership between Proterra and Optimal-EV announced in June 2020 the development of a battery electric low-floor cutaway bus for North American markets (Figure 19). The Proterra battery system will feature 113 kWh of energy capacity with a range of up to 125 miles on one charge. According to the OEM, the vehicle can fully charge in two hours and does not have a reduced carrying capacity due to the onboard battery. The vehicle is slated to debut at the American Public Transportation Association (APTA) EXPO 2021 and be available for purchase

[14] https://thelionelectric.com/en/products/electric_minibus

beginning in 2021. Optimal-EV has noted that this is the first vehicle in a line of multiple ZEBs for a variety of applications[15].

Figure 19: Optimal-EV low-floor cutaways bus using Proterra battery system

Table 9 provides an overview of current and emerging battery-electric cutaways on the North American market, including some of the vehicles discussed in greater detail above.

Table 9: Summary of battery-electric cutaway options

Lightning Systems E450 Shuttle Bus		
Chassis	Ford E450	
Wheelchair Access	Unknown	
Dimensions L x W x H roof	Unknown	
Seating Ambulatory (Wheelchair)	Varies	
Range	80-120 miles	
Battery size	86 kWh or 129 kWh	
LionM		
Chassis	OEM	
Wheelchair Access	Side Ramp	

[15] https://www.metro-magazine.com/10122170/optimal-electric-vehicles-proterra-partner-to-produce-all-electric-low-floor-cut

Dimensions L x W x H roof	313” x 95” x 111”	
Seating Ambulatory (Wheelchair)	22 (6)	
Range	75-150 miles	
Battery size	160 kWh	
UMS Mission		
Chassis	ProMaster	
Wheelchair Access	Side or Rear Ramp	
Dimensions L x W x H roof	295” x 87” x 106”	
Seating Ambulatory (Wheelchair)	16 (1)	
Range	Unknown	
Battery size	Unknown	
Optimal-EV S1LF		
Chassis	Ford E450	
Wheelchair Access	Side Ramp	
Dimensions L x W x H roof	Unknown	
Seating Ambulatory (Wheelchair)	12 (3)	
Range	125 miles	
Battery size	113 kWh	
Phoenix Motorcars Zeus 400 Shuttle Bus		
Chassis	Ford E-series	
Wheelchair Access	Rear lift	
Dimensions L x W x H roof	Variable	
Seating Ambulatory (Wheelchair)	23 (2)	
Range	160 miles	
Battery size	150 kWh	

Overall, the current ZE cutaway market is more limited than the ZEB market for standard transit buses. However, demand for ZE cutaways is increasing as transit agencies look to transition demand response and dial-a-ride fleets to ZE fleets, and the industry is responding by providing more options. It will be important to continue to monitor the market as new options become available that feature longer ranges as the technology continues to evolve.

2.4.2 Other Battery-Electric Vehicles

This section provides an overview of smaller electric vehicle (EV) passenger vans on the market, which could serve as potential replacements for paratransit vans or other services agencies provide with passenger vans.

One promising vehicle that could be leveraged by paratransit operations is the electric Ford E-Transit slated for release in 2022. With several body and battery sizes available[16], the E-Transit van can deliver up to 120 miles on a single charge.

Table 10: Zero-emission vehicle options for dial-a-ride and paratransit use

Lightning Systems Transit Passenger Van		
Chassis	Ford Transit 3500	
Wheelchair Access	Unknown	
Dimensions L x W x H roof	Unknown	
Seating Ambulatory (Wheelchair)	15	
Range	60-120 miles	
Battery size	86 kWh – 105 kWh	
GreenPower EV STAR ADA		
Chassis	OEM	
Wheelchair Access	Side Lift	
Dimensions L x W x H roof	300" x 80" x 106"	
Seating Ambulatory (Wheelchair)	16 (2)	
Range	<150 miles	
Battery size	118 kWh	

Lightning Systems has developed a range of new electric product offerings based on the Ford Transit and Ford E450 chassis. The company is also developing a larger bus based on the Ford F550 chassis. The range is between 60-120 miles depending on the vehicle configuration.

AVTA procured six of the GreenPower EV STAR ADA vehicles at a cost of $95,780 per vehicle. The cost is inclusive of California HVIP grants of $100,000 per vehicle, which these vehicles are eligible for as they are based on an OEM chassis. The cost is exclusive of sales tax and charging infrastructure. This vehicle is also Altoona-tested and Buy America approved.

Concerning non-revenue fleets, there are several manufacturers producing battery-electric options for these light-duty vehicles, including GM, Ford, Chevy, Tesla, and others. Transitioning the non-revenue fleet is likely easier since the vehicles are likely not in service to the degree that revenue vehicles are, and battery ranges may not be as significant an issue. A draft study of one agency's non-revenue fleet

[16] 2022 Ford® E-Transit | All-Electric Chassis Cab, Cutaway & Cargo Van; also notes that Ford will announce more about additional range and capability offerings at a later date, indicating that this battery size can increase over time.

shows that non-revenue light-duty vehicles travel a maximum of 60 miles in a day, and operational ranges of current ZE vans, sedans, and SUVs range from 60 to 259 miles[17]. Still, considerations regarding charging infrastructure for light-duty vehicles should be made when transitioning the non-revenue fleet.

One transit agency example is the Orange County Transportation Authority (OCTA), which announced in 2020 the intent to purchase up to 55 Chevy Bolt vehicles to replace part of its non-revenue fleet that has reached the end of its useful life, to help the agency's ongoing effort to convert its fleet to ZE[18]. Similarly, LA Metro purchased ten Chevy Bolts in 2017 for its non-revenue fleet, with the intent to assess life cycle costs of the vehicles to determine the feasibility of replacing the entire Metro sedan fleet with electric vehicles. The agency has noted that preliminary research indicates that the higher capital costs are matched with lower operating costs (for maintenance and fuel) and will continue to be reduced as battery technology continues to advance[19]. Based on the initial success of the pilot project, Metro expanded to an additional 20 Chevy Bolts in 2018-2019. These vehicles are primarily used to support driver relief operations[20].

Table 11 provides some examples of zero-emission vehicle options for non-revenue fleets.

Table 11: Zero-emission vehicle options for non-revenue fleet

Chevy Bolt		
Length	14 ft	
Seating capacity	4 ambulatory	
Battery size	66 kWh	
Range	259 miles	
Hyundai Ioniq SE		
Length	15 ft	
Seating capacity	4 ambulatory	
Battery size	38 kWh	
Range	170 miles	

[17] https://mountainline.az.gov/wp-content/uploads/2021/01/Phase-2-Implementation-ZEB-Plan-DRAFT.pdf
[18] https://www.octa.net/News/About/OCTA-Adds-All-Electric-Support-Vehicles-to-Fleet/
[19] https://www.metro-magazine.com/10033624/la-metro-purchases-electric-vehicles-for-non-revenue-fleet
[20] http://media.metro.net/projects_studies/sustainability/images/Green_Procurement.pdf

2.5 OVERVIEW MAIN ZEB-ASSOCIATED COSTS

2.5.1 Bus Purchase Price

An overview of purchase prices of 35-ft. and 40-ft. BEBs by different manufacturers is shown below (see Table 12). The collected information includes different bus configurations and the location where the buses were deployed, in addition to the year of purchase. Purchase prices reported to the California eProcure Portal[21] under state contracts from Proterra and New Flyer provide the most current values (shaded gray in the table below); generally, 35-ft. BEBs are equipped with smaller batteries.

Table 12: Purchase prices of a sample of ZEBs[22]

Manufacturer	Battery Size	Length (ft.)	Bus Type	OEM - Operator	Bus Unit Price	Purchase Year
BYD	324 kWh	40	Depot-charging BEB	AVTA	$770,000	2016
BYD	324 kWh	40	Depot-charging BEB	UCI	$833,400	2017
Gillig	444 kWh	40	Depot-charging BEB	Santa Monica BBB	$990,500	2019
Green Power	320 kWh	40	Depot-charging BEB	N/A	$850,000	2018
Proterra	88 kWh	40	On-route charging BEB	Foothill Transit	$904,500	2014
Proterra	105 kWh	40	On-route charging BEB	King County	$798,000	2015
Proterra	106 kWh	40	On-route charging BEB	Foothill Transit	$879,900	2016
Proterra	220 kWh	40	Depot-charging BEB	California eProcurement	$699,000	2019
Proterra	220 kWh	35	Depot-charging BEB	California eProcurement	$689,000	2019
Proterra	440 kWh	40	Depot-charging BEB	California eProcurement	$799,000	2019
Proterra	440 kWh	35	Depot-charging BEB	California eProcurement	$789,000	2019
Proterra	660 kWh	40	Depot-charging BEB	California eProcurement	$899,000	2019
New Flyer	311 kWh	40	Depot-charging BEB	California eProcurement	$741,800	2019
New Flyer	311 kWh	35	Depot-charging BEB	California eProcurement	$732,600	2019
New Flyer	388 kWh	35	Depot-charging BEB	California eProcurement	$775,600	2019
New Flyer	466 kWh	40	Depot-charging BEB	California eProcurement	$828,200	2019

[21] Cal eProcure is an online portal designed for businesses to sell products and services to the state of California.
[22] Rounded to nearest hundred dollars.

Note that the prices in Table 12 represent either historical purchase prices or prices from statewide contracting. As such, actual costs may differ depending on service elements and are subject to competitive bids during a procurement process.

Procurement prices are currently limited for ZE cutaways, vans, and motor coaches; nonetheless, discussions with OEMs and research indicate that ZE vans and cutaways can range from $90,000-$220,000.

2.5.2 Cost of Charging Infrastructure

Estimating the cost of charging infrastructure quickly becomes complex since the level of electrical modifications necessary to install equipment can widely vary depending on the garage location and current equipment. Additionally, different arrangements with local utility companies and equipment manufacturers have proven to drastically affect the investment cost.

Our literature review regarding the cost of charging infrastructure of different demonstration projects presents combined installation costs without distinguishing between the cost of labor or electrical equipment such as transformers, generators, etc. Furthermore, the data collection shows a lack of reporting on the cost of chargers for operators since often the purchase contract combines the cost of the buses and cost of chargers. The average cost per charger was estimated based on literature and data presented in Table 13 and Table 14. Additionally, Table 15 presents a summary of charging equipment cost by vendor that was collected via an RFI.

Table 13: Cost of depot charging infrastructure[23] [24]

OEM - Operator	Equipment Cost per Depot Charger	Installation Cost per Depot Charger
BYD - AVTA	$19,100	$ 55,900
BYD - UCI	$40,600	$ 77,400
Proterra - King County	$60,500	-[25]
CTE	$50,600	$17,600
CARTA	$51,200	-

[23] A. Castillo, “Technology Mix Optimization for Zero-Emission Fleets Adopting a Multi-Criteria Decision Analysis within a Life Cycle Assessment Framework,” University of California, Irvine, 2019.
[24] Rounded to nearest hundred dollars
[25] Information on the installation cost of on-route chargers was not provided by the source.

