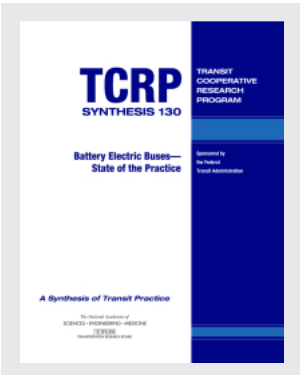

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP SYNTHESIS 130

Battery Electric Buses—State of the Practice

A Synthesis of Transit Practice

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Subject Areas
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TRB
TRANSPORTATION RESEARCH BOARD

2018

TRANSIT COOPERATIVE RESEARCH PROGRAM

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Special thanks are extended to all of the participating transit agencies that shared their experiences for this synthesis report. Thanks are also extended to all of the pioneering agencies and sponsoring organizations that took the risk to pave the way for future generations of battery electric bus fleets.

FOREWORD

Transit administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to the transit industry. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire transit community, the Transit Cooperative Research Program Oversight and Project Selection (TOPS) Committee authorized the Transportation Research Board to undertake a continuing study. This study, TCRP Project J-7, "Synthesis of Information Related to Transit Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute a TCRP report series, *Synthesis of Transit Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Mariela Garcia-Colberg
Staff Officer
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The synthesis prepared by Jason Hanlin and his team documents current practices of transit systems in the planning, procurement, infrastructure installation, operation, and maintenance of battery electric buses (BEBs). The study strives to provide unbiased information from the perspective of the transit systems on the deployment of BEBs. The synthesis is intended for transit agencies that are interested in understanding the potential benefits and challenges associated with the introduction and operation of battery electric buses. The synthesis will also be valuable to manufacturers trying to better meet the needs of their customers and to federal, state, and local funding agencies and policy makers.

A literature review and detailed survey responses from 18 transit agencies that submitted information are provided. Detailed case examples of five different systems are also included in the report and provide additional insights into the state of the practice, including lessons learned, challenges, and gaps in information.

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SUMMARY

Battery Electric Buses—State of the Practice

Battery electric buses (BEBs), also known as all-electric buses, are attractive to transit agencies because they are cleaner, quieter, simpler, and smoother than their conventionally fueled counterparts due to their all-electric propulsion and auxiliary systems. These attributes result in zero tailpipe emissions (including zero local criteria air pollutants and carbon emissions), zero dependence on foreign oil, better experiences for passengers and drivers, and potentially lower operational costs. Because of the broad range of benefits and product availability within the market, transit agencies are purchasing BEBs on a much larger scale than in the past. However, there are still challenges associated with the technology, including range limitations, required charging times, high electricity rates for some locations, complicated utility rate structures, and higher capital costs. While some of these challenges are being addressed or mitigated through industry efforts and continuing improvements to the technology, there are still critical needs to be addressed in order for widespread deployment and full commercialization of the technology.

Executives of transit systems considering introduction of BEBs into their fleets and agencies wanting to improve or expand their BEB fleets should collect all of the information necessary to make educated decisions. This synthesis report will provide relevant information and considerations by reporting on the current state of a rapidly progressing technology. Through a literature review, a survey of 21 agencies with BEB experience (18 of 21 responded for an 86% rate) and five current case examples, this synthesis report represents a comprehensive analysis on the state of the practice for deploying BEBs, including planning, procurement, infrastructure installation, and operations and maintenance. The synthesis should also be valuable to another wide range of industry stakeholders including bus and component manufacturers trying to better meet the needs of their customers and federal, state, and local funding agencies and policy makers.

As of the writing of this report, there are at least 13 BEB models available and more than 70 transit agencies with BEB deployments in the United States. In addition, there are almost 600 BEBs on order or in service. Half of the transit agencies reported they implemented BEBs due to a combination of board direction, environmental regulations, and environmental or sustainability programs, while a third of the agencies were doing it to test the buses in their service. As the number of BEB deployments has grown, so has the maturity level of the technology. Industry improvements include increased propulsion system reliability, increased battery energy capacity, and decreased capital costs of the BEBs.

The benefits of BEBs have been reported in the literature. BEBs have demonstrated energy efficiencies of four times greater than diesel and compressed natural gas (CNG) buses through the Federal Transit Administration's Altoona testing. While the buses have zero tailpipe emissions, studies show that even life cycle global warming emissions are almost

75% less than CNG and diesel buses. Further, BEBs produce significantly lower life cycle NO_x emissions than diesel and CNG buses and lower life cycle particulate matter emissions than diesel and, in some energy production cases, CNG buses. The Altoona Bus testing also demonstrated reduced noise levels both inside and outside BEBs compared with conventional buses.

Currently there are also many challenges for BEB deployments. Most of the agencies surveyed agree that decisions regarding the overall approach to BEBs and their supporting infrastructure should be carefully evaluated during the planning stage prior to deployment. For successful BEB deployments to occur, transit agencies must carefully plan how to integrate the technology in their specific operations and must undertake a strategic, coordinated approach to deploying both the buses and the appropriate charging infrastructure. These charging methods include plug-in charging, overhead conductive charging, and wireless charging. Transit agencies must not only determine which buses to purchase but also plan how, when, and where to charge their buses. These inter-related decisions depend upon a range of variables that are unique to individual agencies. Further, it is important for agencies to consider scale-up potential during initial planning as it is more economical to install certain infrastructure components (e.g., conduit, wiring, and transformers) at once rather than continually upgrade them as the fleet grows.

Another challenge is the lack of technology support tools and practices to assist with BEB procurement and planning activities. Only half of the agencies surveyed stated that they factored electricity rates and/or demand charges into their decision to purchase BEBs and about half of respondents did a life cycle cost analysis during the procurement. More than half of the transit agencies used their own agency experience in combination with bus manufacturer predictions and bus trials to evaluate vehicle range, select suitable routes, and determine the type of charging method best suited for their agency. Advanced modeling and simulation techniques that help to predict some of the operational issues that have been reported were used by a third of the agencies. The majority of transit agencies responded that such tools and services would be beneficial when making decisions regarding range predictions, utility rate analysis, and life cycle cost analyses and adjustments.

While the cost for BEBs has always been considered a challenge and capital costs are still approximately 40% to 50% higher than diesel and CNG buses, they are dropping significantly with economies of scale and technology improvements. The technology improvements are most pronounced for the traction batteries. The availability of federal, state, and local funding incentives also help offset the incremental capital costs of BEBs and the new charging infrastructure. Early indications from maintenance cost data point to lower costs than conventional buses due to the relative simplicity of the buses and the lower number of bus parts.

Operating costs for BEBs can also be lower than conventional buses due to the efficiency gains and the potential for cheaper energy costs. However, these costs (and the total cost of ownership) are heavily dependent on utility rates. Despite an almost four times improvement in fuel economy for the buses, energy costs were higher for BEBs than for CNG buses as reported by a National Renewable Energy Laboratory (NREL) study and some of the agencies responding to the survey conducted as part of this synthesis.

Transit agencies with experience deploying BEBs noted that recurrent BEB driver training is critical for project success and lowering operating costs. First, driving habits can significantly affect BEB efficiency and performance and on-route charging adds a new, unfamiliar requirement for drivers. Second, agencies reported more efficient deployments when they coordinate early in the process with a wide group of stakeholders including community leaders, public groups, and unions in order to avoid issues after deployment.

In general, notwithstanding all the previous challenges, the transit agencies reported that BEB operations went smoothly, the buses worked well, and there were minimal problems. Availability and reliability of BEBs is reportedly approaching that of conventional vehicles. And reliability of charge infrastructure is reported to be excellent. In fact, when asked to rank their overall satisfaction with BEB deployments on a scale of 1 to 10, 12 of the 13 agencies responded positively by ranking satisfaction at 5 or above and 8 of those agencies provided a very high ranking of 9 or 10. Eighty-six percent of the responding agencies plan on purchasing more BEBs. One agency is fully electric, and three other agencies responded that they intend to be fully electric by years 2018, 2025, and 2030, respectively.

This synthesis report identifies some gaps in knowledge and challenges to implementation that should be addressed with both further research and actions. In order to see large, full fleet conversions, there is a need to document successful responses to challenges associated with deploying charging infrastructure at scale. Challenges include land use, space constraints, grid demand impacts, fleet staging for charging, labor requirements for making manual connections and maintaining charging equipment, and maintaining operability during power outages. These challenges affect almost all stakeholders, and the industry needs to continue to work together to find solutions.

Given that BEB operating costs are heavily dependent on utility rates, understanding the rates, their variability, their effect on the business case, and the optimization of rate structures for BEBs is another significant need for the industry. Agencies reported that more experience and data are needed to be able to fully evaluate and understand actual life cycle costs associated with BEB deployment. Further, life cycle cost assessment methods should be developed and utilized in the procurement phase.

To ensure interoperability, charge standards must be developed for all forms of BEB charging. Procurement guidelines for BEBs and charging infrastructure likewise need to be established similar to those that are available for conventional buses. Transit agencies, bus manufacturers, component suppliers, industry nonprofits, and transit associations are participating in working groups that are actively addressing these issues.

In summary, the benefits of deploying BEBs can be extensive. BEBs are matching reliability of conventional buses, and battery technology continues to advance at a rapid pace driving down costs and offering increased range capabilities. However, capital costs must continue to be reduced to be on par with diesel and CNG technologies. Utility costs, particularly demand charges, need to be better understood and structured to be affordable, especially in comparison to diesel and CNG costs. BEB fleet scale-up concerns must be addressed both from an industry perspective and within individual fleets. Finally, technical support and advanced tools need to be utilized for making objective BEB procurement and planning decisions specific to the individual needs of the transit agency. If done correctly, transit agencies can, and are, realizing benefits ranging from lower total cost of ownership, reduction of environmental impact, performance improvements, and improved customer experience.

CHAPTER 1

Introduction

Project Background and Objectives

Transportation accounts for 28.5% of U.S. energy consumption and petroleum accounts for 91.5% of the transportation energy consumption in 2015. In 2014, buses consumed 98,000 barrels of petroleum per day or 413 million gallons of diesel over the year. This is equivalent to more than 4 million tons of carbon dioxide emissions in one year. In 2014, all highway vehicles accounted for 22.26 million tons of carbon monoxide, 4.49 million tons of nitrogen oxides, 2.16 million tons of volatile organic compounds, and 470,000 tons of particulate matter emissions (Davis et al. 2016). Reducing emissions and reliance on petroleum from the U.S. transportation sector is seen as an important step in realizing health benefits, reducing global warming effects, improving national security interests, and creating jobs.

Battery electric buses or BEBs, also known as all-electric buses, do not rely on petroleum for operation and have zero tailpipe emissions. BEBs are also attractive to transit agencies because they have proved to be quieter, simpler, and smoother than their conventionally fueled counterparts due to all-electric propulsion and auxiliary systems. These attributes result in zero tailpipe emissions (including zero local criteria air pollutants and carbon emissions), zero dependence on foreign oil, better ride quality and experiences for passengers and drivers, and potentially lower operational costs. However, there are still challenges associated with the technology, including range limitations, long charging times, potentially high electricity rate charges (including demand charges), and higher capital costs. These challenges are being accommodated through a wide range of approaches, including improved planning methods, making operational changes (e.g., bus blocking and layovers), increasing the amount of resources (including number of chargers and/or buses), and striving for technology improvements. Ultimately, many of these challenges are expected to be addressed or mitigated through battery improvements with respect to costs, energy density, power density, and charge rate acceptance. As a result of the broad range of benefits, transit agencies are purchasing BEBs on a much larger scale than ever before and more and more BEB products are being introduced to market.

A discussion about BEBs begins with the fundamental differences between them and conventionally fueled diesel and compressed natural gas (CNG) buses. BEBs are driven using an electric motor rather than an internal combustion engine and therefore are also referred to as an “electric drive” vehicle. Fuel cell and series hybrid electric vehicles (EVs) are also considered electric drive vehicles for the same reason. However, for BEBs, all of the energy used by the vehicle to power the traction motor and auxiliaries comes from the energy stored in an electrochemical battery pack. Compared with diesel, CNG, fuel cell, and hybrid technologies, all-electric vehicles significantly reduce the amount of energy conversion on board the vehicle and use very efficient electrical power conversion components to power the driveshaft and auxiliary systems, such as lighting and air conditioning. This is the simplest, most efficient, and cleanest method of powering a vehicle. While a fuel-cell-powered vehicle is also a zero emission, electric drive vehicle, it adds hydrogen energy storage and the fuel cell to convert hydrogen to electricity to be stored in the batteries and power the vehicle. This additional energy conversion step, while clean, is roughly 50% to 55% efficient and results in additional energy losses. The benefit of fuel cell technology is its ability to store more energy on board the bus and provide longer ranges than BEBs. Fueling with gaseous hydrogen as opposed to charging is also a faster way to add energy to the vehicle. A diesel or CNG series hybrid bus also works like a fuel-cell-powered bus but in this case the energy conversion efficiency of the engine is only 35% to 45%, resulting in greater energy losses in addition to the vehicles having tailpipe emissions (U.S. Environmental Protection Agency's National Vehicle and Fuel Emissions Laboratory 2017). Also diesel and CNG powered vehicles require that the engines are running during stops and brief idling, further reducing their efficiency. Finally, conventionally fueled buses without energy storage on board are not able to recover energy from regenerative braking, also further reducing vehicle efficiency. Ultimately, the U.S. Environmental Protection Agency states that only about 14% to 30% of the energy from gasoline put into conventional passenger vehicles (using combustion engines) is used to move it down the road while all-electric vehicles used 74% to 94% of the electricity put into the vehicle to move them down the road (Fueleconomy.gov 2017).

Altoona Bus Testing reports provide a convenient way to compare overall fuel economy specifically for transit buses. The Altoona Bus Research and Testing Facility provides testing for all new bus models under the Federal Transit Administration's (FTA's) bus testing program. "The program's goal is to ensure better reliability and in-service performance of transit buses by providing an unbiased and accurate comparison of bus models through the use of an established set of test procedures" (The Altoona Bus Research and Testing Center 2015). Evaluation of tests across New Flyer's Xcelsior 40′ low floor bus platform provides a basis for a direct comparison of all four propulsion methods: diesel, CNG, hybrid-electric, and all-electric. The measured fuel economy for each technology is converted to the miles per diesel gallon equivalent (MPDGE) value to allow for comparison. As shown in Figure 1, the electric

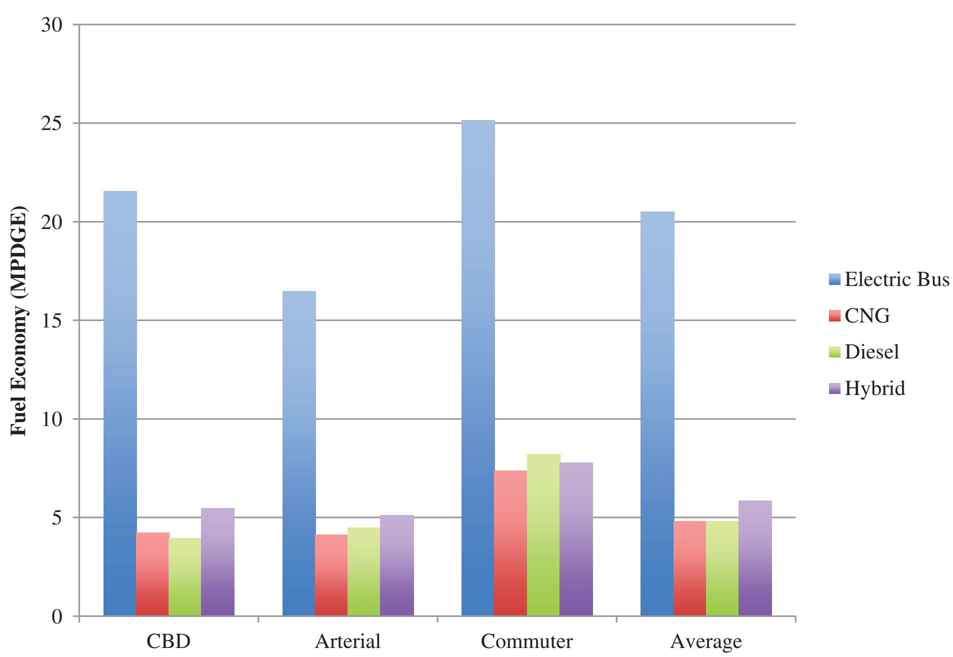


Figure 1. Altoona measured fuel economy—New Flyer buses.
Source: Center for Transportation and the Environment.

bus fuel economy far exceeds the CNG, diesel, and hybrid bus fuel economy in every test track phase. The average fuel economy for the electric bus (20.5 miles per diesel gallon equivalent [MPDGE]) is greater than four times the average CNG (4.8 MPDGE) and average diesel (4.8 MPDGE) fuel economies, and just under four times more efficient than the average hybrid bus (5.84 MPDGE) fuel economy.

Description of Bus Charging Methods

Deployment of BEBs requires careful consideration of deploying the associated charging infrastructure. A topical understanding of power and energy is important when considering and comparing BEBs and their charging systems. Energy is the property that must be transferred to an object in order to perform work on the object. In this case, electrical energy is being considered and will use the units of kilowatt hours (kWh). Power is the amount of energy consumed per unit time and can be expressed in SI units of watts or kilowatts (kW).

BEBs are "fueled" through charging. Three types of charging are used for BEBs in the United States today: plug-in charging, overhead conductive charging, and wireless inductive charging. The attributes, pros, and cons of each type are highlighted below.

1. The attributes of plug-in charging (manually plugging in the vehicle to a power supply) are as follows:
   - Typically installed at the depot, shop, or garage.
   - Typically used to charge overnight.
   - Typically used as sole charging method for buses with large battery packs and higher range.
   - Charge type: AC or DC.
   - Charge power: 40–120 kW.
   - Recharge times (depending on charge power and battery pack size): 1–8 hours.
   - Applicable U.S. Standards: SAE J1772; SAE J3068 (in progress).

   The pros of plug-in charging are as follows:
   - Minimal infrastructure and installation requirements.
   - Lower cost per charger than other options.
   - Able to take advantage of lower off-peak electricity rate when charging overnight.
   - More flexibility for route selection and future route changes.

   The cons of plug-in charging are as follows:
   - Buses must be taken out of service to charge.
   - Buses use larger, heavier battery packs that can reduce bus efficiency, reduce passenger capacity, and increase wear on suspension components.
   - Charging process is manually intensive (plugging in and monitoring).
   - Charging is typically slower than other options.
   - Charging can require a lot of space with a charger for each bus.
   - Charging can require a lot of power with each bus charging at the same time.
2. The attributes of overhead conductive charging (automated connection using an overhead conductive coupler) are as follows:
   - Typically installed on route or at transit center where layovers occur, allowing for opportunity charging; may also be installed at the bus depot or yard.
   - Typically serve multiple BEBs operating on routes or from transit centers.
   - Typically used with buses with smaller battery packs and less range.
   - Charge type: DC.
   - Charge power: 175–450 kW.
   - Recharge times: 5–20 minutes.
   - Applicable U.S. Standards: SAE J3105 (in progress).

The pros of overhead conductive charging are as follows:
- Buses use smaller, lighter battery packs.
- There is full-range charge in 5–20 minutes.
- Can support 24-hour bus operation if implemented correctly.

The cons of overhead conductive charging are as follows:
- Higher cost of charging infrastructure.
- Requires charging infrastructure, equipment, and civil work.
- Peak demand charges can significantly affect operational costs.
- Land use and/or rights must be obtained at deployment sites.
- Overhead systems may interfere with road clearances or require dedicated/restricted pull-off.
- Fixed infrastructure constrains route changes for BEBs in the future or can be costly to relocate.

3. The attributes of wireless or inductive charging are as follows:
   - Typically installed on route or at transit center where layovers occur but could also be used at bus depot.
   - Typically serve multiple BEBs operating on routes or from transit centers.
   - Typically used with buses with medium-to-large battery packs and medium range.
   - Charge power: 50 kW (up to 250 kW planned).
   - Applicable U.S. Standards: SAE J2954/2 (in progress).

   The pros of wireless or inductive charging are as follows:
   - Can remain in service while charging on route.
   - Decreased infrastructure footprint.
   - Charging interface does not interfere with road clearances or require dedicated/restricted pull-off.
   - No manual connection or moving parts.

   The cons of wireless or inductive charging are as follows:
   - Slightly less efficient than conductive methods (90% versus 95%).
   - Higher cost of charging infrastructure.
   - Requires charging infrastructure, equipment, and civil work.
   - Peak demand charges can significantly affect operational costs.
   - Land use and/or rights must be obtained at deployment sites.
   - Fixed infrastructure constrains route changes for BEBs in future or can be costly to relocate.

BEB History and Development

In the mid to late 1990s and early 2000s, a wave of BEBs hit the United States with transit agencies in Santa Barbara, California; Chattanooga, Tennessee; and Tempe, Arizona, ordering BEBs from start-up BEB manufacturers, including AVS and Ebus. Due largely to the bankruptcy of AVS and to the poor performance of lead acid and NiCad battery technologies at the time, the BEB industry stalled from about the years 2000 to 2010. Led by the success of start-up manufacturer, Proterra, the BEB industry saw resurgence around the turn of the decade. Proterra's early success was followed closely by BYD's introduction to the U.S. market. The major North American bus original equipment manufacturers (OEMs) followed suit when New Flyer built upon their extensive electric drive experience (including trolleys and hybrid buses) to develop and offer all-electric bus products. NovaBus followed suit and, most recently, GILLIG began offering a BEB product. Complete Coach Works also introduced a remanufactured bus product complete with an all-electric drive system. The resurgence of the U.S. BEB industry was largely due to FTA's investment into electric drive technologies with programs including the National Fuel Cell Bus Program, the Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) Program, the Clean Fuels Grant Program, and the Low or No Emission Vehicle

Program. The National Fuel Cell Bus Program helped develop new fuel cell, electric drive prototype vehicles. The other programs have helped to offset the higher capital costs of BEBs, thus enabling more transit partners to deploy. In addition to FTA's programs, the Fleet Rule for Transit Agencies from the California Air Resources Board (CARB) has helped spur the market by requiring that urban buses meet stricter California exhaust emission standards. Figure 2 highlights the growth in the U.S. zero emission bus market since 2009.

From 2009 through 2016, the total number of BEBs awarded, contracted, and/or sold in the United States grew from 17 to 582, while the number of fuel cell electric buses grew from 35 to 76.

There are approximately 78 BEB deployments planned or deployed in the United States and 72 of those are public transit operations, with the remaining being universities and private fleets, as shown in Table 1. Approximately 35 agencies out of the 72 have deployed BEBs and the vehicles are operating in transit service. In early 2017, King County Metro announced an individual order for 73 BEBs. One transit operator has successfully converted its full fleet to all-electric and mid-size California transit agencies are committing to convert their entire fleets to BEBs as well.

Nine companies are currently manufacturing BEBs. Some are focused on a full suite of vehicle types, including conventionally powered to electric drive while other OEMs are solely manufacturing BEBs. As shown in Table 2, the OEMs offer a wide range of BEB and charging configurations geared toward meeting the unique individual needs of a variety of agencies.

The wide variety of bus configurations and charging options provided by the bus OEMs are designed to meet a variety of deployment scenarios with range and charge time limitations. Transit agencies must consider their unique characteristics and needs when planning, procuring, and deploying BEBs and the associated charging infrastructure to determine the appropriate configuration and charging options best suited to their deployment. These characteristics include

- route demands (speeds, grades, stops, length, layovers);
- bus service or blocking demands (deadheads, duration, and frequency);
- seasonal temperatures;

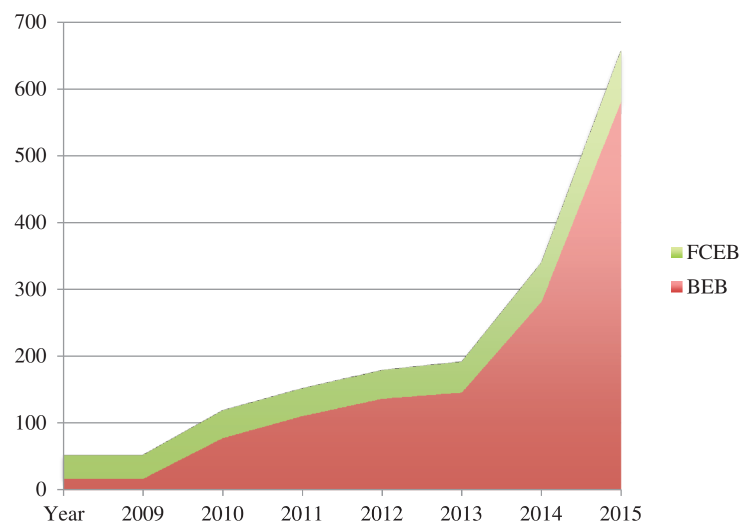


Figure 2. U.S. zero emission bus cumulative sales and awards. Source: Center for Transportation and the Environment.

Table 1. Current BEB deployments in the United States.

Fleets with BEBs Awarded, On Order, or Deployed	# of Deployments	Total # of BEBs
AC Transit	1	5
Albuquerque Rapid Transit	1	18
Anaheim Transportation Network (ART)	1	4
Antelope Valley Transit Authority	2	41
Ben Franklin Transit	1	1
California State University- Fresno	1	3
Capital District Transportation Authority	1	1
Central Contra Costa Transit Authority (CCCTA)	2	8
Chattanooga Area Regional Transit	1	3
Chicago Transit Authority	2	6
City of Columbia (COMO Connect)	3	16
City of Fresno	1	2
City of Gardena (GTrans)	2	6
City of Seneca	1	7
Clemson Area Transit	1	10
Dallas Area Rapid Transit (DART)	1	7
Delaware Transit Corporation	1	6
Denver RTD	1	36
Duluth Transit Authority	1	7
Everett Transit	1	4
Foothill Transit	3	31
Frederick County (TransIT)	1	5
Fresno County Rural Transit Agency	1	4
Hartsfield Jackson Airport	1	2
Indianapolis Public Transportation Corporation (IndyGo)	1	21
JLL Jones Lang LaSalle	1	10
King County Metro	3	84
Kitsap Transit	1	1
Lane Transit District	2	10
LEWT - Napa Valley Wine Tour	1	1
Link Transit	4	20
Long Beach Transit	2	13
Los Angeles Dept of Transportation	1	4
Los Angeles Metro	1	5
Massachusetts Bay Transportation Authority	1	5
Metro McAllen	1	2
Metro St. Louis	1	1
Miami-Dade County	1	4
Modesto Transit	1	4
Monterey Salinas Transit	2	3
Mountain View Transportation Management Association (MVGo)	1	4
Nashville Metropolitan Transit Authority	1	9
Navajo Transit System	1	1
Park City Transit	1	6

(continued on next page)

Table 1. (Continued).

Fleets with BEBs Awarded, On Order, or Deployed	# of Deployments	Total # of BEBs
Pierce Transit	1	2
Pioneer Valley Transit Authority	1	3
Port Arthur Transit	1	6
Porterville Transit	1	9
Quad Cities Metrolink	1	2
Regional Transit Agency of Central Maryland (Howard County)	1	3
RTC (Reno Regional Transportation Commission)	2	8
San Joaquin Regional Transit District	4	11
Santa Barbara MTD	1	2
Santa Catalina Island Company	1	3
Santa Clara Valley Transportation	1	5
Santa Cruz Metropolitan Transit District	1	3
Shreveport Area Transit System (SporTran)	1	5
Solano County Transit (SolTrans)	1	2
Sonoma County Transit	1	1
Southeastern Pennsylvania Transportation Authority	1	25
Stanford University	2	39
Star Metro	1	6
SunLine	1	3
Thunder Bay Transportation	1	4
Transit Authority of Lexington (Lextran)	2	6
Transit Authority of River City (TARC)	2	16
Tri Delta	1	2
Tri-County Metropolitan Transportation District of Oregon (TriMet)	1	4
Twin Transit	1	1
UCLA	1	2
Univeristy of California Riverside	1	1
University of Georgia	1	19
University of Montana	1	2
Utah Transit Authority	2	6
VIA Metro	1	3
Visalia Transit	1	2
WMATA	1	1
Worcester Regional Transit Authority	1	7
Grand Total	**102**	**655**
Count	**78**	**568**

- passenger loads;
- available garage space and power;
- layover or transit center locations and space; and
- utility rate schedules and costs.

Agency characteristics must be evaluated collectively and in conjunction with the various bus configurations and charging options as they affect the performance (specifically range), capital, and operating costs for BEBs. For instance, hot or cold temperatures can have a significant effect on air conditioning or heating loads, bus efficiency, and range, whereas the time, length, and amount of charging can have a significant effect on demand charges and total energy costs.

Table 2. BEB manufacturers and products.

Bus Manufacturer	Model	Style	Infrastructure	Energy Storage
BYD	K7	30′ transit bus	80 kW Depot Charge	182 kWh
	K9, K9S	40′, 35′ transit bus	80 kW Depot Charge	324 kWh
	K11	60′ articulated transit bus	200 kW Depot Charge	547 kWh
	C6, C9, C10	23′, 40′, 45′ coaches	100-300 kW Depot Charge	135-394 kWh
CCW	ZEPS	40′ transit bus	Depot Charge	213-242 kWh
Double K	Villager	30′ trolley	Depot Charge	
Ebus	Ebus	22′ city bus	Depot Charge	
	Ebus	40′ transit bus	On Route Charge	89 kWh
Gillig	Standard LF	29′ transit bus	Depot/On Route Charge	100 kWh
Green Power	Varies	30′-45′	Depot Charge	210-478 kWh
New Flyer	Excelsior	40′ transit bus	Depot/On Route Charge	99 kWh
				198 kWh
				297 kWh
		60′ transit bus	Depot/On Route Charge	250 kWh
Nova Bus	LFSe	40′ transit bus	On Route Charge	76 kWh
Proterra	Catalyst FC	35′, 40′ transit bus	On Route Charge	79 kWh
				105 kWh
	Catalyst XR	35′, 40′ transit bus	Depot/On Route Charge	220 kWh
				330 kWh
	Catalyst E2	35′, 40′ transit bus	Depot Charge	440 kWh
				550 kWh
				660 kWh

Source: Center for Transportation and the Environment.

There is no one-size-fits-all solution with BEBs and charging infrastructure; thus procurement and planning decisions must be made carefully based on the individual needs and characteristics of the transit agency in order to achieve and maximize the benefits of all-electric technology.

To date, agencies have relied on high-level information as well as on trial and error to make decisions regarding BEB deployment. However, detailed analyses and tools are beginning to emerge to assist agencies in making objective, data-driven decisions. Additionally, most BEBs are being deployed on the least demanding routes and bus blocks in order to mitigate any risks to service. As the boundaries for BEB service are pushed, the need for information and tools to ensure that service can be met and deployments are cost effective will become even more critical. No two business cases or BEB deployments have been exactly alike. The pioneering effort of each agency that has chosen to deploy BEBs has contributed significantly to the body of knowledge. The following sections highlight these deployments and lessons learned contributing to more informed deployments of BEBs and mass adoption by the transit industry. This synthesis report is intended to be a resource for transit agencies looking to procure and deploy BEBs for the first time, as well as for experienced agencies to learn what others are doing and adopt best practices in their current and future BEB fleets.

Technical Approach

To document the current state of the practice of BEBs, three approaches were taken to collect, organize, and present data on BEB deployments. First, a literature review was performed; second, a comprehensive survey of experienced agencies was completed; and third, case examples involving five agencies provided a more in-depth examination of their BEB deployment experience.

The literature review section is organized to address the following topics.

Planning

- Life cycle cost analysis;
- Bus technical specifications, operational requirements, and route selection;
- On-route charging infrastructure;
- Layover location characteristics;
- Electricity rate structure;
- Planning and support tools; and
- Scalability.

Service, Maintenance, and Operations

- Training (maintenance, operators, first responders, and dispatching systems);
- Availability and reliability of buses;
- Resiliency and emergencies;
- Equipment longevity and risk mitigation (vehicles, battery, chargers, and unknowns);
- Technology for managing, charging, and dispatching; and
- Stakeholder involvement (utilities, operators, unions, communities, executive boards, regulatory agencies, and so forth).

Costs and Benefits (What benefits at what costs?)

- External funding opportunities (federal funding, carbon credits, and so forth);
- Customer acceptance;
- Social;
- Environmental;

- Health;
- Cost of energy (utilities); and
- Return on investment.

Research into relevant literature included a Transport Research Information Documentation database search using the keywords “battery electric bus” and other relevant terms. This search was augmented with other pertinent materials collected from industry-related sources and web sources.

The survey questions were established to address the broad scope of synthesis topics using established survey methods. Based on actual BEB deployment experience and industry input, the questions are both quantitative and qualitative. Twenty-one transit agencies were surveyed to represent a wide range of BEB experience, agency size, agency location, OEMs, and bus and charging technology types. The survey was structured in a time-based manner to reflect the process an agency undergoes to accomplish a deployment project. This was partly done to get the respondents thinking through the process of procuring and deploying their BEBs and partly because the respondents were all at different stages of the process. The approach considered two stages: (1) planning and (2) experience after deployment. The planning stage addressed the events and considerations leading up to actually placing the BEBs in service and included assessment of procurement and preparation. The experience after deployment stage provided insights into the experience and results from active deployment, including assessment of operations, maintenance, and administration impacts as well as actual costs and benefits.

Finally, five transit agencies representing a variety of locations and experience were interviewed for case examples. These interviews added an additional layer to the state-of-the practice assessment; the agencies reported their challenges, solutions to those challenges, and advice to other agencies.

Content Organization

The report is organized as follows:

- Chapter 1 provides the background and introduction into the study.
- Chapter 2 provides the results of the literature review and attempts to characterize the current state of available information regarding BEB deployment experience.
- Chapters 3 through 5 provide the survey results. The survey results section is split into three separate parts, based on the category of each question. Chapter 3 of this synthesis report is the first of the survey results and provides general information about the agencies’ characteristics and BEB fleets. Chapter 4 delves into the planning aspect of BEB deployment, addressing life cycle cost analyses, bus technical specifications and operational requirements, route selection, infrastructure planning, standards and interoperability, scalability, and other bus and infrastructure capabilities. Chapter 5 presents the agencies’ postdeployment experience, addressing training, operations, charging specifics, service and maintenance, availability, stakeholders, electricity rate structure, public perception, and overall satisfaction with BEBs.
- Chapter 6 presents case examples of five agencies that have deployed BEBs and charging infrastructure.
- Chapter 7 provides a summary of major synthesis findings and suggestions for future research.
- Appendix A is the survey questionnaire and Appendix B provides the full survey details.

CHAPTER 2

Literature Review

This literature review addresses the three overarching topics of BEB deployment. They are planning; service, maintenance, and operations; and costs and benefits associated with deployment. Each category includes its own subcategories, presenting current literature on specific aspects of each topic. For the planning section, this review addresses topics such as a life cycle cost analysis, technical specifications of the BEBs, route selection, charging infrastructure, and scalability. The service, maintenance, and operations section includes training, availability and reliability, and stakeholder involvement. Finally, the costs and benefits section addresses external funding opportunities, energy costs, and social, environmental, and health benefits. If the current available literature is lacking for a specific topic, the subject is included in a list at the end of the review as a suggestion for further research.

The rapid growth of BEB technology and market is reflected in the literature's progression. Two early BEB studies—the Center for Urban Transportation Research's *Realizing Electric Bus Deployment for Transit Service* and the Federal Transit Administration's *Analysis of Electric Drive Technologies for Transit Applications*—provide information about BEB experiences and were published in 1998 and 2005, respectively. The latter study evaluated an electric bus produced by a manufacturer that no longer exists and the former study concluded that "perhaps the ultimate reality is best expressed [by the statement] 'there may never be a future for big electric buses because of their power requirements, but it could work well for the smaller ones"' (*Realizing Electric Bus Deployment for Transit Service*, page 32). Judging solely by the number of BEB models currently available and the number of BEB deployments, it is clear that BEB technology has evolved significantly and agency experience with the technology has grown exponentially since these reports were published. As with any developing technology, documented results and information will lag behind actual experience. Although somewhat limited in availability, this literature review has focused on empirical reports published within the last decade for relevance.