Table 14: Cost of on-route charging BEBs and charging infrastructure[26]

OEM - Operator	Bus Unit Price	Equipment Cost per on-route Charger	Installation Cost per on-route Charger
BYD - AVTA	$ 779,000	$353,900	$252,800
Proterra - King County	$806,600	$606,600	$244,200
Proterra - Foothill	$797,700	$505,500	$202,200
CTE	$897,100	$501,100	$205,100

Table 15: Summary of charging equipment costs

OEM	Charger Type	Rated Output (kW)	Type/ Interface	Max Disp'r per Charger	Max Active Disp'rs	Comments	$ Cost Ea.
ABB	In-depot	150	J3105 / Mast down	1		One dispenser	$110,000
ChargePoint	In-depot	156	J1772 / CCS	8	2	Two dispensers	$120,000
Proterra	In-depot	125	J1772 / CCS	1	1	All in-depot chargers are 1:1	$65,000
Proterra	In-depot	125		2		Two dispensers	$79,500
Siemens	In-depot	150	J1772 / CCS	3	1	single dispenser	$130,000
ABB	In-depot or on-route	450	J3105 / Mast down	N/A	N/A	On-route	$339,000
Proterra	In-depot or on-route	500	J3105 / Mast down			Charger with pole, catenary down charge head and related wiring and controls	$349,000
Siemens	In-depot or on-route	450	J3105 / Mast down	N/A	N/A	On-route	$500,000
Siemens	In-depot or on-route	600	J3105 / Mast down	N/A	N/A	On-route	$620,000

2.5.3 Maintenance Cost of BEBs

The total cost of maintenance for BEBs was reported by CTE to be $0.23 per mile[27]; this includes scheduled and unscheduled repairs. A similar value was reported by the National Renewable Energy Laboratory (NREL) for the BEB deployed at Foothill Transit in southern California[28]. For comparison, maintenance cost of diesel buses has been reported to be between $0.25 and $0.68 per mile by transit agencies in the California Bay Area[29]. Table 16 presents the maintenance cost by system type. In Table

[26] Rounded to nearest hundred dollars
[27] Matt Boothe - CTE, "Critical Answers for Smart Deployments."
[28] L. Eudy and M. Jeffers, "Foothill Transit Battery Electric Bus Demonstration Results: Second Report," 2015.
[29] L. Eudy and M. Post, "Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Fourth Report," NREL, no. July, 2015.

16, the propulsion-related repairs for the BEBs include low-voltage batteries, battery equalizer, cooling system, and DC-AC converter.

Table 16: Maintenance cost per mile by system component in battery electric buses[30]

System	Maintenance of BEB ($/mi)
Propulsion-related	0.05
Cab, body, and accessories	0.13
PMI	0.03
Brakes	0.01
Frame, steering, and suspension	0.00
HVAC	0.01
Lighting	0.01
General air system repairs	0.01
Axles, wheels, and drive shaft	0.00
Tires	0.01
Total	**0.26**

2.6 TRANSITION TO BEBS—CONSIDERATIONS

Diesel or gasoline refueling is quick and can be done within scheduled layovers and maintenance. To refuel an electric bus, the on-board batteries must be charged. This can take anywhere from three minutes to many hours depending on the bus battery size and charging infrastructure type. When these considerations are taken together with electric utilities coordination, there may be restrictions on the number of vehicles that can charge concurrently at one location. Because of the substantially larger demand on electricity at transit facilities, agencies need to transform their relationship with their utility from one that is based on electricity for typical industrial uses, to one a relationship where electricity is now 'fuel'.

Early consultation with the electric utilities could help to mitigate this since they need to be active participants in the ZEB transition plan. In addition, when planned properly, the new electric load could represent a benefit to the local utilities since a high demand during the day is desirable to help balance the grid from intermittent renewable sources. During the day, solar and wind power generation are at their peak, but during such times the demand is traditionally low; therefore, much of such produced electricity is then curtailed. Transit fleets tend to have fixed schedules, which create a reliable demand that can be satisfied by excess renewables, opening the door for an increase in the share of renewables in the local grid.

Diesel prices can fluctuate with the market and per season, factors which transit agencies do not have control over. On the other hand, electricity prices tend to be more predictable for each season (e.g., winter vs. summer) but times of use (TOU) heavily dictated the final price per kWh. Meaning, charging buses during non-peak hours – which are determined by the utility company (usually morning hours) – can be significantly cheaper than charging buses at peak hours (e.g., 4 pm to 9 pm). The extra cost is

[30] L. Eudy and M. Post, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018," 2018.

determined by the price rate per kWh, as well as additional charges due to max power (kW) utilization, called demand charges.

Transit agencies can efficiently design their charging infrastructure to minimize such demand charges while ensuring enough charging time to have their fleet ready for operations. Therefore, for every bus depot considering a BEB fleet, several facility issues need to be considered.

2.6.1 Mitigating Charging Demand

For BEB fleets, the two most common methods for regulating charging are smart charging and charge buffering using energy storage, both described below.

2.6.1.1 Smart Charging

Smart charging refers to software, artificial intelligence, and processes that control when and how much charging occurs. This requires chargers that are capable of being controlled as well as a software platform that can effectively aggregate and manage these chargers. A best practice is to select chargers where the manufacturers are participants in the Open Charge Point Protocol (OCPP), a consortium of over 50 members focused on bringing standardization to the communications of chargers with their network platform.

Well-planned and coordinated smart charging can significantly reduce the electric utility demand by timing when and how much charging each bus receives. Estimations on the ideal number of chargers is critical to the successful implementation of smart charging strategies.

2.6.1.2 Energy Storage

The final mitigation measure which will most likely be required to electrify entire fleets is the use of stationary energy storage as “charge buffers”. Energy storage, in the form of containers of lithium-ion batteries or other technologies, can be charged during periods of low facility electricity demand or even from renewable energy resources like solar or wind, and then discharged during periods of high electricity demand when the buses also need to receive a charge. Such storage systems deployed Behind the Meter (BTM) can react to charge events quickly so that the utility does not see the entire impact of the charging event. In this way, the electricity demand (and associated cost) can be reduced.

Many of the larger bus charging equipment companies like ABB and Siemens are exploring the pairing of such battery storage systems with their charging infrastructure. An Ontario company named eCamion focuses exclusively on storage systems for electric vehicle charge buffering.

2.6.2 Site Assessment

On the outside of the facility, finding space to install a larger service transformer will be the first hurdle. Due to the additional charging, it is possible that a secondary utility service may also be required. In addition, since bus service during emergency situations must still be maintained, the backup power service will also need to be upgraded (see Figure 20).

Electrical Servicing Conduits *Upgraded Service Transformer*

Figure 20: Typical electrical servicing conduits and upgraded service transformer

2.6.2.1 Facility Interior Infrastructure

Inside the facility, an electrical room must be designated for the BEB equipment such as the A/C distribution panels, the “charger” room (the power inverters used to create the DC), DC distribution equipment, the actual charging equipment (charging cables and/or overhead inverted pantographs) and all associated Lock-Out-Tag-Out (LOTO) and Emergency Stop stations.

If on-route charging is not feasible or desired by the agency, due to range limitations from BEBs, accommodating extra buses (i.e., a larger fleet) might be required to maintain the same service level. Furthermore, with additional buses needed to serve the routes, additional charging equipment would be required. Also, daily cleaning routines would increase in tandem with a larger fleet to keep standards constant as well as vehicle incremental needs (licensing, parking spaces, etc.).

Conduits Servicing Switchgear *New/ Modified Switchgear*

Figure 21: Typical conduits servicing switchgear and new/modified switchgear

2.6.2.2 Infrastructure in Other Facility Areas

Other considerations within the facility include plug-in chargers required in the shop, harness system for mechanics to access batteries located in the bus roof, overhead cranes with increased capacity to handle battery modules and other heavy power electronics (likely 2-Ton or more), and specialized shop retooling to accommodate the new equipment and accessories. There will also need to be an area set aside for battery storage and testing with special fire prevention considerations. More personnel-related items (e.g., fall-arrest outfitting) will also be required.

From an IT standpoint, there will be additional wireless access points required throughout the facility for the communication of pantographs with the smart charging software control system, therefore, requiring significant wireless upgrades. Additionally, the facility will require the associated control systems, for both pantographs and plug-in type dispensers, as well as a supervisory control and data acquisition (SCADA) room.

2.6.2.3 AC versus DC Fast Charging

The BEB market is divided on the method of electricity delivery to charge the bus. One of the largest BEB and battery suppliers, BYD, primarily utilizes AC charging to the bus and then performs the conversion to DC on-board to charge the battery. This is similar, in concept, to home Electric Vehicle (EV) chargers, which deliver 200-240 V AC to the car where an on-car converter changes this to DC so that it can charge the battery. The benefit of this method is that far less additional power infrastructure is required to facilitate charging (no charging cabinets). In addition, since the power delivered to the bus is AC, future migration to non-contact inductive charging is possible. The trade-off is that each bus must be equipped with enough on-board converters at additional cost and weight. Although the standards are evolving, there are currently some restrictions as to how fast an AC-charged bus can charge.

Most of the other BEB suppliers accommodate fast DC charging whereby the conversion to DC occurs external to the bus (via a charger cabinet), and the DC is delivered to the bus and directly to the battery. Standards are evolving for this method of charging as well to facilitate future charging of transport as well as transit fleets.

2.7 OTHER CONSIDERATIONS WHEN IMPLEMENTING BEBS

As with the introduction of any new technology, the introduction and deployment of BEBs requires that relevant agency personnel become familiarized with batteries and associated procedures. Best practices from the literature review reveal that the following components should be included in all training programs:

- Training programs should be tailored for the local context within which the agency operates, including accounting for regional safety requirements.
- Training should include both theoretical and practical elements. Anecdotal evidence from agencies suggests that “on-the-bus” training results in more engaged personnel and increased efficiency.

- Preparation and provision of written training manuals along with oral and hands-on instruction. These training manuals should be kept on-hand at all facilities to ensure employees remember important safety procedures.
- An additional important component of training is expectation management. BEBs do not have the same level of technical maturity as diesel or CNG buses and issues are likely to occur, especially during the early/initial stages of deployment.

3.0 CURRENT OPERATIONS AND SERVICE ANALYSIS

This section provides an overview and analysis of CARTA's transit operations, with the overall intent of laying the groundwork for the subsequent ZEB analysis, modeling, and BEB rollout plan for CARTA. All information has been provided by CARTA unless stated otherwise.[31]

3.1 KEY OPERATIONAL CHARACTERISTICS

CARTA provides a variety of transit services to the people of the Charleston Area:

- **Fixed Route**
  - **Local fixed routes:** Traditional fixed-route service within Charleston and North Charleston, and to outlying communities such as James Island, West Ashley, Mt Pleasant, and others. Seventeen routes operate, with most providing 6- or 7-day service.
  - **Express fixed routes:** In addition to local routes, CARTA operates three limited-stop express services, which provide commuter services from the outlying suburbs of Summerville, James Island, and West Ashley, through the central Charleston core to North Charleston, and Mt Pleasant. These routes operate only on weekdays and have a higher fare than local services.
  - **DASH:** The Downtown Area Shuttle (DASH) provides free circulator service in Charleston's downtown area, primarily servicing the tourist demographic and destinations on peninsular Charleston. Three routes operate seven days a week.
- **Demand Response[32]**
  - **Tel-A-Ride:** CARTA's FTA-mandated complementary ADA paratransit service that operates within a ¾ mile of the located fixed route services.
  - **OnDemand:** Pilot project with Uber and UZURV to provide demand-response service to seniors (55+) and Tel-A-Ride customers travelling to/from medical facilities. Trips are requested using a smartphone app or contacting the call center.

[31] All data based on pre-COVID-19 pandemic unless otherwise stated.
[32] The BEB Plan pertains only to fixed-route services, so analysis of demand response services is omitted from this report

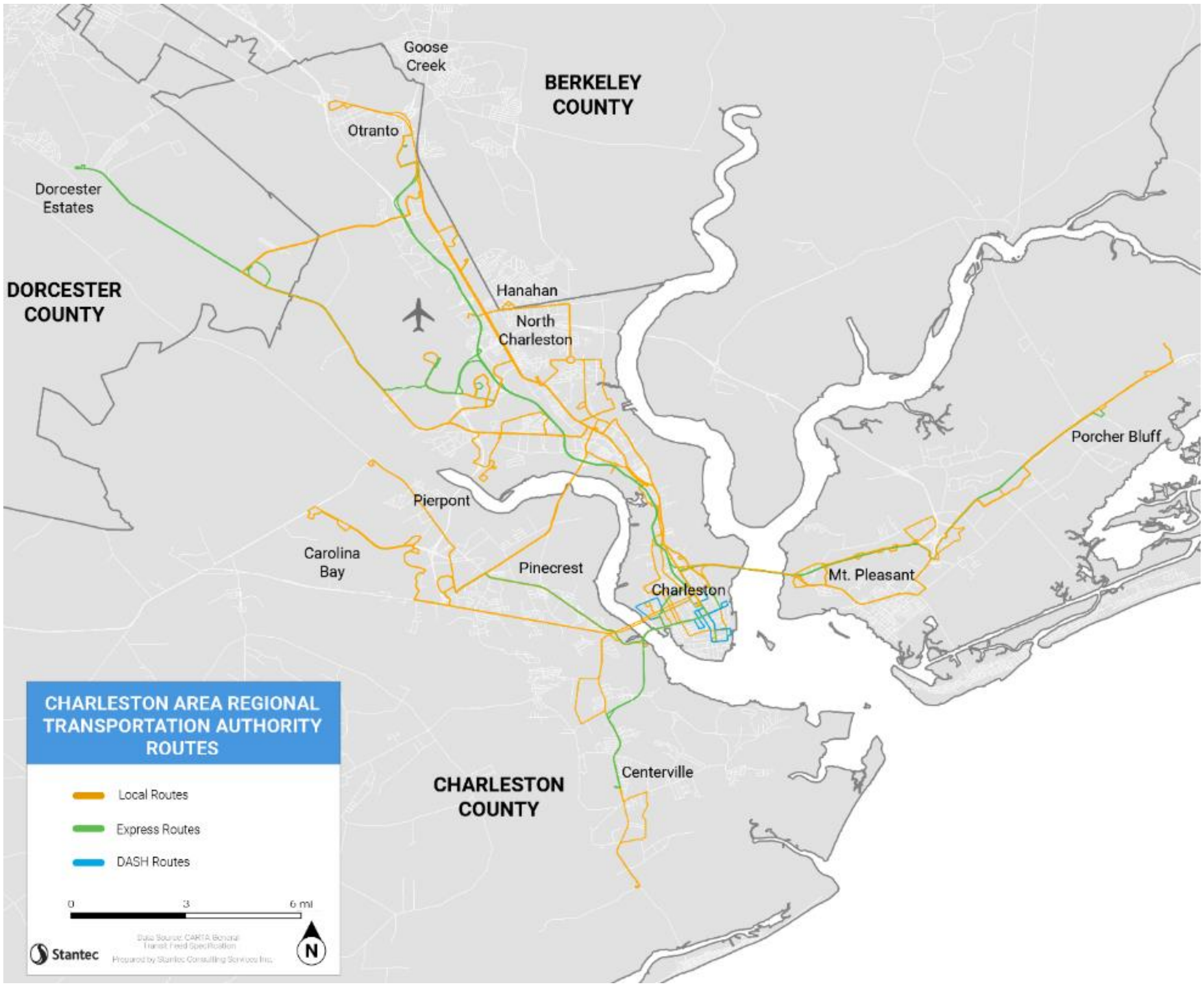

Figure 22: CARTA routes by service type

Table 17: Key operational characteristics by service type, 2018-2019 (NTD)[33]

	Annual Revenue Miles			Annual Revenue Hours		
	2018	2019	% Change	2018	2019	% Change
Local bus	2,336,821	2,428,519	3.9%	191,989	200,472	4.4%
Express bus	195,476	200,024	2.3%	8,203	8,381	2.2%
	Annual Unlinked Passenger Trips			**Passenger per Hour**		
	2018	2019	% Change	2018	2019	% Change
Local bus	2,955,646	2,991,215	1.2%	15.39	14.92	-3.1%
Express bus	158,120	133,744	-15.4%	19.27	15.96	-17.2%

Examining key operational characteristics of CARTA service by service type reveals some interesting patterns across the different service types between 2018 and 2019 (Table 17).

Local service saw a modest increase in revenue miles and revenue hours, but this did not translate into a proportionate increase in ridership. As a result, the passengers per hour fell by approximately 3%.

Express services also saw a small increase in revenue miles and revenue hours, although less than that of the local services. Despite this, ridership on express services fell by over 15% year-over-year, leading to an approximately 17% reduction in passengers per hour.

Now that a general understanding of CARTA and the services it provides has been established, we next provide an overview of some of the main operational characteristics that need to be considered and can impact BEB implementation and overall feasibility, including developing an understanding of daily block and vehicle mileage and how much deadheading contributes to overall vehicle mileage.

3.2 FLEET COMPOSITION

CARTA's current revenue fleet is comprised of 14 cutaways, 20 vans/SUVs, 16 30-foot buses, 36 35-foot buses, and 30 full-size 40-foot buses (Table 18). Fuel types are a combination of gasoline for paratransit or lower-demand local fixed-route service, diesel for local and express fixed-route, and battery-electric for local fixed-route. With the exception of the 1996 New Flyers, which are scheduled to be replaced this year, all vehicles are within their useful life benchmark (ULB) as outlined by the FTA's guidance for ULBs

[33] Please note that when reporting to the NTD, the NTD does not count all express routes and "Express Bus" because they are less than six miles from the CBD. These routes are reported to the NTD as "Local Bus" which pulls down passengers per hour due to reverse trips on these routes which do not carry riders.

for the Transit Asset Management (TAM) program and have yet to exceed their minimum useful life. As of the end of 2021, all vehicles should be operating in a state of good repair.

Table 18: CARTA current fleet information

Year	Quantity	Make	Seating capacity	Fuel type	CARTA useful life[34]	FTA useful life benchmark[35]	Service type	Summary
2016	1	Ford E450 cutaway	14	Gas	6 years	10 years	Paratransit	4 cutaways for paratransit services
2018	1	Ford E450 cutaway	14	Gas	5 years	10 years	Paratransit	
2019	2	Ford E450 cutaway	14	Gas	5 years	10 years	Paratransit	
2016	9	VPG MV-1	5	Gas	6 years	8 years	Paratransit	20 vans/SUVs for paratransit services
2017	10	Dodge Caravan	5	Gas	5 years	8 years	Paratransit	
2018	1	Dodge Caravan	5	Gas	5 years	8 years	Paratransit	
2016	5	Ford E450 cutaway	14	Gas	6 years	10 years	Local Fixed-Route	10 cutaways for fixed-route local services
2019	4	Ford E450 cutaway	14	Gas	6 years	10 years	Local Fixed-Route	
2020	1	Ford E450 cutaway	14	Gas	6 years	10 years	Local Fixed-Route	
2013	3	Alexander Dennis Enviro200	24	Diesel	12 years	14 years	Local Fixed-Route	15 30-ft. buses for fixed-route local services
2014	3	New Flyer MD30	24	Diesel	12 years	14 years	Local Fixed-Route	
2016	3	New Flyer MIDI	24	Diesel	12 years	14 years	Local Fixed-Route	
2016	4	New Flyer XN60	24	Diesel	12 years	14 years	Local Fixed-Route	
2018	2	Alexander Dennis Enviro200	24	Diesel	12 years	14 years	Local Fixed-Route	
1996	18	New Flyer D35HF	34	Diesel	*15 years*	*14 years*	Local Fixed-Route	36 35-ft. buses for fixed-route local services
2010	9	New Flyer D35LF	34	Diesel	12-14 years	14 years	Local Fixed-Route	
2010	2	New Flyer D35LFR	34	Diesel	12-14 years	14 years	Local Fixed-Route	
2012	3	New Flyer D35LF	34	Diesel	12 years	14 years	Local Fixed-Route	
2012	2	New Flyer D35LFR	34	Diesel	12 years	14 years	Local Fixed-Route	
2019	2	Alexander Dennis Enviro200	35/36	Diesel	12 years	14 years	Local Fixed-Route	
2014	2	New Flyer XDE40	39	Diesel	12 years	14 years	Local Fixed-Route	Eight 40-ft. buses for fixed-route local services
2019	3	Proterra E2	38	BEB	12 years	14 years	Local Fixed-Route	
2020	3	Proterra ZX5	38	BEB	12 years	14 years	Local Fixed-Route	

[34] https://www.transit.dot.gov/funding/grant-programs/capital-investments/fta-circular-50101d-november-2008
[35] https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/FTA%20TAM%20ULB%20Cheat%20Sheet%202016-10-26.pdf

Year	Quantity	Make	Seating capacity	Fuel type	CARTA useful life[34]	FTA useful life benchmark[35]	Service type	Summary
2018	1	Alexander Dennis Enviro200	24	Diesel	12 years	14 years	Express Fixed-Route	One 30-ft. bus for fixed-route express services
2015	3	New Flyer D40LF	39	Diesel	12 years	14 years	Express Fixed-Route	22 40-ft. buses for fixed-route express services
2019	19	Gillig 40' Commuter	40	Diesel	12 years	14 years	Express Fixed-Route	

The fleet has a range of vehicle types used to cover the different transit services provided by CARTA. Certain vehicle models can be dispatched for multiple types of transit services, such as Ford E450 cutaways which are used for both paratransit and local fixed-route service (Table 19). However, each individual vehicle is dedicated only to the service type to which it is assigned; for example, a particular vehicle designated for paratransit will not be dispatched for fixed-route service in normal operating situations. Multiple vehicle sizes can be used across routes to accommodate fluctuations and changes in demand.

Table 19: CARTA fleet by service type

Vehicle Type	Vehicle Make	Local Fixed-Route	Express Fixed-Route	Paratransit
Van/SUV	Dodge Caravan			
	VPG MV-1			
Cutaway	Ford E450			
30-ft. Bus	Alexander Dennis Enviro200			
	New Flyer MD30			
	New Flyer MIDI			
	New Flyer XN60			
35-ft. Bus	Alexander Dennis Enviro200 (2019)			
	New Flyer D35HF			
	New Flyer D35LF			
	New Flyer D35LFR			
40-ft. Bus	New Flyer XDE40			
	Proterra E2			
	Proterra ZX5			
	Gillig 40' Commuter			
	New Flyer D40LF			

3.3 DAILY BLOCK MILEAGE

It is important to understand how the agency's vehicles are used throughout the day, and specifically when these vehicles are in and out of service to understand constraints and opportunities in regards to charging schedules, and also to inform the preliminary fleet mix and energy requirements.

Vehicle requirements for a typical weekday[36] for fixed-route services are shown in Figure 23. This includes hourly vehicle requirements for all fixed-route services.