The literature review relied heavily on an NREL analysis of Foothill Transit's deployment of BEBs. This evaluation is an appealing reference because it captures the agency's path toward its goal of becoming 100% battery electric by describing the measured results and lessons learned from its initial deployment of 12 on-route fast charge buses to fully electrify one route. NREL's evaluation objective was ". . . to provide comprehensive, unbiased evaluation results of advanced technology bus development and performance compared to conventional baseline vehicles" (Eudy et al., 2016, page 6). Foothill Transit, located in California's San Gabriel and Pomona Valleys, currently operates 361 buses in revenue service. Of those 361 buses, 344 are CNG and the remaining 17 are fast-charge BEBs. Foothill Transit began its conversion to CNG buses in 2003 and has continued to integrate cleaner technology, retiring its last diesel bus in 2013. The Foothill Transit fleet evaluation provides information relevant to many of the subjects that this synthesis was intended to address. Each topic is also supported throughout the report with references to other available literature.

The literature review will start with brief reviews of international activity to give context to the U.S. market and to trolley buses as a foundational electric drive technology for BEBs.

International Activity

An estimated 173,000 BEBs were deployed worldwide as of 2015. China has the vast majority of deployments, with more than 170,000 BEBs. The Chinese government has established a policy and program for "new energy buses," with a goal to produce 1.67 million EVs (including BEBs) and to create 1.2 million jobs annually for the period 2010–2020. Shenzhen City alone currently has 4,887 BEBs in operation. By the end of 2017, all of the city's buses will be fully electrified, with 16,493 BEBs.

Europe follows Asia with more than 956 BEBs delivered or on order. Of those, 64% are overnight charged and 36% are opportunity charged. The United Kingdom has more than 18% of the total European fleet, while the Netherlands, Switzerland, Poland, and Germany each account for about 10%. Europe also has an established electric bus program, called ZeEUS (Zero Emission Urban Bus System), with more than 40 participants and a budget in excess of 22 million euros. The ZeEUS eBus Report is an informative synopsis of the European BEB market and developments. European cities and countries are primarily motivated by the desire to address global warming and make less of an impact on the environment. International government relations, such as the Paris Agreement to limit global warming to 2°C (United Nations Framework Convention on Climate Change 2016) and the U.S.–China Race to Zero Emissions Challenge (Zero Emissions Bus Benefits 2016), are stimulating the zero emissions market overseas.

Other worldwide efforts include South Korea's research, development, and deployment of wireless charging infrastructure and BEBs. Trolley buses with autonomous off-wire operation (equipped with batteries) are being tested throughout Russia, Belarus, Moldova, Kyrgyzstan, and Serbia. Two BEB demonstration projects have taken place in India. A solar-electric bus service has been established in Australia. In Canada, the Societe de transport de Montreal has purchased three BEBs and is installing four fast chargers to test the technology.

Trolley Buses

First introduced in 1882, trolley buses—also known as trackless trolleys—were the earliest all-electric buses. While trolley bus propulsion is provided by electric motors and accessories are all electric, they are different from BEBs in that they draw power from overhead wires (suspended by roadside poles) instead of from energy stored in batteries. Currently around 300 trolley bus systems are in operation around the world and more than 800 systems have existed over time. They are an attractive option for agencies because they are quiet, have "powerful but smooth accelerations," and give the public a sense of "permanence of service" (Arieli Associates, n.d., page 7). Their use and development over the last century have contributed to the introduction of BEBs through development of electric components for traction systems and accessories and through public acceptance and familiarity with electric transportation. They share many of the benefits and challenges associated with BEBs, especially BEBs utilizing on-route charging. While trolleys offer an advantage to BEBs in that they do not carry the weight of the batteries onboard the vehicles, they have significant drawbacks, with more extensive fixed infrastructure and wires that are very expensive to install and maintain and that are often considered to be unsightly. Trolley buses are now being deployed that are equipped for limited off-wire operation. This capability is achieved by adding a small auxiliary power unit such as a diesel engine. This is also known as dual-mode capability. For full electric operation, dual-mode capability is being accomplished with on-board batteries that are charged with the catenary while on wire and then used for off-wire excursions (Trolleybus 2017).

Planning Considerations

Life Cycle Cost Analysis

An important aspect of planning for BEB deployment is analyzing the cost over the total life cycle of the vehicle, including upfront capital costs, component replacement costs, maintenance costs, and electricity costs, as shown in Table 3.

Many agencies are hesitant to purchase BEBs because of the higher capital costs compared with diesel buses. The common response to that argument is that BEBs can make up for the higher capital costs in their lower fuel consumption and maintenance costs relative to diesel costs. Due to the nascent stage of BEB development and deployment, accurate BEB capital and operations cost data are limited and difficult to obtain. First, BEB purchase costs are continuing to drop and have not yet stabilized. Second, deployments have not seen enough operational time to collect real maintenance data, especially with respect to battery replacement costs. However, one analysis established and compared costs between BEB and diesel buses, as shown in Table 3. Note that these costs were developed to be inputs to a life cycle environmental analysis and use manufacturing costs, instead of purchase costs, in order to exclude profit and tax components. The life cycle costs of BEBs were similar to those of diesel buses when the cost of diesel fuel is high (Table 4). However, the assessment shows a wide range of fuel costs for the diesel buses. While the assessment provides a framework for accomplishing a life cycle assessment and provides some details (at 2013 costs), its shortcomings prevent making broad conclusions. The assessment does not take into account variability in electricity cost structures (only costs at $0.11/kWh) and sensitivity to power demand while charging. Additionally, there are numerous state and local funding opportunities that a transit agency may be able to utilize to reduce the capital costs of BEBs, which are explored in the Costs and Benefits section of this report. Third, BEB manufacturing costs (identified as Additional

Table 3. Life cycle costs of BEBs.

Life Cycle Cost Component	BEB Cost Compared with Conventional Bus Cost
Capital Costs	
Bus Costs	Typically higher
Operating Costs	
Component replacement costs	It depends; battery cost replacement costs are high and suspension wear may be higher with increased curb weight, however there are fewer moving components in BEBs, brake components wear slower due to regenerative braking capability. Costs should particularly be compared based on mid-life overhaul expectations where major components such as engines and batteries are designed to be replaced or overhauled.
Maintenance labor	Comparable, but has potential to become lower once technicians become familiar with electric systems
Preventive maintenance	Lower; no oil systems, less brake wear
Electricity costs	Typically lower than conventional fuel costs; BEBs are much more efficient, however electricity rates and rate structures can vary tremendously depending on location; diesel costs fluctuate and are relatively unpredictable

Source: Center for Transportation and the Environment.

Table 4. Life cycle inventory summary.

Bus Type	Cost Component	Cost (2013 $)	Total Cost	Process-LCA data (if applicable)
Diesel	Manufacturing	$300,000	$1,164,728 (using lowest of the FC range)	
	Maintenance	$444,000	$1,361,664 (using highest of the FC range)	
	Fuel Consumption (FC)	$420,728-$617,664		
BEB	Manufacturing	$300,000	$1,330,462 (using lowest of the RI range)	GREET's Battery Model run for these specifications:
	Additional Manufacturing (related to the electric drive system)	$570,000	$1,332,962 (using highest of the RI range)	• 12 years lifetime
	Maintenance	$328,560		• 37,000 annual miles
	Refueling Infrastructure (RI) (grid mix scenario)	$22,500-$25,000		• 40 ft long; 112,000 lb
	Fuel Consumption	$109,402		• 112 Wh/kg; 1814 kg (Li-ion)

Manufacturing costs in Table 4) have continued to show reductions since 2013, particularly with respect to battery costs (Ercan and Tatari 2015).

Due to the highly variable degree of electricity costs as well as to the downward progression of the costs for BEB components as technological improvements and economies of scale, it is difficult to make general conclusions regarding BEB life cycle costs. It is imperative to properly evaluate and understand the variables associated with life cycle costs for an individual transit agency, especially when comparing the variables with conventional technologies.

In order to better balance the cost components for buses purchased with federal funds, FTA now allows major component capital costs such as batteries to be procured under a lease arrangement in order to reduce the upfront capital costs of BEBs. This financing arrangement allows the purchase of BEBs to be on par with conventional buses with the expectation that ongoing operational costs (plus the battery lease) will be comparable with conventional buses due to savings in other areas of electric bus operations and maintenance. FTA codified this change in the most recent transportation bill, the FAST Act (FAST Act 2017). No industry guidelines or standards were identified for calculating life cycle cost analyses for electric buses, especially for establishing operation and maintenance costs.

Bus Technical Specifications, Operational Requirements, and Route Selection

APTA released its most recent version of the Standard Bus Procurement Guidelines in 2013 (APTA Standards Development Program 2013). The Guidelines provide guidance for a complete procurement for buses from 30′ to 60′ that can be customized to suit an individual agency's needs. The document is written specifically for conventional drivetrain technologies and does not currently include considerations for zero emission technologies. A multidisciplinary team that includes bus manufacturers, transit agencies, industry consultants, and other public and private organizations was organized by APTA to update the Guidelines to address the procurement of BEBs. The expected to release date for this document is in early 2018. It is important to note the update does not include specifications for procurement of charging infrastructure.

Planning BEB deployments requires the transit agency to consider multiple factors, including specific vehicle capabilities, duty cycle requirements (route speeds and grades), deadhead requirements, service requirements (layovers and bus blocking), environmental conditions, passenger loads, and charging schemes. All of these factors are codependent, which can make establishing bus technical specifications, route locations, charging type and locations, and operational planning difficult but important to consider holistically.

Table 2 from the Introduction of this report lists current BEB manufacturers and the energy storage options within the product offerings. The examples that follow highlight how different transit agencies have planned for BEB deployments. A Columbia University study about BEB integration into NYC's transit system explains the importance of battery characteristics when purchasing BEBs:

> For an electric vehicle, the key battery characteristics are the range (distance) that can be traveled on a full charge and the time required to recharge the battery. However, it is important to understand that these characteristics act differently in the electric vehicle world than they do with gasoline or diesel powered vehicles. For example, most cars have a range of about 400 miles. That range can vary depending on whether the car is being driven primarily on the highway or in the city. Stop and go traffic impacts the fuel economy and therefore the range of the car. In the case of electric vehicles, ambient temperature can influence battery efficiency and therefore fuel economy more than in a gasoline/diesel powered vehicle. The impact will vary by battery type and by the actual ambient temperature in addition to bus load, speed, incline of the bus route, etc. (Aber, 2016, page 23).

Variables such as HVAC loads, passenger loads, bus speeds, and route grades can have a significant impact on the energy consumption of a BEB and, depending on the battery size and condition, will have a commensurate impact on range. Many OEMs cite baseline energy consumption based off their Altoona testing results, which occur on flat grades, at seated load weight, and no HVAC loads. The baseline energy consumption estimates are similar between the various bus products. One BEB OEM provides Altoona-tested efficiencies of 1.61 kWh/mile to 1.89 kWh/mile, depending on bus size. However, once duty cycle and HVAC impacts become more demanding, the efficiencies can more than double, effectively halving the range. Modeling and simulation results have shown that expected efficiencies in winter with maximum passenger loads can surpass 3 kWh/mile with the worst case conditions being over 6 kWh/miles (Hanlin 2016). Empirical data for two different BEB fleets operating in cold northern U.S. climates that were collected and analyzed by the SAE J3105 committee also suggest that these variables can have a significant effect on bus efficiency and range, as shown in Figure 3.

Chicago Transit Authority (CTA) has two BEBs. Figure 4 depicts the operational requirements of the buses. The agency needed to organize its use of the BEBs in such a way that accounted for available charge time both overnight as well as throughout the day. In addition, they also had to account for range requirements for each bus block (a bus block is the daily schedule of travel for a given bus from depot pull-out to pull-in).

For its initial BEB demonstration, Foothill Transit selected Line 291, a 16.1-mile route. Line 291 was the most viable option because of its minimal deadhead distance and suitability to an on-route, fast-charging system because it loops through the transit center in both directions. Line 291 requires seven buses during peak hours; the additional BEBs are used as spares for maintenance downtime as well as for serving other appropriate routes that go through the Pomona Transit Center such as Line 855. Foothill Transit made minor adjustments to its schedule to

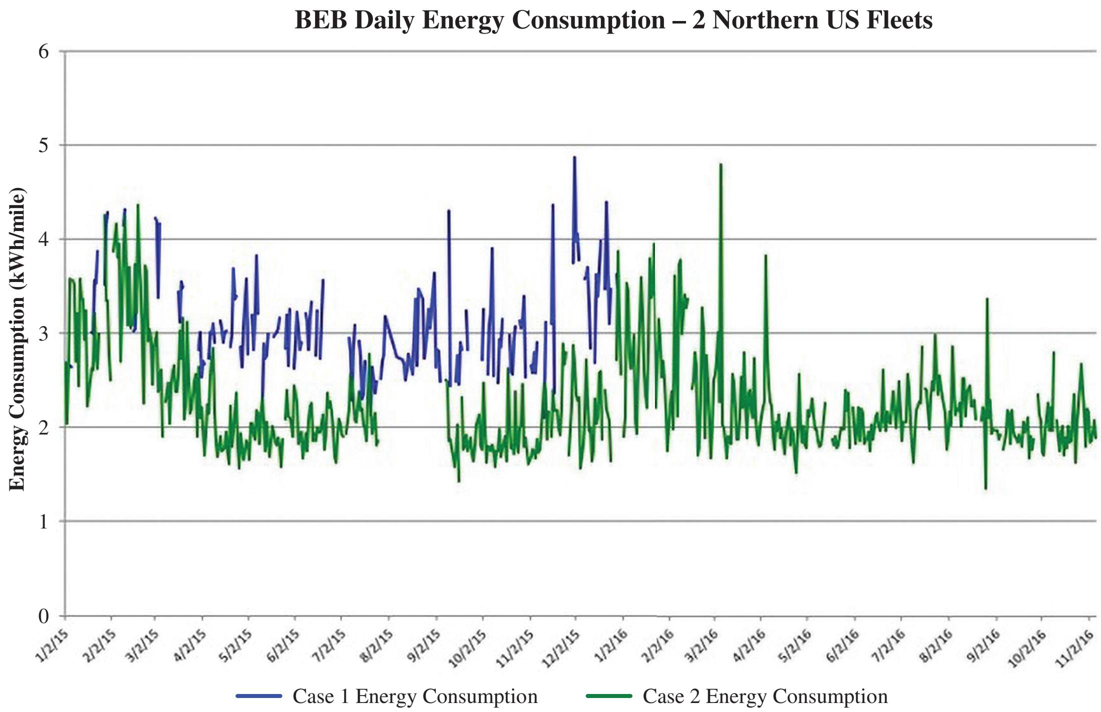


Figure 3. Empirical BEB efficiency data comparison. Source: Center for Transportation and the Environment.

accommodate additional layover time to allow for connection to the on-route charger. Figure 5 shows how Foothill Transit's extended layover time allows the batteries to operate between 30% and 80% state of charge (SOC).

Figure 5 also highlights how a single duty cycle variable can affect BEB operations. NREL's fleet evaluation of Foothill Transit's Route 291 revealed that the SOC of the battery decreased faster between 4:18 p.m. and 4:38 p.m. than between 4:38 p.m. and 4:58 p.m. due to the grade of

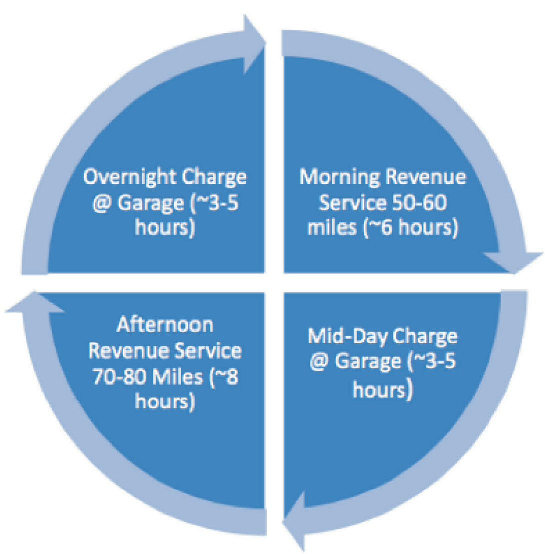


Figure 4. CTA's operational requirements. Source: Chicago Transit Authority.

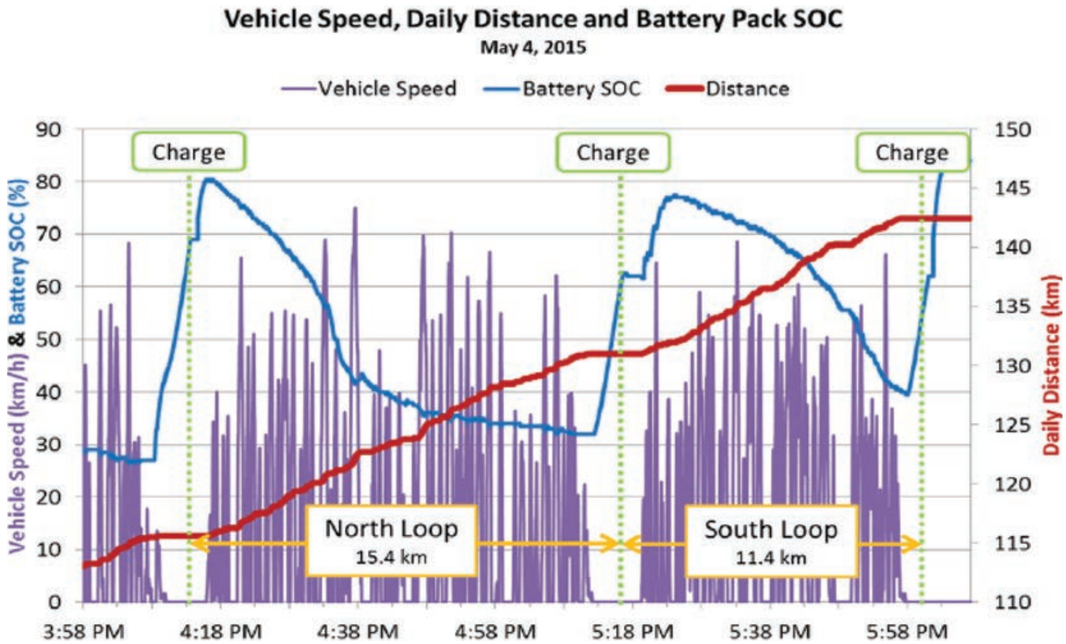


Figure 5. Foothill Transit's route characteristics. Source: Prohaska et al.

the route changes. The first part of the loop is uphill, and the second part is downhill as the bus returns to the charging station.

The Center for Transportation and the Environment (CTE) has developed an approach with tools for holistically accounting for multiple factors when selecting, procuring, and deploying BEBs. The approach is rooted in model development to understand the effects of the different variables on operations to life cycle costs. The first model in CTE's approach establishes the capabilities and performance of available bus models and charging systems in specific agency environments and duty cycles. Outputs include power capability and energy consumption. This model is augmented to show the effects of various charging options on range. The second model accounts for local electricity rates and evaluates the effect of various rate structure components. The third model accounts for the full costs of a BEB deployment by using results from the previous models and other up-to-date costs. This comprehensive tool enables agencies to make data-driven decisions, including purchasing (buses and charging infrastructure), deployment (route planning and charging system locations), and operations (bus blocking, layovers, and charging schemes). Figure 6 shows the approach that an agency can take when planning BEB deployments utilizing the tools developed by CTE.

Charging Infrastructure and Layover Location Characteristics

Transit agencies must also be able to support charging for BEB bus deployments, which can be achieved in a variety of ways. There are numerous infrastructure considerations when deploying BEBs. According to the Planning and Optimization of a Fast-Charging Infrastructure for Electric Urban Bus Systems 2014 report, three main factors are key to creating optimal distribution of the charging points: replenishment of energy consumption for the individual buses, local and institutional structural reservations, and intersections of the agency's other lines with the charger so as to optimize the agency's network. The optimal distribution of charging points is the end result from a number of prior considerations: the grid power, battery type, and battery SOC affect the schedule, which in turn affects the dwell (charging) time, which then affects the level

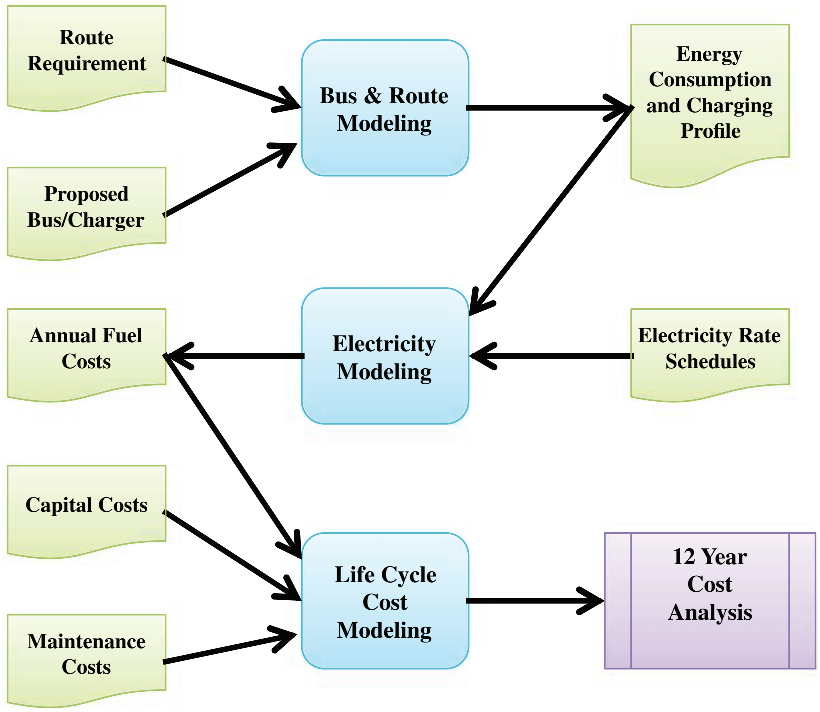


Figure 6. Steps an agency can take when analyzing routes. Source: Center for Transportation and the Environment.

of replenishment of the energy consumption. If the energy is adequately replenished, then the charging points are optimally distributed, assuming they comply with infrastructure standards and are placed such that other routes can potentially use them in the future (Kunith, 2014, page 44).

Another challenge that transit agencies have to address when planning for infrastructure is determining the optimum method of charging to support their particular service needs. Transit agencies have the option of purchasing BEBs that utilize plug-in charging, overhead (conductive) fast charging, or wireless (inductive) charging. Plug-in charging is almost always done at the depot or shop because of its slow rate of charge. Overhead fast charging and wireless charging are typically done on route but can also be installed at the depot. BEBs can be designed and deployed to work with one or a combination of these charging options.

Foothill Transit chose to utilize both overhead fast chargers as well as plug-in depot charging:

> At the end of each day, operators typically charge the BEBs at the Pomona Transit Center (PTC) prior to returning to the depot. A slow charger is used at the operations and maintenance facility for times when a bus needs additional charging. . . . Foothill Transit plans to eventually add a fast charger at this facility (Eudy et al., 2016, page 22).

With funding awarded through the second round of the TIGGER program, Foothill Transit replaced the old chargers with two on-route conductive fast chargers (Eaton 500 kW chargers) and purchased 12 more BEBs. The old chargers were replaced because the original manufacturer, AeroVironment, stopped supplying plug-in chargers to the bus market. The two chargers are co-located at the same station.

> Both chargers are housed in the same climate-controlled building with charge heads positioned on either side. The two chargers operate as separate units with a dedicated control system for each. A common communication network serves both units with sensors to detect which charge head a bus is approaching to enable proper bus-to-charger communication for docking. Emergency shut-off switches for each

charge head are located on either side of the building. The system is designed to fully charge a bus in under 10 minutes. For Line 291, the BEBs charge an average of 12.5 times a day for an average duration of around five minutes (Eudy et al., 2016, page 23).

A major consideration in planning for BEBs is selecting suitable locations for the chargers. Fast chargers "can only be connected to the grid where utilities can provide a dedicated supply line capable of delivering the very high currents demanded" (Air Resources Board, Oct. 2015, page III-5). Furthermore, fast chargers can only be deployed where an agency has access or rights to property to install the infrastructure. These restrictions can significantly limit options for locating on-route charging, particularly in dense urban environments.

Foothill Transit chose to locate the fast-charging station at PTC for a number of reasons (charger shown in Figure 7). At a mid-way point in the route (shown in Figure 8), PTC can accommodate fast charging infrastructure for two buses simultaneously and the transformer is within the vicinity. Perhaps most important, Foothill Transit already had rights to use the property through a 40-year lease with the City of Pomona. The city was supportive of the agency's efforts to deploy BEB. Finally, the PTC is a transfer point for eight local routes, allowing Foothill Transit the flexibility to expand or modify its BEB service without needing to move or add more charging infrastructure.

According to NREL's analysis of Foothill Transit,

Costs for the chargers and installation continue to drop. Installation costs will vary from site to site depending on a number of factors including the distance to a transformer. The total cost for the charging station being installed at the Azusa Intermodal Transit Center was $998,000. The installation includes two 500-kW fast chargers at $349,000 each. The cost to install the chargers was $300,000 (Eudy et al., 2016, page 24).

The Society of Automotive Engineers (SAE) International typically establishes the North American standards for electrical connectors for EVs. The standards cover the general physical, electrical, communication protocol, and performance requirements for EV charging systems and couplers. The intent is to define a common EV charging system architecture, including operational, functional, and dimensional requirements for the vehicle and connector interface. Plug-in charging for electric buses is generally based off methods and standards developed for the automotive industry. SAE J1772 chargers are typically used for high power DC charging and SAE J3068 (coming in early 2018) chargers for high power three-phase AC charging. This type of charging requires manual plugs and is typically provided or specified by the bus OEM for purchase and installation at the bus base or depot by a certified electrician.

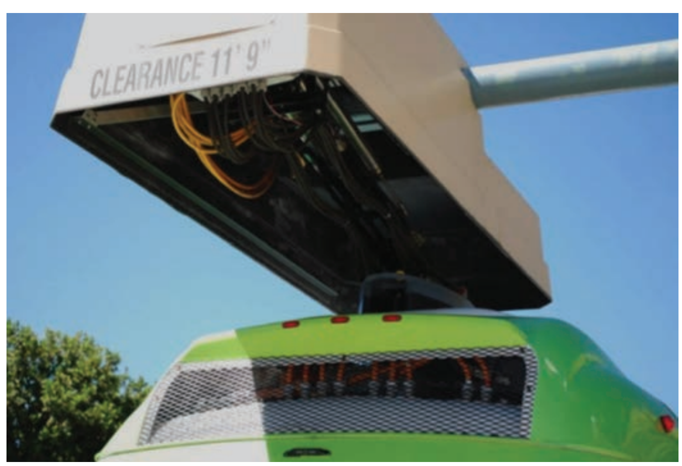


Figure 7. Foothill Transit's on-route conductive fast charger. Source: Eudy et al.

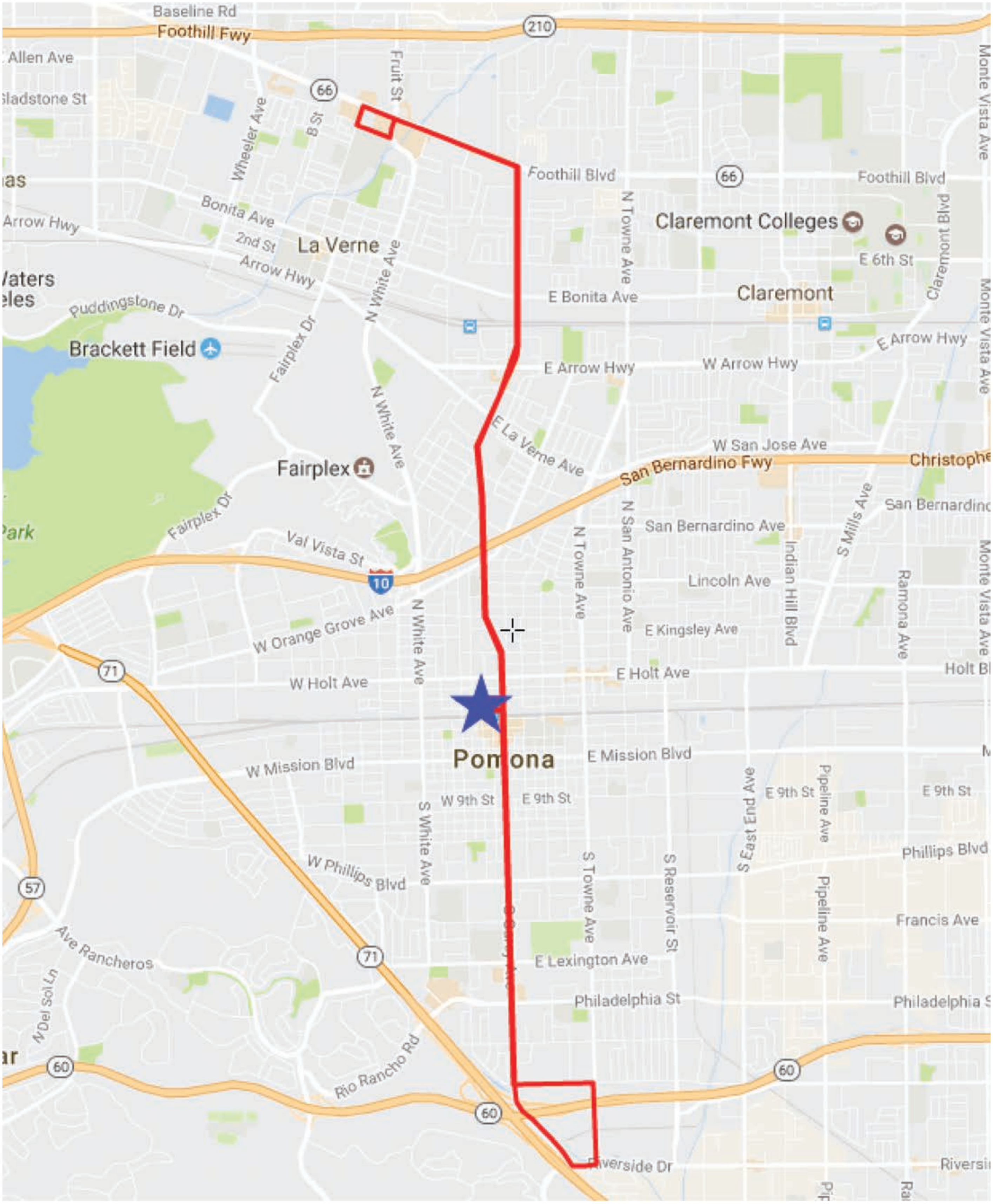


Figure 8. Foothill Transit's BEB route with the blue star showing where the charging station is located. Source: Foothill Transit.

Standards for overhead conductive and for wireless charging are currently under development. A committee has been established to develop the SAE J3105 standard for overhead conductive charging specifications for transit buses. In addition to ensuring safe, efficient, and effective operation of overhead charging systems, this standard will allow for interoperability of any charging system with any bus that follows the standard. A similar effort is being established for wireless charging systems under SAE J2954/2. Much like using appliances in our homes, establishing charge standards and interoperability for BEBs is an important step toward achieving widespread use of electric buses and full commercialization.

Foothill Transit's depot chargers were $50,000 each, which is consistent with CARB's analysis of average depot charger cost. When assessing the total cost of charging infrastructure, CARB suggests incorporating the following costs for the analysis: the actual charging station hardware; other hardware and materials associated with construction; labor costs; construction time including an initial on-site consultation; and municipal permitting costs (Air Resources Board October 2015).

Where, when, and how an agency charges its fleet of BEBs will affect the amount of power consumed that is captured at various utility meters. The usage affects the demand charges and time of use charges from the utility and can significantly affect the cost of electricity consumed. Understanding the electricity rates and utility rate structures is key to optimizing a fleet charging scheme. Undertaking this exercise at that outset of a project or fleet conversion can significantly lower overall energy costs and total cost of ownership for BEBs (Air Resources Board October 2015).

Electricity Rate Structure

Utility costs, or electricity rates, contribute to overall BEB operating costs, as addressed later in this literature review. Electricity rates are designed by utilities to be based on the cost of service. These costs are often made up of multiple components including usage, or "energy" charges (cost per kWh) and power or "demand" charges (cost per kW). Energy charges are based on how much electricity a customer uses and demand charges are based on the maximum amount of power a customer draws at once (typically over a 15-minute period).

The impact of demand charges is explained by the Union of Concerned Scientist's BEB analysis:

> Electricity rates often include an additional "demand charge" related to the maximum power consumed during a 15-minute interval for the month. This means that spikes in electricity demand can add significantly to the cost of vehicle charging and erode the savings of electricity compared to other fuels.
>
> The impact of demand charges can be most acute when fleets have a small number of electric vehicles and charging causes large, relative spikes in electricity demand. With a larger number of vehicles, fleet owners can space out charging over a period of time, minimizing the spikes (Chandler et al., 2016, page 27).

As also shown in CALSTART's Peak Demand Charges and Electric Buses white paper, demand charges can have a significant impact on total energy costs. The white paper also analyzes and illustrates the beneficial effects of using a single charger to charge more than one bus (Gallo et al. 2014). Figure 9 provides a relative comparison of the impact of demand charges (shown in light green) versus the energy costs (in dark green) versus costs for diesel and CNG. The graphs show how demand charges can be reduced on a cost-per-mile basis as more buses utilize the same charger, while other costs stay consistent. The graphs also show the significant impact that demand charges can have on the operational costs for the buses. In the example for demand charges of $20/kW, they are 3.6 times the energy costs on a per-mile-basis when using a single bus per charger.

More on Demand Charges [Excerpt from Air Resources Board, *Electricity Costs for Battery Electric Bus Operation*, n.d.]

Making an analogy to plumbing, it is comparable to how many gallons of water a person draws at any given moment. In a plumbing example, a user could choose to turn the faucet on low and fill a five gallon bucket over ten minutes (a low demand), or choose to turn the faucet on high and fill the five gallon bucket in one minute. In both cases, the person drew five gallons of water, but in the latter case, the rate of flow was much higher.

If the user above wants to fill the bucket in one minute rather than ten minutes, the water utility may need to widen the pipes to the faucet, maintain a higher reserve, and have bigger pumps to deliver the water at the higher rate. Therefore, the water utility may charge the user more to recover the costs of infrastructure and/or reserve needed to deliver the water faster. In both cases the person still has to pay the same amount for the total volume of water used. The total bill for drawing the water faster is higher even though the same amount (five gallons) of water is drawn.

This analogy applies to electricity use. A demand charge, simply, is a fee paid based on the rate (think: gallons per minute) at which the customer draws electricity. In the case of electricity, the "gallons per minute" is measured in kilowatts (kW). Kilowatts are useful to think of as kWh/h, where kilowatt-hours (kWh) are equivalent in this analogy to gallons—they're the total volume of electricity delivered—and kWh/h is how many kWh are delivered in a given amount of time. It is useful to think of demand charges as fees assessed for being able to draw a lot of energy in a short amount of time.

It is important to note that this analysis used a specific set of assumptions, including diesel fuel costs ($4/gal), fuel economy (4 miles per gallon), CNG fuel costs, CNG fuel economy, maximum charge power (500 kW), electric bus efficiency (2.5 kWh/mile), energy cost ($0.10/kWh), and demand charges ($10/kW, $20/kW), among other variables. Each of these variables can change considerably over time and, depending on location, by a factor of two or more. For example, as of the writing of this synthesis report, many agencies are paying less than $2 per gallon for diesel fuel, which would bring the cost of diesel down to less than $0.50 per gallon in Figure 9. Thus transit agencies should perform similar detailed analyses for their individual conditions when making purchasing and planning decisions.

When comparing diesel, CNG, and electricity costs, it should be noted that over time, electricity costs are far more stable than conventional fuels. Figure 10 shows a general 3.5% trend for California electricity costs, while CNG and gasoline can spike or fall 200% to 300% in periods of 2 to 3 years. Electricity costs can be further complicated based on the time of day that the charging occurs (time of use) and/or the season, because increasing power production capability has a direct impact on utilities costs, as shown in Table 5. In the example, on-peak, mid-peak, and off-peak each corresponds to a time period throughout the day. Utility costs can fluctuate significantly depending on when the charging is occurring within 15-minute periods throughout the day. Accounting for these variables and properly planning a charging scheme can significantly reduce energy costs for a BEB fleet.