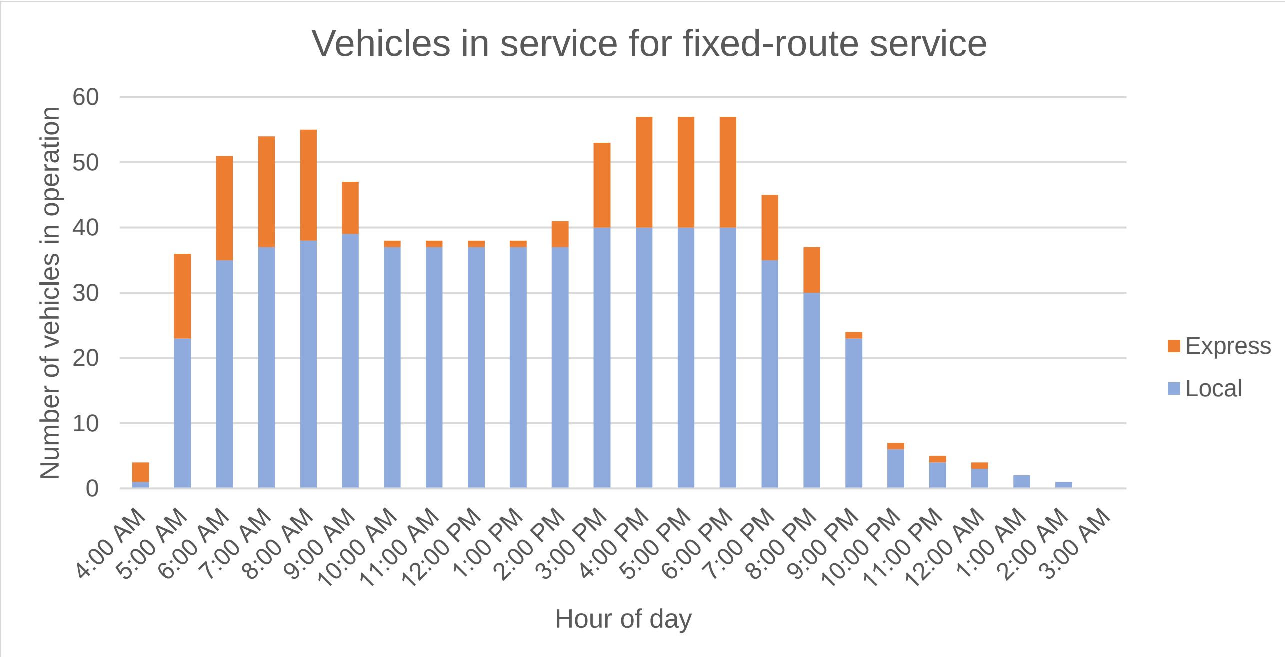

Figure 23: Hourly weekday vehicle requirements for fixed-route services

Figure 23 shows that total vehicle requirements peak from 4-6PM with 57 total vehicles in peak service. This is likely related to the additional fleet requirements to operate Express services which mostly provide service during peak hours. Overall, CARTA's service displays typical patterns of peaks during traditional AM and PM commuting hours, as much of CARTA's service is geared towards commuters. However, local routes remain in steady operation throughout the day to provide service for those traveling for other purposes.

[36] An example service day of May 10, 2021 was used for the majority of services along with scheduling data from Fall 2019 for routes 4 and 7 to capture a full service schedule with all routes fully operating.

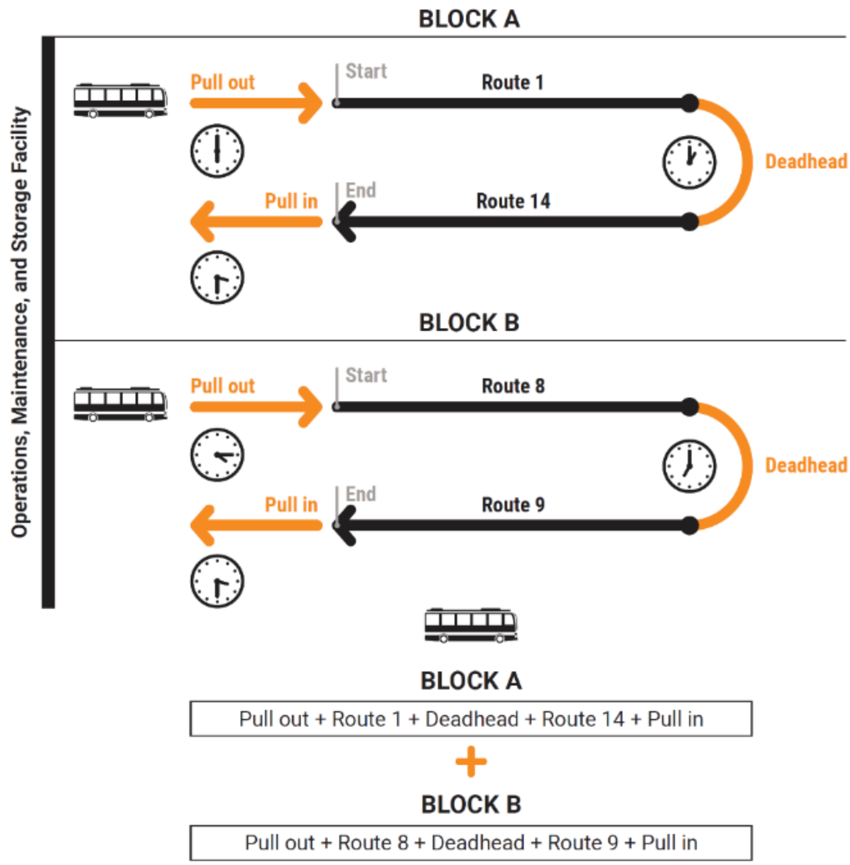

Figure 24: Relationships between routes, block, and vehicle assignments

Figure 24 shows the relationship between routes, blocks, and vehicle assignments in fixed-route scheduling and dispatching. In this example, Bus 1 pulls out of the garage to complete Block A (which is made up of Route 1, deadhead, and Route 14), pulls back into the garage, and completes Block B later in the day. On this example day, Bus 1 completed two blocks that included service on four routes. Block design typically remains the same during a service period (i.e., Block A always includes service on routes 1 and 14 on a weekday), but the assignment of blocks to vehicles can change day-to-day. In addition, while some vehicles may be assigned multiple blocks on a given day, other vehicles may only be assigned a single block. Thus, it is important to first understand how long CARTA's blocks are, and then to combine it at the vehicle level (according to the scheduled vehicle assignments for the example service day chosen) to gain an understanding of the distance vehicles travel on an average day.

Figure 25 shows how many vehicle (revenue plus deadhead) miles all fixed-route service blocks[37] travel for the representative service day for CARTA. As mentioned, it is important to understand block mileages and how long blocks are because they represent daily duties of the different buses in the fleet. Long block

[37] Refers to a vehicle schedule, the daily assignment for an individual bus. One or more runs can work a block. A driver schedule is known as a "run."

lengths can potentially exceed range capabilities of current BEBs, which could pose a challenge to an agency's BEB transition.

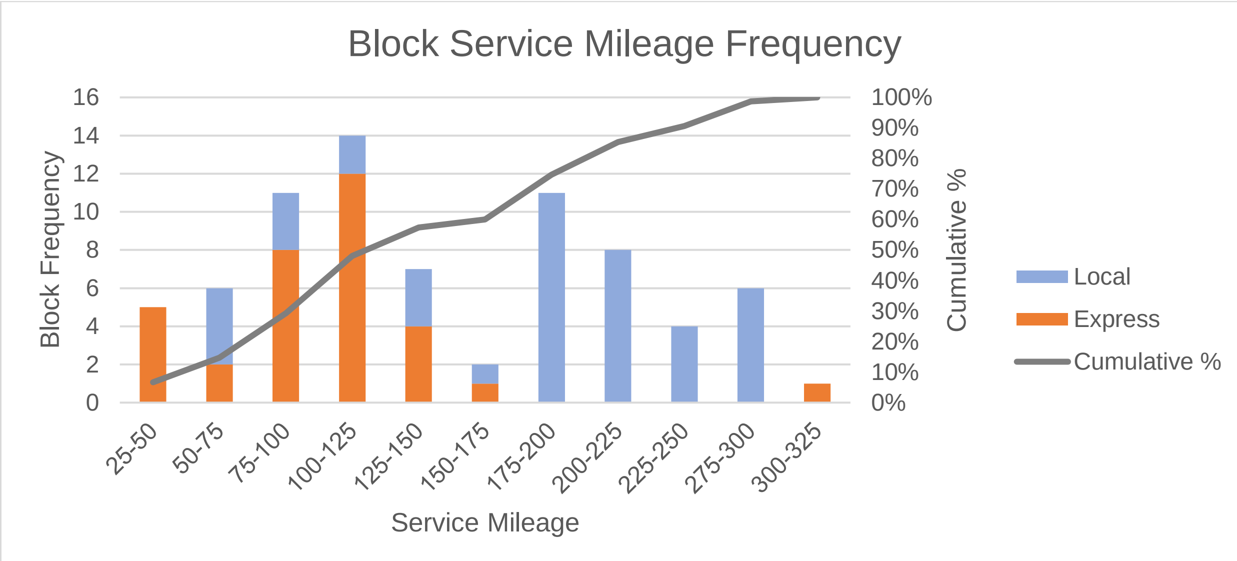

Figure 25: Block frequency by daily service miles (weekday)

Specifically, block lengths in Figure 25 are displayed by frequency of blocks (e.g., 11 blocks have mileages of 75-100 mi, 6 blocks are 275-300 mi, and so on). On an average service weekday, a total of 75 blocks are completed across the fleet. Block lengths are an average of 148 miles, ranging from a minimum block length of 33 miles to a maximum of 315 miles. Express services see lower block distances on average compared to local services.

Twenty-two (or 29% of weekday blocks) blocks travel less than 100 miles, which is encouraging as these blocks are comfortably within the daily range limitations of BEBs (the average current operational range of a standard 35-ft or 40-ft BEB is between 120 and 150 miles without on-route charging). However, it is still important to consider that 19 blocks (or 25% of blocks) travel over 200 miles on an average weekday. There are multiple strategies that an agency can employ to mitigate this, such as reblocking to create shorter block lengths, installation of on-route opportunity charging for BEBs, or splitting up the block and using two BEBs to complete a block that was previously completed by one existing vehicle.

It is also important to consider how CARTA assigns vehicles to blocks, how many vehicles are assigned to multiple blocks, and ultimately how many miles each vehicle travels on an average day. Most vehicles are only assigned one block (45 vehicles – 75%), where the remainder are assigned to two blocks (15 vehicles – 25%). Express vehicles were typically assigned to two blocks, while local vehicles were typically assigned to one block.

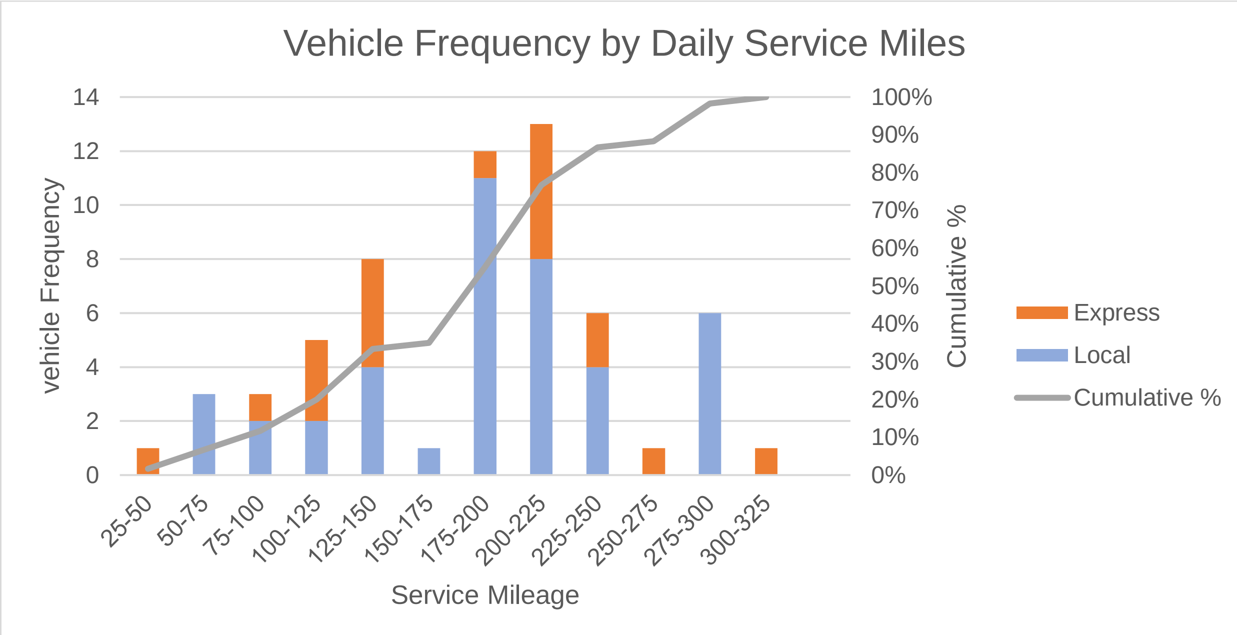

Figure 26: Vehicle frequency by daily service miles (weekday)

Figure 26 shows that there is indeed a difference between daily mileages of blocks and when they are combined at the vehicle-level among commuter services where multiple blocks are assigned to one vehicle. This also shows that while local route vehicles only complete one block in a day, they are typically longer blocks that are in service for the majority of the service day (which could minimize opportunities for midday charging in the case that modeling shows these blocks cannot be completed within one charge). Table 20 provides a high-level overview of the differences in lengths between blocks and vehicle assignments, as well as a breakdown between distances traveled by commuter vehicles vs. vehicles on local routes.

Table 20: Summary of differences in distance between blocks and vehicle assignments (weekday)

	Average distance	**Minimum distance**	**Maximum distance**
Blocks	148 miles	33 miles	316 miles
Vehicles (all)	185 miles	42 miles	316 miles
Express vehicles	175 miles	42 miles	316 miles
Local route vehicles	190 miles	65 miles	298 miles

Table 20 shows that on average, CARTA vehicles travel 185 miles on an average weekday. This is higher than the average block length of 148 miles. The table also shows that while express vehicles are assigned to multiple blocks, the total distance completed (sum of these blocks) tends to be shorter than daily distances completed by vehicles on local routes (an average of 175 miles for express vehicles compared to an average of 190 miles per local route vehicle). This means that while express vehicles complete more than one block each service day, the blocks are shorter, while vehicles operating on local routes are assigned to one long block each day.

While vehicles operating on local routes travel slightly longer distances each day than express vehicles, there are vehicles in each service category that are traveling nearly or above 300 miles in a service day, which pushes the current range limitations of BEBs, reiterating the earlier comment that strategies such as midday or on-route charging or reblocking exercises to create shorter blocks may be required to transition CARTA operations to BEBs[38].

Finally, it is important to understand how much deadheading (non-revenue mileage) contributes to overall service mileage, seen in Table 21. Across all weekday fixed-route services, blocks see an average of 15.4 deadhead miles per block. Local service blocks see an average of 13.4 deadhead miles, and express blocks see 18.0 deadhead miles on average. This is unsurprising, as commuter vehicles often deadhead back to the depot after the AM run or deadhead to the first stop prior to the PM run. Deadheading also contributes much more to total daily service mileage for express services than local routes—specifically, an average of 18% of express block mileage is attributed to deadheading, while this number is only 7% for local services.

Table 21: Deadheading mileage

	Average service mileage	Average deadheading block mileage	% of service mileage	Median deadheading block mileage	85th Percentile deadheading block mileage
All Blocks	148 miles	15.4 miles	8%	16.5 miles	20.2 miles
Local Blocks	186 miles	18.0 miles	18%	17.8 miles	19.6 miles
Express Blocks	101 miles	13.4 miles	7%	14.1 miles	21.3 miles

4.0 CURRENT BEB EXPERIENCE

CARTA provided Stantec with daily records (maintained by CARTA's operator) from January 2020 through March 2021 of its 3 Proterra 440 kWh depot-charging BEBs. These records included pull-out and pull-in times, mileage, battery usage estimates, fuel efficiency, assigned bus operator, and other information. The review here will provide some insights into CARTA's actual experience operating BEBs and can help provide some context for the modeling going forward.

From January 2020 through early March 2021, the three buses accumulated roughly 20,000 miles. The three buses operated between 154 and 174 days in the data sample, and on average, operated 120 to 130 miles daily (Table 22).

[38] A similar analysis for Saturday operations is not included because each vehicle completes one block for Saturday services.

Table 22: Current BEB daily mileage summary

Bus ID	Total Miles	Days operated	Average mi per day
4500	22,037	169	130.40
4501	19,923	154	129.37
4502	21,006	174	120.72

The buses operated on a variety of routes, but most (80%) of the assignments were on Route 10, while 12% of the assignments were on Route 12, 6% on routes 30 and/or 40, and 1% on Route 32. While the table above shows the average daily mileage, we also examined ‘block’ mileage, that is, the mileage operated by a bus during a single assignment, even if that bus operates more than one assignment on a single day (Table 23). Block mileage is shorter than the total daily average mileage of the BEBs, and ranges from 40 miles to 180 miles.

Table 23: Current BEB block mileage summary

Bus ID	Average miles per service period (block)	Min miles	Max miles
4500	100.2	43.0	181.0
4501	102.2	40.0	188.0
4502	98.6	33.0	180.0

Similarly, looking at the span of operation of each block demonstrates that on average, BEBs are in service about seven hours per day, but this can range from two hours to over 12 hours on a given day (Table 24).

Table 24: Current BEB block service span summary

Bus ID	Average hours per service period (block)	Min hours	Max hours
4500	6.91	2.97	13.65
4501	6.91	2.00	13.30
4502	6.89	1.42	12.75

One key aspect of route modeling is the prediction of fuel efficiency, that is, the energy (in kWh) expended by the BEB to move one mile. The elements impacting fuel efficiency are familiar because these are many of the same elements that impact the fuel efficiency of diesel buses or gas cars—the weight of the vehicle (which includes the vehicle itself, passengers, batteries, and so on), the use of climate control in response to exterior temperature, operator behavior (use of regenerative breaking, acceleration and deceleration), and other operating factors (traffic, the number of impediments like servicing a stop, etc.). The more efficient the operation is, less energy consumed per mile, allowing for a greater operating range.

Table 25 displays the average, minimum and maximum fuel efficiency recorded by the three Proterra BEBs. The averages of the three BEBs are very similar, about 2.5 to 2.6 kWh/mi. The minimum recorded efficiency (the most efficient) was 1.03 kWh/mi, while the least efficient was 7.94 kWh/mi.

Table 25: Current BEB fuel efficiency summary

Bus ID	Average kWh/mi	Min kWh/mi	Max kWh/mi
4500	2.63	1.59	6.42
4501	2.56	1.03	7.30
4502	2.51	1.33	7.94

Interestingly, the variation in fuel efficiency between routes is minimal, as shown in Table 26. However, the sample size for routes other than Route 10 are small, so drawing more specific conclusions is difficult.

Table 26: BEB fuel efficiency by route

Route	Average fuel efficiency (kWh/mi)	Sample size (blocks)
10	2.61	504
12	2.43	78
30	2.82	2
32	2.38	9
40	2.51	19
30/40	2.22	17
40/30	2.69	1

Based on the recorded fuel efficiency, we estimated the operating range of the BEBs. In other words, by using actual recorded fuel efficiency and accounting for the actual 80% usability of the 440-kWh battery (i.e., CARTA operators can actually safely ‘consume’ 352 kWh of energy), we estimated the operating range of the BEBs. Table 27 reveals that, on average, each BEB can operate about 140 to 150 miles on a single charge, but that the fuel efficiency, i.e., operating conditions, can either severely lower expected range (44-55 miles) or extend expected range (220-240 miles). Stantec notes that recorded averages of fuel efficiency and expected range fall within modeling results of previous exercises for other clients, as well as real-world outcomes we have reviewed in the literature.

Table 27: Estimated BEB operating ranges

Bus ID	Average operating range (based on kWh/mi and 80% of 440 kWh)	Min operating range (based on kWh/mi and 80% of 440 kWh)	Max operating range (based on kWh/mi and 80% of 440 kWh)
4500	139.2	54.9	221.8
4501	144.9	48.2	340.6
4502	148.2	44.3	265.5

This variety in fuel efficiency, and as a result, operating range, stems from the operating environment that is often uncontrollable (traffic, the number of stops needed to be served, exterior temperature), but also factors that can be controlled, such as training operators to utilize regenerative braking and use other techniques to prolong operating range. For example, Figure 27 plots both the monthly high ambient temperature and the monthly average fuel efficiency experienced by CARTA's BEBs. Fuel efficiency (orange line) decreases (i.e., the value is higher) during colder months like January and February as well as during hotter months like June and July, like because of the greater parasitic draw of the HVAC on the battery.

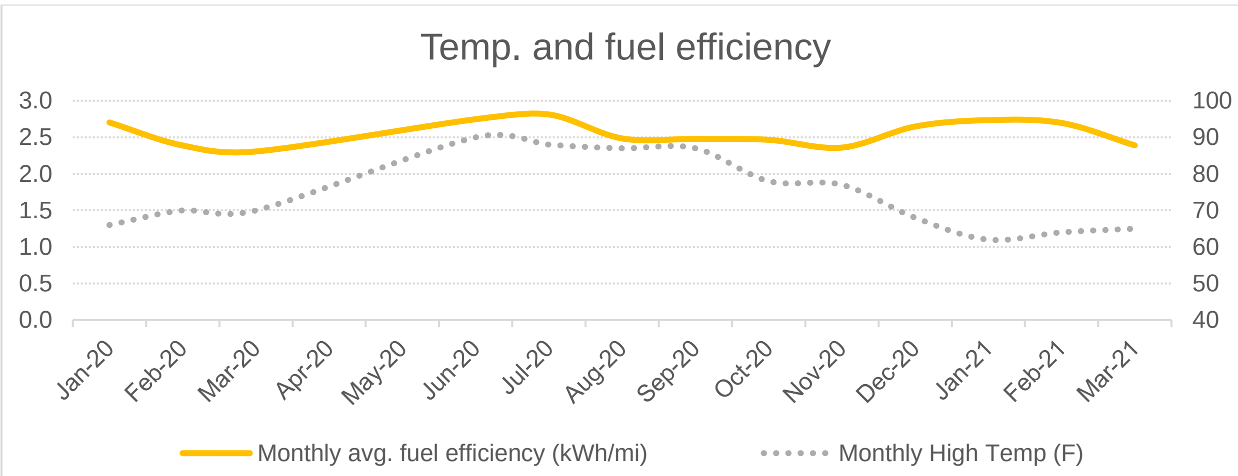

Figure 27: Fuel efficiency and ambient temperature

On the other hand, operator training and driving behavior have a significant impact on fuel efficiency. Figure 28 plots recorded fuel efficiency by operator.[39] The values recorded in the red-dashed box by one operator, for example, has a smaller spread and lower maximum value than the values recorded in the blue-lined box by another operator. Evaluating efficiency by operator, similar to assessing running time or on-time performance, should be used to coach operators on best practices for operating a BEB and prolonging operating range.

[39] Each operator was assigned a random number to ensure anonymity.

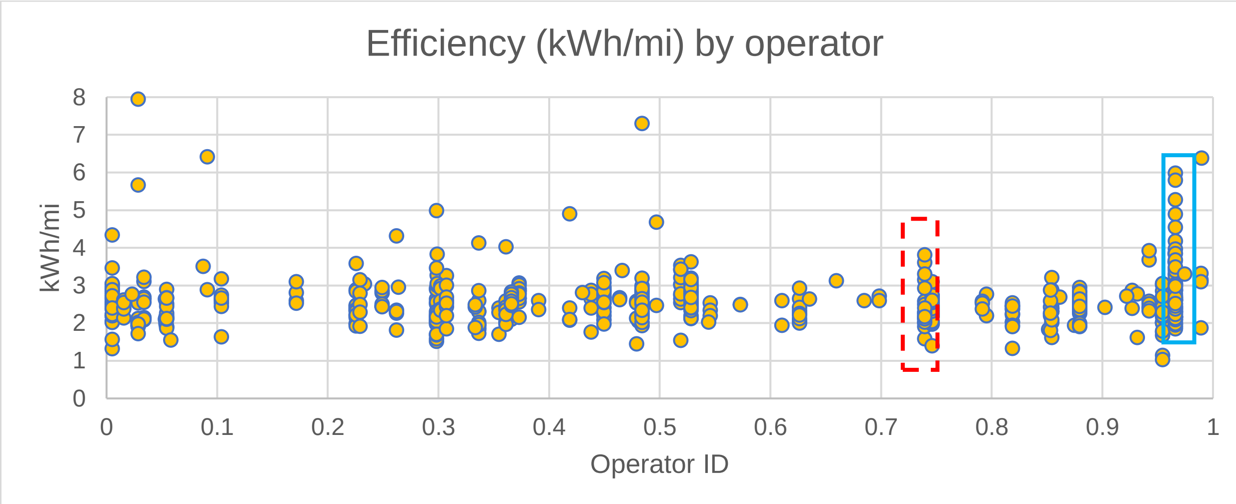

Figure 28: Fuel efficiency and operator

Finally, in addition to reducing GHGs, BEBs are typically more fuel efficient compared to fossil fuel buses. For example, diesel buses typically operate at 5 miles per gallon (MPG). CARTA's calculated equivalent for its BEBs fluctuates between 14 MPGe and 17 MPGe (Figure 29), about three times more fuel efficient than a diesel bus.