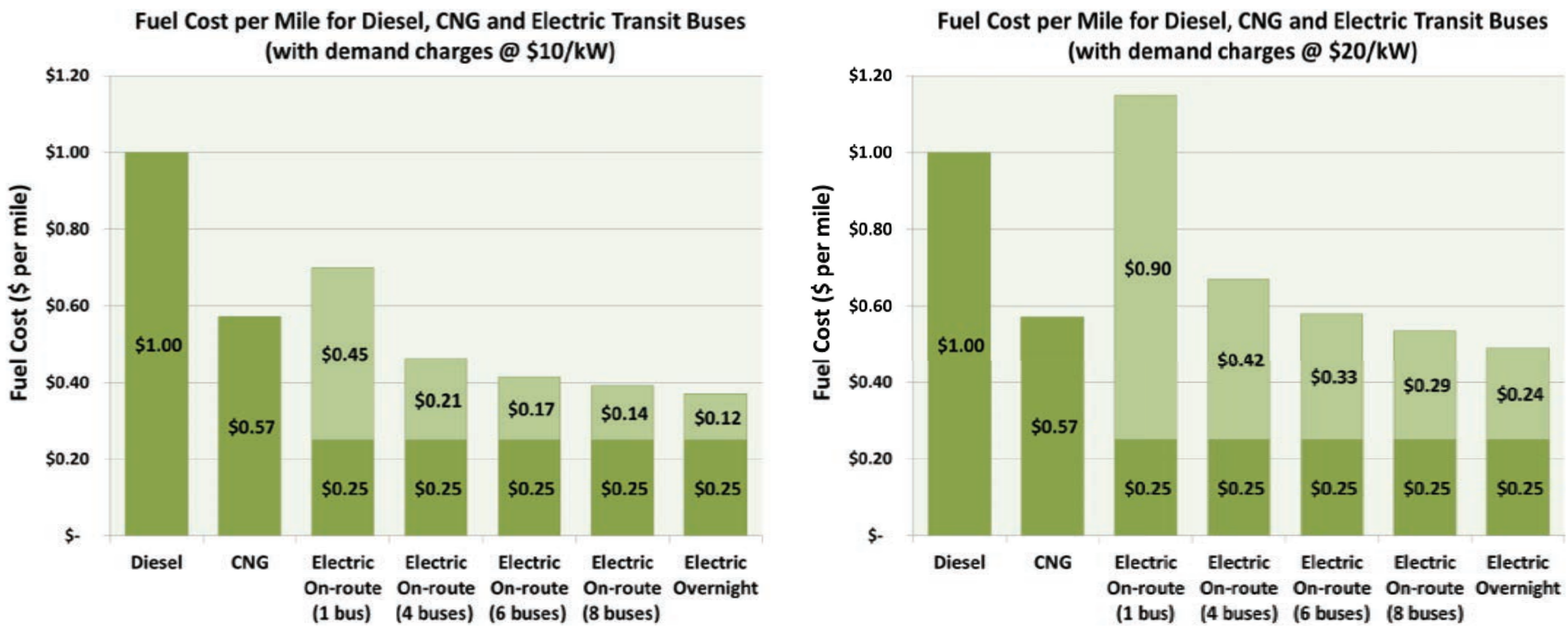


Figure 9. A comparison of fuel and electricity costs and the impacts of demand charges. Source: Gallo et al.

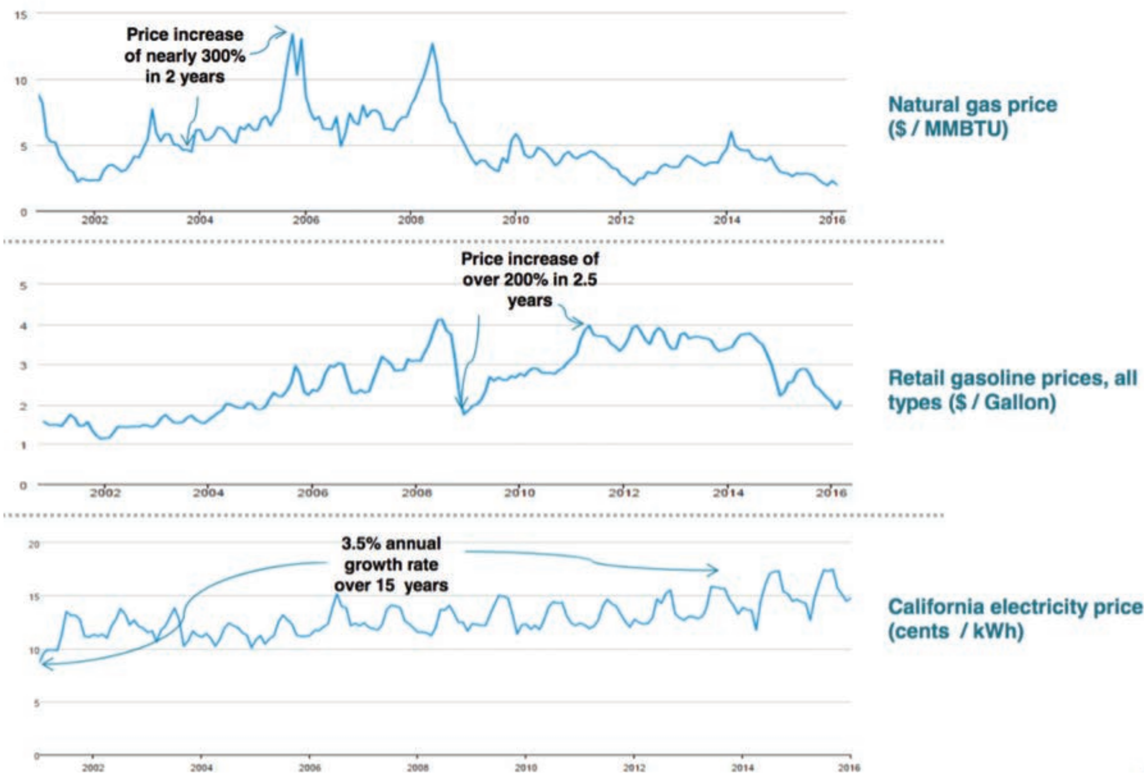


Figure 10. A comparison of the stability of fuel and electricity costs. MMBTU = millions of British thermal units. Source: U.S. Energy Information Agency.

Electricity rate structures can be complicated and decisions related to bus type, fleet size, charger type, charging scheme, charge locations, route selection, and route planning can all have an effect on electricity costs. Electricity rates structures and costs should be evaluated early in the project in order to minimize these costs.

Planning and Support Tools

CTE and BEB OEMs are using tools and methods to predict bus range in a variety of conditions and a variety of charging options. CTE uses Argonne System Modeling and Control Group's Autonomie, a tool that can perform powertrain modeling and simulation but that must be adapted to a given situation. By supplying different duty cycles, powertrain configurations, and bus components, Autonomie can run a simulated operation of a bus on route to determine how the bus will perform in the given situation. CTE is combining results from Autonomie with outputs from utility rate modeling tools to help agencies make data-driven procurement and operational decisions. Some bus OEMs are using internally developed models designed specifically for their buses to predict operational capabilities. No other planning tools or automated applications were identified to support transit agencies efforts to plan for the deployment of BEBs.

Studies specific to an individual agency's experience are available, such as the Planning and Optimization of a Fast-Charging Infrastructure for Electric Urban Bus Systems 2014 report or the Electric Bus Analysis for New York City Transit 2016 report. Such studies provide insight into topics such as electricity rate modeling or a life cycle cost analysis for a particular agency's situation, but they lack methodologies that are applicable to the transit industry as a whole.

Table 5. Example of utility rate structures.

Rate Structure	**A**	**B**	**C**	**D**	**E**	**F**
Allowable Max Demand Range	below 20 kW	20 kW-200 kW	200 kW-500 kW	200 kW-500 kW	above 500 kW	20 kW-500 kW
Fixed Charges						
Customer Charge [$/Meter/Month]	$25.92	$198.79	$441.93	$441.93	$319.93	$198.79
Three Phase Service [$/Month]	$18.60	$-	$-	$-	$-	$-
Demand Charges						
Facility Demand Charge [$/kW]	$-	$13.20	$16.37	$16.37	$14.88	$13.20
Time-of-Use Demand Charge [$/kW]						
Summer On-Peak	$-	$-	$-	$18.86	$24.15	$-
Summer Mid-Peak	$-	$-	$-	$5.53	$6.66	$-
Summer Off-Peak	$-	$-	$-	$-	$-	$-
Winter On-Peak	$-	$-	$-	$-	$-	$-
Winter Mid-Peak	$-	$-	$-	$-	$-	$-
Winter Off-Peak	$-	$-	$-	$-	$-	$-
Energy Charges [$/kWh]						
Summer On-Peak	$0.24	$0.36	$0.36	$0.14	$0.14	$0.29
Summer Mid-Peak	$0.19	$0.15	$0.14	$0.09	$0.08	$0.12
Summer Off-Peak	$0.16	$0.07	$0.06	$0.06	$0.06	$0.05
Winter On-Peak	Not applicable	N/a	N/a	N/a	N/a	$0.11
Winter Mid-Peak	$0.16	$0.09	$0.09	$0.09	$0.09	$0.09
Winter Off-Peak	$0.15	$0.07	$0.07	$0.07	$0.07	$0.06

Source: Center for Transportation and the Environment.

Scalability

While there are approximately 600 BEBs on order or in service, most transit agencies deploying BEBs have a BEB fleet size of less than 10 buses, as shown in Figure 11. There are only four transit agencies currently operating more than 10 BEBs in service and the largest fleet is 21 buses. Recent orders show that larger deployments are planned, but transit agencies are struggling with how to deploy and manage the practical aspects of a larger fleet of BEBs. As the BEB fleet grows, transit agencies will likely need to incorporate different BEB deployment approaches to ensure the buses meet the needs of varying routes.

One challenge is how to address deploying infrastructure at scale. Transit agencies will need to consider issues related to land use, space constraints, grid demand impacts, fleet staging for charging, networking on-route charging, labor requirements for making manual connections and maintaining charging equipment, and maintaining operability during power outages. Transit agencies must also account for utility costs associated with scalability and recognize that utility rate schedules (including energy and demand charges) can vary significantly both within a city as well as nationally and can significantly affect the business case for owning BEBs. A comparison of peak loads alone for different fleets is displayed in Figure 12, which shows that 60 kW of charging a fleet of 50 BEBs simultaneously can lead to peak loads of 3.0 megawatts, which could be infeasible for some agencies given demand charges and utility infrastructure requirements.

There is a need for coordinated and well-documented practices and tools that will support transit agencies' efforts to deploy BEBs. Coordinated and well-documented practices and tools can also help ensure that transit agencies realize all the benefits of the technology as well as understand the risks and challenges associated with BEB fleet scale up.

Service, Maintenance, and Operations Considerations

Training

When deploying a new technology, transit agencies need to ensure they have the necessary resources to train staff on the new technology. In the case of BEBs, drivers and maintenance

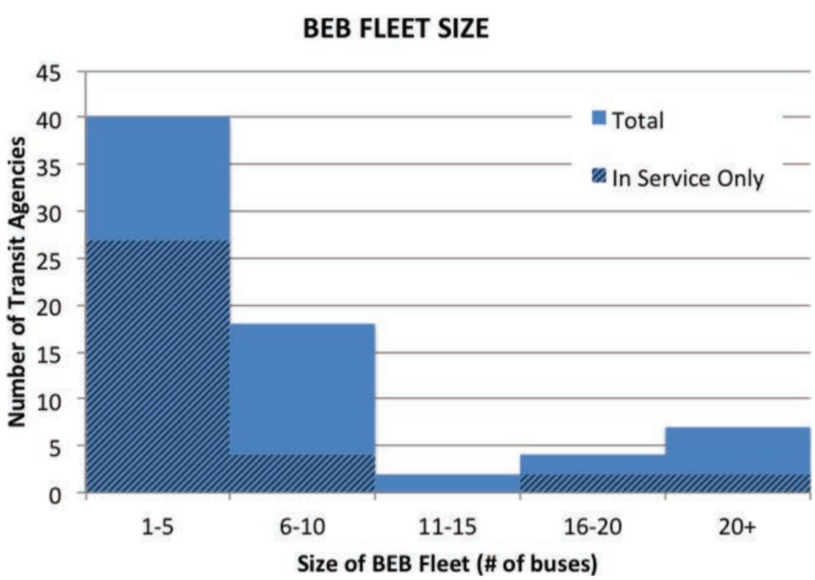


Figure 11. BEB fleet size. Source: Center for Transportation and the Environment.

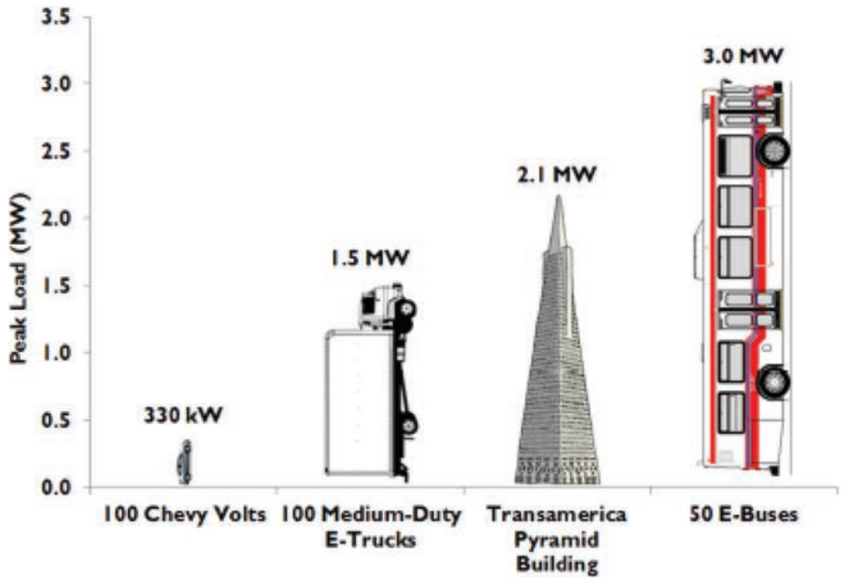


Figure 12. An example of utility rate structures. Source: CALSTART.

staff need to know how to effectively and efficiently operate and maintain the vehicles. An example of this is highlighted in the NREL report. Foothill Transit encountered low-voltage starter battery issues and had to replace them not because of a technology issue but as a result of a driver training issue (Eudy et al., 2016, page 37). The operators were not turning off the buses at the end of a shift, most likely because they could not hear it running as they could with conventional buses.

Compared with diesel or CNG buses, fueling—or charging—is different for BEBs. The case of Foothill Transit's docking (or positioning the bus correctly for the on-route fast charger to connect) is operationally unique because the driver applies the accelerator instead of the brake to begin the automated process. This has required Foothill Transit to implement extensive and ongoing training in order to educate its drivers.

Maintenance training for BEBs differs from conventional buses in that technicians must understand how to work on all-electric propulsion systems and auxiliary systems as well as be concerned with the safe handling of high voltage systems. The 2005 FTA report on electric drive technologies for transit applications is out-of-date in some aspects, but the section on training remains applicable:

> There is a need for mechanic training in how to service and troubleshoot electric propulsion components, and understanding how to work with the on-board diagnostics systems. While transit agencies that operate rail systems are familiar with the requirements of operating and maintaining high voltage electrical propulsion systems, there is often no overlap between the maintenance staff for rail and for buses (*Analysis of Electric Drive Technologies for Transit Applications* 2005).

Limited maintenance training experience or guidance was found in this review of the literature. This topic will be further explored in the Survey and Case Example sections of this synthesis report.

Operations

The NREL report provides operations and maintenance data on the Foothill Transit BEBs from April 2014 to July 2015. The report also compares these data to a baseline fleet of CNG buses. The average monthly operating mileage for the BEBs during the evaluation period is

2,333 miles, which is consistent with the requirements of the route on which they operated (Line 291). "The average runtime per day is 13.2 hours with an average of 13 charges per day. Each charge averages 20 kWh of energy delivered" (Eudy et al., 2016, page 35).

Availability (defined as the number of days that the buses are actually available compared with the number of days the buses are planned for operation) for the BEB fleet was 93% during the period (excluding one outlier that was out for extended periods) compared with 94% for baseline CNG buses. "The majority of the issues were for general bus problems—repair of accident damage and the air conditioning system—and not due to any advanced technology component" (Eudy et al., 2016, page 27).

Through 399,663 miles of use, "the BEBs had an overall average efficiency of 2.15 kWh per mile, which equates to 17.48 miles per diesel gallon equivalent (DGE). The CNG buses had an average fuel economy of 4.04 miles per gasoline gallon equivalent (GGE), which equates to 4.51 miles per DGE" (Eudy et al., page 19). It should be noted that accessory loads for the CNG buses contribute to lower fuel economy and lower range capability, as more than 50% of "system on" time is spent at a speed of zero miles per hour where lighting and HVAC loads are still required. Ultimately, the BEB fuel economy was almost four times higher than that of CNG buses. Despite this improvement, NREL reported that the battery electric bus fuel cost was $0.39 per mile compared with the $0.23 per mile for the CNG buses during the evaluation period. The utility rate was reported to be $0.18 per kWh during this period. The report goes on to say that "Foothill Transit is working with [their utility] on a new agreement to set a reasonable rate charge. This will be a major challenge for any fleet looking to deploy electric buses that charge during peak times. The industry needs to work on a permanent solution for all BEB adopters to keep costs reasonable in the future" (Eudy et al., 2016, page 36).

Resiliency and Emergencies

In 2013, FTA released the Innovative Safety, Resiliency, and All-Hazards Emergency Response and Recovery Demonstrations program. In one of the selected projects, the Center for Transportation and the Environment partnered with the University of Texas Center for Electromechanics and Hagerty Consulting to develop a Bus Exportable Power Supply (BEPS) system that will give electric and hybrid-electric buses the capability to act as on-demand, mobile, electrical-power generators. This technology will be especially useful in emergency disaster response and recovery when traditional power supplies are not reliable. Emergency response involves a variety of organizations with different core objectives in addition to the general public. In order to capture the knowledge of emergency response professionals, a team of cross-industry experts has been organized to investigate technologies, methods, practices, and techniques for utilizing the BEPS system. The project team is responsible for system design, demonstration, and a documented recommended methodology for implementation in real-world applications (Center for Transportation and the Environment, University of Texas at Austin 2017).

Equipment Longevity and Risk Mitigation

As shown in Figure 2, current growth of the electric bus market did not begin in earnest until 2010. Buses and equipment have not yet realized sufficient operation in the field to allow for full assessment of equipment longevity.

Component replacement data for a new technology are generally limited in the early stages of deployment, whether because there is only one manufacturer or because the products evolve quickly in their early stages, resulting in design changes. Foothill Transit encountered the latter situation with its first charging infrastructure that became no longer available after the manufacturer ceased production. Eventually they were unable to find replacement parts and determined to replace the chargers all together (Eudy et al., 2016, page 11).

One component of concern is the traction battery due to its cost and relatively unknown life in a transit bus application. To alleviate this concern for transit agencies, most BEB manufacturers are offering a standard 6-year warranty for the batteries to get operators through the midway point of bus life and offering extended warranties up to 12 years to mitigate further risk (Proterra 2017). One BEB manufacturer has "no doubt they will outlast the life of the bus" and is providing a 12-year unconditional warranty for the batteries (BYD Motors, Inc. 2015). Alternatively, manufacturers are also offering battery lease programs to help mitigate potential risk.

Technology for Managing, Charging, and Dispatching

In 2017, the California Energy Commission awarded nearly $2 million to Prospect Silicon Valley and an innovative Silicon Valley collaborative including the Santa Clara Valley Transportation Authority (VTA) to research, develop, and demonstrate an advanced energy management and grid services system for electric transit bus fleets. The system is intended to reduce costs for charging electric buses, minimize the impact of bus charging on the grid, and provide valuable services that assist the integration of intermittent renewables like solar and wind. The project will integrate systems to reduce charging costs by managing demand, demand response, and wholesale ancillary services such as frequency regulation. These features will be integrated with commercial fleet management tools for what is expected to be the first fully integrated energy management in a heavy-duty fleet. VTA has acquired innovative smart networked charging stations and will provide engineering services, fleet management requirements, in field testing, and collection of charging/energy usage data from the fleet. Working with its Clever Devices, VTA dispatch software provider, VTA will be updating the dispatch software to improve EV fleet management and coordinating with utility (Pacific Gas and Electric) on rate usage and interaction with the VTA one megawatt solar installation (Valley Transportation Authority 2017).

Stakeholder Involvement

At the end of NREL's Foothill Transit report, the agency lists the lessons learned from the experience, and the first bullet is regarding stakeholder involvement. Foothill Transit advises planning ahead to identify stakeholders that need to be engaged at specific points in the planning process. Stakeholder engagement is addressed in more detail later in the synthesis report.

Costs and Benefits

External Funding Opportunities

The availability of external funding sources can drive the adoption of new technology. Transit agencies benefit from federal, state, and local financial support to help offset the higher incremental capital costs associated with advanced technologies such as BEBs.

Funding to support deployment has been vital to the growth of the BEB market. Federal funding through FTA for the purchase of buses typically covers 80% of the purchase costs to help offset the higher capital costs of BEBs and associated infrastructure; transit agencies have taken advantage of other federal and state funding opportunities. Foothill Transit utilized a 2009 American Recovery and Reinvestment Act grant to purchase its first three BEB that were deployed in 2011. It purchased the next 12 buses through a TIGGER II grant for $10.2 million (*Foothill Transit Business Plan and Budget* 2015). Foothill Transit also used California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project funds to further reduce the purchase cost of the bus.

Other transit agencies in California are using state funds to support their purchase of BEBs. Antelope Valley Transit Authority (AVTA), close to Foothill Transit, recently unanimously voted to fully convert its entire bus fleet to BEBs by the end of fiscal year 2018. The agency is supporting the deployment through multisource funding, including a $24.4 million grant from the California State Transportation Agency (CalSTA) and additional federal funds (AVTA 2017).

FTA's Low or No Emission Vehicle Program (Low-No) supports adoption of technologically advanced vehicles to help the transit industry become cleaner and more energy efficient. FTA's 2016 Low or No Emission Vehicle Program provided $55 million for supporting transit agencies' transitions to "the lowest polluting and most energy efficient transit vehicles" ("Low or No Emission Program," 2016). The Low-No program is included in the current transportation bill, FAST Act, and there are provisions for annual funding opportunities through FY2020. More than 30 agencies have purchased buses with Low-No funding. The Low-No program encourages transit agencies to use the funding to cover the incremental costs associated with the technologically advanced vehicles and allows for a higher federal share—85% for buses and 90% for infrastructure.

FTA's Clean Fuels Grant Program has also supported BEB deployments, including Central Contra Costa Transit Authority, Denver's Regional Transportation District, Nashville Metropolitan Transit Authority, Transit Authority of River City, and Worcester Regional Transit Authority, among others.

In addition to discretionary funding opportunities, regulations also drive the adoption of new technology. Foothill Transit incorporated BEBs into its fleet in response to CARB's "Fleet Rule for Transit Agencies." The 2000 rule required that urban buses meet stricter California exhaust emission standards and that 85% of a transit agency's annual urban bus purchases be alternatively fueled (*Fact Sheet: Fleet Rule for Transit Agencies Urban Bus Requirements*). Furthermore, agencies with more than 200 buses must include zero-emission buses as 15% of new bus purchases. Foothill Transit deployed its initial fleet of BEBs with the "goal of evaluating the technology to determine if it could meet service requirements" implemented through the rule (Eudy et al., page 7). The regulation is one of the primary drivers for demonstration and deployment of advanced technology buses in the state of California. CARB has also proposed the Advanced Clean Transit Fleet Rule (California Air Resources Board 2017). Recognizing the role public transit will play in reducing emissions from the mobile sector, the rule would require transit agencies to transition their entire fleet to zero emission vehicles by 2040.

Transit agencies nationwide have responded to more stringent national and state air quality regulations by deploying alternative fuel vehicles in their fleets. Areas classified as nonattainment by the U.S. Environmental Protection Agency for exceeding the National Ambient Air Quality Standards often benefit from the deployment of cleaner transit technologies ("FAQ's about Attainment and Nonattainment" 2008). The U.S. Department of Transportation asserts that implementing one BEB will eliminate "10 tons of nitrogen oxides and 350 pounds of diesel particulate matter [over its lifespan], improving air quality in the communities that they serve." More and more areas classified as nonattainment are looking to their local transit agencies to help meet their attainment goals ("Zero Emissions Bus Benefits" 2016).

Public Opinion

While there are plenty of anecdotal statements and observations that the public enjoys riding on BEBs due to the clean, smooth, quiet operation of the buses, actual rider surveys were difficult to find.

One quantitative measure of ride quality is noise, and documentation of the reduced noise associated with BEBs is available through Altoona Test results. Data are available for New Flyer's 40′ bus platform using four different propulsion technologies. Figure 13 shows the recorded

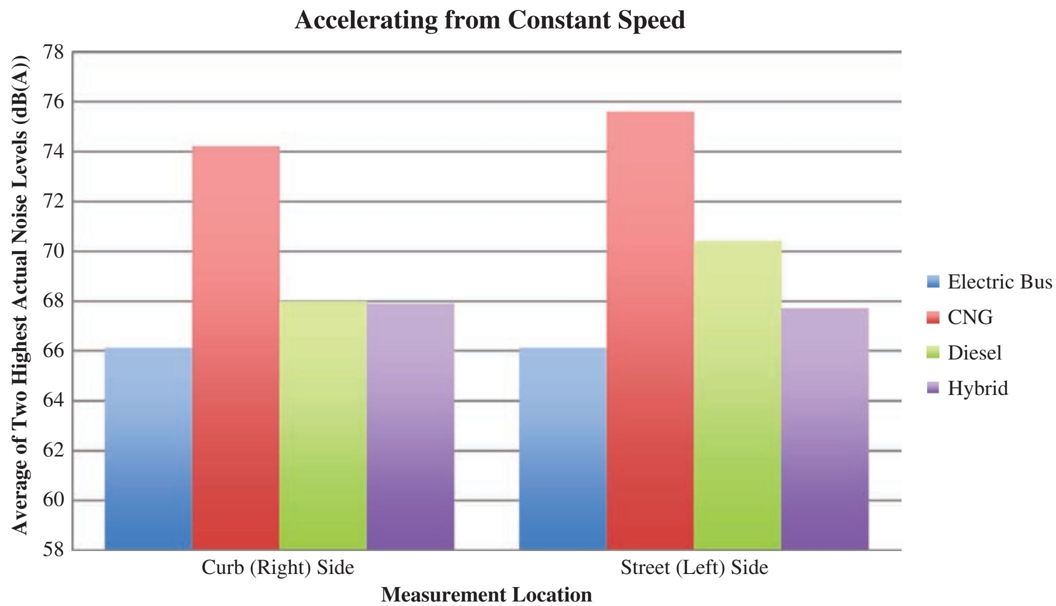


Figure 13. Exterior noise data comparison. Source: The Altoona Bus Research and Testing Center.

exterior noise levels for each bus model when accelerated from standstill at full throttle. The CNG bus produced the highest noise levels and the electric bus produced the lowest noise levels consistently on both sides of the vehicle. For reference, 80 dB is typically the level of an airplane at one mile while 60 dB is typically the level of conversational speech.

Noise levels were also measured in the interior during acceleration from 0 to 35 mph. Figure 14 displays the recorded noise levels for each vehicle at each measurement location. The

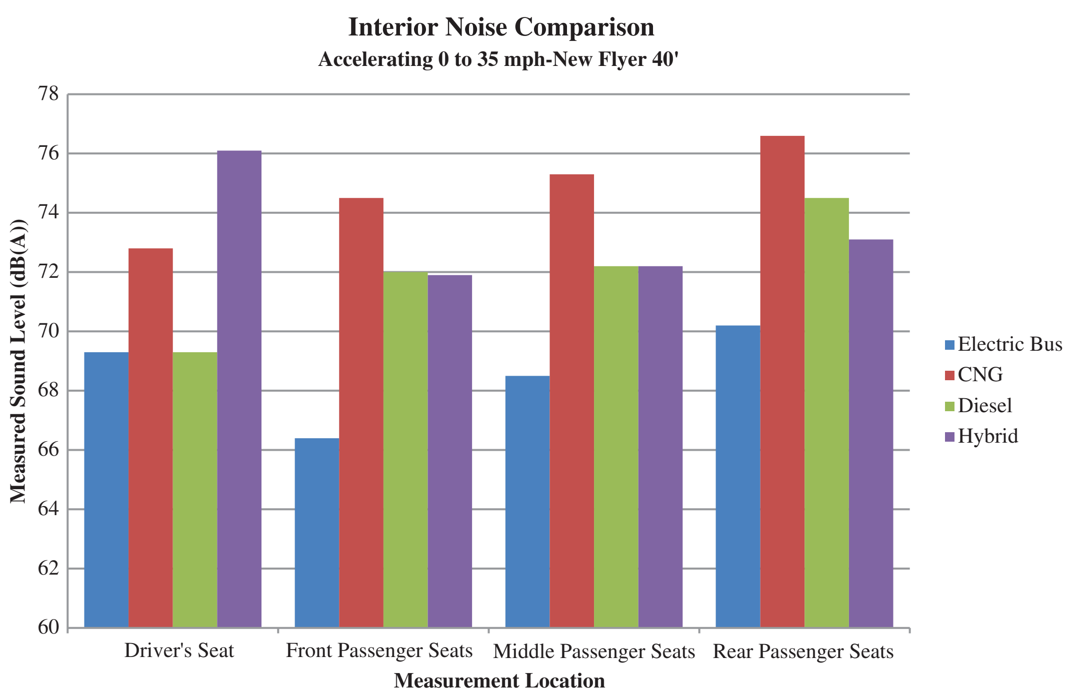


Figure 14. Interior noise data comparison. Source: The Altoona Bus Research and Testing Center.

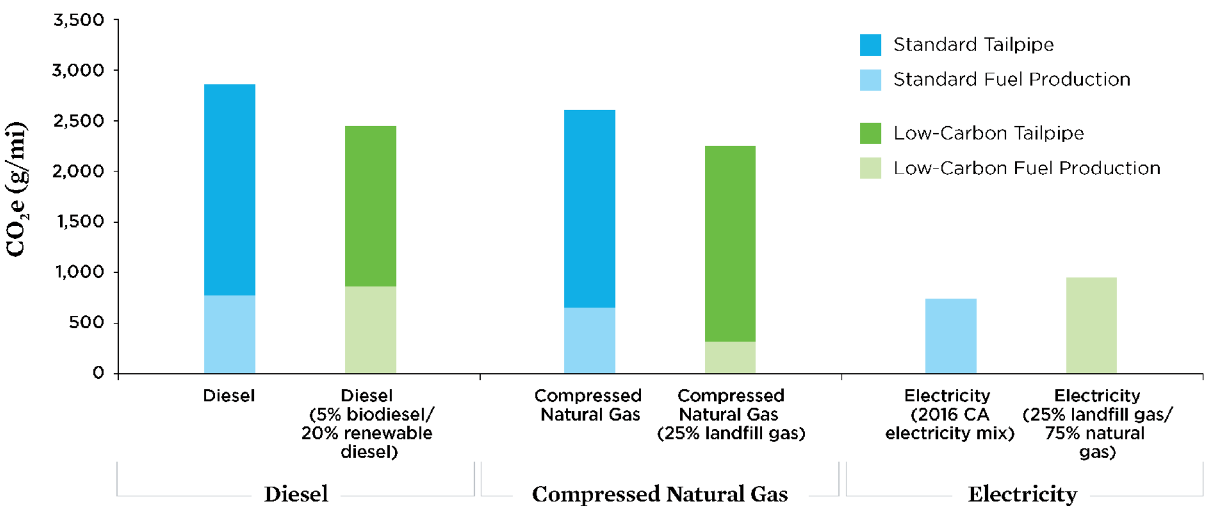
BEB and diesel bus had the same measured sound level for the driver's seat location, but for all other measures BEBs were noticeably more quiet than CNG, diesel, and hybrid models.

Environmental and Health Benefits

Heavy-duty buses and trucks are major contributors of pollutants. In California, 7% of all global warming emissions are from heavy-duty vehicles and that is predicted to rise over the next 30 years. In 2012, heavy-duty vehicles emitted more anthropogenic particulate matter (2.5 micrometers and smaller) than all of California's power plants combined (23 tons per day versus 7 tons per day, respectively). Trucks and buses also contributed to more than 30% of the nitrogen oxides emitted across the state (Chandler et al. 2016).

BEBs have no tailpipe emissions. Their "well-to-wheel" emissions depend solely on how the electricity is produced. Using 100% renewable energy to generate the electricity would eliminate emissions entirely from transit bus operations. In a 2016 report, the Union of Concerned Scientists and Life Cycle Associates adapted models from Argonne National Laboratory and California Air Resources Board to analyze transit bus emissions on a life cycle analysis basis (Figures 15 and 16). Life cycle global warming emissions are almost 75% less than CNG and diesel buses. BEB life cycle NO_x emissions are significantly lower than diesel (approximately 80% lower) and CNG buses, including those using the new Near Zero NO_x CNG engines (less than 0.02 NO_x/brake horsepower-hour). Life cycle particulate matter emissions can be reduced by over 20% (CA electricity mix) when replacing diesel buses with BEBs. When using an energy mix of 50% renewables/50% natural gas, particulate matter emissions are reduced relative to both diesel and CNG buses. As electricity energy production technology continues to develop nationwide, the energy grid will become cleaner and the particulate matter emissions levels will continue to decrease.

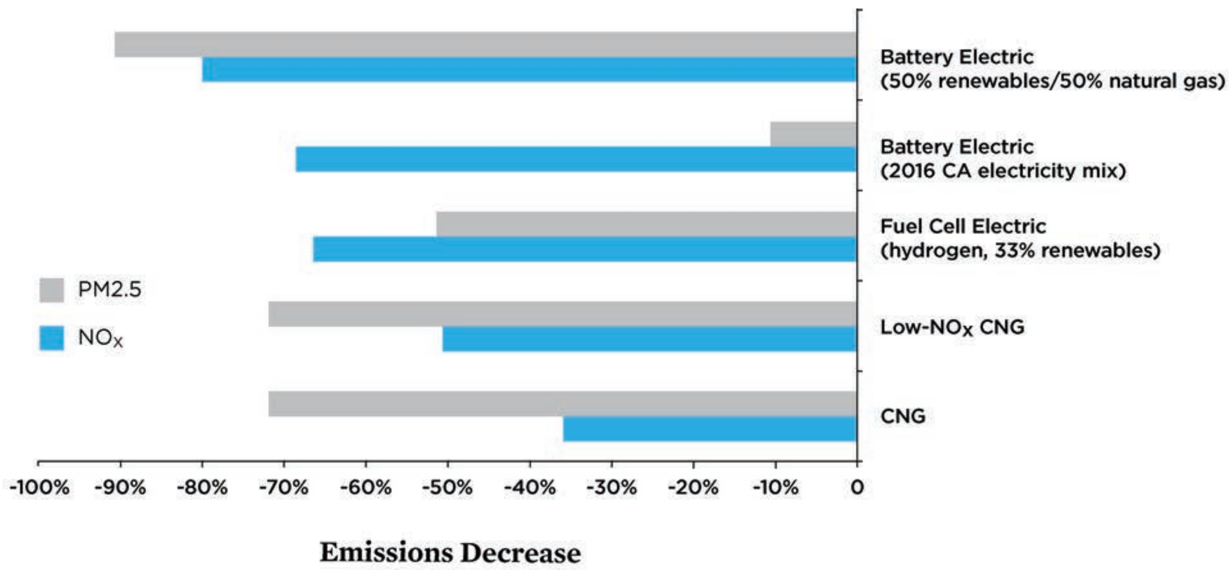
Additionally, meeting emissions requirements for diesel buses requires sophisticated and sensitive add-on emissions control equipment. Maintaining these emissions control systems can be cumbersome and expensive for transit agencies, while utilizing battery electric



Global warming emissions from transit buses powered by low-carbon fuel blends are lower than those from vehicles powered by conventional fossil fuel–based diesel and natural gas.

Note: CO_2e stands for carbon dioxide equivalent.

Figure 15. Buses powered by low-carbon fuel blends produce fewer global warming emissions. Source: Chandler et al.



Life cycle emissions of particulate matter (PM) and nitrogen oxides (NO_x) for battery electric, fuel cell electric, and compressed natural gas transit buses are low relative to a diesel bus.

Notes: PM2.5 emissions refer to particles with diameters 2.5 micrometers and smaller. Comparison based on emissions from 40-foot transit buses.