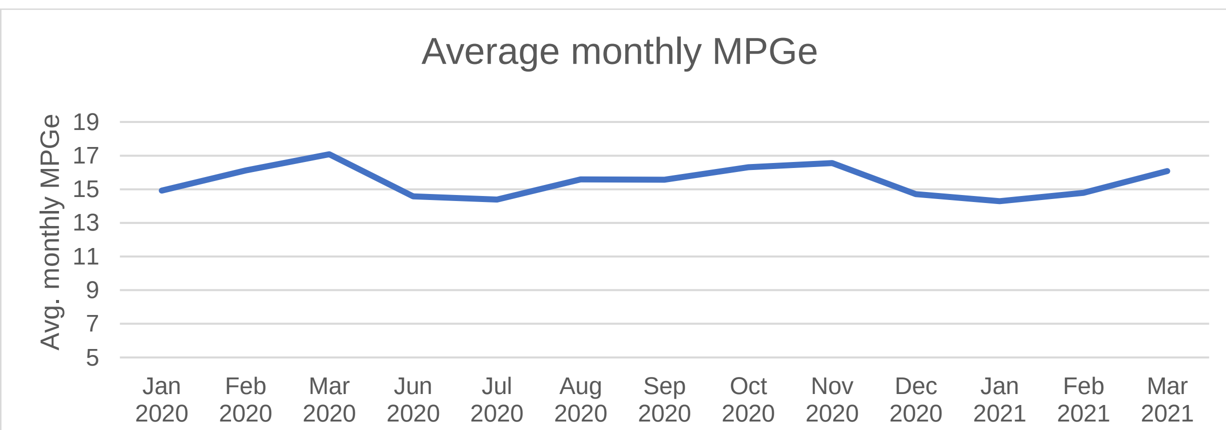

Figure 29: Average monthly MPGe

5.0 FACILITIES EXISTING CONDITIONS

This section provides an overview of the existing conditions of the infrastructure and facilities at CARTA's operations and maintenance facility.

5.1 CARTA OPERATING BASE AND MAINTENANCE FACILITY

This section provides a high-level overview of the existing conditions of the infrastructure and facilities at CARTA's yard, and also provides general guidance on what facilities and infrastructure may be required and/or considered as part of the agency's BEB implementation plan. These preliminary considerations will be built upon in greater detail in the implementation plan to outline required upgrades and modifications to support ZEB operations.

5.1.1 General Site Information

CARTA's facility is located at 3664 Leeds Avenue in the City of North Charleston (Figure 30). The site is approximately 7.2 acres. CARTA is currently leasing a portion of the adjacent parcel at 3680 Leeds Avenue from SCE&G / Dominion Energy for additional parking space. There is a currently a large photovoltaic array located within a fenced enclosure that occupies the majority of the adjacent parcel to the south. CARTA also leases a portion of the Dominion Energy property for bus storage - this area contiguous to the bus parking and drive area on the southwest corner of the site and can only be accessed via the parking (there is no direct access from Leeds Avenue). Including the leased parking, the total site area currently utilized by CARTA is estimated to be approximately eight acres. The facility includes areas for administration, operations, vehicle service, vehicle fueling, minimal employee parking, and fleet parking.

Figure 30: Aerial view of site showing CARTA property bound in red and leased Dominion Energy- property bound in green (source: Google Maps)

5.1.2 Architectural & Maintenance Equipment

5.1.2.1 Summary

The existing facilities were not observed or inspected in depth during the site visit, but appear to meet the needs for CARTA's current operational and maintenance functions. In general, they appear to be in average condition for buildings of their age. No obvious issues with building envelope were visible and the employees present did not indicate that there are any issues with existing building systems. Over time, several of the maintenance bays throughout the facility have been converted to storage areas or other uses. They no longer provide drive through capability as originally intended, which limits circulation and functionality of the site in certain areas.

The existing facility is approximately 60,000 SF total, including and includes a two-story 27,000 sf administrative and operations component. The lobby of the administrative facility includes a retail fare store for the sale of passes, which is the only public area of the facility. The administrative area includes offices, meeting spaces, dispatching, a lounge, and a parts room, as well as employee locker rooms and parts storage for vehicle maintenance.

Figure 31: Facility main visitor entry

Limited employee parking is located on the north portion of the site in a fenced lot accessed from Dorchester Road (and not accessible by automobile from any entrance on Leeds Avenue or from within the bus parking and servicing area). There is pedestrian access between the Dorchester Road employee parking and the main facility.

Within the employee parking area, there is a 1,400 sf building that occupied by CARTA's sign and bus stop maintenance group (Figure 32). This "sign shop" is not associated with fleet maintenance activities at the main facility.

Figure 32: Sign and bus stop maintenance facility

Located between the employee parking area and the main facility is a farebox storage and collection building which directly faces the fueling station and canopy, and is accessed from the main bus operations yard (Figure 33). The pedestrian entrance to the employee parking area is adjacent to the fare collection building.

Figure 33: Farebox storage and collection building, with employee parking beyond

There are approximately 16 angled automobile parking spaces on the east side of the administration building along Leeds Avenue; these appear to be intended for visitors, but they are also utilized by employees due to limited parking availability. Ad hoc parking in adjacent grass areas in non-marked spaces was also observed during the site visit.

The maintenance facility includes a wash bay with covered exterior steam cleaning bay, a paint shop, tire facility, body shop, and maintenance bays. There are multiple detached structures, including the vehicle fueling station which is protected by a canopy.

The maintenance wing of the building has ten (10) maintenance bays, grouped into the main service area (6 bays), and the paint shop and tire area (4 bays). Within the paint/tire area, one bay is used for tire storages. Only the westernmost two bays within the paint/tire area (one of which is adjacent to the tire storage bay) can work as drive-through pair, but they are currently not used for this purpose. None of the bays within the paint/tire area contain lifts.

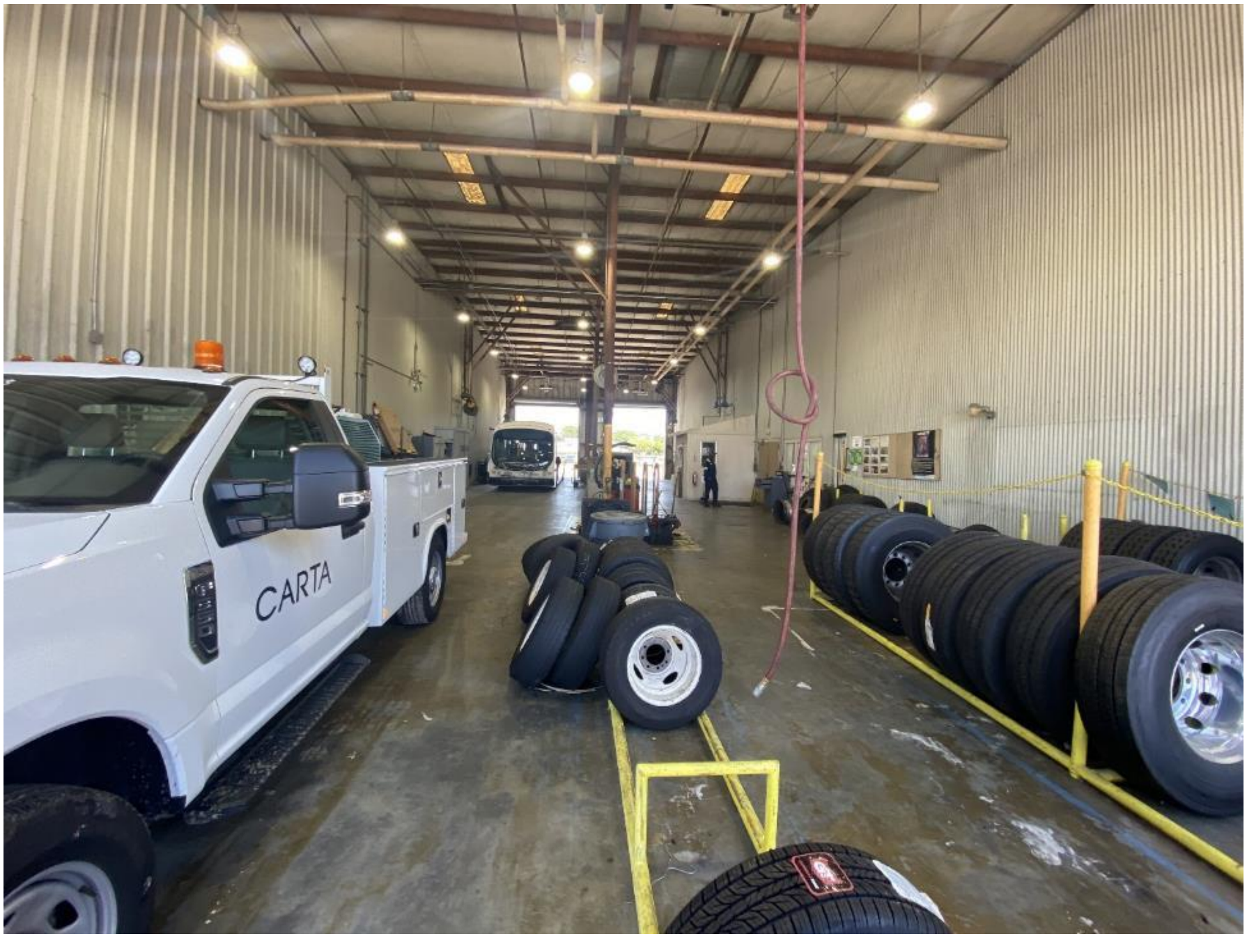

Figure 34: Tire Area and Storage (2 bays in forefront) and Paint Shop (2 bays at far end)

The space between the six bays of the main service area is used for storage of various equipment, including oil and mobile lifts. Vehicle exhaust reels and other typical vehicle maintenance equipment was generally observed at the facility but was not assessed as a part of this study.

Figure 35: Main Service Area (3 bays visible of 6 total)

There are twelve bays located within portion of the building which houses the administrative offices, six located on the south side, and six on the north side. Three bays on the south end of the admin building function as the bus body shop, and these are accessible through the garage doors on the west side. The three bays which exit to the east act as a storage area for equipment and supplies and are not available for buses or bus maintenance.

Figure 36: Body shop exterior (3 bays)

Figure 37: Body shop interior area (3 bays)

Similarly, the six bays on the north end of the building are not currently used for servicing of buses or vehicles. This area is utilized as a large all-purpose room for storage of equipment and supplies, operator assembly area and training[40], etc. Much of the stored equipment could be moved or consolidated if CARTA found it necessary to make some of these bays available for the use of vehicles.

[40] Operator training will return to the conference room after COVID-19.

Figure 38: "All-purpose" room

5.1.2.2 Conditions

The facility and associated maintenance equipment appear to be in good working condition. CARTA staff had no statements regarding inoperable or failing maintenance equipment.

There is one bus maintenance bay which offers fall protection. As the BEB fleet grows in the future, additional fall protection may be required for the safety of those working on batteries located on the tops of BEB vehicles. See Section 5.2.3, below.

5.1.2.3 Preliminary Considerations

CARTA has already begun the transition to ZEB vehicles and has six battery electric buses in operation as part of their initial procurement, with additional vehicles arriving shortly. These vehicles are serviced in the maintenance building, and CARTA has staff trained for the proper maintenance and repair of BEBs.

5.1.3 Vehicle Service Cycle

5.1.3.1 Summary

There are two vehicular entry / exit points along Leeds Avenue that are shared by the fleet and employee or visitor's vehicles. Fleet parking is located on the western side of the site within a secure perimeter. Access to the secure bus area is controlled by gates situated approximately the same distance from Leeds Avenue as the face of the main building. Due to space constraints the size of the bus determines the gate used to enter and exit the site at the beginning and end of a trip – for example, paratransit buses use only gate 2 (north entrance) for both ingress and egress. The property is fenced/gated beyond the employee parking such that the entire bus storage area and maintenance buildings are fenced-in while the office building and all of the employee parking is open to the street.

The property provides service for a fleet of 121 buses, with designated (striped) parking for 40 full size (44' x 12') bus stalls, 6 full sized battery electric buses (44' x 12') bus stalls, 15 medium (30' x 12') bus stalls, and approximately 30 standard (9' x 18') stalls. There are additional open areas (unstriped) to accommodate the remining vehicles not assigned to a designated space. All overnight vehicle storage is outdoors.

There are currently six bus parking spaces with power dispensers for electric buses located on the southwest corner of the site, adjacent to the leased overflow bus parking leased from SCE&G / Dominion Energy.

Vehicles are washed and cleaned typically 3-4 times per week, depending on the weather (less frequently in dry conditions). The bus wash and adjacent steam cleaning bay are located at the end of the maintenance building on the west side.

5.1.3.2 Conditions

The current service cycle facilities and functions appear to be in good working condition and are suitable for CARTA's current operations on the property. The ages of the existing equipment and facilities were not assessed but should be assumed to need replacement during the normal life cycle of such equipment and could be considered for optimization during the course of BEB implementation at the facility.

5.1.3.3 Preliminary Considerations

CARTA's affirmative move toward transition of their rolling stock to BEB vehicles and extensive planning with their stakeholder partners has moved forward their implementation of a ZEB fleet. The initial procurement of six BEB buses has established a charging station and six charging dispensers installed by Proterra for the use of the pilot BEB fleet. CARTA is also working with Proterra and Dominion Energy to install an additional 40 charging dispensers, one at every striped full-sized 40-ft bus parking space on the south side of the facility. These would be supplied by two 1.2MW charging stations to be situated on what is now the fenced concrete dumpster pad. Slight modifications to the current plan for 40 more charging dispensers may be required for successful operations (for example, the dispensers will require the protection of bollards capable of protecting from full-sized buses), but these infrastructure improvements are unlikely to require changes to the current service cycle.

5.1.4 Fueling Infrastructure

CARTA's fleet include gasoline- and diesel-powered vehicles, which are fueled onsite at a fueling station protected by a 1,300 sf canopy located on the north side of the maintenance building (see Figure 39). There is a pump for standard gasoline and a pump for diesel fuel.

Figure 39: Fueling station and canopy (gasoline and diesel)

Located at the southwest corner of the property are the six charging dispensers and the charging station array (Figure 40 and Figure 41). The electrical service for the charging station is supplied by Dominion Energy from Dorchester Road and is routed along the west property line of the facility. This service is independent of the electrical supply for the administration and maintenance building.

Figure 40: Electrical charging dispensers (five of six total dispensers visible)

Figure 41: Electrical charging station array (six units - 125 kW per unit)

5.1.5 Gas-Leak Detection System

As CARTA operates only, gasoline, diesel vehicles, and battery-electric buses; as such, the facilities are not required to have hydrogen gas-leak detection systems. This is only relevant if CARTA decides to incorporate fuel cell electric buses as an alternate electric bus in the future.

5.1.6 Electrical

Dominion Energy is the electrical utility serving North Charleston and the CARTA offices and bus facility. Electrical power is supplied to the CARTA offices and bus yard complex from a pad mounted transformer located along the east face of the building between the main entrance and the north garage doors. The service connection is from overhead power lines that run along Leeds Avenue. An electrical substation is located approximately 0.25 miles south of the CARTA facility on the west side of the Leeds Avenue right-of-way.

As noted in the section above, the existing electrical service for the six existing charging dispensers and associated charging station is supplied by an independent connection from Dorchester Road. The future 1.2MW charging station will also be a new, independent service line originating from Leeds Avenue and running along the south property line until it is bored under the bus apron concrete to the location of the charging station at the dumpster pad.

5.1.6.1 Conditions

The existing electrical distribution system is sufficient for the current operations of CARTA, and there are no reports of failure or degradation of the infrastructure serving the administration or maintenance wings of the building. The system appears to be satisfactory for the current, non-BEB demands of the CARTA operations. Primary electrical demands in the administration building are lighting, HVAC, and typical office support loads. The bus maintenance building has air compressors, portable bus lifts, bus wash and steam cleaning stations, lighting, and HVAC loads.

The procurement of CARTA's first six BEBs has been accompanied by the construction of independent charging infrastructure for the vehicles, with a service connection from Dorchester Road. There is no net increase in electrical demand to the established electrical service connection for the facility from Leeds Avenue, and no operations within the building will be negatively impacted by the electrical service demands of the BEBs.

5.1.6.2 Preliminary Considerations

As CARTA is already well along with its plans for a future BEB fleet, the necessary planning for additional electrical infrastructure has already taken place with partner stakeholders Proterra and Dominion Energy. Plans for an additional 40 charging dispensers and two 1.2 MW charging stations have been prepared, with a service connection independent of both the admin/maintenance building and the existing six BEB chargers. Transition of more of the fleet from carbon-based fuels to BEBs and full buildout of charging infrastructure will not cause any negative impacts to the existing service loads.

5.2 GENERAL MAINTENANCE FACILITY CONSIDERATIONS

5.2.1 Fire Protection Considerations

With the implementation of either FCEBs or BEBs, fire protection and life-safety concerns can be significant. However, due to the relatively new advent of these technologies, building and fire protection codes have not specifically addressed many of these concerns. The National Fire Protection Association (NFPA) 855 'Standard for the Installation of Stationary Energy Storage Systems' is a standard that can potentially be applied to BEB storage, but this particular standard is certainly overkill relative to the capacity of the batteries onboard buses and is more applicable for an indoor application/storage of batteries. The need for enhanced fire protection systems has not been determined as a baseline requirement for BEB implementation and would be left up to the discretion of the local fire marshal and the local building officials. Early coordination with the local building authorities is highly recommended to understand their requirements and concerns.

5.2.2 Fall Protection and Safety Infrastructure Considerations

Safety is of paramount importance at all bus maintenance facilities and should be assessed at a very detailed level for any future facility modifications. A detailed safety assessment is outside the scope of this report, but assumptions can be made that the existing fall protection system located at one maintenance bay is currently adequate for safely accessing rooftop equipment. This requirement will not be going away with the implementation of BEBs and may even require an increase in fall arrest systems at this facility due to battery packs or fuel cells being located on the roof of vehicles.

6.0 FINANCIAL ANALYSIS

Financial analysis is an important component of the BEB rollout plan to ensure that the resulting plan is actionable and will result in tangible operational and financial benefits. Prior to evaluating the anticipated financial impacts of BEB implementation, however, it is important to review the current state of CARTA's operating and capital expenses. Doing so will provide valuable insights for crafting the rollout plan while also acting as a basis upon which financial forecasts may be completed.

6.1 OPERATING EXPENSES

To consider the financial stability of CARTA, operating expense trending was examined for the data provided by the agency and through NTD annual reports. A gradual increase in operating expenses over time is expected (to account for ongoing service expansions and inflation).

The graph in Figure 42 displays the percent increase in operating expenses for CARTA and peer agencies[41] between 2014 and 2019.

[41] Peer agencies were chosen based on geographic location and similarities in the amount and types of service provided.

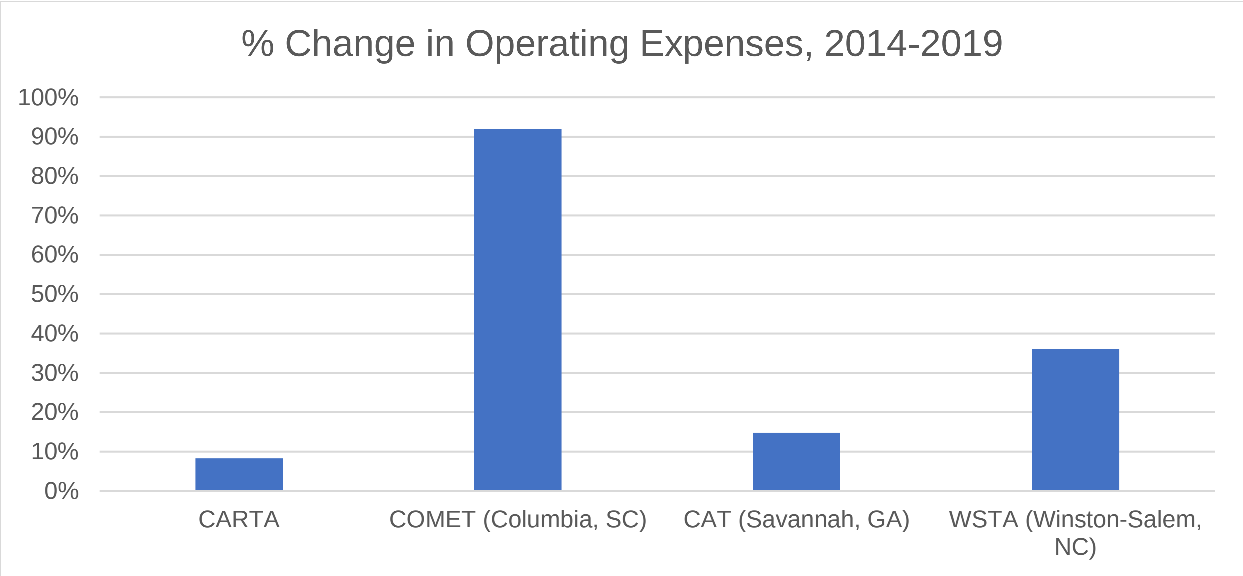

Figure 42: Percent change in operating expenses, 2014-2019

CARTA fixed-route service increased at a much slower rate than peer agencies. This reflects the slight reduction in fixed-route service (~3.65M revenue hours in 2014 vs. 3.21M in 2019), while other agencies have increased service to varying degrees during the analysis period.

Diving a little deeper, a breakdown of operating expenses for CARTA in 2019 as reported to the NTD for all services is illustrated in Figure 43.