Figure 16. Emissions decrease. Source: Chandler et al.

technology inherently provides an emissions reduction strategy that does not rely on additional vehicle systems.

Improvements to power generation are helping reduce the life cycle emissions associated with BEBs. Air pollution control equipment and changes in electricity sources have reduced acid-rain-causing SO_2 emissions by 73% from 2006 to 2015 and continue to lower emissions (DeVilbiss and Ray 2017). BEBs allow the United States to extend emissions benefits gained in energy production to the transportation sector.

Tools are available to assess life cycle environmental effects attributed to transportation. Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model was sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy and "allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis" (GREET Model 2017).

An analysis of deployment of electric buses in New York City documented potential social cost savings. The analysis utilized the U.S. Environmental Protection Agency's Diesel Emissions Quantifier tool to assess the health benefits of implementing BEBs. The tool "considers the cost of hospitalization, cost of emergency room visits, and the cost of absence from work." The analysis concluded that if New York City Transit switches to a fully electric fleet, the "total health care savings is roughly $100 per NYC resident per year." The analysis also concludes that the "social cost of carbon" savings over the lifetime of a BEB is "a little over $36,000" (Aber, 2016, page 18).

Capital and Operational Costs

A common hesitation with investing in any new technology is the upfront costs and the unknowns associated with ongoing operating expenses. According to NREL's Foothill Transit analysis:

> The capital costs for BEBs are currently higher than that of conventional technology, although the costs have dropped considerably over the last few years as orders for the buses have increased. The increase in orders allows the manufacturers to take advantage of economies of scale to reduce the productions costs (Eudy et al., 2016, page 18).

From 2009 to 2015, Foothill Transit's per bus purchase cost dropped from $1.2 million to $789,000. For comparison, a CNG bus cost $575,000 in 2015 according to the NREL report (Eudy et al., 2016, page 8).

Differences in operational costs for BEBs are primarily driven by fuel efficiency, electricity costs, component replacement costs, and maintenance labor reductions. Foothill Transit's analysis supports claims that BEBs generally have lower maintenance costs. When calculating the maintenance cost per mile, Foothill Transit included the price of parts and labor rates at $50 an hour. Foothill Transit determined that the total BEB cost per mile was $0.08 and $0.09 for scheduled maintenance and unscheduled maintenance, respectively. The scheduled maintenance cost of CNG was higher at $0.14 per mile for scheduled and lower at $0.04 per mile for unscheduled. Cumulatively, the BEB maintenance cost per mile was 11% lower than CNG buses. Maintenance costs for both bus fleets were low due to the fact that they were still under warranty during the period.

Challenges and Lessons Learned

Challenges from the Foothill Transit BEB deployment included BEB operations and maintenance training, the learning curve that comes along with a new technology, and availability of parts. The report on Foothill Transit's experience also summarized the lessons learned, which included encouraging strong working relationships between the agency and bus OEM, deploying the BEBs on routes that accommodated their capabilities, adjusting the route schedules instead of trying to fit the BEBs' needs into the existing schedule, and ensuring that the charging station is readily available (Eudy et al., 2016, pages 36–38).

The ZeEUS project partners identified five challenges that must be addressed in Europe. These recommendations are consistent with the needs of the U.S. BEB market and the findings of this synthesis report. The challenges include addressing each of the following:

1. The higher upfront cost of electric buses and their charging infrastructure compared with conventional vehicles.
2. The importance of identifying suitable technology solutions for specific local operational contexts.
3. The necessity to review current procurement and contractual frameworks.
4. The requisite to standardize charging interfaces to ensure the interoperability of e-buses, which allows multibrand fleets to recharge with multibrands infrastructures.
5. The need to develop trust and cooperation with the electricity power generation and distribution sector, as well as with grid owners and energy regulators.

Summary

An estimated 173,000 electric buses have been deployed worldwide, with more than 170,000 deployed in China. BEB technology is certainly not new and is arguably commercialized in other parts of the world.

The planning phase of any purchase starts with developing the business case. Capital costs of BEBs are higher than conventional buses but by all indications are continuing to fall (21% from 2009 to 2015 in Foothill Transit's case) as a result of technology improvements and economies of scale. Transit agencies have several options to address how to offset remaining incremental costs. First, the transit agency may be able to take advantage of federal and state funding opportunities. Second, given that there are potential operations and maintenance cost reductions associated with BEBs, costs should be evaluated and compared on a life cycle or total-cost-of-ownership basis. Maintenance costs for Foothill Transit's BEBs were reported to be 11% better than CNG costs. With an efficiency that was approximately four times better than diesel and CNG buses, the fuel costs of BEB are typically less. However, variability of electricity costs, and demand charges in particular, can significantly affect these operational costs. Utility rates vary tremendously throughout the country and eligible rate plans vary significantly within a utility. More work is required to understand the true impact of utility rates on BEB fleet operational costs as well as how to analyze rate structures and obtain the most reasonable rates. Ideally, the industry can establish rate plans specifically suited to fleets of BEBs that bring operations on par with conventional buses while still allowing utilities to cover the costs of electricity. In many areas of the country, the costs of charging a BEB are already lower than fueling diesel or CNG buses. New provisions that allow for leasing traction batteries (as opposed to purchasing traction batteries) can help shift some or all of the incremental capital costs to operational costs, creating a scenario that more closely resembles the total cost of ownership and competes with the cost structure of conventional buses.

Regulations are also driving BEB deployment. This is particularly evident in California, where the Air Resources Board Fleet Rule for Transit Agencies requires that buses meet strict emissions standards and that, for larger agencies, a percentage of new bus purchases be zero emission.

The decision process is complex when planning for bus technical specifications, charging methods, charger locations, and route selection due to a vast set of co-dependent agency and environmental variables. Optimizing a fleet-charging scheme at the outset of a project can significantly lower overall energy costs and the total cost of ownership for BEBs. Given that these decisions can have a significant effect on the cost, performance, and operations for a transit agency, access to evaluation tools and established methodologies is important. Limited tools and technical support are available but more development is needed in this area. While information was provided on why Foothill Transit chose their charging location and made adjustments to schedules to accommodate the buses, it is more anecdotal in nature. Little guidance or information was found in the literature on how agencies should plan for an overall BEB deployment.

Foothill Transit identified that scaling up a BEB fleet presents challenges not encountered with the deployment of a small number of vehicles and noted these challenges need to be addressed by the BEB industry. Only three transit agencies are currently operating more than 10 BEBs within their fleets. While larger orders have been placed, transit agencies are trying to understand how to deploy and manage the practical aspects of a larger fleet of BEBs. Challenges are primarily related to managing charging at scale and having the available space and power for large fleets as well as how to make charger connections in an efficient manner. In addition, transit agencies need to ensure that drivers are adequately trained on the operational differences between BEBs and conventional technologies and that recurring training is available.

Availability and reliability of BEBs was comparable to that of CNG buses during the Foothill Transit evaluation. Transit agencies are concerned about the durability of the traction battery due to its cost and limited amount of data regarding life expectancy for a BEB application. However, most BEB manufacturers are offering 6-year warranties on the batteries and one manufacturer is offering a 12-year unconditional warranty.

BEBs emit no emissions at the tailpipe. When considering electricity production in the total emissions profile, life cycle emissions for BEBs have 75% less global warming emissions and significantly lower NO_x emissions than CNG and diesel buses when considering a California energy production mix. Life cycle particulate matter emissions can be reduced by approximately 20% when replacing diesel buses with BEBs. Transitioning bus fleets to electric drive can have a significant positive impact on local, regional, and global emissions.

Overall, the current literature provides information regarding early stage BEB deployment; however, published data and summaries on nationwide experience are still needed to assist transit agencies in their efforts to procure BEBs.

CHAPTER 3

Survey Results and Agency Characteristics

Full Fleet Characteristics

As part of this synthesis report, a survey was developed to capture the current state of the practice for transit agencies deploying BEBs. This extensive survey, provided in Appendix A, captured the many aspects and considerations related to deploying this technology, which is new to many agencies. The survey results are split up into three chapters. This chapter describes the agency characteristics for the 21 agencies selected and surveyed out of approximately 72 agencies that are currently in the process of procuring BEBs. Chapter 4 addresses the planning considerations for procuring and deploying BEBs. Chapter 5 collects information on in-service experience from the operation of BEBs. Full survey details can be found in Appendix B.

The survey had an 86% response rate, with 18 out of the 21 respondents submitting information. Not all respondents answered every question either because they chose not to answer or because the question was not applicable to them. Therefore, the following results are provided in terms of how many agencies answered the particular question, in which case the number of respondents is indicated by "*n* = ". The transit agencies surveyed ranged in size, location, and experience with BEBs. The transit agencies that responded were distributed throughout the United States, as depicted in Figure 17.

BEB Fleet Characteristics

The survey accounted for 163 BEBs either delivered or on order (not including options to purchase BEBs) at the time the survey was conducted, which was February 2017. A summary of the agencies' characteristics is shown in Tables 6 and 7 and Figure 18. BEB fleet composition for the respondents ranged from 0.1% to 100%. Most of the agencies reported BEB fleets that are between 1% and 10% of their total fleet size, with a minimum of two, an average of six, and a maximum of 18 buses deployed during peak periods. Fifteen of the agencies currently operate the BEBs while the other three agencies are planning for them, that is, either they have buses on order or they have received the buses but have not deployed them in service yet. One responding transit agency has operated BEBs since January 1991 (more than 3 million miles), but most of the responding transit agencies have operated BEBs anywhere from 12 to 40 months.

The size of the BEB traction battery is an important specification for BEBs because it identifies the amount of energy a bus can store on board and is indicative of the range between recharges. It is also a component that bus OEMs carefully size because it has an effect on many factors, including bus weight, cost, range, and charge strategy. The reported size of the traction batteries generally fell into three size categories. Seven agencies use buses with traction batteries that are between 72 to 105 kWh, one agency uses buses with a 200 kWh battery, and

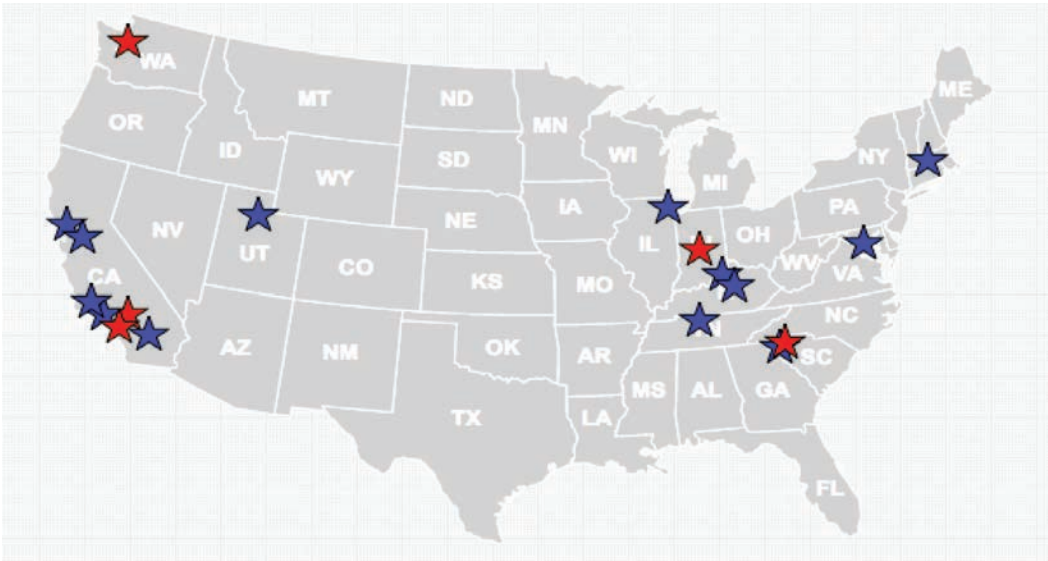


Figure 17. Map of agencies that responded to the survey. Blue stars indicate agencies that responded to the survey. Red stars indicate agencies that responded to the survey and were also selected to participate in the case examples. Source: Center for Transportation and the Environment.

Table 6. Fleet information of the agencies surveyed (*n* = 18).

Fleet Information			
Transit Agency #	Total BEBs	Total Buses	Percent of BEBs
1	3	113	3
2	1	1583	0.10
3	30	370	8
4	2	75	3
5	2	68	3
6	34	163	21
7	16	31	52
8	15	304	5
9	6	66	9
10	6	53	11
11	3	1474	0.20
12	5	681	0.70
13	2	1870	0.10
14	9	274	3.30
15	4	185	2
16	6	6	100
17	14	105	13
18	5	64	8

Source: Center for Transportation and the Environment.

Table 7. BEB fleet size distribution for the agencies surveyed ($n = 18$).

BEB Fleet Size Distribution						
Transit Agency #	35′	40′	60′	Cutaway	Other	Total
1	-	3	-	-	-	3
2	-	1	-	-	-	1
3	15	15	-	-	-	30
4	-	2	-	-	-	2
5	-	2	-	-	-	2
6	-	21	13	-	-	34
7	5	1	-	-	10	16
8	9	6	-	-	-	15
9	-	6	-	-	-	6
10	5	1	-	-	-	6
11	-	3	-	-	-	3
12	-	5	-	-	-	5
13	-	2	-	-	-	2
14	9	-	-	-	-	9
15	-	-	-	-	4	4
16	5	1	-	-	-	6
17	-	-	-	-	14	14
18	-	-	-	-	5	5
Total	**48**	**69**	**13**	**0**	**33**	**163**

Source: Center for Transportation and the Environment.

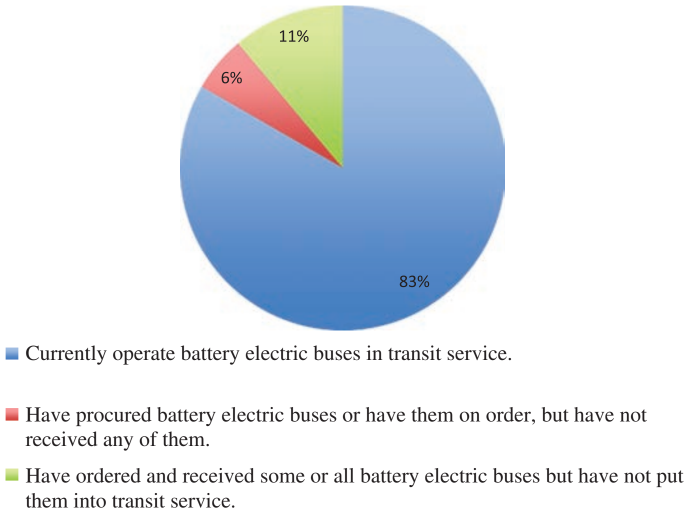


Figure 18. BEB deployment status of the transit agencies surveyed (n = 18). Source: Center for Transportation and the Environment.

seven agencies use buses with traction batteries between 300 to 325 kWh. As expected, BEBs with the larger batteries were typically used in a depot charge configuration, while on-route charged BEBs were able to use smaller battery packs, as shown in Figure 19. However, agencies also combined large battery buses with on-route charging (both overhead conductive and wireless) in two cases.

Charging Characteristics

While all 18 agencies utilize depot (or shop) charging, half of the respondents also have on-route overhead conductive chargers. Additionally, two agencies utilize on-route inductive wireless chargers, as shown in Table 8.

The transit agencies reported they had anywhere from 3 hours to 10 hours available to charge at night (defined as reliable time parked in a stall to a plug-in charge), with 60% reporting less than 5 hours available. Almost all BEBs on the market (including the longest range/largest battery models) can fully charge with a plug-in charge in less than 5 hours.

Three of the respondents stated that they operate on a pulse system, which can make on-route charging more difficult to implement since all buses are scheduled to depart from a transit center at the same time and layovers generally coincide with each other. When the layovers and hence available charge times for the buses overlap, it becomes difficult to coordinate charging and share chargers.

In order to meet the extended range needs of certain fleets, agencies appeared to utilize on-route charging methods. For daily ranges of over 200 miles, on-route conductive and on-route wireless were utilized, as shown in Figure 20.

Figure 21 provides a summary of how battery sizes and charge methods have been paired to address range needs of various routes. Large battery, depot charged, buses as well as small battery, on-route charged, buses were used to meet route lengths of less than 200 miles. On-route charging was used with any battery size configuration to meet longer daily range requirements.

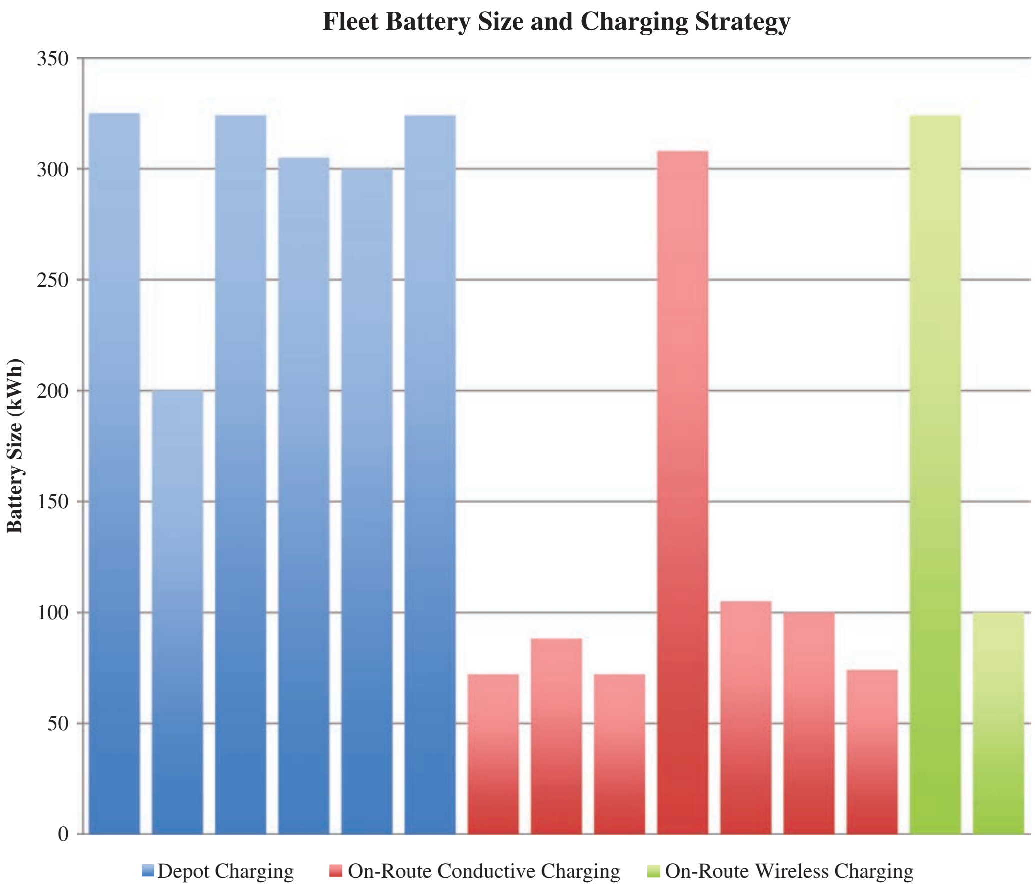


Figure 19. Fleet battery size and charging strategy (n = 15). Source: Center for Transportation and the Environment.

Table 8. Charging characteristics of the agencies surveyed.

Charger Type	Number of Agencies with Charger Type	Minimum Number of Chargers Used for BEB Fleet	Average Number of Chargers Used for BEB Fleet	Maximum Number of Chargers Used for BEB Fleet	Bus-to-Charger Ratio*
Depot Plug-in	17	1	4	22	1.5
On-Route Overhead Conductive	9	1	2	5	6
On-Route Inductive/Wireless	2	1	2	2	1
Depot Overhead	1	1	1	1	6

*Based on fleet with maximum number of chargers in each category.
Source: Center for Transportation and the Environment.

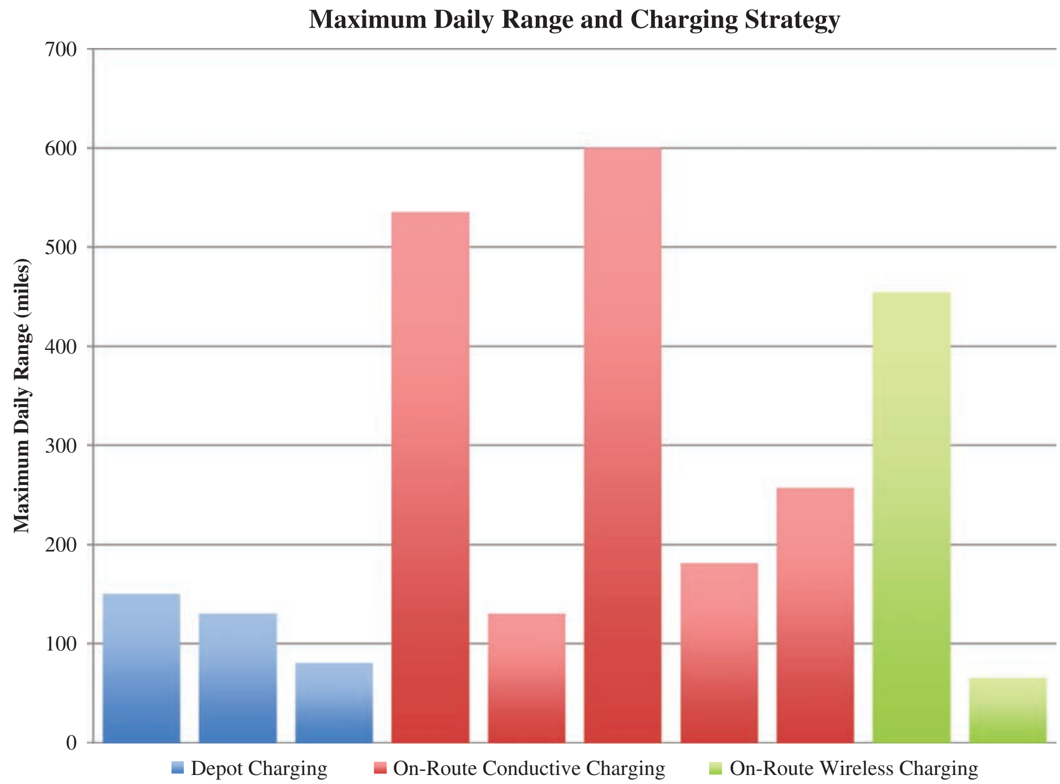


Figure 20. Maximum daily range requirements and charging strategy (n = 10). Source: Center for Transportation and the Environment.

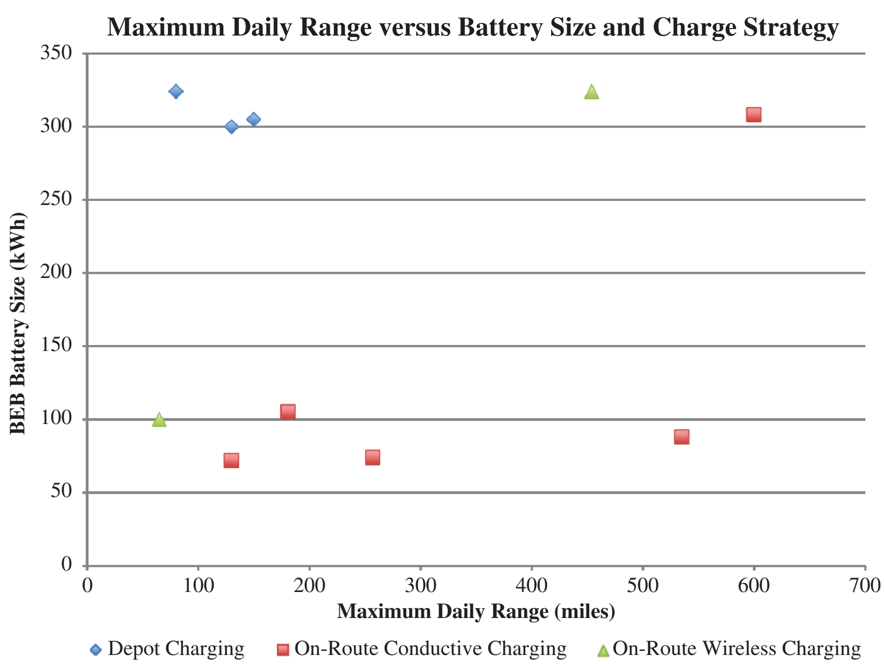


Figure 21. Meeting daily range requirements (n = 10). Source: Center for Transportation and the Environment.

CHAPTER 4

Survey Results and Planning

Procurement and Deployment

The primary drivers for deploying BEBs were generally split into two groups. Half of the transit agencies reported they implemented BEBs due to a combination of board direction, environmental regulations, and environmental/sustainability programs, while a third of the transit agencies were doing it to test the buses in their service. One agency stated that it was "just the right thing to do."

Figure 22 shows that 17% of reporting transit agencies have procured BEBs through standard procurements (suppliers competing through a transit agency's request for proposal) and 39% procured BEBs directly through a federal or state competitive grant opportunity such as FTA's TIGGER or Low-No programs. Twenty-two percent of the agencies used a combination of both methods. Other forms of procurement included leasing and piggybacking on other procurements.

Transit agencies participating in the survey took a variety of approaches to procuring BEBs. When developing BEB specifications, agencies used a combination of methods, including developing their own method, basing them on another agency's specifications, using a consultant experienced with BEBs, and using a guide. All transit agencies rated the forthcoming APTA Zero Emission Bus Standard Bus Procurement Guideline as 4 or above on a scale to 10 of importance, with 12 agencies rating it very important (7 or above). Two-thirds of respondents procured the charging infrastructure with the buses under the same contract.

An important aspect of infrastructure procurement and installation is coordination with the local utility. Most of the transit agencies reported that they involved the local utility early in the process when making procurement decisions (78%) and when making installation decisions (83%).

Life Cycle Cost Analysis

Only about half of the respondents did a life cycle cost analysis during the procurement. Nine out of 16 respondents stated they factored electricity rates and/or demand charges into their procurement decisions. Transit agencies addressed risks associated with battery life cycle costs very differently, ranging from a 12-month battery warranty to purchasing extended warranties to cover 15 years of bus use, as shown in Figure 23. Battery costs and life have improved significantly over the past decade, which has led to commensurate improvements in warranties. Table 9 provides reported capital costs for the bus projects.

Average costs for BEB purchases were just under $900K, depot-charging equipment was $50K, and on-route charging equipment was $500K. It is important to note that these data reflect the survey sample group regardless of when they actually purchased the buses, so the current cost of buses is somewhere less than the average provided in this report. Considering that the upfront capital costs are higher for BEBs than the upfront capital costs for traditional technologies,

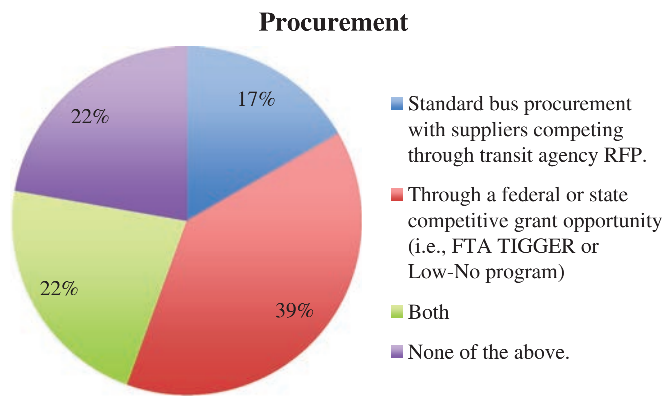


Figure 22. Procurement methods for the agencies surveyed (n = 18). Source: Center for Transportation and the Environment.

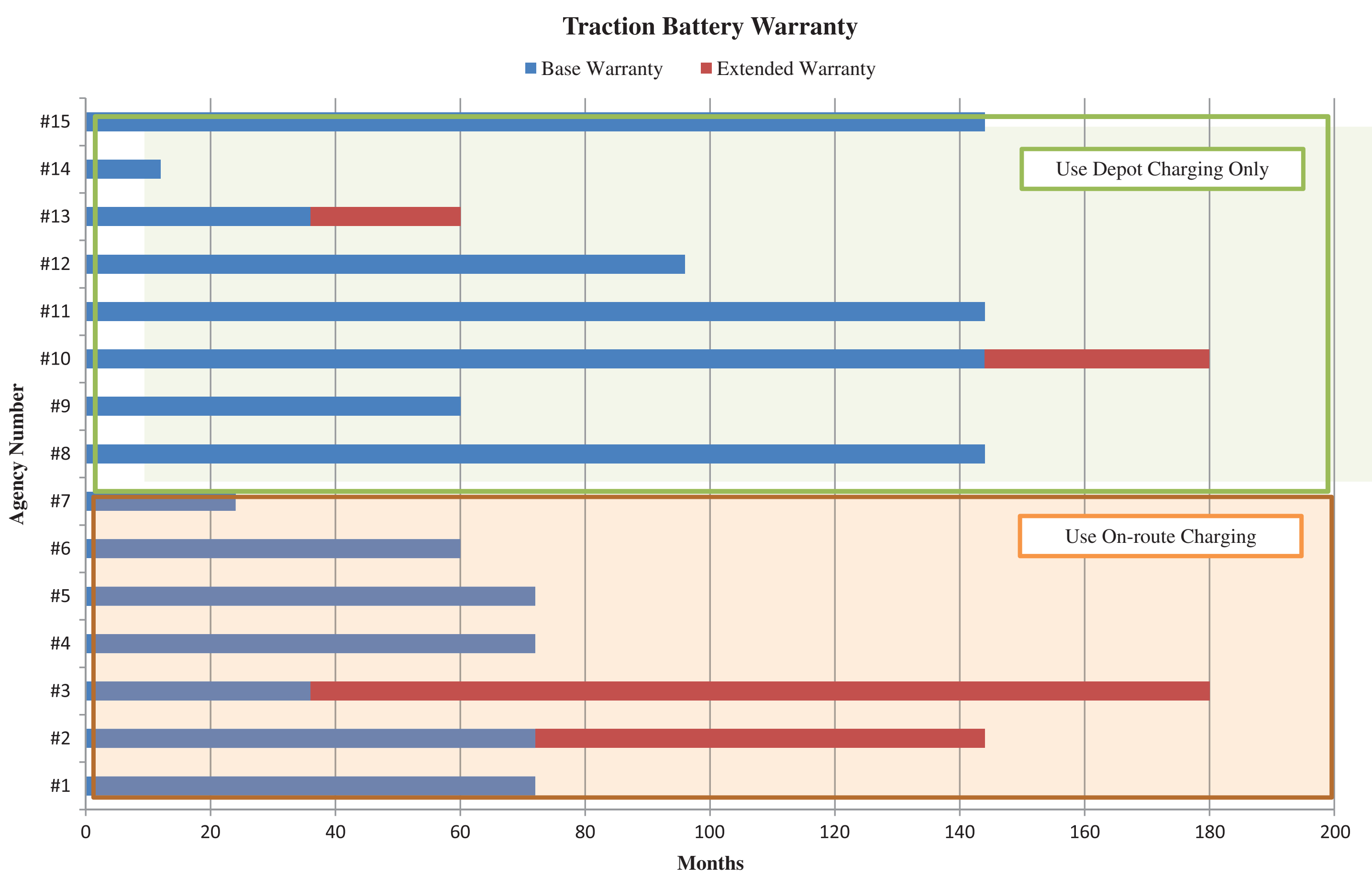


Figure 23. Traction battery warranties of the agencies surveyed (n = 15). Source: Center for Transportation and the Environment.

Table 9. Upfront costs of BEB procurement.

Deployment Costs	Minimum	Average	Maximum
Buses (average per bus)	$579,000	$887,308	$1,200,000
Depot Charging Equipment (per charger)	$2,000	$50,000	$100,000
Depot Charging Installation (per charger)	$2,000	$17,050	$64,000
On-Route Charging Equipment (per charger)	$330,000	$495,636	$600,000
On-Route Charging Installation (per charger)	$50,000	$202,811	$400,000

Source: Center for Transportation and the Environment.

transit agencies emphasized the importance of continued public investment in the deployment of BEBs (15 out of 16 respondents said it was "very important").

Bus Technical Specifications, Operational Requirements, and Route Selection

Evaluation of range and charge methods for BEBs is an important step for transit agencies planning to deploy BEBs. Table 10 shows that more than half of the transit agencies used their own agency's experience in combination with OEM predictions and bus trials in order to evaluate vehicle range, select suitable routes, and determine what type of charging method would be the best fit for their agency. One-third of respondents used consultants and/or advanced modeling and simulation techniques.

On-route Charging Infrastructure

Transit agencies selected the location of on-route charging stations in a variety of ways; however, locating them at existing transit centers was the most popular choice. Transit centers are ideal infrastructure siting locations because the real estate is already agency owned and maintained, route layovers are typically built in at these locations, the centers are typically at the midway or at the end of the line for routes, and they are typically closed to other vehicular traffic. Being closed to other vehicular traffic allows protection for overhead chargers. Transit centers make future expansion easier as well. Agencies reported that they were restricted to installing charging infrastructure at locations where they had dedicated access to the property or where the property was owned by the agency.

Agencies responded that they coordinated deployment of on-route infrastructure in conjunction with arrival of the BEBs. The primary goal in coordinating the two was ensuring that the charging infrastructure was in place before the BEBs arrived and could be accepted with the

Table 10. Route planning methods (n = 18).

Method Used	Evaluation of Range with Respect to Route Needs	Account for Variables When Verifying Range	Determination of Charge Method
Used agency experience	10	9	9
Used consultant	5	6	1
Used OEM predictions	10	9	8
Operated demo bus on routes	10	9	2
Modeling and simulation	7	6	4

Source: Center for Transportation and the Environment.

charging infrastructure in place. Most respondents also involved the local utility in the process, as shown in Figure 24.

More than half (61%) of the transit agencies installed the infrastructure themselves instead of using the bus OEM, infrastructure provider, or consultant. For most agencies, the installation was uneventful because the power requirements were well understood by all and communication between relevant stakeholders (OEMs, local utilities, construction architecture and engineering companies, public works, local and state DOTs, and local planners) minimized the learning curve. Nine out of 11 respondents stated the agency owns the infrastructure; two respondents stated the public municipality owns the infrastructure. There were no responses stating the utility owns the infrastructure.

The transit agencies were split when asked if they would like other medium and heavy-duty vehicles (such as delivery vans or refuse trucks) to have access to the on-route infrastructure. Respondents against making access available stated such access would interfere with bus operations and would complicate electricity billing. Respondents in favor of making access available thought such access could be an encouragement for deployment of more electric vehicles.

Responses were evenly split between the types of entrances that agencies used for accessing the on-route charging infrastructure, whether it is on road, a pull-off lane, or a pull-in driveway entrance. Most of the transit agencies (73%) have the buses align with the charger using visual cues on road or roadside as opposed to other methods such as video cues, audible cues, and cues on the dash. Almost half of the buses also use semi-automated control to align with the charger. NREL's Foothill Transit fleet evaluation accurately depicts a semi-automated docking process:

> The docking process requires very little driver interaction as it is a semi-automated process. Each vehicle is equipped with a unique radio-frequency identification tag that the charging heads use to initialize the docking procedure. The vehicle is stopped by the driver in front of the charging head, the charging head recognizes the vehicle, and the vehicle is put into a semiautonomous creep mode and driven forward as the charging head lowers from the overhead dock to align with the vehicle's roof-mounted guide. Once the vehicle is in place, it is automatically stopped, and the driver places it in park before charging commences (Prohaska et al., n.d., page 5).

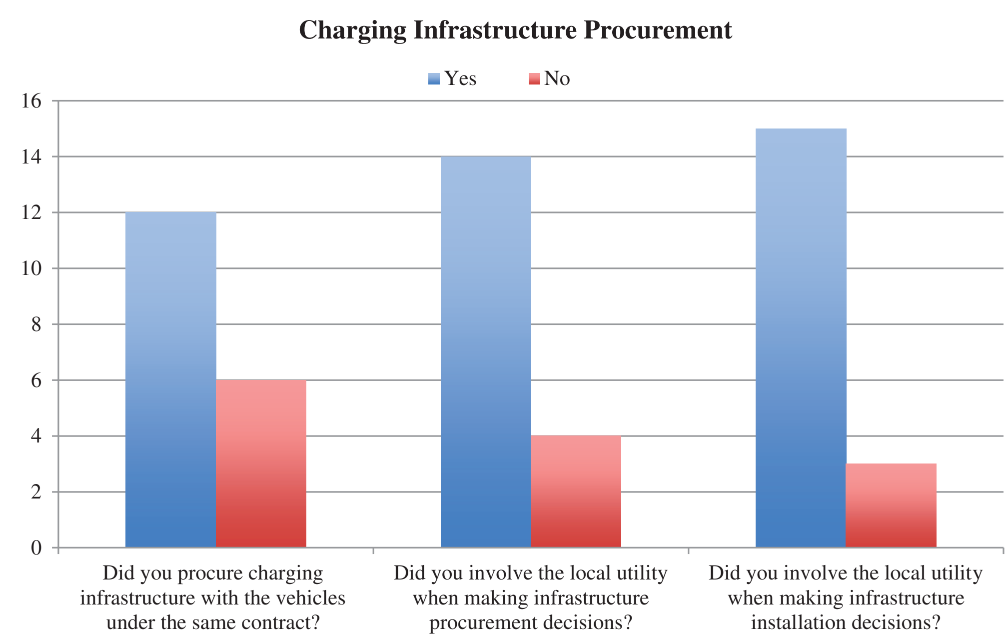


Figure 24. Local utility involvement in the procurement process (n = 18). Source: Center for Transportation and the Environment.

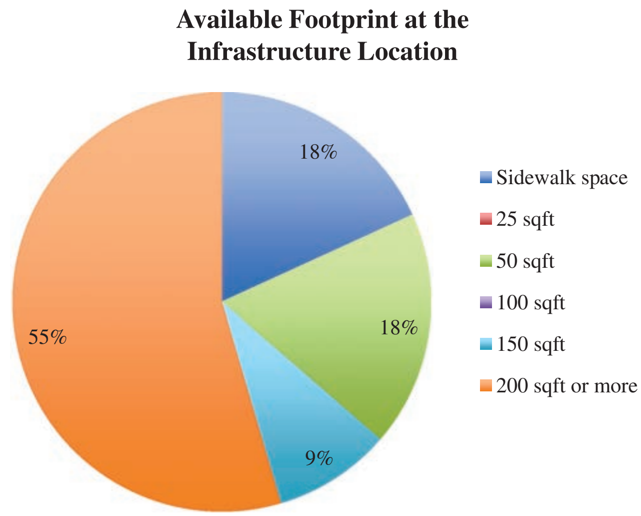


Figure 25. Available footprints at infrastructure locations (n = 11). Source: Center for Transportation and the Environment.

Layover Location Characteristics

The responding transit agencies located on-route charging infrastructure at transit centers in seven instances, that is, at an agency-owned property in four instances and on the side of a public street in three instances. Most transit agencies have 200 square feet or more of available footprint for the charging infrastructure and light-to-no traffic density at the location they selected, as shown in Figures 25 and 26. Four out of 11 transit agencies have had incidents associated with other vehicles colliding with the infrastructure (see Chapter 6, Case Examples: King County Metro). Eight out of 11 respondents do not have clearance requirements or clearance restriction bars at the infrastructure to help prevent such incidents.

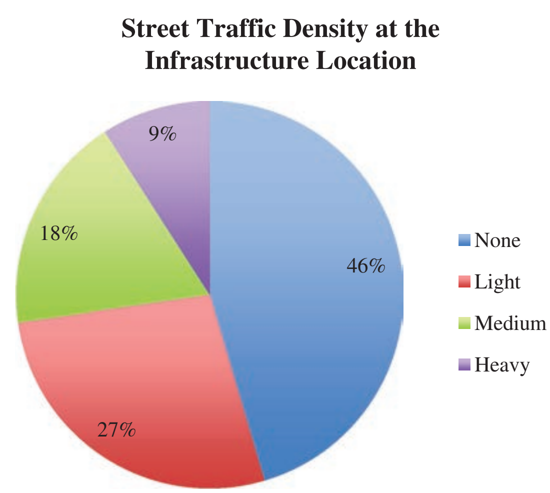


Figure 26. Street traffic density at infrastructure locations (n = 11). Source: Center for Transportation and the Environment.

In many cases, transit agencies had to adjust bus schedules to accommodate the charge times. The agencies were split between being able to accommodate either 5 to 10 minutes of charge time (55%) or able to accommodate more than 15 minutes. No agencies stated that they had between 10 to 15 minutes to charge. Irregular charge schedules can sometimes be required due to numerous factors such as traffic delays, missed charges that need to be made up, and high utility demand rates. Fifty-five percent of agencies reported having the flexibility to accommodate irregular charge schedules while 45% of agencies did not have that flexibility.

The agencies reported that communication between the stakeholders (utility, public works, local and state DOTs, OEM, and local planners) was key to having a successful procurement. One agency emphasized that the charging power requirements must be understood by all. However, as one agency reported, "Working with the local utility company became trying at times as well as agreeing on the actual installation of the equipment."

Electricity Rate Structure

BEB operation costs are highly dependent on utility electricity rates, both energy costs and demand charges. These rates vary from utility to utility across the country and can even vary within a utility price schedule. Eighty percent of respondents monitor their utility bills to understand their impacts on operating costs and to determine if alternate rate structures can be considered. All of the transit agencies that responded to this question believe there is a need for development of a utility rate specifically suited to the needs of BEB fleets. According to the survey, 66% of respondents said that it was not difficult selecting an optimum electricity rate structure, most likely because those agencies only had one rate structure available to them from the utility or because they were not analyzing how BEB operations and charge schemes can affect rate plans. Agencies continued to stress the importance of working with their utility early in the process to obtain the best electricity pricing for the fleet.

Planning and Support Tools

The BEB industry appears to be lacking in standardized technical support and software tools to aid agencies in making procurement decisions and managing BEB fleets. The majority of transit agencies responded that these tools would be beneficial when making decisions regarding range predictions, utility rate analysis, and life cycle cost analyses and adjustments, as shown in Figure 27. About half of the agencies stated that enhanced tools would be beneficial when making complex procurement decisions when selecting the appropriate BEB technology for the given application; the other half of agency respondents were not sure if they would help.

Scalability

An important aspect of planning for BEB implementation is considering the scalability of the project. As addressed later in the case examples, sound advice to newer transit agencies is to have the end goal in mind when installing infrastructure in order to prevent the possibility of repeating expensive construction activities. As reported, many transit agencies were primarily looking to the initial BEB deployment to gain experience with the technology and to understand how it works within their operation and service. It is understandable that 39% of the respondents were not planning in advance for scale up at this stage. However, 50% of the respondents anticipated issues with not having adequate depot or on-route property and right-of-way to support charging infrastructure for full BEB fleets, 28% anticipated issues related to not having adequate electrical power, and 50% anticipated issues with inadequate resources (e.g., scheduling and manual connections) for charging BEBs at scale, as shown in Figure 28.

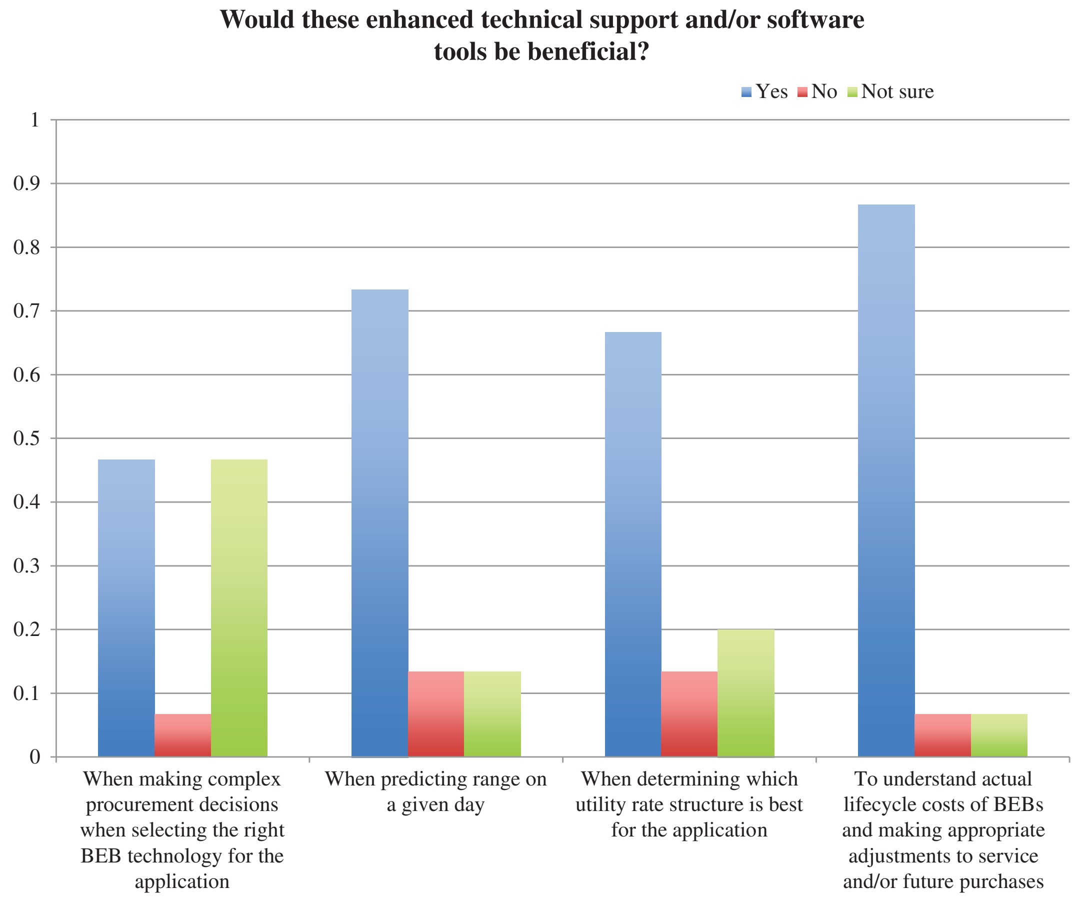


Figure 27. Planning and support tools (*n *= 15). Source: Center for Transportation and the Environment.

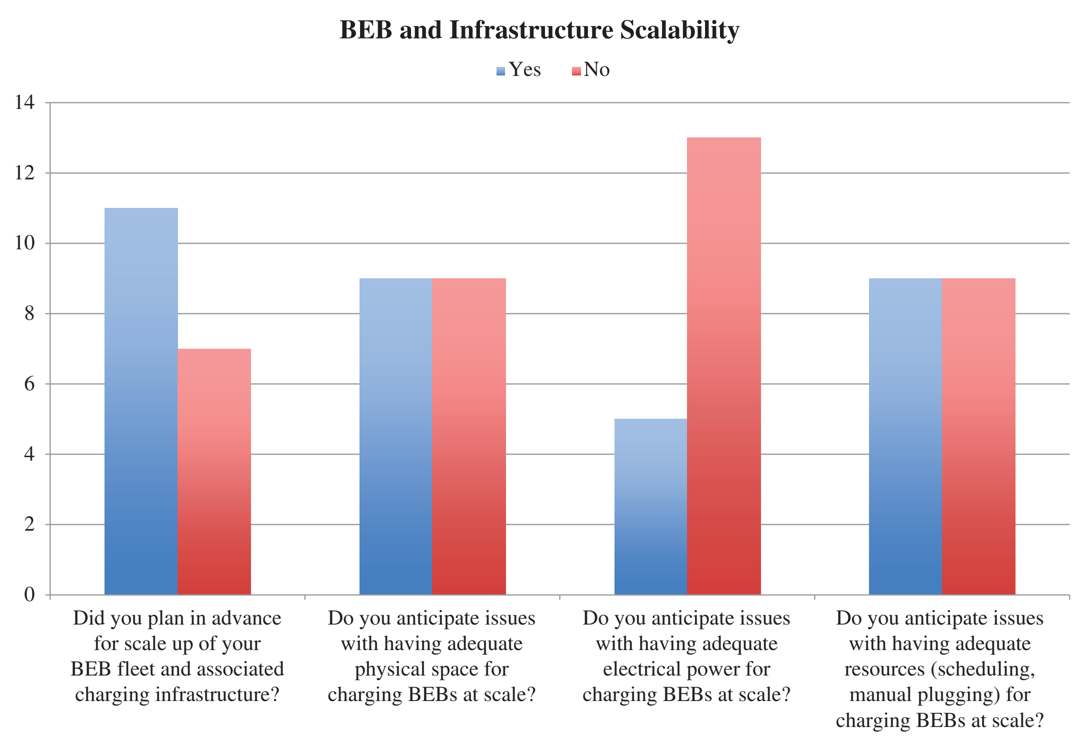


Figure 28. BEB and infrastructure scalability planning (*n *= 18). Source: Center for Transportation and the Environment.

Some examples follow from transit agencies that did plan in advance for accommodating scale up:

- "Analyzing a 24 year roadmap and producing model simulations."
- "Collaborating with the city to ensure that it will provide more service for increased demand."
- "Doing as much underground work as possible when the trenches were open."
- "Planning future routes and locations based on maximum scalability."
- "Locating chargers to serve existing and planned routes."
- "Development of a bus maintenance facility to accommodate fleet expansion."

CHAPTER 5

Survey Results and Post-Deployment Experience

Training

Transit agencies reported training an average of 70% of their drivers and an average of 58% of the maintenance staff to support their BEBs. Operations and maintenance training was predominately provided by the bus OEM for both the bus and the supporting infrastructure. The transit agency, equipment providers, and third-party organizations also occasionally supplemented this training. Sixty-one percent of respondents stated local first responders were also trained in responding to BEB incidents.

Most transit agencies found that the OEM was well prepared and invaluable to the training process. However, one agency encountered a bus OEM trainer who initially was not appropriately prepared to conduct the training, but this appears to have been an early deployment for the OEM. In general, training obstacles that transit agencies encountered were

- The unfamiliar nature of SOC for new operators—the agency suggested providing an estimated range (time of operation remaining) for them,
- Understanding range capacities of different products and batteries, and
- Uninformative training manuals.

Some training practices that worked well for agencies include

- Training in smaller groups for one-on-one development,
- Hands-on training with the bus present,
- Working with third party trainers,
- Having a factory technical representative on site and operating an initial shadow service because it gave the agency the flexibility to pull BEBs off the line to train personnel,
- Training first responders, and
- Training the drivers and first responders together for consistency in the response methods.

Operations

Respondents are operating anywhere from two to 18 BEBs during peak periods, with an average of six buses operating for all respondents. A primary consideration with integrating BEBs into a fleet is the potential need to adjust their existing operations to support bus charging. To accommodate the unique operational needs of BEBs, 60% of respondents had to adjust their schedule. Layover times were the second most adjusted at 40%, followed by bus blocking at 20%, and number of buses serving a route at 13%. However, 33.3% of transit agencies did not make any adjustments. Although some bus OEMs define maximum SOC, minimum SOC, and expected operating range differently, the buses generally left the depot with battery SOC above

90%. As expected, SOC upon return varied widely depending on bus service and charge method, with the minimum reported SOC at 25%, as shown in Figure 29.

Generally, the transit agencies reported that BEB operations went smoothly, the buses worked well, and there were minimal problems. However, some issues were noted in the survey responses. For one agency, bus energy consumption was greater than anticipated during the winter months and fleetwide modifications had to be made to the heating system. Another transit agency struggled with ensuring that the BEBs have ample time to charge when unplanned events occur, like a late plug-in to the charger and following missed charge opportunities. It is important to note that these issues are unique to BEBs and can be addressed with proper analysis and planning early in the deployment.

Respondents were split when asked whether it was important to avoid making manual connections to a charger. Some respondents said it was fine and easier to plug in a BEB than to fuel a CNG bus. Other respondents said it would be easier to have the connections be automated and avoid reliance on human interface, which can introduce risk of error (i.e., missed charges) and oversight requirements.

Availability and Reliability

On-route charging can be extremely useful because it can enable BEBs to meet extended range and duty cycle requirements. One agency reported that their BEBs remain charged without having to return to the depot and could easily operate 24/7. However, they also stated that it can be risky for the agency to rely solely or primarily on on-route chargers because if one charger goes down, service is affected. Even with multiple chargers at the same location for redundancy, power outages will affect service. Many agencies plan for such risks by having multiple buses charging at the depot or deploying backup diesel or CNG buses. The general consensus of agencies is that on-route charging works well as long as there is adequate planning, testing, training, and practice docking. In general, after going through the process of initial deployment and

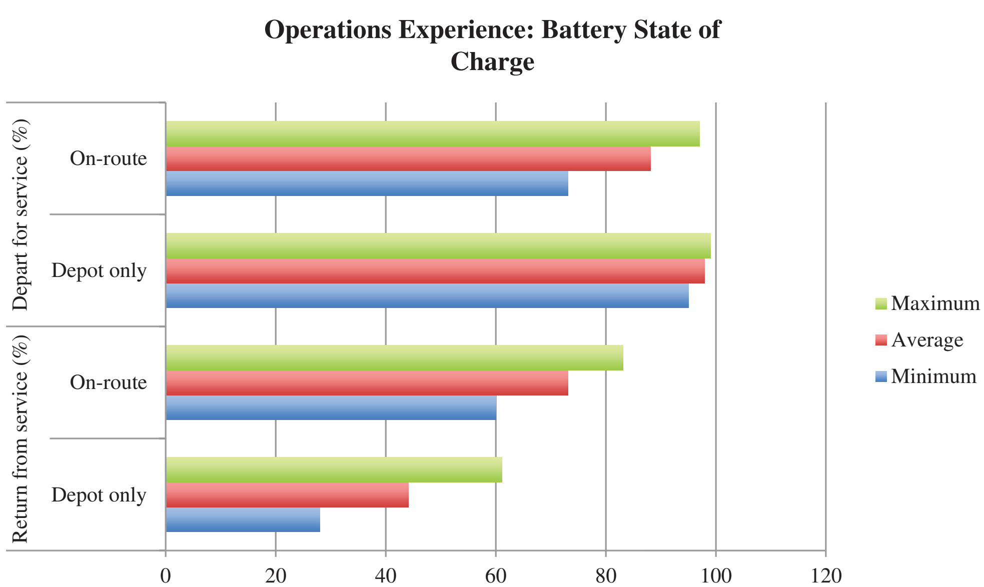


Figure 29. Operations experience: battery SOC with respect to the agency's charging method (n = 13). Source: Center for Transportation and the Environment.

shakeout, agencies reported that BEB availability was an average of 86%, depot charger availability was 99%, and on-route charger availability was 86%.

Most agencies using on-route charging reported that 90 to 95% of charges attempted were successfully made. The lowest reported successful connection rate was 75% of the time. Charges were missed due to a variety of reasons, including mechanical malfunction of chargers, buses behind schedule, misalignment, loss of power to chargers, and blocked paths.

When asked if it was important to provide audible or visual communication to pedestrians that the bus was approaching, 72% of the agencies said yes. Some recommendations for communicating approach included combinations of visual and audible cues, interactive signs, mobile application notifications, and technologies that communicate the bus IT systems to monitor conditions and provide notification. The respondents did not believe that it was important to provide audible or visual communication to passengers that a bus is charging.

Service and Maintenance

Respondents reported that BEB and associated charging infrastructure maintenance was provided by the bus OEM, a third party, or the transit agency itself. As highlighted in Figure 30, the majority of transit agencies rely on their staff to provide the maintenance on BEBs and preventive maintenance and repair on the charging infrastructure. However, bus manufacturers provide maintenance support on the advanced propulsion systems and charging infrastructure.

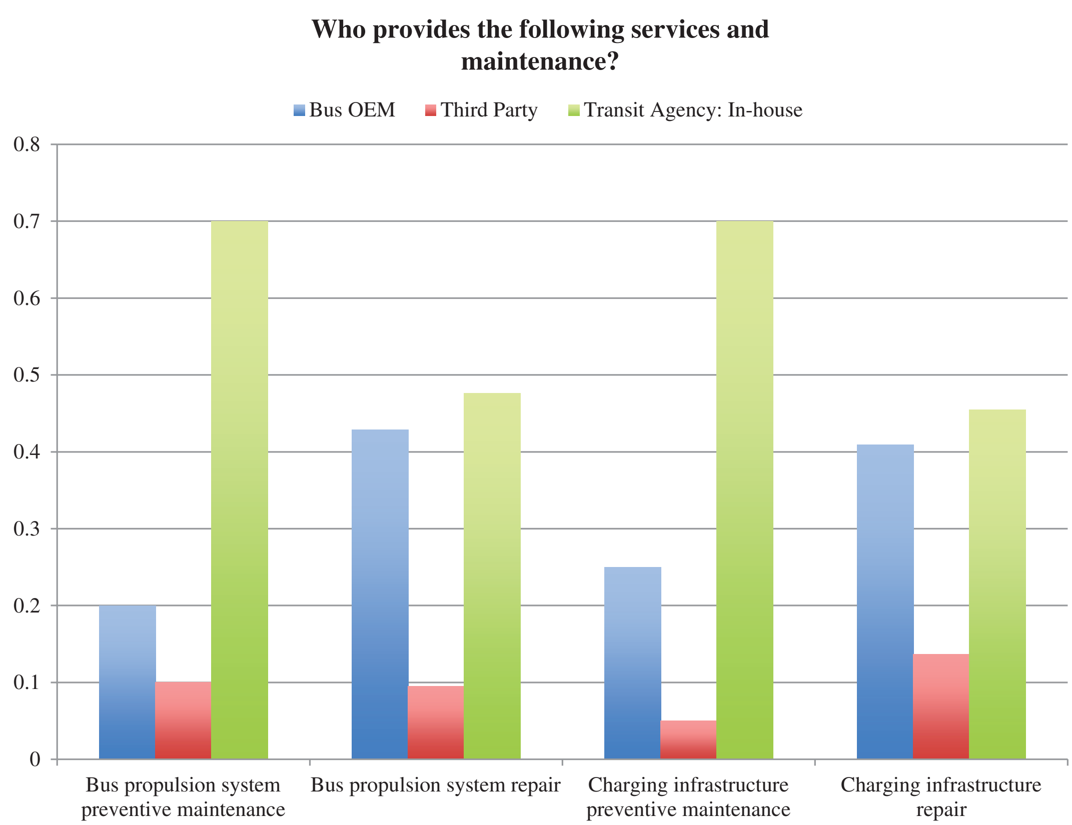


Figure 30. Bus service and maintenance providers (n = 14). Source: Center for Transportation and the Environment.

A majority of the agencies (79%) reported no issues with the traction battery. An early concern associated with traction batteries is battery degradation and end of life, but most of the respondents (54%) do not track that data. The agencies that do track that data are reliant on the bus OEMs to test and provide that information upon request.

Agencies report that spare parts inventories for BEBs are either the same (46%) or lower (46%) compared with diesel buses because BEBs require fewer components and because some components, such as brakes, do not need to be replaced as often. However, parts availability and long lead times have been problematic due to the relatively small scale of BEB deployments and the lack of a mature supply chain.

The agencies reported very little maintenance issues and liked the relative simplicity of the vehicles. The challenges that agencies have encountered with BEB maintenance center on the learning curve associated with the new technology, which can be addressed with robust training programs and, ultimately, experience.

Costs

A majority of the transit agencies are tracking their costs, including capital costs and maintenance and operational expenses. Capital costs were covered earlier in this chapter. An important component of operational costs is unscheduled maintenance requirements. In a direct comparison of maintenance costs, CNG bus costs are reportedly less according to one agency; BEB costs are $0.09 per mile, and CNG bus costs are $0.12 per mile. Table 11 presents the distribution of the operational costs associated with the BEBs based on the survey.

Care must be taken when considering these reported costs since they are heavily dependent on utilization of the buses. If the buses were not utilized to their fullest potential, then operational costs per mile would rise significantly and could be misleading.

The agencies reported electricity costs of anywhere from $0.15 per mile to $0.89 per mile, with an average of $0.36 per mile. This massive range (almost 600%) in fuel costs is likely due to the broad range of utility charges across the country and complex rate structures. It could also be due to underutilization of the buses when demand charges are in place. Note that NREL reported that the battery electric bus fuel cost was $0.39 per mile compared with the $0.23 per mile for the baseline CNG buses during the evaluation period. Electricity rates and their optimal use must be better understood by the industry (and, in particular, utilities) in order to get fuel costs down to, or below, those for conventional buses.

For a cost comparison, the survey polled the agencies on two different categories: actual BEB cost to original budgeted amount and BEB cost to existing diesel or CNG buses. In comparison with budgeted amounts, responses varied equally that actual costs were less than, greater than, or equal to budgeted amounts. It is not surprising that the actual capital costs of BEBs were reported to be greater than existing diesel/CNG buses; however, 46% of respondents

Table 11. BEB operational costs.

Costs ($/mile)	Min	Avg	Max
Scheduled Maintenance	$0.09	$0.36	$0.92
Unscheduled Maintenance	$0.09	$0.28	$0.55
Fuel/electricity for BEB Fleet	$0.15	$0.36	$0.89

Source: Center for Transportation and the Environment.

reported that operations and maintenance costs were less than those of their diesel/CNG fleet. Twenty-three percent reported that BEB O&M costs were greater than their conventional fleet. As previously mentioned in the literature review, government or state funding can be used to help offset capital costs.

When asked about life cycle costs compared with budgeted or conventional fleet costs, many of the agencies stated that they were unsure due to the early stage of commercialization of BEBs and not having enough data, as shown in Figures 31 and 32. One agency stated that they "did [have] a very high level analysis of the BEBs cost. However we are trying to fine tune that as we implemented sub-meters to take data more accurately." One takeaway is that there simply is not enough data yet to begin to understand true BEB life cycle costs.

Social, Environmental, and Health Benefits

Fifty-three percent of respondents do track the social, environmental, and health benefits of BEBs, specifically those related to greenhouse gas (GHG) emission reduction. The California agencies tracked GHG emission estimation because many of them used state funds with requirements for tracking. In general, the public reaction to BEBs was reported to be high on a scale of 1 to 10 (60% positive, with a rating between 5 and 8; the rest being very positive with a rating of either 9 or 10). One agency reported that, when compared with the buses it has replaced, it is avoiding more than 3,000 pounds per year of criteria air pollutants with its fleet of 15 BEBs. Another agency utilized the Diesel Emissions Quantifier Health Benefits Methodology (U.S. Environmental Protection Agency 2010) to track its pollutant reductions, as reported below.

- "Carbon dioxide (CO_2): a 121-ton reduction per year, per electric bus. Over the anticipated 12-year lifetime of the bus, this equates to 1,452 tons per bus.

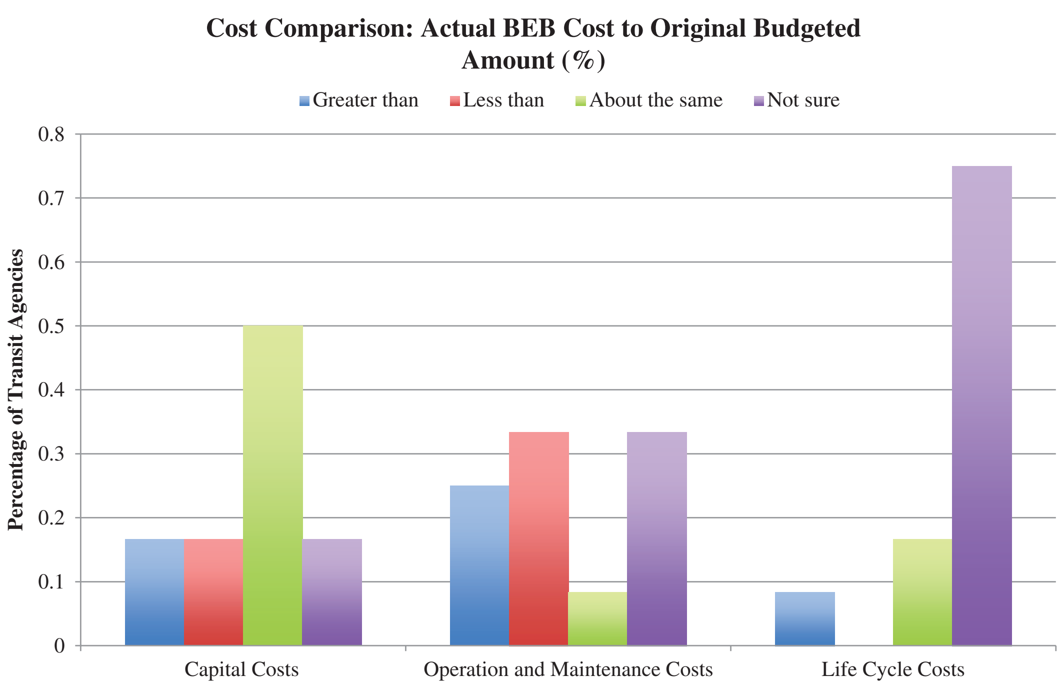


Figure 31. Actual BEB costs versus original budgeted amount (n = 12). Source: Center for Transportation and the Environment.

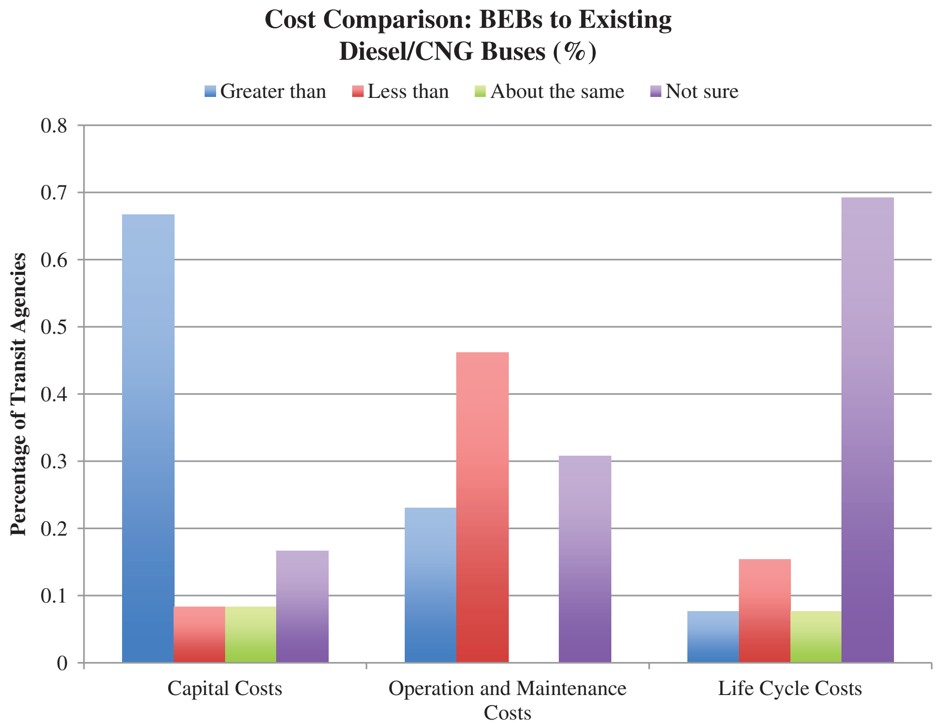


Figure 32. Battery electric buses cost versus existing diesel/CNG buses cost (%). Source: Center for Transportation and the Environment.

- Hydrocarbons (HC): reduced by 0.0428 tons per year or 0.5136 tons over the 12-year lifespan of each bus.
- Carbon monoxide (CO): reduced 0.310 tons annually or 3.72 tons over the lifetime of the bus.
- Nitrogen oxides (NO_x): less 0.5938 tons per year, or 7.1256 tons over the lifetime of the bus.
- Particulate matter (PM): reduced by 0.0274 tons per year, or 0.3288 tons over the 12-year lifespan of each electric bus" (U.S. Environmental Protection Agency 2010).

One agency responded that merchants and residents like the quiet operation of the buses.

Resiliency and Emergencies

Finally, for resiliency and emergencies, 57% of respondents provide assistance for community critical functions, such as evacuations, mobile climate center, and temporary shelter that may require them to consider backup power generation by using the BEBs or consider additional battery storage capacity. Most of the agencies (86%) would expect to have some assistance in place 2 hours after an event or an outage takes place. A common method, according to responses, is to have back-up generators. One agency can use its BEBs as a power source for vehicle-grid technology: vehicle-to-building or V2B, vehicle-to-load or V2L, and bidirectional vehicle-to-grid or V2G services.

Other agencies believe that emergency support with BEBs is not feasible at this early stage due to long-range support requirements. One respondent stated that "The current and near term BEB percentage of the fleet is far too small to require planning of that nature." And another respondent stated that "We would not use the BEB in these situations, and likely would not go to a 100% fleet for that reason."

Stakeholder Involvement

Stakeholder involvement is an important part of the BEB procurement and deployment process, as later emphasized in the case examples of this synthesis. Common stakeholders include utility companies, operators, unions, communities, executive boards, and regulatory agencies. According to the survey responses, regulatory agencies repeatedly suggested demonstrating the positive environmental impacts and operational cost savings of BEBs in order to engage stakeholders, such as executive boards and communities, and to motivate them to support the process. One agency stated that some stakeholders question BEB effectiveness due to increased power plant emissions as well as the upfront costs of the buses. These items, in particular, need to be analyzed and addressed early in the BEB procurement process in order to make an objective case for stakeholders. One respondent also stressed the importance of strategic planning to determine the best BEB type for the given operation, as well as effective placement of charging stations.

Overall Satisfaction with BEBs

Overall satisfaction with BEBs was very positive. On a scale from 1 to 10, 77% of respondents are either satisfied with the BEBs (ranking between 4 and 7) or very satisfied (ranking between 8 and 10), and 86% of the reporting agencies plan on purchasing more BEBs. While one agency has already gone fully electric, three agencies responded that they intend to be fully electric by years 2018 (with 79 buses), 2025, and 2030. One agency even reported that they plan to replace their 17-year-old BEBs with new BEBs soon.

CHAPTER 6

Case Examples

Antelope Valley Transit Authority

AVTA provides transit service for the cities of Palmdale, Lancaster, and Northern Los Angeles County. AVTA deployed two 40′ BYD electric buses onto Route 1 in November of 2014 using a local grant from the Los Angeles County Board of Supervisors. The agency plans to fully convert its fleet to BEBs by 2018, becoming "fully green by 2018" with a total of 89 BEBs supported by 89 plug-in depot chargers and 13 on-route inductive (also known as wireless) chargers ("Electric Bus Fleet Conversion" 2017). The full fleet conversion will be funded using a $24.4 million CalSTA grant plus another $15 million of AVTA and federal formula funds. The agency expects to begin with the introduction of its first five articulated BEBs. The expansion will continue with receipt of one additional articulated bus every week until reaching a total of five buses. Ultimately, the agency's goal is to acquire 13 articulated, 30 commuter, and 34 40-foot all-electric buses. The articulated and 40-foot all-electric buses will both utilize the on-route wireless charging infrastructure.

AVTA's Experience

Table 12 presents the dashboard information of the AVTA BEB fleet, as well as climate considerations on Table 13 during BEB deployment in 2014. The two buses (shown on Figure 33) are supported by two on-route 50 kW WAVE inductive chargers (locations shown on Figure 34) in addition to the bus-OEM supplied plug-in depot chargers. The buses use the wireless chargers for opportunity charging during layovers and the plug-in chargers to top off the buses overnight. Inductive on-route charging relies on a charging architecture that transmits power wirelessly through inductively coupled electromagnetic circuits. A typical installation uses a coil buried in the roadway. An initial challenge was encountered by AVTA related to the installation of the inductive chargers. Because the chargers were new technology and were being installed in two different city jurisdictions, the building inspector required UL field certifications to be accomplished to ensure there was no shock hazard present. AVTA and WAVE ensured that the UL field certifications were complete as well as the electromagnetic field testing. AVTA will install the industry's first 250 kW on-route wireless charger later in 2018 and is planning for the same rigorous certification. AVTA paid for the charger installations using local grants from Los Angeles County and the Antelope Valley Air Quality Management district. The agency installed the chargers 50 to 60 feet apart so the communication signals from each charger would not overlap and would not attempt to "handshake" with a bus that was not sitting over the charger.

AVTA has planned in advance for power requirements necessary to charge their full BEB fleet expansion. While AVTA has sufficient physical space at the depot to provide for a plug-in charger for every bus, they encountered obstacles regarding the scale up of power supply to support the charging. With two separate power lines (for redundancy) entering the facility at

Table 12. AVTA BEB characteristics.