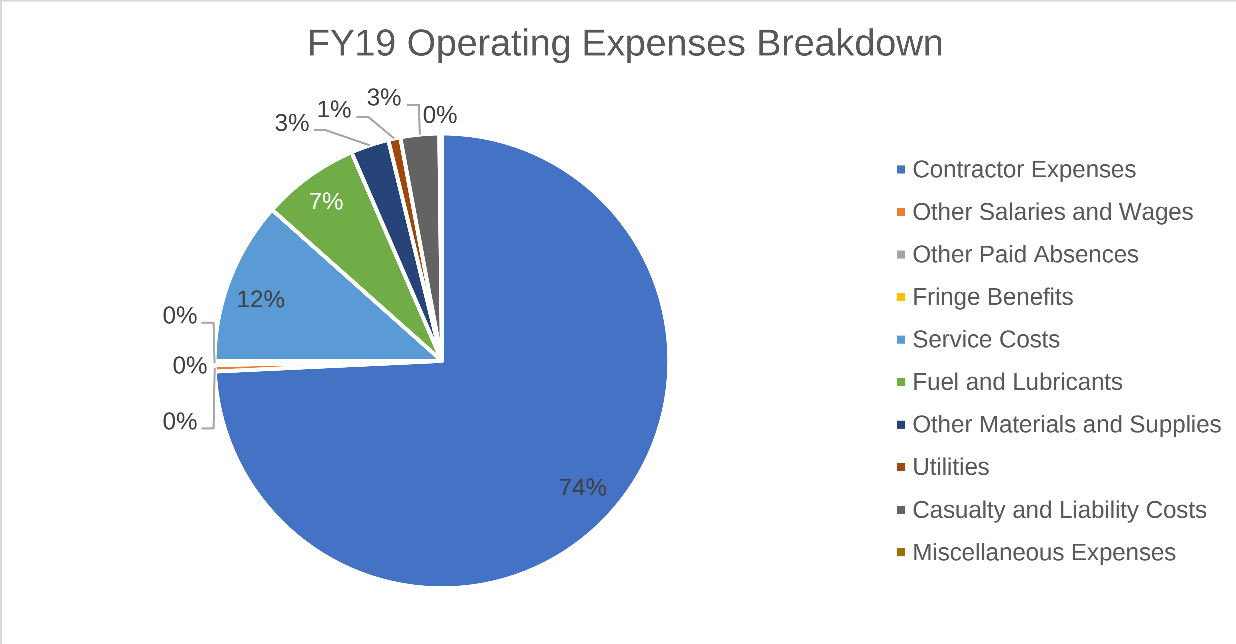

Figure 43: FY19 operating expenses breakdown

Overall, most operating costs are allocated to contractor expenses, as Transdev is contracted to operate and maintain the service. Other significant expenditure categories include service costs and fuel and lubricants. With the implementation of BEBs, we could expect short-term increases related to salaries (i.e., FTE) and maintenance as CARTA goes through likely growing pains with the adoption of new technologies. However, fuel and lubricants costs could likely decrease, since lubricants and similar types of fluids are no longer necessary. Fuel, however, would shift from fossil fuels to electricity, which could be more or less costly; future analysis is required and will occur in future steps.

It is also important to look at operating expenses in terms of miles and hours of service provided (Table 28).

Table 28: Operating cost per revenue hour and mile by mode, 2014-2019.

	Cost per revenue mile		**Cost per revenue hour**	
	2014	2019	2014	2019
Fixed-route	$5.50	$6.93	$75.50	$83.93
Express	$5.28	$4.75	$92.40	$113.25

Fixed-route costs per revenue-mile have increased by approximately 25% between 2014-2019, and per revenue-hour by 11%, which correlates to the reduction in service through the analysis period. Conversely, the express routes saw a 23% increase in costs per revenue-hour, but a 10% decrease per revenue mile.

Key metrics to track during the adoption of BEBs are operating costs per mile and hour, with the assumption that as agencies become more accustomed to operating these vehicles and maintenance costs manifest, cost per mile and hour should drop, although they may initially spike due to capital costs (vehicle acquisition, charging infrastructure, etc.).

6.2 CAPITAL EXPENSES

In addition to operating expenses, it is important to consider the trending of capital expenses and funding, since the most substantial immediate impact of BEB adoption will be an increase in capital expenditures.

Capital expenses are dependent on capital needs and funding availability. The funds received over the last few years have been reviewed to understand funding availability for bus transit peer agencies (Figure 44).

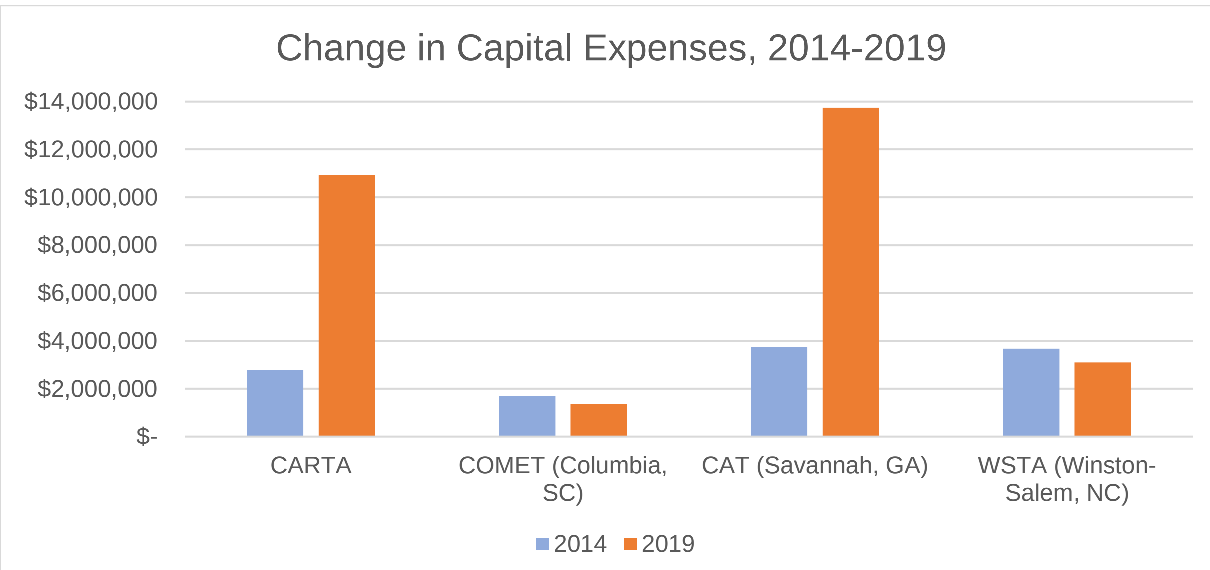

Figure 44: Change in capital expenses, 2014-2019

Overall, changes in capital funding fluctuates widely, with certain agencies seeing an increase and others a decrease. The amounts vary by agency; for example, CAT spent nearly $10,000,000 more in 2019 than 2014. CARTA's capital spending also varied quite significantly, with roughly $8,000,000 more spent in 2019 than 2014.

It is best practice to typically ensure that capital spending is as consistent as possible year-over-year rather than subject to significant peaks and valleys in case funding availability changes in the future. In addition BEB infrastructure will require high initial capital costs, so consistency in baseline capital spending will allow for easier budgeting/forecasting of overall capital expenses when BEB infrastructure is considered.

CARTA's funding sources for capital expenditures vary from year to year, as shown in Figure 45.

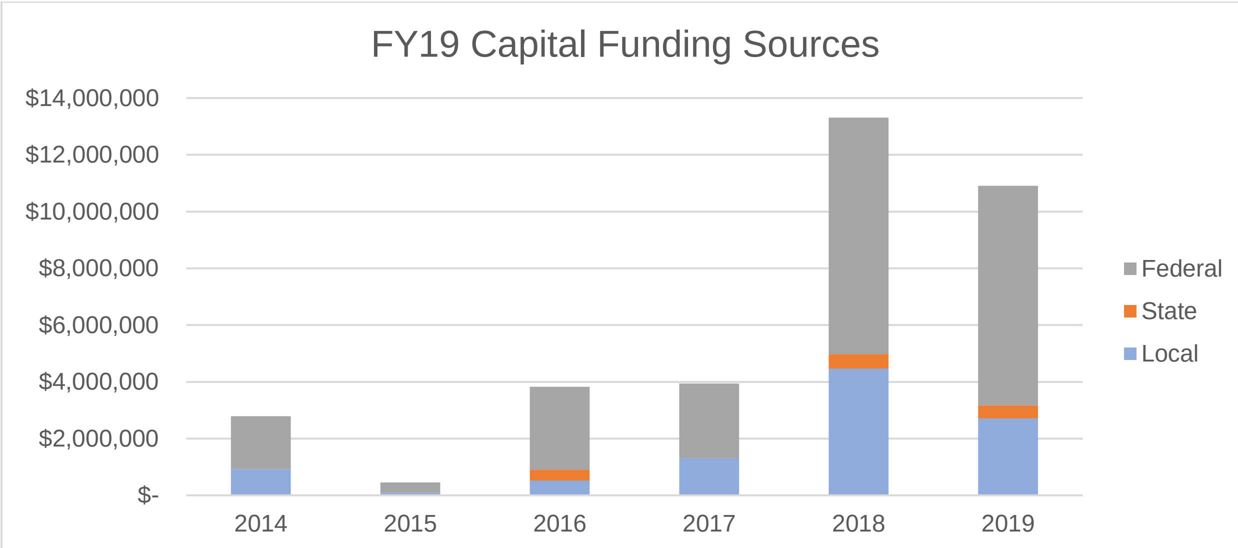

Figure 45: FY19 capital funding sources

Figure 45 shows that CARTA receives the bulk of its capital funding from federal funds with a lower proportion of local funds and occasional limited state funding. Specifically, major sources of capital funding include:

- FTA Section 5307 Urban Funds; Bus and Bus Facilities (5339)
- State Mass Transit Funds
- Charleston County Sales Tax

Going forward, CARTA will need to explore diverse funding opportunities, some traditional federal and state grants, while also taking advantage of new grant programs geared toward BEBs and related greenhouse gas reduction and sustainability. Programs which can provide funding for BEBs and related infrastructure are:

- 5307/5309/5311 FTA funds
- 5339(c) FTA Low or No-Emission Vehicle Program (Low-No)
- 5339 FTA Bus and Bus Facilities
- USDOT RAISE Grants
- NHTSA Autonomous Funds
- Beneficiary Mitigation Plans for Volkswagen Settlement Funding

7.0 SUMMARY AND NEXT STEPS

This report presented a comprehensive review of CARTA's existing conditions, encompassing operations, facilities, and finances with an emphasis on their relevance to the BEB transition and implementation and some initial observations and takeaways regarding current service that will have an impact on the ongoing transition to BEBs.

- Overall, the majority of CARTA's service is within the mileage ranges of BEBs, though some blocks and vehicle assignments exceed current BEB range capacities. Nonetheless, it is likely that the majority of CARTA's BEB transition will be straightforward.
- While CARTA operates a variety of different vehicle sizes to fit the needs of its different service types and diverse service area, this can add complexity to the BEB transition as different vehicle types have different BEB equivalents with different operating ranges, and it will be important to ensure vehicles are scheduled on the correct block to avoid operational issues.
- CARTA already has BEBs in operation, which is helpful as operators and other staff are already familiar with the new technology and the agency has real-world data on fuel efficiency and estimated operating range, which will be a helpful tool to help compare the results of the predictive power and energy modeling.
- CARTA's operating base and maintenance facility are in good operating conditions and fit the needs of CARTA. There are currently six bus parking spaces with charging dispensers (125 kW per unit) for charging CARTA's six BEBs. CARTA is currently working with Proterra and Dominion Energy to install an additional 40 charging dispensers that would be supplied by two 1.2MW charging stations. Future facility modifications and infrastructure improvements are unlikely to require changes to the current service cycle.
- Compared to peer agencies, CARTA's operating expenses increased at a much lower rate between 2014 and 2019. The vast majority of CARTA's operating expenses are allocated to contractor expenses as Transdev maintains and operates CARTA's services. It is the assumption that as agencies become more accustomed to operating BEBs and vehicle costs manifest, cost per mile and hour should drop. Thus, it will be important for CARTA to closely track these metrics.

Now that a thorough understanding of current fixed-route operations has been produced, next steps include:

- Modeling to forecast energy usage and to determine the feasibility of BEBs to meet CARTA's current operations, and developing strategies to optimize a BEB fleet for CARTA based on their unique operational characteristics
- Detailing the required infrastructure modifications and enhancements to support a 100% BEB fleet, including charging requirements and any on-route charging needs and a fleet charging strategy
- Development of a ZEB rollout plan and strategy, including a fleet replacement schedule
- Financial analysis to determine the financial implications of the BEB transition