AVTA Dashboard

BEB fleet size (OEM)		2 - 40′ (BYD)
Total fleet miles accumulated per month		11,581
Total months in operation		37
Number of depot chargers		1
Number of on-route chargers		2 (50 kW inductive/wireless)
Average route length (mi) – BEB Fleet		21 miles
Daily range requirement – BEB Fleet		185 miles
Average BEB route speeds		17
BEB cost		$770,000
Depot Charger cost	Equipment (per charger)	$19,000
	Installation (per charger)	$55,000
On-route Charger cost	Equipment (per charger)	$350,000
	Installation (per charger)	$250,000
Funding sources	LA County grant, Antelope Valley Air Quality Management District, LA Metro Call for Projects	

Source: Antelope Valley Transit Authority.

Table 13. Antelope Valley average annual climate.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Av. High (°F)	59	62	67	73	82	91	98	98	91	79	67	58
Av. Low (°F)	31	35	39	45	54	61	67	64	57	46	36	30

Source: U.S. Climate Data.

Figure 33. AVTA's battery electric bus.
Source: Antelope Valley Transit Authority.

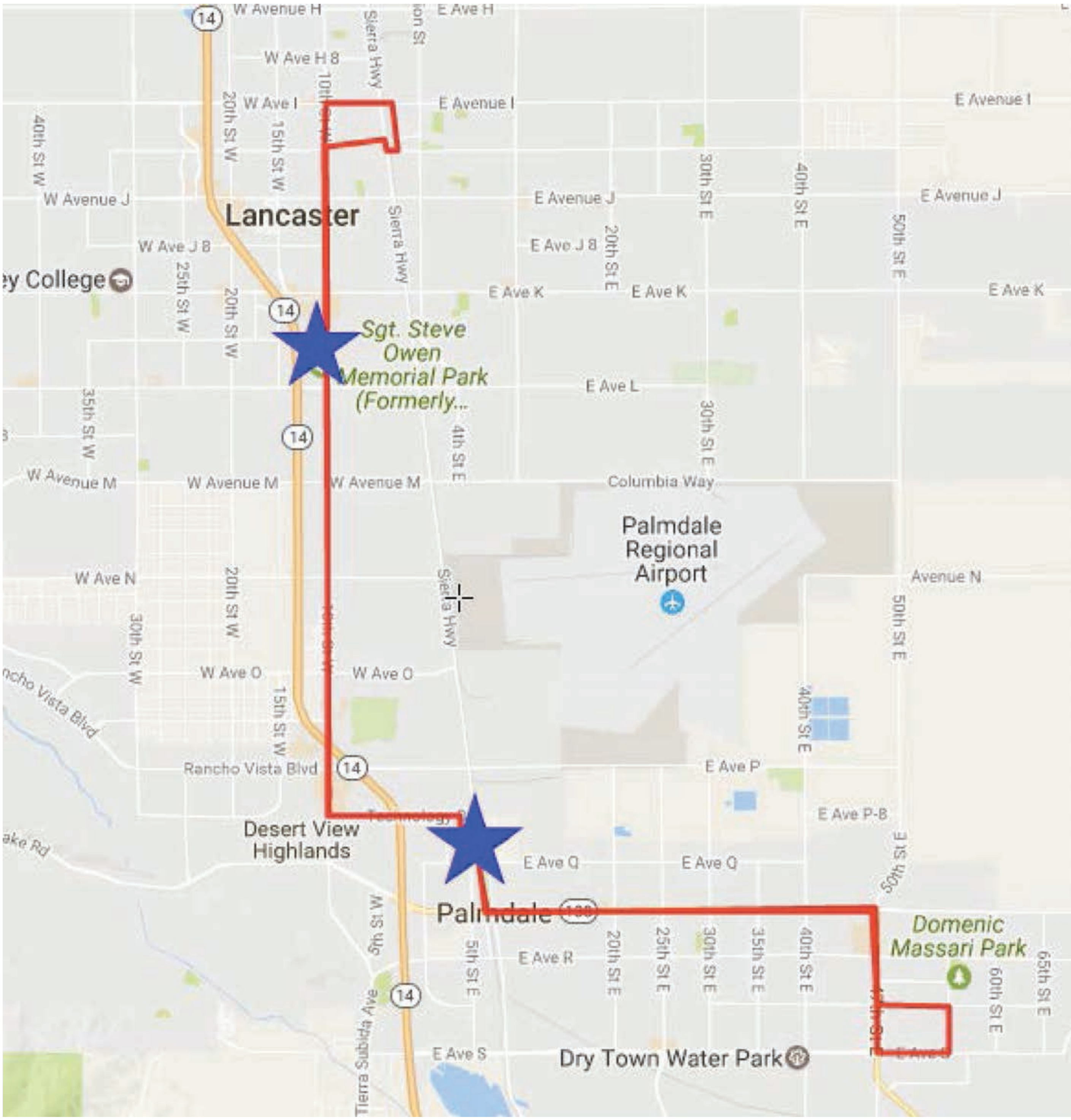


Figure 34. AVTA's electrified route, with the blue stars representing the charging stations. Source: Antelope Valley Transit Authority.

12.5 kV each, heating due to high current demands from the charger accumulates to a point where the electricity transfer becomes too inefficient. In order to solve this problem, the local utility—Southern Cal Edison—and AVTA decided to install the wiring in an open trench (covered in plates), which allows for safe dissipation of heat and increased system efficiency. The open trenches have the added benefit of being easily serviceable.

Initial estimates suggested that operation of the full fleet of BEBs would require 18,000 amps of current to run successfully. Once AVTA built the schedule around the charging management system and broke it up into four zones with transformers, the estimation decreased to 5,000 amps.

AVTA has coordinated closely with their utility to provide rate structure assistance for their growing BEB fleet. Southern Cal Edison has a transportation division and has been very supportive throughout the deployment process and encouraged the transit agency to go 100% electric.

BYD Motors' buses have an integrated data logger and charge management system from I/O Controls that tracks information about the BEBs. The charging management system allows AVTA to turn the charger on and off, control the charging demands, check battery SOC, and monitor individual driver's performance.

After evaluating bus efficiency performance for their initial fleet of BEBs, AVTA determined that driving style (such as aggressive driving and heavy manual braking instead of relying on regenerative braking) can have a significant effect on bus performance. For example, AVTA reported that two operators on the same route and under the same conditions had a 4 kWh/mile difference in efficiency due to driving technique. This equates to a reduction in range from 220 miles to 80 miles. Training has been an important factor for AVTA to address this issue by teaching efficient operation of the electric vehicles and having trainers ride along on route to re-enforce more effective driving practices. The agency is also considering establishing an incentive program to encourage efficient driving.

AVTA's Advice

AVTA encourages transit agencies considering deployment of BEBs to invest in initial preparation. Agencies need to build strong relationships with stakeholder groups, including utilities, bus suppliers, major component suppliers, and funding agencies. Agencies should consider what their ultimate deployment goal is and plan for that and not just for their initial deployment. For example, it makes more economic sense to initially build out all the underground infrastructure rather than to retrofit as the fleet size increases. AVTA was able to accommodate the growth from zero BEBs to 50 much easier than the transition from 50 to 89 BEBs. BEB scale up is challenging due to infrastructure demands, financial requirements, and political preparation, in particular. However, AVTA is on track to complete its "fully green by 2018" goal.

King County Metro

Located in Seattle, Washington, King County Metro operates 1,474 buses. King County Metro has operated three 40′ Proterra electric buses (pictured in Figure 35) in its fleet since January 2016, accumulating 100,000 miles as part of a pilot project on Routes 226 and 241 as shown on Figure 36 with charging station locations. Local funding and a federal TIGGER grant supported the deployment. King County Metro recently announced that it will acquire 120 additional BEBs by 2020, starting with an order of up to 73 BEBs from Proterra (Fryer 2017). The King County Metro BEB dashboard information is presented on Table 14 as well as climate considerations on Table 15.

Figure 35. King County Metro's BEB. Source: Fryer.

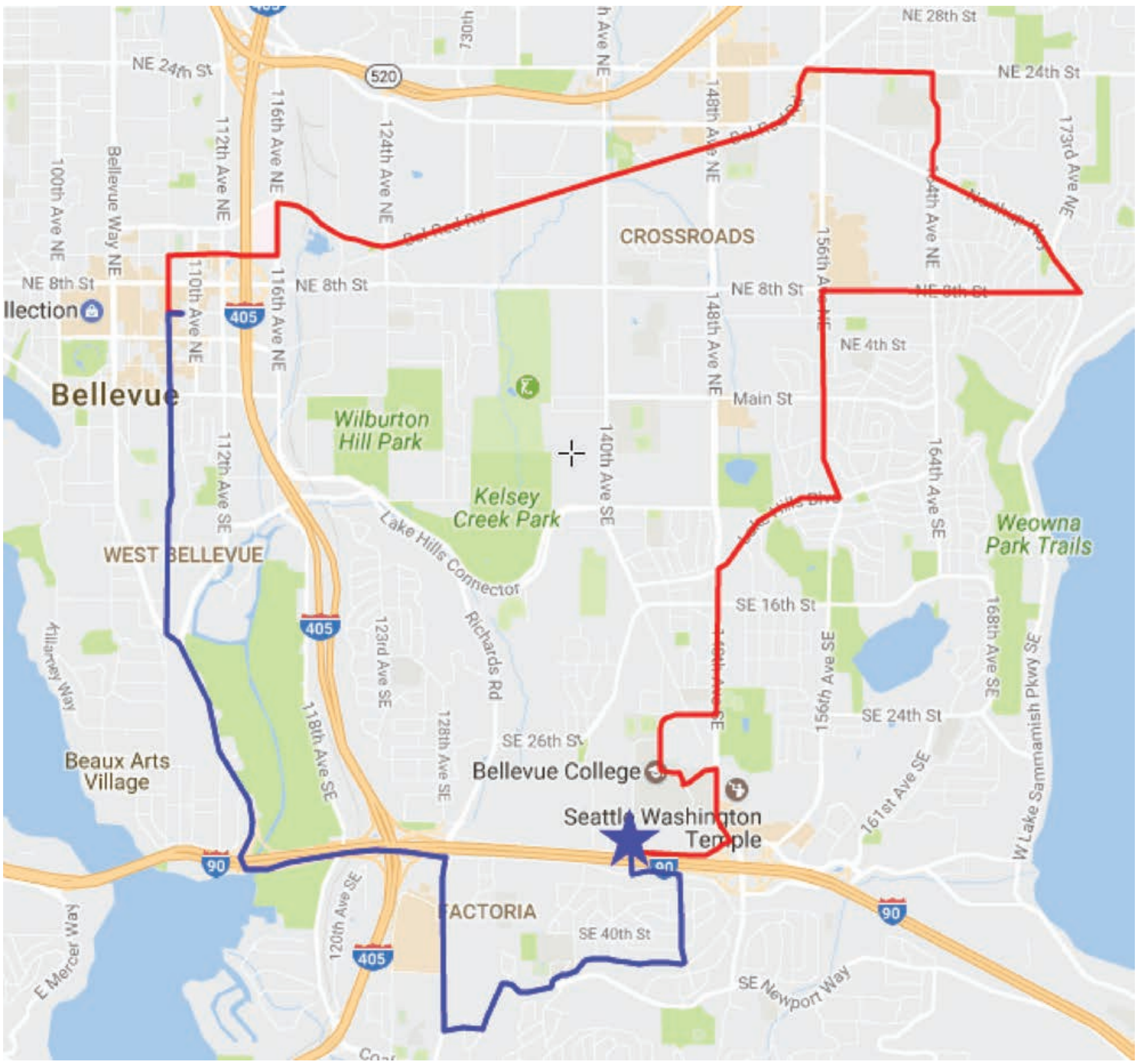


Figure 36. King County Metro's BEB routes, with the charging station shown as a blue star. Source: Fryer.

Table 14. King County BEB characteristics.

King County Metro Dashboard		
BEB fleet size (OEM)		3 - 40′ (Proterra)
Total fleet miles accumulated (per month)		100,000
Total months in operation		12
Traction battery size		105 kWh
Number of depot chargers		1
Number of on-route chargers		1 (overhead conductive)
Average route length – BEB Fleet		18.3 miles
Daily range requirements – BEB		181 miles
Average route speeds (mph)		15.7 mph
BEB cost		$797,882
Depot charger cost	Equipment (per charger)	$60,000
	Installation (per charger)	included
On-route charger cost	Equipment (per charger)	$600,000
	Installation (per charger)	$241,510
Funding sources	TIGGER and local funds	

Source: Center for Transportation and the Environment.

King County Metro's Experience

King County Metro focuses on providing the best operator experience with their BEB pilot program. In doing so, they have established a close working relationship with Proterra, the bus OEM, to address the challenges associated with deploying the new technology and, in particular, the novel ground-up electric bus design. King County Metro needed to ensure that some of the overall design elements of the buses satisfied their operator requirements, such as proper site lines, mirror placement, and regenerative braking feel. Proterra worked closely with King County Metro to address operator feedback and ultimately modified certain design elements of their buses, going as far as building a mock-up driver cabin to test various design options. The relationship that formed throughout the process was not only advantageous to King County Metro because it received better buses but also aided Proterra in product development. Proterra and King County Metro continue to work together to address issues that came to light when validating the buses in King County's specific operational environment. For instance, bus tuning was required when the transmission began "hunting" between gears on Seattle's hilly streets.

King County Metro currently has one on-route overhead conductive charger, which is located at the East Gate Park and Ride. With the procurement of more buses, the agency plans on adding more stations after addressing anticipated challenges with scaling up overhead on-route charging infrastructure. For example, software upgrades will be required so that the chargers can communicate and coordinate signals to "pick up" multiple buses and move them into the correct position for connection to chargers. Because King County Metro is planning to eventually add three to five more chargers at the park and ride along a common rail, it anticipates

Table 15. King County Metro's average annual climate.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Av. High (°F)	47	50	54	58	65	70	76	76	71	60	51	46
Av. Low (°F)	37	37	39	42	47	52	56	56	52	46	40	36

Source: U.S. Climate Data.

having fast chargers next to each other with multiple signals competing to connect to one or more buses within the same proximity. The agency is working with Proterra to determine how the chargers will determine the correct bus to "shake hands with," control, and charge, which is a technology issue that must be resolved.

Another infrastructure challenge that King County Metro and Proterra have experienced involves overhead clearance. If it snows and the bus drives on the packed snow, the height of the bus will be greater and the charger will either have to automatically adjust itself or be raised. Similarly, a semi-truck has already hit the charger because it accidentally pulled into the charging lane. The agency's solution of raising the charge head would help address both problems, but King County Metro is working on putting up clearance requirements and/or restriction bars for the charging lane as a short-term solution and they have added signage and striping to keep tall vehicles from entering the charger lane.

A problem that naturally arises with having three BEBs to one charger is managing the logistics of ensuring that each bus is allowed sufficient charge time. Buses currently only overlap charging time slots if there are delays due to traffic. Each BEB's layover location is 15 minutes at the charging station, but it only takes around 8 minutes for the bus to charge. A minor challenge that King County Metro experiences is that the bus drivers will get out and walk around during the layover, and if another bus pulls up during the layover, the first bus will be done charging but lacking a driver to disconnect and pull out. King County has now made sure the drivers stay near the buses during charging in case another bus needs to charge. King County Metro does have a depot plug-in charger; however, mechanics generally only use the plug-in charger sparingly if at all during maintenance. The plug-in charger functions primarily as a backup. King County is currently evaluating all of the trade-offs associated with depot-charged extended range buses versus overhead fast-charged buses. Seventy percent of King County Metro's bus blocks are greater than 140 miles and must be provided for.

As with other agencies deploying BEBs, King County Metro has worked closely with their two utilities, which have been supportive of the deployment. King County Metro does not actively manage the utility rates, as they have limited options available to them, but they do track the electricity costs. Eventually with the procurement of more buses, King County Metro is likely to shift toward slow charging at the depot and will train employees on smart charging practices, that is, assessing when buses need to be charged and to what extent.

King County Metro is also looking to advance support technologies and software to help manage and optimize on-route charging during the day. For example, this could be technologies and software for managing buses that are competing for a charge and letting the drivers know the minimum SOC that a bus needs to have before the driver can pull out of a charge station and still complete the next loop.

King County Metro's training program focuses on informing operators of the key differences between BEBs and conventional buses and how to adapt to them. The biggest obstacle that the agency had to overcome was filtering out "phantom" complaints from real ones; that is, determining if complaints needed to be fixed by the agency or were simply due to the operator not understanding any new or unique functionality of the BEBs. It also found that verifying that operators understood and retained the information through follow-up training was useful. Proterra provides an onsite support person to address issues throughout the warranty period, which has also been helpful for consistent training.

King County Metro's Advice

Community plays an important role in the success of a project, whether it is local stakeholders, political leaders, or other transit agencies. The local stakeholders that King County

Metro involved included the utility companies, climate action nonprofit groups, low-income groups, and people disproportionally affected by the poorer air quality, and it interacted with them by holding community outreach meetings and releasing a "feasibility report" to solicit input on their plans of action. The community input provided a good guideline and not necessarily a direct plan of action for the agency. Political leaders played an important role in the project. Their support is critical to program success. King County Metro found it very useful to stay up-to-date on developments and lessons learned in the BEB industry by designating a team from its staff to stay involved in industry committees and meetings, such as APTA's Zero Emission Bus Standard Bus Procurement Guidelines development committee.

According to King County Metro, the factors that a transit agency needs to consider when transforming its fleet to BEBs come down to five questions: What are your service and fleet needs? What are the costs? Do you have supporting infrastructure? What will be the environmental impact? What is the financing for the project? After assessing these and other topics, the transit agency will be prepared to move forward with the transition.

City of Seneca

The City of Seneca (Seneca), South Carolina, provides three fare-free transit routes, including a business circulator route, a residential circulator route, and an express service linking downtown Seneca to the City of Clemson, Clemson University, and routes within the Clemson Area Transit (CATBUS) system. These routes are shown on Figure 37, with charging stations marked. The City of Clemson is 8 miles from Seneca. Seneca has been operating the "first in the nation" all-electric fleet of transit buses (example displayed on Figure 38) and has demonstrated successes in operability, reliability, cost savings, and environmental benefits. Seneca replaced its three-diesel bus fleet with six Proterra BEBs under three procurements. Seneca prepared extensively for the conversion and approached it with a "no turning back" attitude. Seneca simply considered it a purchase of new transit buses that happened to be alternatively fueled. The BEBs were expected to provide the same level of performance and keep the drivers and passengers as comfortable as the previous diesel buses. These expectations were well defined, and there was a concerted effort to ensure all stakeholders involved shared in these expectations. The bus manufacturer, Proterra, provided assistance to Seneca throughout the entire project and helped the city overcome any technical hurdles with the new technology. CATBUS staff, experienced in bus procurement, was vital to overseeing the construction and deployment of the Seneca fleet. City officials and, in particular, the City Administrator played a pivotal role in engaging the community and involving the appropriate stakeholders throughout the process. Seneca's attitude and approach to their BEB deployment, while relatively small, set a good example for any transit agency looking to deploy BEBs in their fleet. The Seneca BEB fleet dashboard information is presented in Table 16 as well as climate considerations in Table 17.

The City of Seneca received awards through FTA's TIGGER and Livability programs to support the purchase of the all-electric buses. Seneca deployed the buses in 2014, and within a 2-year period the buses had recorded approximately 400,000 miles. Seneca's deployment is supported by both on-route fast chargers and depot plug-in chargers. Seneca placed its two fast chargers in locations that are served by different electrical grids in case one lost power. Seneca has found that both the bus operators and mechanics rely predominantly on the fast chargers. The buses usually come back to the depot with a 98% battery SOC since the operators prefer to top off charge at the fast charger. Seneca did note that utilizing two separate types of charging infrastructure requires knowledge of separate systems and architecture, but the benefits of having both outweigh any drawbacks.

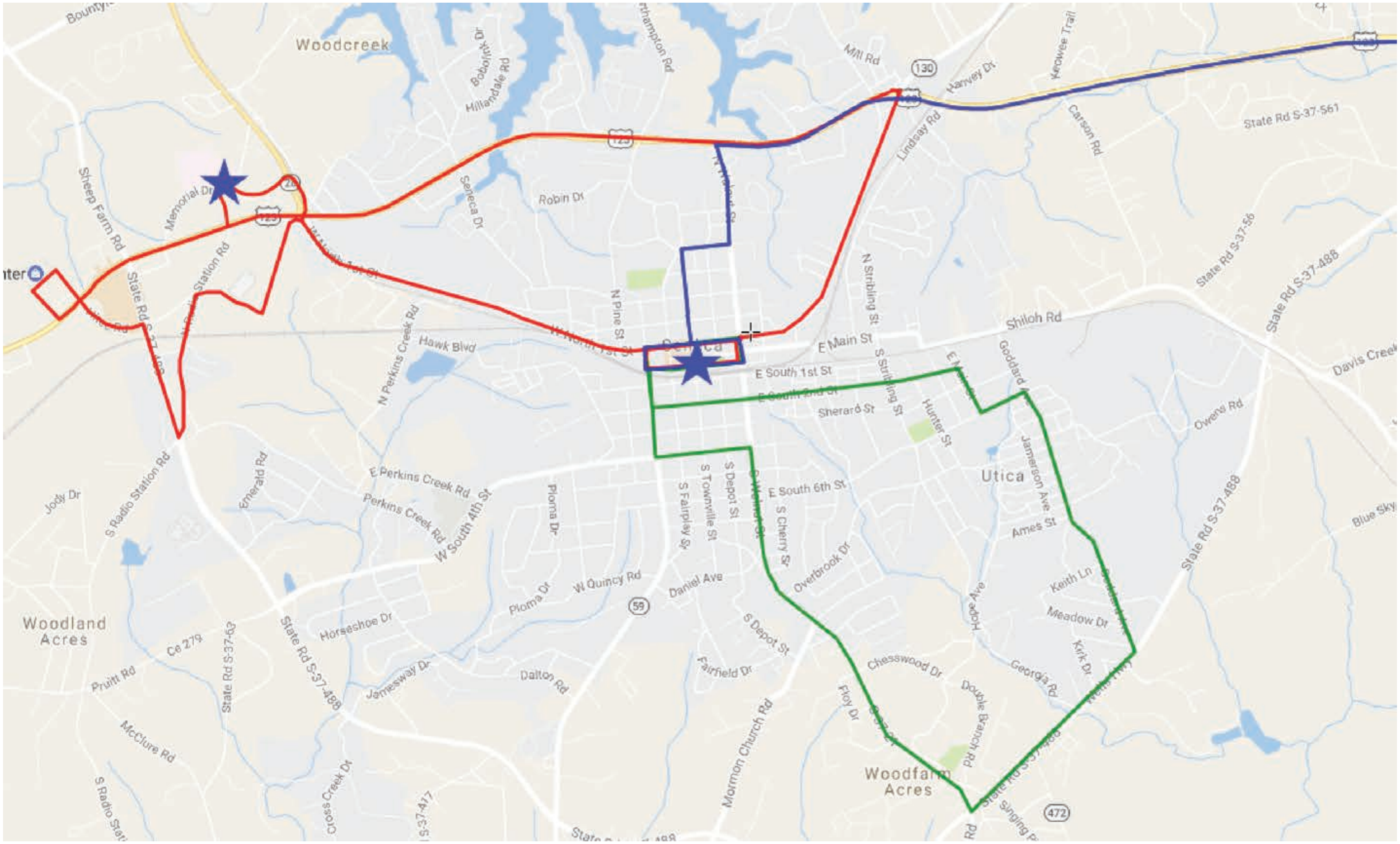


Figure 37. City of Seneca's BEB routes, with charging stations at the blue stars on the map. Source: City of Seneca.

Figure 38. City of Seneca's BEB. Source: Young.

Table 16. City of Seneca BEB characteristics.

City of Seneca Dashboard

BEB fleet size (OEM)		5 - 35′; 1 – 40′ (Proterra)
Total fleet miles accumulated (per month)		32,818
Total months in operation		29
Traction battery sizes		74, 88, 105 kWh
Number of depot chargers		1
Number of on-route chargers		2 (overhead conductive)
Average route length – BEB Fleet		15 miles
Daily range requirements – BEB Fleet		257 miles
Average route speeds		40 mph
BEB cost		$950,000
Depot charger cost	Equipment (per charger)	$60,000
	Installation (per charger)	$8,000
On-route charger cost	Equipment (per charger)	$600,000
	Installation (per charger)	$225,000
Funding sources	TIGGER III, Livability, State Vehicle Replacement Funds, local general funds	

Source: Antelope Valley Transit Authority.

Table 17. Average annual climate of Clemson, South Carolina.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Av. High (°F)	52	56	63	72	80	87	90	89	83	73	64	54
Av. Low (°F)	30	33	39	47	56	65	68	68	61	49	40	32

Source: U.S. Climate Data.

Seneca's Experience

Operations. Seneca operates a business loop, a residential loop, and an express route. Buses serve the business loop and the residential loop in a figure 8 manner. Seneca's operation occurs on a pulse schedule. All buses meet at the Railroad Park transit center in downtown Seneca after each trip and leave at the same time. A pulse schedule allows passengers to easily transfer and connect to the other bus routes. One of the overhead fast chargers is located at the downtown transit center, while the other fast charger is located at a stop midway through the business loop. The express bus takes priority at the downtown charger, while the buses serving the residential/business loops primarily charge on the business loop charger. If a bus is low on battery SOC, then it takes priority over the others at either charger. All of the drivers communicate to ensure that the buses stay sufficiently charged.

Utility Rate Structure. The agency originally was on an electricity rate plan that had demand charges, which involved a flat fee of $13 per kilowatt hour for first demand on each on-route charging station. The fee was assessed at the first use in the month. While intended to help manage utility costs, the rate structure had an unforeseen negative effect: the bus drivers did not want to be the ones responsible for incurring the first demand charge, often in the thousands of dollars, at the second station. The fast-charger locations are close enough that drivers opted to charge only at the first station. The resulting overuse of the first charging station caused increased charger traffic at the main station, additional stress on the drivers, and reliability issues with the second charger due to lack of use. Seneca then chose to switch to a rate structure with higher energy use charges but no demand fees to alleviate these issues. The energy costs decreased from $1.50 per kWh to $0.90 per kWh.

Since switching to the new rate structure, use of the second charging station has increased. However, the new rate structure does not capture the cost of usage as accurately as demand charges do, prompting Seneca to consider switching back to the demand-charge rate. If the city pursues this option, they plan to educate drivers that incurring the demand charge is expected and the cheapest overall option.

Performance in a Hot, Humid Climate. Deployment in Seneca was an opportunity to evaluate the performance of BEBs in a hot, humid climate where temperatures reach into the 100-degree range in summer months. There was concern as to how the batteries would perform and react in the environment. In the summer, the battery temperatures start off cool and then naturally increase with each charge cycle on the route loops. While they go through periods of heating and cooling with each loop, the peak temperature gradually increases throughout the day. Seneca found that the best solution is to utilize one of its spare BEBs during hot days and replace the longest route bus, the "express" bus, with a bus that has been sitting at cooler ambient temperatures. Seneca also employs one of Proterra's "catalyst" buses that have a longer range on the longest route in order to decrease the amount of charge cycles that the bus needs.

Seneca's Advice

Seneca encourages any transit agency deploying BEBs to establish a set of key performance indicators at the beginning of the deployment and monitor the results versus results from conventional buses. The city had access to detailed utility cost records, which allowed the city to make informed decisions regarding rate structures. The key performance indicators are also useful for tracking and analyzing life cycle costs that are specific to the agency. While it is valuable to learn from others' experience, each agency will have its own unique set of operating characteristics that will influence the costs associated with electricity charger siting, electricity rates, environmental effects on bus efficiency and operations, and other factors associated with the deployment.

Table 18. Foothill Transit characteristics.

Foothill Transit Dashboard

BEB fleet size (OEM)		15 - 35′, 2 - 40′ (Proterra)
Total fleet miles accumulated (per month)		29,000
Total months in operation		Initial order: 3 years and 9 months; Second order: 2 years and 8 months
Traction battery sizes		72 kWh
Number of depot chargers		0
Number of on-route chargers		2 (overhead conductive)
Average route length		16.1 miles
Daily range requirement		171 miles
Average route speeds		10.6 mph
Bus capital cost		$789,000 (base price); $823,000 (with add-on equipment)
Depot charger cost	Equipment (per charger)	Not Applicable
	Installation (per charger)	Not Applicable
On-route charger cost	Equipment (per charger)	$500,000
	Installation (per charger)	$200,000
Funding sources		ARRA, TIGGER, TIGER, Low-No, California HVIP

ARRA = American Recovery and Reinvestment Act of 2009; HVIP = Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project.
Source: Center for Transportation and the Environment.

Another successful aspect of deployment, CATBUS insisted on a month-long period of shadow service to ensure the BEBs were capable of meeting the same duty cycle of the diesel buses that they were replacing. Not only did shadowing verify the range capabilities of the BEBs but it also rung out any technical issues with the advanced buses. The shadow service was important because it demonstrated that the BEBs would perform comparably to the diesel buses and gave the city of Seneca confidence that the transition to all-electric transit service would be successful.

Foothill Transit

An evaluation describing Foothill Transit's BEB operations experience was synthesized in the literature review earlier in this report, but Foothill Transit remains a useful case example as it provides the opportunity for the agency to share additional experience, share considerations, and provide advice. As shown in Tables 18 and 19 and Figures 39 through 41, Foothill Transit's current BEB fleet consists of 15 35′ Proterra Fast-Charge and two 40′ Proterra Catalyst Fast-Charge BEBs that are supported by two on-route overhead chargers located at the Pomona Transit Center. The 17 fast-charge BEBs have a range of just 35 miles on a single charge and are deployed on Line 291, a 16.1 mile-round-trip route shown in Figure 42. The buses charge at mid-point of the route at the transit center, which is part of the route's regular stop. Foothill Transit also has a shop charger that it used to charge buses that had undergone maintenance activities, if necessary. Foothill Transit is in the process of expanding its all-electric fleet with an additional 13 40′ Proterra E2 extended-range BEBs and two additional overhead fast chargers that will be installed at a transit center in the City of Azusa adjacent to the Metro Gold Line Station.

Table 19. Average annual climate of Pomona, California.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Av. High (°F)	68	69	69	74	77	82	89	89	87	80	73	68
Av. Low (°F)	42	44	45	47	51	55	59	59	58	53	45	41

Source: U.S. Climate Data.

Figure 39. Foothill Transit's BEB. Source: Piellisch.

Figure 40. Foothill Transit's 40-ft Catalyst BEB. Source: Foothill Transit.

Figure 41. Foothill Transit's 35-ft Catalyst BEB. Source: Foothill Transit.

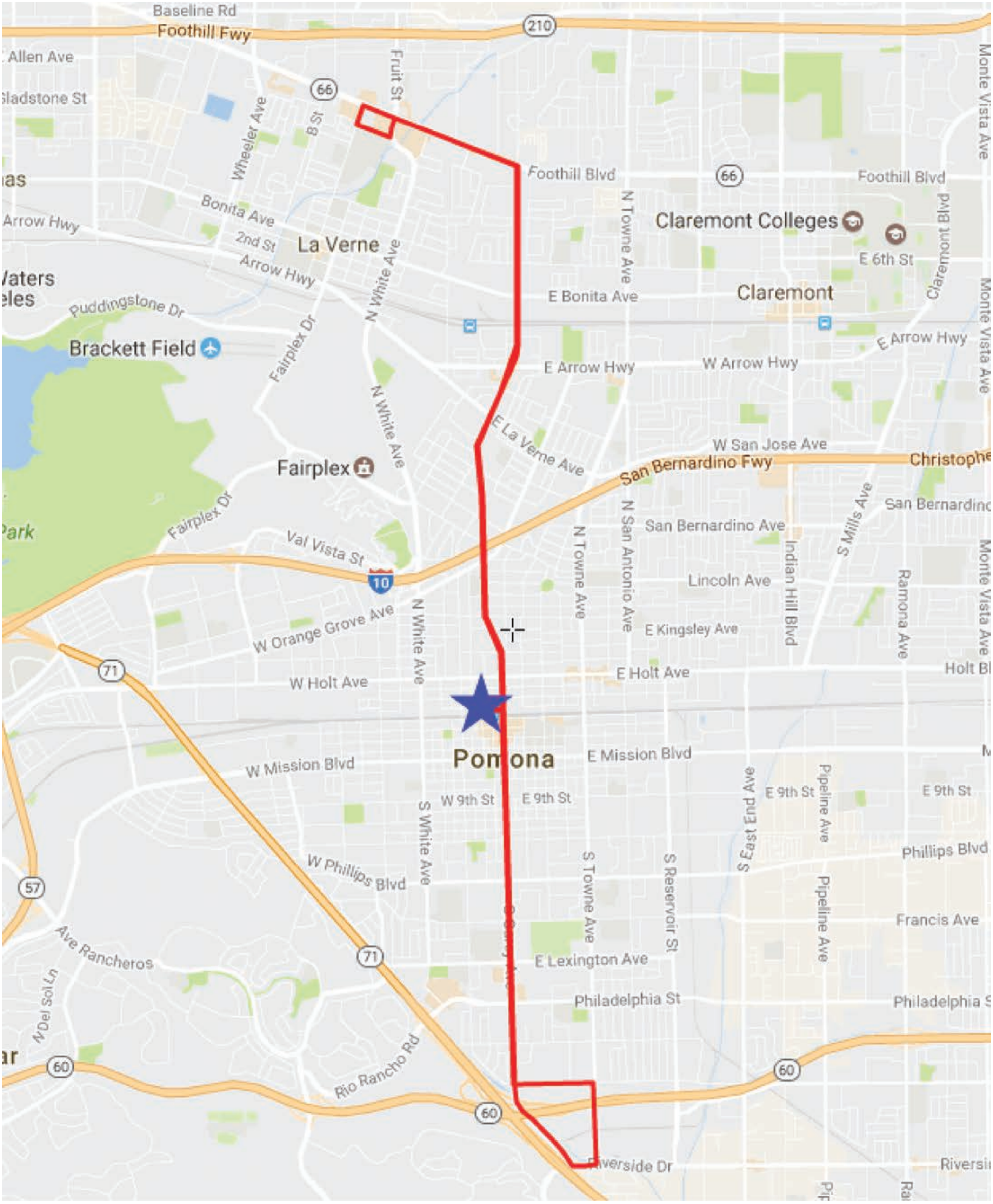


Figure 42. Foothill Transit's BEB route, with the blue star showing where the charging station is located. Source: Foothill Transit.

Foothill Transit's Experience

While the NREL report on Foothill Transit does an excellent job of providing a documented comparison between the agency's CNG and BEB fleets, this TCRP case example focuses on the agency's experience in deploying electric buses and lessons learned from its operation. One of the biggest maintenance items that the agency has with CNG buses is the engine itself, some of which have been breaking down with only 60,000 miles on them due to premature cracking of pistons in the CNG engines. In addition, the CNG buses require additional consumable products (i.e., oil, filters, and other fluids) to replace during planned maintenance inspections as opposed to just labor hours on BEBs. The BEB propulsion system is much simpler and requires less planned and unplanned maintenance. Battery replacement costs are usually identified as the weakest link for BEBs, but the agency points out that with any internal combustion engine, the transit agency will still have to perform mid-life heavy maintenance, most likely replacing the engine and transmission. However, an admitted trade-off for BEBs in large-scale deployments is the complexity of operations and the need to micro-manage service planning. Foothill Transit expects that in the coming years BEBs and their support tools will continue to advance, which will alleviate this complexity.

The agency recently installed an overhead fast charger at its Pomona Operations and Maintenance facility. Installation of the fast charger would allow the quickest "refueling" and be comparable to the experience of fueling their CNG buses. Installation of fast chargers allows Foothill Transit to address a number of scale-up issues by requiring much less infrastructure than plug-in slow chargers to accommodate its future expansion. Installing the infrastructure to support future deployment presents a challenge for Foothill Transit. The agency lacks the physical space at the depot to install slow chargers to support all planned BEBs. Therefore, overhead fast charging would allow semi-automated, 10-minute charging as the bus is going through the end-of-the-day wash and checkout. Multiple buses can be charged rapidly from a single charger and would help alleviate the space requirements that would be required for having one or two plug-in slow chargers installed per bus, which would ultimately be a more cost-effective solution. As it scales up its BEB fleet with 14 extended range BEBs, Foothill Transit is investigating its bus depot charge strategy and has carefully considered plug-in slow charging as well as strategies such as combining the overhead fast charging with a blocking schedule, in which the buses come into the yard in different waves in order to level out the charge profile.

The buses have successfully made the in-service charge connection approximately 95% of the time. The 5% of missed charges is due to a combination of alignment requirements inherent to the charging infrastructure (including the autonomous functionality and geometry), operator error, and lack of sufficient training. In its early deployments of BEBs, Foothill Transit was able to utilize a select, well-trained group of three drivers to operate the buses. However, as the BEB fleet has grown, the agency has expanded the pool of bus drivers, which has affected the level of operator experience.

Foothill Transit also adjusted its service in order to balance the layover times and the demand rate and optimize its overall electricity costs. Because the costs substantially increase if the agency goes over a specific amount of power at one time, it decided to reduce its maximum charge power level and extend the layover length from 5 to 7 minutes to remain under the power threshold.

Currently within the BEB industry overhead fast-charging methods and equipment are unique to each BEB manufacturer. For instance, a Proterra-supplied overhead fast charger will only fast charge a Proterra BEB, and vice versa. Foothill Transit supports standardization of overhead charging infrastructure in order to allow for interoperability between BEBs and the chargers. An initiative is under way through SAE to address standardization of the charger interface for overhead fast charging. The SAE J3105 standard aims to address "on-route conductive charging solutions that serve to promote all day operation of high capacity electric vehicles," which is currently not addressed in other SAE plug-in charge standards. Standardization and interoperability allow agencies and fleets to invest in fast-charge infrastructure that meets the standard and then have the freedom to purchase any bus that also meets the standard and expect that they will safely and effectively work together. This combination thus addresses a barrier to BEB market growth and commercialization.

Public interaction with the BEBs has been mixed for Foothill Transit. As with most transit agencies, riders, especially younger generations, generally react positively to the agency's shifting toward more environmentally friendly transportation. However, the agency's BEBs provide service to a larger portion of the working commuter class as well as to passengers who rely solely on public transit as their means of transportation. Many of these passengers understand that the buses are electric and that they are good for the environment but place a much higher priority on reaching their destination reliably and as fast as possible. Thus they become frustrated and react negatively when the buses require a longer layover and/or have (early stage) technical issues. Additionally, Foothill Transit reported that riders get confused when the bus is docking at the charging station. In the autonomous docking process, the bus will halt for a few seconds after the driver stops and allows the automated process to take control. Passengers or people around the bus then assume that it is stopped and proceed to stand up or walk in front of it. The bus then lurches forward again, shifting on-board passengers or startling passengers attempting to pass in front of the bus or stow bikes. For these reasons, on a scale of 1 to 10 with 10 being the most positive, the agency gives its public's reaction a rating of 6.

Early in deployment, Foothill Transit also encountered issues with pranksters pushing the Emergency Stop button on the overhead charger at the transit center. The agency put a plastic covering over the button with a sign saying that the area is under surveillance, which helped cut down on the incidents, but the button is still pushed on occasion.

Foothill Transit's Advice

Partnering with the local utility, as has been mentioned in other case examples, proved to be a vital part of Foothill Transit's BEB program development. While the agency's utility, SCE, was involved early in the process, they were originally not aware of the agency's intentions to scale up their BEB fleet. Issues arose regarding application of electricity rates—the agency had initially obtained a waiver from demand charges by the California Public Utilities Commission, which expired in December 2015. Foothill Transit's advice is to engage the utility early in the planning process for BEBs and understand the impacts of the planned scale-up deployment on the transit agency's energy needs. Prior to engaging with the utility, the transit agency needs to have an understanding of the power requirements on the planned routes. Modeling and simulation were useful tools for Foothill Transit because they allowed for energy and power demand projections in different operating environments, for example, fluctuations in temperature due to seasonal changes.

The agency also emphasized the value of stakeholder involvement. The agency suggested early engagement with any groups or individuals who may be affected or who may need to support the deployment of BEBs. Educating groups such as the yard managers, permitting agencies, community groups, and the board of directors regarding both the limitations and the benefits of BEB technology will help the project run more smoothly. Foothill Transit was fortunate to have two internal support staff, or champions, working on the BEB program—one of whom was focused on technical aspects and one of whom was focused on legislative issues. The technical staff handles anything regarding operations, while the legislative staff not only manages funding opportunities but also interacts with the utility companies and other political stakeholders. Foothill Transit would encourage as many champions as feasible to help support a successful BEB program.

Table 20. IndyGo BEB characteristics.

IndyGo Dashboard

BEB fleet size (OEM)		21 - 40′ (Complete Coach Works)
Total fleet miles accumulated (per month)		500
Total months in operation		16
Traction battery size		305 kWh
Number of depot chargers		22
Number of on-route chargers		0
Average route length – BEB Fleet		90 miles
Daily range requirements – BEB Fleet		150 miles
Average route speeds		15 mph
Bus capital cost		$579,000
Depot charger cost	Equipment (per charger)	$10,000
	Installation (per charger)	$5,000
On-route charger cost	Equipment (per charger)	Not Applicable
	Installation (per charger)	Not Applicable
Funding sources	TIGER	

Source: Center for Transportation and the Environment.

IndyGo

As shown in Tables 20 and 21 and Figures 43 and 44, the Indianapolis Public Transport Corporation, IndyGo, currently has 163 buses, including 21 BEBs. IndyGo used funding from a $10 million Transportation Investment Generating Economic Recovery grant awarded in 2013 to deploy 21 40′ BEBs provided by Complete Coach Works, which converted IndyGo's existing GILLIG low-floor buses with its zero emissions propulsion system. IndyGo is also in the process of procuring 13 additional 60′ articulated buses to begin electrification of their Bus Rapid Transit lines. IndyGo utilizes depot charging to support the BEBs that serve routes that are an average of 90 miles long. IndyGo stressed the importance of involvement and education of political stakeholders as well as robust, continued BEB training for drivers and mechanics.

IndyGo's Experience

One of the early challenges for IndyGo was identifying the different ways in which problems were manifesting themselves and determining what was normal for the technology and what was not normal. Recurring issues versus isolated issues were identified as well. Early in the deployment of advanced technology buses, it is difficult to fully train maintenance personnel on the technical details of the new systems, especially troubleshooting. As with many new technologies,

Table 21. Average annual climate of Indianapolis.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Av. High (°F)	36	40	52	63	73	82	85	84	78	65	52	39
Av. Low (°F)	20	24	33	43	53	62	66	64	56	45	35	24

Source: U.S. Climate Data.

Figure 43. IndyGo's BEB. Source: Complete Coach Works.

a simple reboot of the system becomes the general protocol when maintenance staff runs into problems, but it does not necessarily address the root cause of the problem. Furthermore, sometimes technical details and resulting impacts can be misunderstood or lost in translation, especially when communicating issues and solutions to project stakeholders.

Addressing the political needs, both internal and external, associated with a high profile project can also be challenging and was an important, early lesson to learn for IndyGo. Political needs and desires must be addressed in order to sustain support and funding for a project; however, they can sometimes compete with the needs of the technology. Competing needs and desires must be carefully weighed and addressed by the project coordinators. IndyGo also reported that incorporation of a BEB fleet presents unique challenges that are outside the norm for a transit agency and that require careful communication as they are addressed. Minor issues regarding systems that management may not be familiar with can inadvertently be perceived as big issues. Therefore, education and proper framing of issues become important when reporting project status.

IndyGo has found that drivers can forget some of the unique operating characteristics associated with BEBs when they switch between diesel buses and BEBs, an omission that can be addressed with recurrent training. IndyGo's training department now hosts annual in-service training in an effort to continue to educate drivers and ensure the most efficient and effective operation of the BEB fleet. IndyGo also received support from the bus OEM, Complete Coach Works, which provided a resident trainer for mechanics that guides a team specifically dedicated to electric vehicle maintenance.

IndyGo supports their deployment with 22 plug-in depot chargers. Depot charging was a more viable option than on-route fast charging because the routes are sometimes adjusted for events and detours, such as when there is a parade. IndyGo reported that the operation of 22 depot chargers requires significant power to meet the demand. To help manage the load, IndyGo established two different circuits to serve the bus islands. IndyGo also supplemented their electricity demand by installing solar panels. The 1-megawatt solar panels were funded through a $3 million State of Good Repair grant through the Federal Transit Administration. The panels were installed on the garage roof and provide the energy required by almost all of the chargers. For scaling-up BEB deployments, the agency is considering adding a battery bank or building a canopy over the workers' parking lot that would allow for the installation of additional solar panels.

IndyGo has a charger for every BEB bay and stated that the plug-in process goes smoothly. IndyGo currently relies on their general service employees on the night shift to plug in the

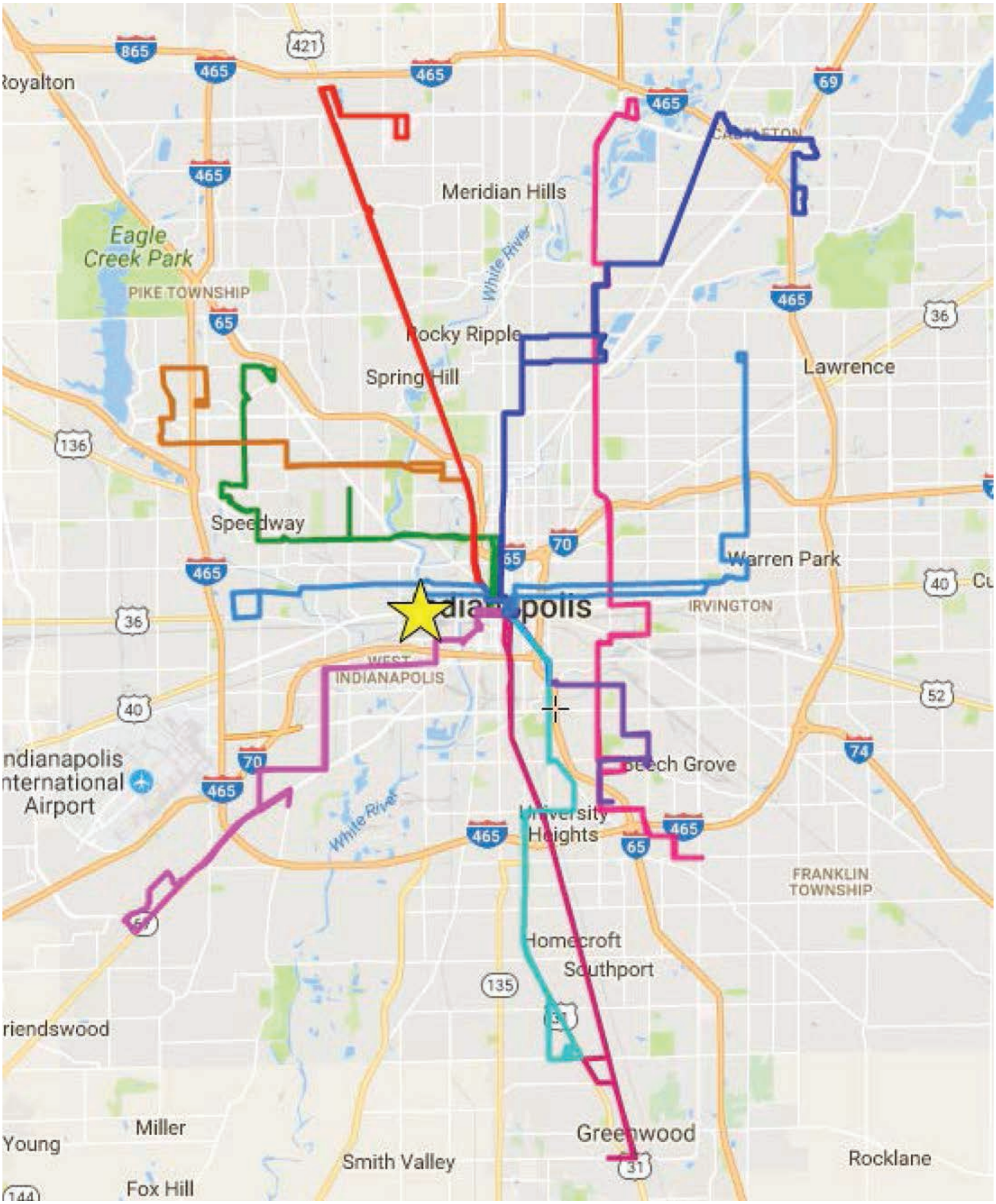


Figure 44. Sample of the routes on which IndyGo deploys BEBs. Yellow star represents the depot where IndyGo houses its 22 chargers. Source: IndyGo.

vehicles. Supervisors provide the oversight during their normal walk around to ensure the charging is properly started. Drivers unplug the buses in the morning before beginning their routes. IndyGo procured the charging infrastructure separately from the BEB procurement, but the process was simple and they encountered no difficulties in coordinating the two deployments. IndyGo is also considering chargers with plug-in cords that drop down into the bays, but this is still in the preliminary planning stages.

IndyGo's Advice

As with the deployment of any new technology, setbacks and challenges are expected. IndyGo's advice to any other transit agency considering deployment of BEBs is to manage expectations, both internally as well as externally. Similarly, IndyGo advises to establish a business case and continue to use it to direct the course of action, paying special attention to the characteristics specific to that transit agency. As mentioned, IndyGo utilizes depot charging because they adjust routes from time to time and have plenty of space to locate the chargers. Also, IndyGo would encourage transit agencies considering deployment of BEBs to look to agencies of a similar size that are already operating BEBs for advice—peers are one of the best resources to truly understand the technology and the benefits and challenges associated with deployments.

Case Example Summary

The case examples allow the transit agencies to give any advice to those agencies that are converting to BEBs. The City of Seneca emphasized asserting that BEBs are expected to perform like diesel buses. The agency obviously understood the limitations with the new technology, but the high expectation kept the project under way. To keep the expectation prevalent in the planning and operation stages, an agency could hold community stakeholder meetings and ensure backing of the project all the way up the chain of command, as King County suggested. King County also found that paying attention to other agencies' practices and developments throughout the process was advantageous but, according to IndyGo, the observed agencies should be similar in size to the on-looking agency. Both Foothill Transit and AVTA suggested keeping the full business plan in mind when making preliminary decisions. However, to have a comprehensive yet successful business plan, all five agencies recommended having at least one or two champions of the project, according to Foothill Transit, to lead it around obstacles.

CHAPTER 7

Conclusions

The number and variety of BEB models on the market have grown significantly in the last decade as has the number of BEB deployments. Most of the agencies surveyed for this synthesis report have BEB fleets that are up to 10% of their total fleet size, although some have fully electrified their fleets or are on the pathway to full electrification. The growth in BEB deployments is due to community and transit agency recognition that BEBs are cleaner, quieter, simpler, and smoother than their conventional bus counterparts due to their all-electric propulsion and auxiliary systems. These attributes result in zero tailpipe emissions, zero dependence on foreign oil, better ride quality and experiences for passengers and drivers, and the potential for lower operational costs.

This is a unique point in time for the emergence of clean transportation technologies. BEBs are being deployed in greater numbers at transit agencies across the country and are being operated successfully in revenue operation. With some exceptions, the BEB fleets are small and have only been in service for around 5 years or less. Much of the bus development and successful deployment practices have been accomplished through trial and error. There are many variables that go into procuring and deploying a BEB fleet, both with the buses and with the associated charging infrastructure. Choosing the right BEB type and charging method in this complex space can have significant implications on bottom line costs and operational impacts. While much has been learned about what works and what does not work when deploying BEBs, more experience, information, tools, and data are needed to be able to reduce the costs associated with BEB fleets and their operational impacts.

The approaches of transit agencies to BEB deployments have been varied, creative, and full of lessons learned. This synthesis was completed through a literature review, a comprehensive agency survey, and multiple case examples to better understand and report the state of the practice for BEB deployments to date. This synthesis report will be a valuable resource for both agencies just beginning to add BEBs to their fleet as well as for experienced BEB fleet owners.

The literature review revealed interesting data-driven statistics about planning and operations. For example, it confirmed that the capital costs of BEBs are more expensive than conventional buses but that costs are coming down and there are opportunities for transit agencies to solicit external funding to offset costs. These costs can also be offset by reduced maintenance costs and operational costs. However, operational costs can be heavily dependent on utility rates, despite an almost four times improvement in fuel economy. Understanding utility rates, their effect on the business case, and the potential to optimize rate structures for BEBs is a need for the industry. Also, BEB availability is reported to be comparable to that of CNG buses, 90% to 93% availability for BEBs versus 94% availability for CNG buses, according to NREL. Ultimately, close coordination with stakeholders including bus OEMs, utilities, and local officials was identified as an important component for a successful BEB deployment.

The survey results provided information regarding a broad variety of BEB deployments and topics. At the time it was conducted, the survey captured 163 BEBs either delivered or on order (not including options). Most of the responding transit agencies have been operating BEBs anywhere from 12 to 40 months. The types of BEBs that are being procured vary widely from bus size to battery size to charge type (about half are using on-route overhead charging, a few are using on-route wireless, and the rest are relying solely on plug-depot charging) to charger size (in terms of charge power).

All transit agencies rated the forthcoming APTA Zero Emission Bus Standard Bus Procurement Guidelines as important. Almost all agencies stressed the importance of continued public investment in the deployment of BEBs. Only nine agencies stated that they factored electricity rates and/or demand charges into their decisions to purchase BEBs and only about half of respondents did a life cycle cost analysis during the procurement. More than half of the transit agencies used their own experience in combination with OEM predictions and bus trials to evaluate vehicle range, select suitable routes, and determine what type of charging method would be the best fit for their agency. But only a third of the transit agencies used advanced modeling and simulation techniques that could have likely been used to predict some of the operational issues that were reported. The majority of transit agencies responded that these tools of this nature would be beneficial when making decisions regarding range predictions, utility rate analysis, and life cycle cost analyses.

More than half of the transit agencies installed the infrastructure themselves instead of using the bus OEM, infrastructure provider, or consultant and did so before the BEBs arrived. For most agencies, the installation was smooth because the utility and power requirements were well communicated and understood by all stakeholders (OEMs, local utilities, construction architecture and engineering companies, public works, local and state DOTs, and local planners). Almost all of the agencies own their charging infrastructure. Despite the majority of transit agencies using on-route charging having low-traffic density and pull-off lanes or pull-in driveways, 4 out of 11 transit agencies still had incidents associated with other vehicles colliding with the infrastructure.

As reported, many transit agencies were primarily looking to the initial BEB deployment to gain experience with the technology and to understand how it works within their operation and service. It is understandable that a third of the transit agencies were not planning in advance for scale up at this stage. However, half of the transit agencies did anticipate having issues with not having adequate depot or on-route property and right-of-way to support charging infrastructure for full BEB fleets, a quarter of the transit agencies anticipated having issues with adequate electrical power, and half of the transit agencies anticipated having issues with adequate resources (e.g., scheduling and making manual connections) for charging BEBs at scale.

Transit agencies trained an average of 70% of their drivers and an average of 58% of the maintenance staff to support their BEBs, and the training was predominately provided by the bus OEM for both the bus and the supporting infrastructure. Training hurdles included the unfamiliar nature of battery SOC for new operators and understanding range capacities of different products and batteries. Agencies stated that having a factory technical representative on site and operating an initial shadow service worked well to promote maintenance and training learning.

To accommodate the unique operational needs of BEBs, 60% of respondents reported adjusting their schedules. Layover times were the second most adjusted at 40%, followed by bus blocking (20%), and the number of buses serving a route (13%). However, 33% of transit agencies did not make any adjustments.

The general consensus of agencies is that on-route charging works well, as long as there is adequate planning, testing, training, and practice docking. After going through the process of initial deployment and shakeout, BEB availability was an average of 86%, depot charging availability was 99%, and on-route charging availability was 86%. The agencies reported little maintenance issues and liked the relative simplicity of the vehicles. The challenges that agencies have encountered with BEB maintenance center on the learning curve associated with the new technology, which can be addressed with robust training programs and eventual experience. A majority of the agencies (79%) have not had issues with the traction battery. Agencies report that spare parts inventories for BEBs are either the same or lower compared with diesel buses because BEBs require fewer parts (for instance, there is no transmission) and have a longer brake life since they do not need to be replaced as often. However, the availability of parts and long lead times have been problematic due to the relatively small scale of BEB deployments and the lack of a mature supply chain. The majority of the transit agencies are tracking their maintenance and operational expenses. One-half of transit agencies also track the social, environmental, and health benefits of BEBs, specifically those related to GHG emission reduction. The California agencies also track GHG emissions because many of them used state funds that required it.

For the survey overall, 77% of transit agencies that responded are either satisfied with the BEBs (ranking between 4 and 7 on a scale from 1 to 10) or very satisfied (ranking between 8 to 10), and 86% of transit agencies plan on purchasing more. While one agency has already gone fully electric, three agencies responded that they intend to be fully electric by years 2020, 2025, and 2030.

The case examples provide context to the report by identifying specific challenges and the methods that agencies used to solve them. AVTA experienced significant changes in energy consumption (in turn, poor range and higher operational costs) due to inefficient driving habits. To address this challenge, AVTA chose to provide recurrent training and is also considering an incentive program to promote efficient driving. AVTA is also using an advanced charge management system that allows them to optimize bus charging based on the needs of the fleet, to check battery SOC, and to monitor individual driver's performance, among other smart controls. The City of Seneca had issues determining the best utility rate structure for their operation. The city has the option of one rate schedule that includes demand charges but lower energy costs and one rate schedule without demand charges but with higher energy costs. The demand charges introduced unexpected driver habits when they were choosing where to charge and increased their station maintenance costs. The transit agency then switched to a rate schedule without demand charges; even though the electricity costs might be higher, the total cost of ownership is expected to be lower. Foothill Transit's public satisfaction with BEBs was rated lower than expected on the survey since many of their passengers expressed frustration with the technology due to associated layover increases and schedule delays. Many of Foothill Transit's passengers use transit as their primary means of transportation and/or for commuting to work, and the benefits of the technology did not outweigh the drawbacks.

Maintaining schedules and minimizing layover times are important for many transit agencies incorporating electric bus technologies, and methods or tools should be developed to allow for this during the planning stage. King County Metro focused on working with the bus OEM to improve the operator experience of the new electric bus model. On the planning side, King County Metro is focused on addressing scale-up issues for their BEB fleet that include bus-charger communication with multiple chargers in close proximity; dealing with space constraints when installing chargers in large quantities; managing the competing needs of BEBs that share on-route chargers, especially during irregular operations; and charge time optimization. Another general case example finding is that some agencies are opting to charge at fast chargers (overhead conductive or wireless) that are either close in proximity to the bus depot or at the maintenance bays. These agencies are choosing to use plug-in depot chargers only for back-up situations. Fast chargers installed at the depot can be a more economical option than plug-in chargers due to the faster charge times, space constraints, and labor requirements. However, agencies with plenty of space at the depot do not have a problem with plug-in charging for larger scale deployments.

Many of the challenges uncovered during the case examples are being solved through better coordination, better training, and more robust planning, including the use of advanced planning methods and tools at the outset of the project.

CHAPTER 8

Future Needs

The primary future needs identified in this synthesis report include the following:

- The need for continued BEB price reductions to reach parity with conventional bus technologies. BEB costs have been dropping consistently over the last 5 years and have not yet shown signs of stabilizing. Further reductions are expected due to continued technology and manufacturing improvements by the OEMs and battery suppliers.
- All transit agencies that responded to the survey believe there is a need to address the impact of utility rates, and demand and time-of-use charges in particular, on BEB operational costs. In some regions, these costs can far exceed equivalent diesel and CNG costs and can be prohibitively expensive. Furthermore, there is a need to clearly understand how an agency's charge scheme and operation will be affected by the various utility rate components.
- The BEB industry is lacking in standardized technical support and software tools to aid agencies in making procurement decisions and managing BEB fleets. The majority of transit agencies responded that these tools would be beneficial when making decisions regarding range predictions, utility rate analyses, and life cycle cost analyses and adjustments. About half of the agencies stated that enhanced tools would be beneficial when making complex procurement decisions when selecting the right BEB technology for a given application.
- There is a need for comprehensive data and comparison methods for accomplishing of life cycle cost analyses for BEBs, especially during the planning and procurement phase. Standard methods and baseline data would allow objective, accurate comparisons between specific BEBs (and charge methods) as well as between other bus technologies (e.g., diesel and CNG).
- There is a continued need for standard bus procurement guidelines designed specifically for BEBs as well as for the development of charge standards to allow for interoperability with overhead conductive and wireless chargers.

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APPENDIX A

Survey Questionnaire

J-07 SA 41: Battery Electric Buses—State of the Practice

General Section—Agency Characteristics

Page description:

As battery electric buses (BEB) technology continues to evolve and more transit agencies are deploying them, data and experience from early adopters is valuable to transit agencies considering the addition of BEBs to their fleets and to those seeking larger scale electrification. As an early adopter that has experience with BEBs, your feedback is extremely beneficial and appreciated.

This survey aims to provide an overview of the state of the practice regarding BEBs. Please complete each question for your BEB fleet as it currently stands and to the best of your ability. For questions that ask for further explanation, please include any additional information that may not have been clear or covered in elsewhere in the survey. Depending on your BEB experience, the survey is estimated to take about 30 minutes to 1 hour to complete and may cover aspects of BEB planning/procurement, deployment, and operation, including bus- and infrastructure-related questions. Therefore, input from multiple departments at your agency may be needed. If you would like to exit it and come back later, click the "Save and continue later" link in the grey bar at the top of the survey window and input your email address. You'll then receive an email with your own "unique link" to go back to the survey where you left off.

This study is sponsored by the National Academies of Science's Transportation Research Board and being conducted by the Center for Transportation and the Environment.

1. Transit Agency Information *

Transit Agency Name

Transi Agency Location

Street Address

City

State

Zip Code

2. Full Transit Agency Fleet Size

Please provide a quantity for each category *

35'

40'

60'

Cutaway

Other

LOGIC Show/hide trigger exists.

3. What is your agency's current experience with Battery Electric Buses?
*

- Have procured battery electric buses or have them on order, but have not received any of them.
- Have ordered and received some or all battery electric buses but have not put them into transit service.
- Currently operate battery electric buses in transit service.
- None of the above.

4. How many battery electric buses do you have, including BEBs on order (but not including options) as well as delivered?

Please provide a quantity for each category that applies.

35'

40'

60'

Cutaway

Other

5. How were your BEBs procured?

Select all that apply.

- ☐ Standard bus procurement with suppliers competing through transit agency RFP.
- ☐ Through a federal or state competetive grant opportunity (i.e. - FTA TIGGER or LowNo program)
- ☐ None of the above. Describe:

VALIDATION Must be numeric

LOGIC Hidden unless: Question "What is your agency's current experience with Battery Electric Buses?
" #3 is one of the following answers ("Currently operate battery electric buses in transit service.")

6. How long have your battery electric buses been in operation?

Total fleet miles (all BEBs)

Total months - Fleet 1

Total months - Fleet 2 (If needed)

Total months - Fleet 3 (If needed)

VALIDATION Must be numeric

7. What size(s) are the traction batteries in your BEBs?

kWh

kWh

kWh

General Section - Agency Characteristics Continued

8. Charging Characteristics

What charging method do you use or will you use with the BEB fleet?
Check all that that apply

- [ ] Depot chargers
- [ ] On-route overhead conductive chargers
- [ ] On-route inductive/wireless chargers

VALIDATION Must be numeric

9.
How many chargers do you use or will use with the BEB fleet?
Provide a number entry for all that apply.

Depot plug-in chargers

On-route overhead conductive chargers

On-route inductive/wireless chargers

Depot overhead chargers

Depot inductive/wireless chargers

VALIDATION Min = 0 Max = 12

10. How long (in hours) is the fueling/charging process opportunity at night?
(This is reliable time parked in a stall to plug in charge for most cases)

11. Battery Electric Bus Route Characteristics

This section will provide an overview of the routes on which your agency runs or will run the battery electric buses. Route length is the total route length between layovers. A layover is a point where a vehicle stops with passengers possible changing buses, and typically takes longer than one minute. Provide a numerical answer for all that apply.

Min: minimum value (excluding extreme outliers) experienced on the BEB routes
Avg: overall average value experienced on the BEB routes
Max: maximum value (excluding extreme outliers) experienced on the BEB routes

	Min	Avg	Max
Route Length (miles)			
Daily Range (miles)			
Layover Duration (mins)			
Route Speeds (mph)			
Deadhead Distance (miles)			
Deadhead Speeds (mph)			

12. How do buses depart from the transit agency layover locations?

A pulse schedule is a timed transfer between multiple routes in one location (or, in some cases, multiple locations) where buses wait for each other in order to allow passengers to transfer between them.

- ○ Pulse schedule
- ○ Continuously

13. Prior Ability to Service Buses and Infrastructure Equipment

	Yes	No	N/A
Did you previously do any maintenance on electric/hybrid vehicles (high voltage >50V)?			
Did you have any existing high voltage infrastructure (light rail, trolley, etc)?			
If you did, do you maintain that high voltage infrastructure?			
Is there staff available to manage the installation of charging infrastructure?			
Are there certified electricians on staff available to service infrastructure and/or industrial electrical equipment (power coming into facilities, backup generators, etc.)?			

General Section - Agency Preferences

14. What is your BEB charging preference?

- AC Charging
- DC Charging
- Don't know
- No preference

15. Standards and Interoperability

Using the scale below, indicate the importance of the forthcoming on-route charging interface standards to you to allow for interoperability of on-route chargers with BEBs. 1 being not at all important, 10 being extremely important

16. How important are other technologies that enhance the operation of BEBs?

From the list below, indicate the importance of each option.

	Important	Not Important
Provide audible or visual communication that the bus is approaching.	○	○
Remote monitoring and control (charge fault notification, charge durations, shutdown capability, reset charge event) of charge events.	○	○
Provide an audible or visual communication to on-board passengers that the bus is charging.	○	○
Provide an audible or visual communication to pedestrians that the bus is charging.	○	○

17. What type of data/telematics are you interested in?

Select all that apply

- ☐ Range anxiety related (state of charge, range to recharge, charger status, traffic status, etc.)
- ☐ Operations (passengers counted, outside and inside temperatures, energy this cycle, energy over life, energy over vehicle life, drive cycle specifics like hard braking)
- ☐ Maintenance (fault codes)
- ☐ Safety
- ☐ Other - Write In

Planning - Procurement General

VALIDATION Must be numeric

18. What were the costs of the following for your most recent BEB deployment?

Buses (avg per bus)

Depot Charging Equipment (per charger)

Depot Charger Installation Cost (per charger)

On Route Charging Equipment (per charger)

On Route Charging Installation Cost (per charger)

19. External funding opportunities

Please describe the funding sources that you used to purchase your BEBs and infrastructure.

How important do you believe continued public investment is to the deployment of BEBs?

1 being not at all important; 10 being extremely important.

20. What incentives or drivers contributed to your agency's decision to purchase electric buses?

Select all that apply.

- ☐ Environmental regulation
- ☐ Board direction
- ☐ Sustainability program
- ☐ Test applicability to your service
- ☐ Other - Write In

21. Life Cycle Cost Analysis

Please indicate the following.

	Yes	No
Was a life cycle cost analysis accomplished when procuring the BEBs?	○	○
Did you factor electricity rates and/or demand charges into your decision to purchase BEBs?	○	○
Did you purchase an extended warranty for the batteries?	○	○

How long was the base warranty for the batteries?

Months

Miles (if applicable)

Planning - Procurement of BEBs

22. Factors in Procurement

How did you evaluate vehicle range with respect to your route needs?

Check all that apply

- ☐ Used Agency experience
- ☐ Used Consultant
- ☐ Used OEM predictions
- ☐ Operated demo bus on routes
- ☐ Modeling and simulation
- ☐ Other - Write In

How did you account for variables (such as ambient temperatures, battery degradation, bus loading, grades) when verifying range capabilities?

Check all that apply

- ☐ Used Agency experience
- ☐ Used Consultant
- ☐ Used OEM predictions
- ☐ Operated demo bus on routes
- ☐ Modeling and simulation
- ☐ Other - Write In

How did you determine which charge method was right for your needs (depot, on-route - overhead conductive, on-route - wireless)?

Check all that apply

- ☐ Used Agency experience
- ☐ Used Consultant

- [ ] Used OEM predictions
- [ ] Operated demo bus on routes
- [ ] Modeling and simulation
- [ ] Other - Write In

How did you develop your electric bus specifications?
Check all that apply

- [ ] Develop your own procurement specifications
- [ ] Consultant
- [ ] Use other agency's procurement specifications
- [ ] Used a guide - Explain:
- [ ] Other - Write In

23. Should drivers have more or less information and control over managing remaining range and battery SOC?

For instance, do you prefer to have range, SOC, and low battery gauges on the dash (allowing drivers to help manage) or not (allowing planners to fully manage.)

- ○ Drivers should have more information/control
- ○ Drivers should have less information/control

VALIDATION Min = 1 Max = 10

24. Using the scale below, identify the degree to which the forthcoming APTA Zero Emission Bus Standard Bus Procurement Guideline will be important you.

1 being not at all important, 10 being extremely important

25. Please describe what worked well and what didn't work well from your experience procuring BEBs?

Planning - Procurement of Infrastructure

26. How did you select the routes to place the BEBs on?

Select all that apply

- [ ] Relied on transit planning experience
- [ ] Used Consultant
- [ ] OEM reccomendation
- [ ] Trial and error
- [ ] Modeling and simulation
- [ ] Other analytical methods
- [ ] Other - Write In

27. Did you procure charging infrastructure with the vehicles under the same contract?

Indicate below

- Yes
- No

28. Who was responsible for infrastructure installation?

- Bus OEM
- Transit Agency
- Infrastructure Provider
- Other - Write In

29. How did you coordinate deployment of infrastructure in conjunction with arrival of the BEBs?

30. Did you involve the local utility when making infrastructure procurement decisions?

- Yes
- No

31. Did you involve the local utility when making infrastructure installation decisions?

- Yes
- No

32. Please describe what worked well and what didn't work well from your experience procuring infrastructure?

Planning - Deployment of On-Route Infrastructure

Page entry logic:
This page will show when: Question "What charging method do you use or will you use with the BEB fleet?
Check all that that apply" is one of the following answers ("On-route overhead conductive chargers","On-route inductive/wireless chargers")

33. Who owns the on-route charging infrastructure?
Select all that apply

- ☐ Agency
- ☐ Utility
- ☐ Public municipality
- ☐ Other - Write In

34. Would you like to see the on-route infrastructure be made available to other medium and heavy duty vehicles?

Indicate below

- ○ Yes
- ○ No

Explain

35. How did you select the location of your on-route charging station(s)?

36. Where is the on-route charging infrastructure located?
Select all that apply

- ☐ Side of public street
- ☐ Transit center
- ☐ Agency owned property
- ☐ Other - Write In

37. How much available footprint did you have for infrastructure equipment?

- No space
- Sidewalk space
- 25 sqft
- 50 sqft
- 100 sqft
- 150 sqft
- 200 sqft or more

38. What type of entrance/exit do you use for on-route infrastructure?
Select all that apply

- ☐ On-road
- ☐ Pull-off lane
- ☐ Pull-in driveway
- ☐ Other - Write In

39. What alignment method for charging is used?

- ☐ Visual cues on road or roadside
- ☐ Video cues on dash
- ☐ Measurement cues on dash
- ☐ Audible cues
- ☐ Semi-automated control
- ☐ Other - Write In

40. What is the street traffic density at the infrastructure location?

- None
- Light
- Medium
- Heavy

41. Clearance Requirements

Indicate below what measures were taken to monitor height restrictions.

	Yes	No
Are there any clearance requirements or height restrictions surrounding curbside infrastructure?	○	○
Was a height clearance restriction bar installed?	○	○
Have there been any incidents associated with other vehicles colliding with the infrastructure?	○	○

VALIDATION Must be numeric

42. How much total time during the day do you have to charge on-route (during stops, layovers, opportunities) for a single bus? (minutes)

Min

Avg

Max

43. How many minutes of charge time per hour can your operation reasonably accommodate at one layover?

- up to 5 mins
- 5-10 mins
- 10-15 mins
- more than 15 mins

44. Do you have flexibility to operate irregular charge schedules that allow for situations like make-up charging, peak times/rush hour avoidance, high demand charges, etc?

- Yes
- No

Planning - BEB and Infrastructure Scalability

Page exit logic: Skip / Disqualify Logic
IF: THEN: Jump to page 16 - Thank You!

45. Scalability Planning

Did you plan in advance for scale up of your BEB fleet and associated charging infrastructure?

- Yes
- No

46. Do you anticipate issues with having adequate physical space for charging BEBs at scale?

Indicate below

- Yes
- No

47. Do you anticipate issues with having adequate electrical power for charging BEBs at scale?

Indicate below

- Yes
- No

48. Do you anticipate issues with having adequate resources (scheduling, manual plugging) for charging BEBs at scale?

Indicate below

- Yes
- No

49. Manual Connections

Using the scale below, indicate the importance of avoiding making manual connections to a charger.
1 being not at all important, 10 being extremely important

Explain

Planning - Training

Page exit logic: Skip / Disqualify Logic
IF: Question "What is your agency's current experience with Battery Electric Buses?
" #3 is one of the following answers ("Have procured battery electric buses or have them on order, but have not received any of them.","Have ordered and received some or all battery electric buses but have not put them into transit service.") **THEN:** Jump to page 16 - Thank You!

50. Who provided operator and maintenance training for the new characteristics associated with BEBs and charging infrastructure?
Select all that apply

	Equipment OEM	Bus OEM	Third Party	Transit Agency	None
BEB Operators and Maintenance Training	☐	☐	☐	☐	☐
Charging Infrastructure Maintenance Training	☐	☐	☐	☐	☐

VALIDATION Min = 0 Max = 100

51. What percentage of your personnel has been trained on the BEB fleet?

Drivers

Maintenance Workers

52. Were first responders trained on responding to BEB incidents? (high voltage cut point location, etc.)

- ○ Yes
- ○ No

53. Can you describe what worked well and what didn't work well when training on BEBs?

Operations Experience

VALIDATION Must be numeric

54. How many electric buses are in service during peak periods?

55. What is the typical state of charge (%) when the BEBs depart for service?

minimum

average

maximum

56. What is the typical state of charge (%) when the BEBs return from service?

minimum

average

maximum

57. Which of the following, if anything, did you have to change to accommodate the BEBs?

Select all that apply

- ☐ Bus Blocking
- ☐ Schedule
- ☐ Layover Times
- ☐ Number of Buses Serving a Route
- ☐ Other - Write In
- ☐ Nothing

VALIDATION Must be numeric

58. If known, what has been the peak charge power at any given time at a charge station that you have currently experienced with your fleet? (kW)

Provide a numerical answer for all that apply

Depot

On-Route

59. Please describe what worked well and what didn't work well when <u>operating BEBs</u>?

Operations Experience with On-Route Charging

Page entry logic:
This page will show when: Question "What charging method do you use or will you use with the BEB fleet?
Check all that that apply" is one of the following answers ("On-route overhead conductive chargers","On-route inductive/wireless chargers")

VALIDATION Must be numeric

60. How many charge cycles have your on-route charger(s) experienced since the implementation of your program?

Charger 1

Charger 2

Charger 3

Charger 4

61. On-route Charges Missed

What is the total percentage of in-service charges successfully made out of those attempted?

62. Please describe what worked well and what didn't work well for charging with on-route infrastructure?

Maintenance Experience

63. Availability and Reliability of BEBs and Infrastructure

Availability is defined as the number of days the buses or chargers are actually available at the start of the day compared to the days that the buses or chargers are planned for operation expressed as percent availability.

After shakeout and initial deployment, what has been the availability of the BEBs and infrastructure during normal operating hours?
(As a percentage)

BEBs

Depot Charging Infrastructure

On-route Charging Infrastructure (Enter "0" if NA)

Explain how availability of the BEBs has affected operations.

Explain how the availability of the charging infrastructure has affected operations.

64. Who provides the following services and maintenance?

Select all that apply

	Bus OEM	Third Party	Transit Agency: In-house	Transit Agency: Consultant
Bus propulsion system preventative maintenance	☐	☐	☐	☐
Bus propulsion system repair	☐	☐	☐	☐
Charging infrastructure preventative maintenance	☐	☐	☐	☐
Chrarging infrastructure repair	☐	☐	☐	☐

65. Traction Battery Experience

Have you had any issues with the traction battery?

- ○ Yes
- ○ No

Do you track battery degradation/end of life?

- ○ Yes
- ○ No

66. Spare Parts Requirements

Do you believe your spare parts inventory needs are greater, the same, or lower for BEBs?

- Greater
- The same
- Lower

Explain

67. Please describe what worked well and what didn't work well when maintaining BEBs?

Cost Experience

68. Costs and Benefits

Cost Tracking

	Yes	No
Are capital costs being tracked for the BEBs?	○	○
Are maintenance and operational costs being tracked for the BEBs?	○	○

Explain

VALIDATION Must be numeric

69. What were the maintenance costs for the BEB fleet?

Scheduled Maintenance (avg $/mile)

Unscheduled Maintenance (avg $/mile)

Must be numeric

70. What are your costs of fuel/electricity for the BEB fleet? ($/mile)

Minimum

Average

Maximum

71. Was it difficult selecting an optimum electricity rate structure for your services?

Indicate below

- Yes
- No

72. Do you monitor utility bills to determine if an alternate electricity rate structure should be considered, especially considering peak demand charges?

- Yes
- No

73. Do you believe there is a need for development of a utility rate specifically suited to the needs of electric transit buses?

- Yes
- No

General Deployment Experience

74. Software tools/support for planning, procurement, and deployment.

Did you use any technical support and/or software tools to help with your electric bus and infrastructure planning, procurement, and deployment?

- Yes
- No

Indicate whether use of the following enhanced technical support and/or software tools would be beneficial.

	Yes	No	Not sure
When making complex procurement decisions when selecting the right BEB technology for the application.			
When predicting range on a given day, under given environmental and loading conditions, available charge time, and the ability to dispatch accordingly.			
When determining which utility rate structure is best for the application.			
To understand actual lifecycle costs of BEBs and making appropriate adjustments to service and/or future purchases.			

75. Ridership

Have you seen increased ridership on the routes that now use BEBs?

- Yes
- No
- Don't Know - mixed fleet or other factors have changed

VALIDATION Min = 1 Max = 10

76. Using the scale below, indicate the public's reaction to your BEB deployment.
1 being not at all positive, 10 being extremely positive

77. Social, Evironmental, and Health Benefits

Have you quantified any social, environmental, and/or health benefits of using your BEBs versus diesel or CNG buses?

- Yes
- No

VALIDATION Accepts 1 file. **Allowed types:** png, gif, jpg, jpeg, doc, xls, docx, xlsx, pdf, txt, mov, mp3, mp4. Max file size: 500 KB

LOGIC Hidden unless: Question "Have you quantified any social, environmental, and/or health benefits of using your BEBs versus diesel or CNG buses?" is one of the following answers ("Yes")

78. Can you provide any reports of those social, environmental, and health benefits?

Browse...

79. Resiliency and Emergencies

Do you provide any assistance for community critical functions (evacuations, mobile climate center, temporary shelter) that may require you to consider back-up power generation or additional battery storage capacity?

- Yes
- No

How long after an event or outage would you expect to have some assistance in place?

- 2 hours
- 6 hours
- 12 hours
- 24 hours or more

Explain

80. Are there any lessons learned for management or motivation of the various stakeholder groups (utilities, operators, unions, communities, executive boards, regulatory agencies, etc.) to engage in BEB procurement and deployment?

LOGIC Show/hide trigger exists.

81. Do you have any additional information regarding your agencies experience with BEBs?

- ☐ Yes, I can provide links to reports.
- ☐ Yes, I can upload reports.
- ☐ No, I don't.

VALIDATION Accepts 1 file. **Allowed types:** png, gif, jpg, jpeg, doc, xls, docx, xlsx, pdf, txt, mov, mp3, mp4. Max file size: 500 KB

LOGIC Hidden unless: Question "Do you have any additional information regarding your agencies experience with BEBs?" #81 is one of the following answers ("Yes, I can upload reports.")

82. Please upload any relevant agency reports you may have on any aspect of your experience with BEBs.

Browse...

LOGIC Hidden unless: Question "Do you have any additional information regarding your agencies experience with BEBs?" #81 is one of the following answers ("Yes, I can provide links to reports.")

83. Please provide links to any relevant agency reports you may have on any aspect of your experience with BEBs.

VALIDATION Min = 1 Max = 10

84. Using the scale below, rate your agency's overall level of satisfaction with BEBs.

1 being not at all satisfied, 10 being extremely satisfied

85. Do you plan to purchase additional battery electric buses?

Indicate below

- Yes
- No

Explain

86. Case Sample

Would your agency be willing to serve as a case sample for this synthesis study on Battery Electric Buses: State of the Practice?

Yes

No

Contact Information

Transit Agency

Contact Name

Contact Email

Contact Phone

APPENDIX B

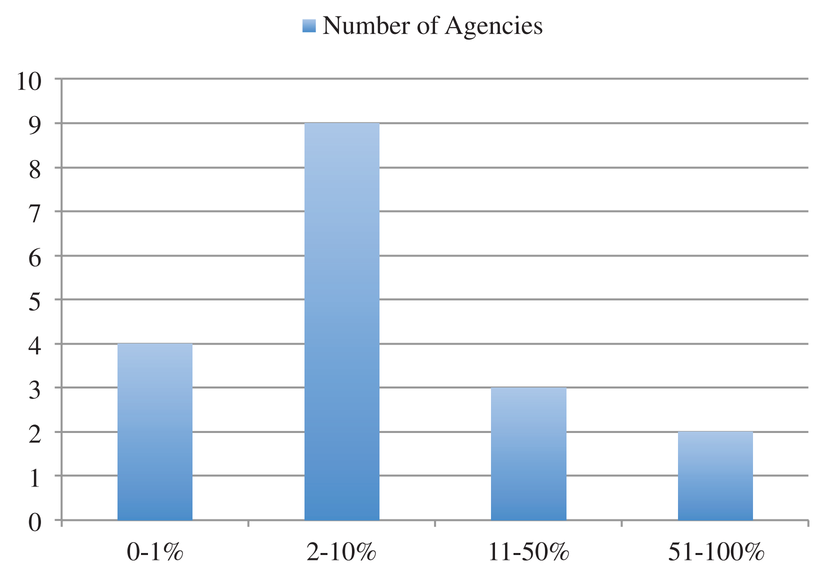
Survey Results

Transit Agency Information

Fleet Information

Transit Agency #	BEBs	Total	Percentage
1	3	113	3%
2	1	1583	0.06%
3	30	370	8%
4	2	75	3%
5	2	68	3%
6	34	163	21%
7	16	31	52%
8	15	304	5%
9	6	66	9%
10	6	53	11%
11	3	1474	0.20%
12	5	681	1%
13	2	1870	0.11%
14	9	274	3%
15	4	185	2%
16	6	6	100%
17	14	105	13%
18	5	64	8%

Percentage of BEBs to Total Fleet Size



BEB Fleet Size Distribution

Transit Agency #	35'	40'	60'	Cutaway	Other	Total
1	-	3	-	-	-	3
2	-	1	-	-	-	1
3	15	15	-	-	-	30
4	-	2	-	-	-	2
5	-	2	-	-	-	2
6	-	21	13	-	-	34
7	5	1	-	-	10	16
8	9	6	-	-	-	15
9	-	6	-	-	-	6
10	5	1	-	-	-	6
11	-	3	-	-	-	3
12	-	5	-	-	-	5
13	-	2	-	-	-	2
14	9	-	-	-	-	9
15	-	-	-	-	4	4
16	5	1	-	-	-	6
17	-	-	-	-	14	14
18	-	-	-	-	5	5

Fleet Information

Transit Agency #	Total BEBs	Total Buses	Percent BEBs
1	3	113	3%
2	1	1583	0.1%
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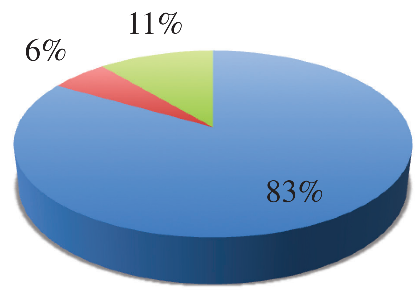
14	9	274	3%
15	4	185	2%
16	6	6	100%
17	14	105	13%
18	5	64	8%

Transit Agency Information

Transit Agencies' BEB Status

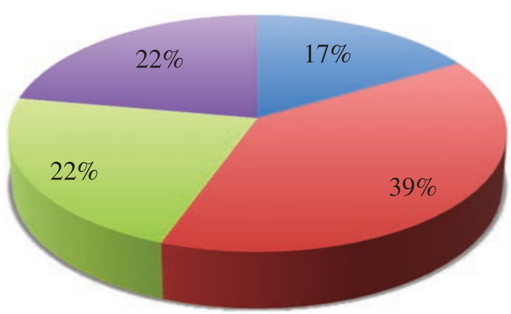
n = 18



- Currently operate battery electric buses in transit service.
- Have procured battery electric buses or have them on order, but have not received any of them.
- Have ordered and received some or all battery electric buses but have not put them into transit service.

Procurement

n = 18



- Standard bus procurement with suppliers competing through transit agency RFP.
- Through a federal or state competetive grant opportunity (i.e. - FTA TIGGER or LowNo program)
- Both
- None of the above

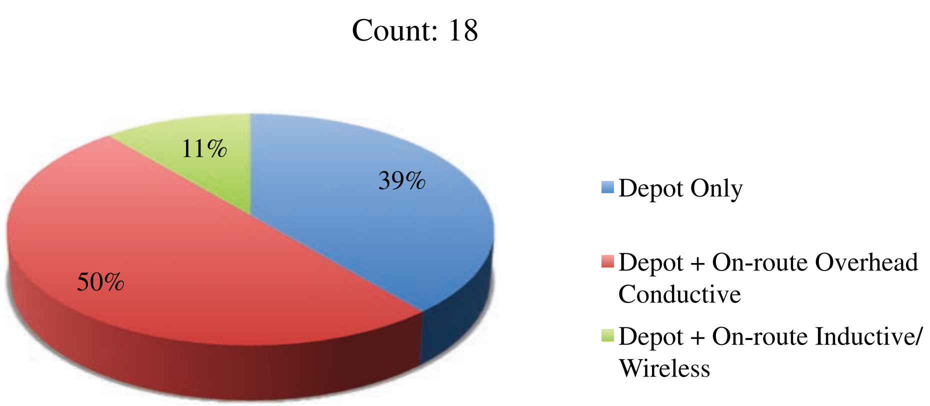
Other forms of procurement include:

- Leased
- Negotiated for no-cost bus from OEM
- County Board of Supervisors gave a local grant to cover two electric buses
- piggyback

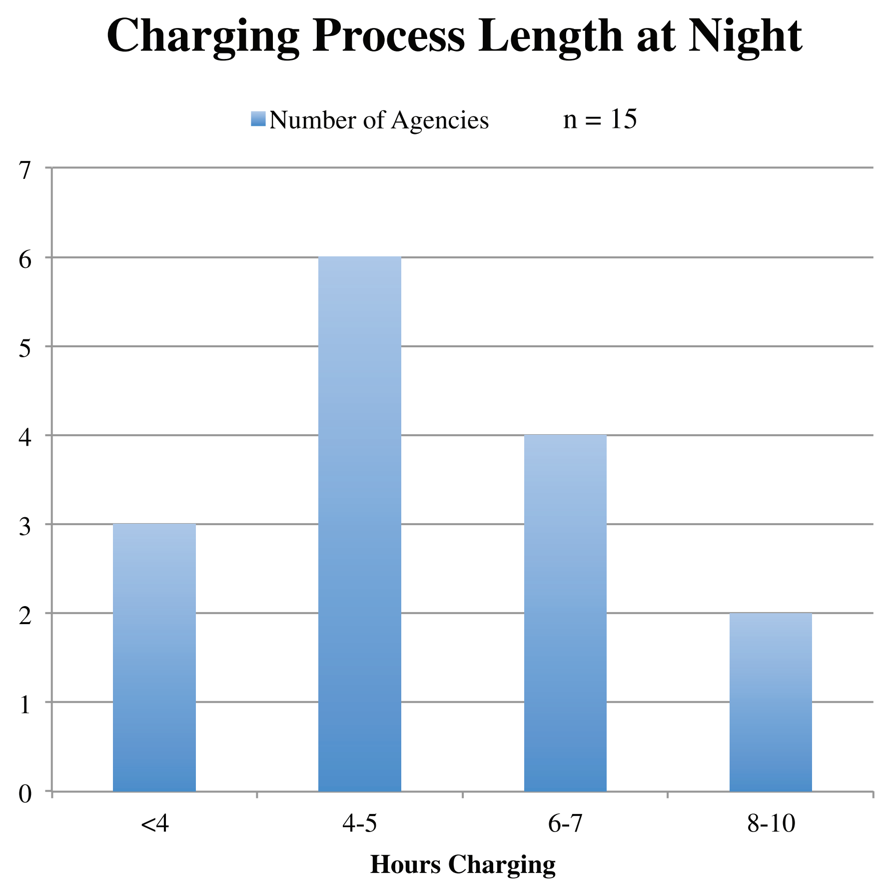
Charging Characteristics

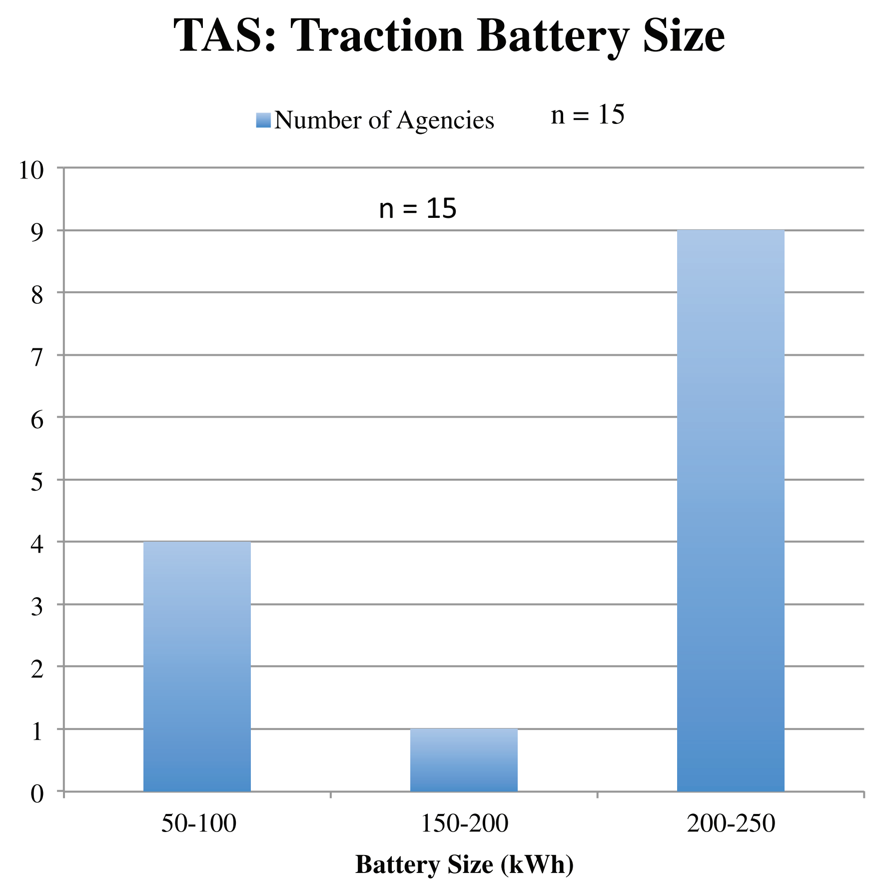
Number of Chargers	Minimum	Average	Maximum	Number Agencies Responded
Depot Only	1	10	89	17
On-route Overhead Conductive	1	2	5	9
On-route Inductive/ Wireless	1	7	13	2
Depot Overhead	1	1	1	1

Route Charging Methods

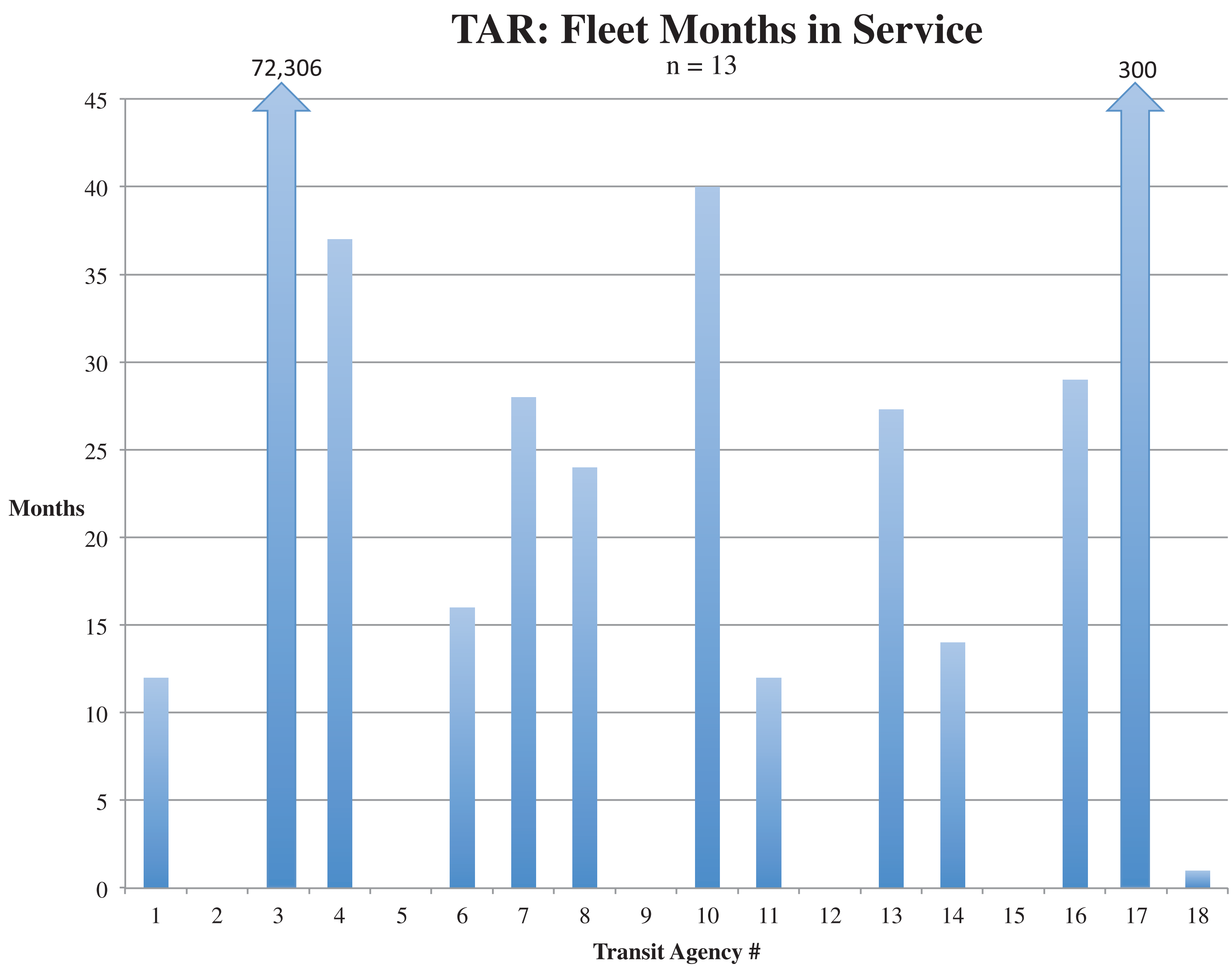


Charging Characteristics

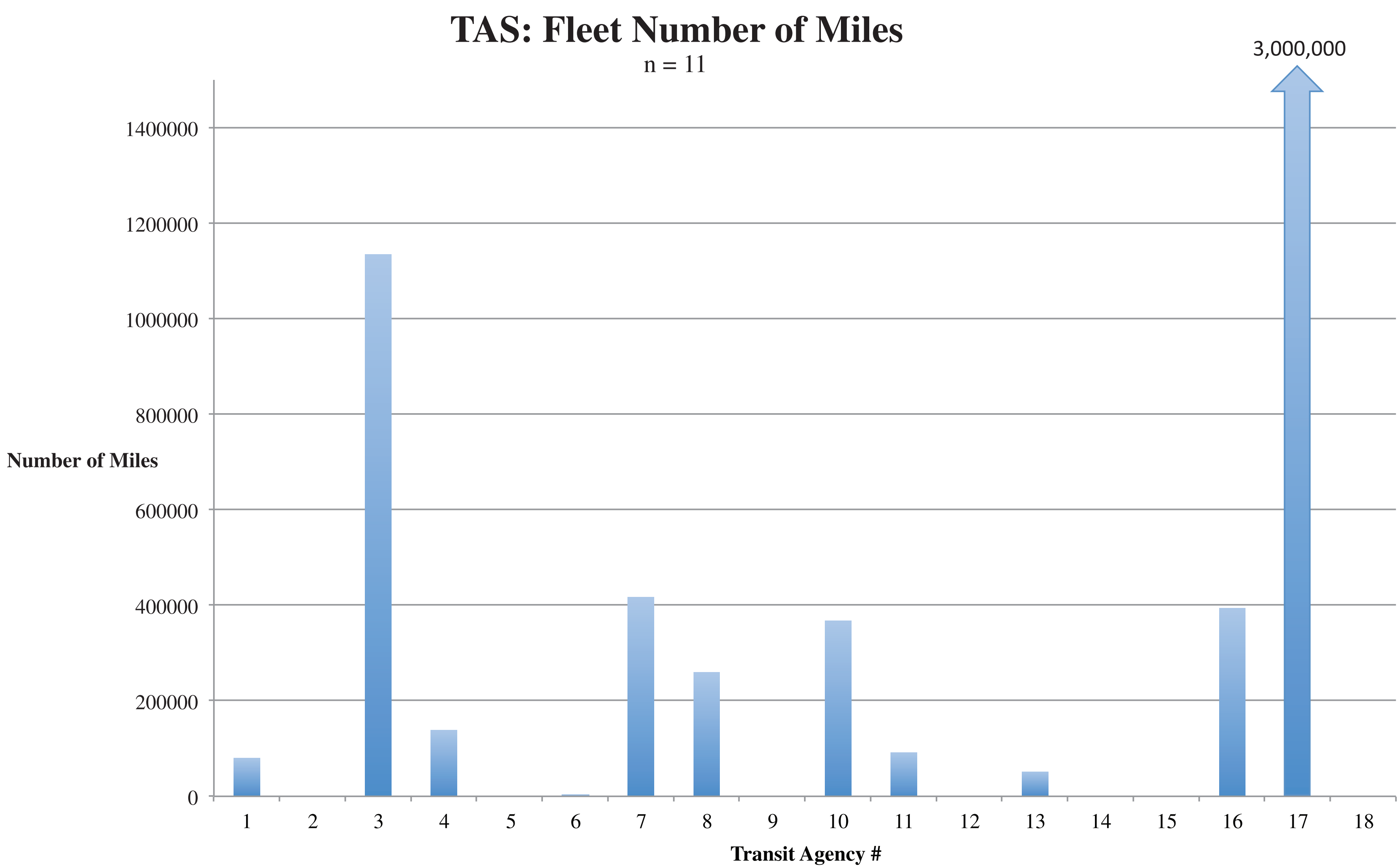




Fleet Characteristics

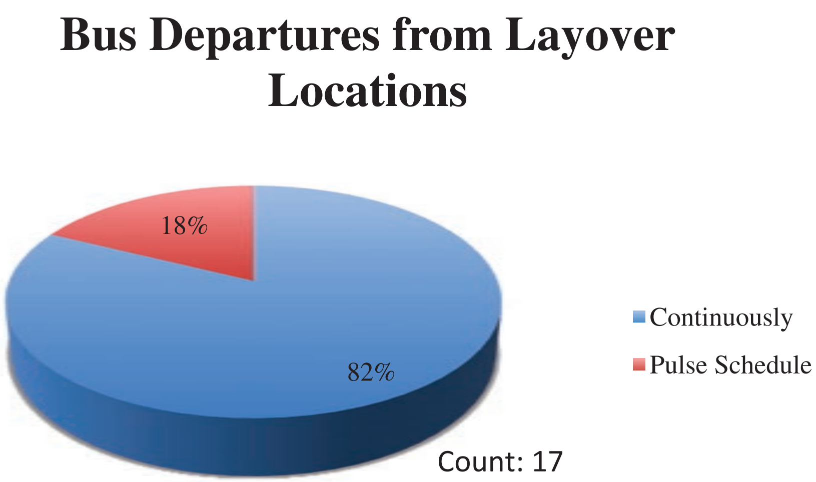


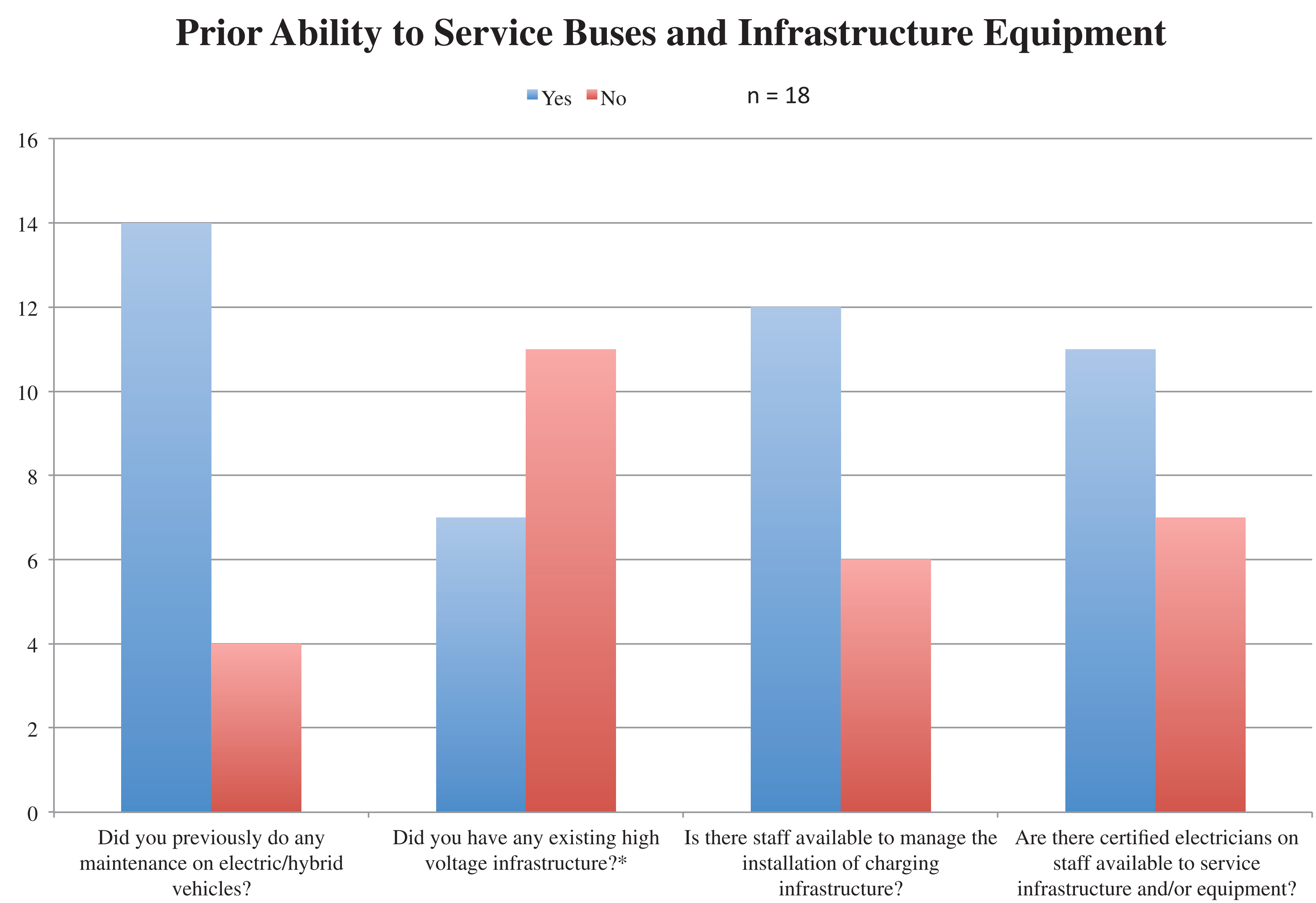
Fleet Characteristics



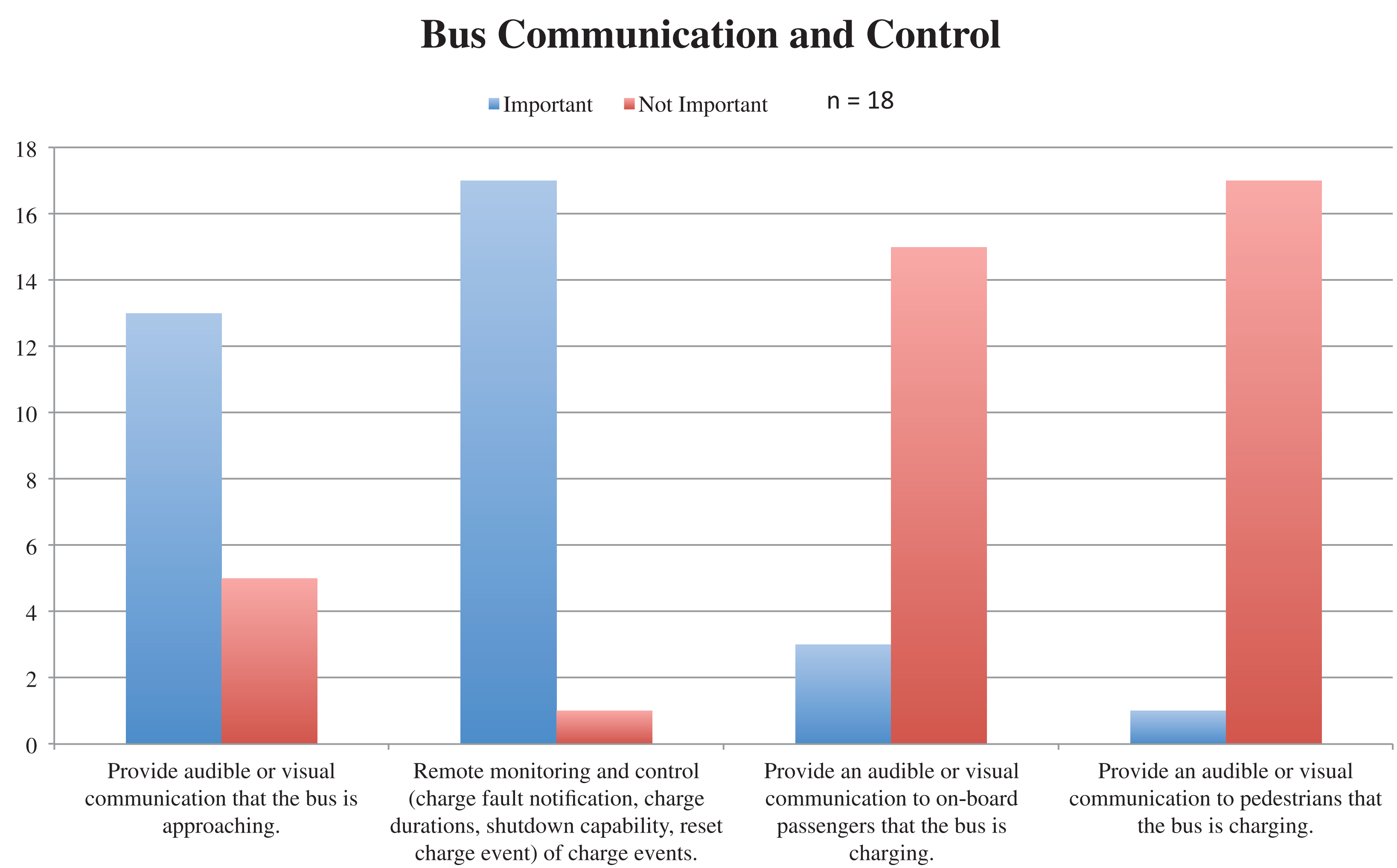
Route Characteristics

Average Route Characteristics	Minimum Average	Minimum Response Value	Average	Maximum Average	Maximum Response Value
Route Length (miles)	15	2	18	64	365
Daily Range (miles)	136	65	188	258	600
Layover Duration (mins)	5	0	9	19	30
Route Speeds (mph)	12	5	18	32	60
Deadhead Distance (miles)	3	0	5	9	25
Deadhead Speeds (mph)	20	6	23	35	60





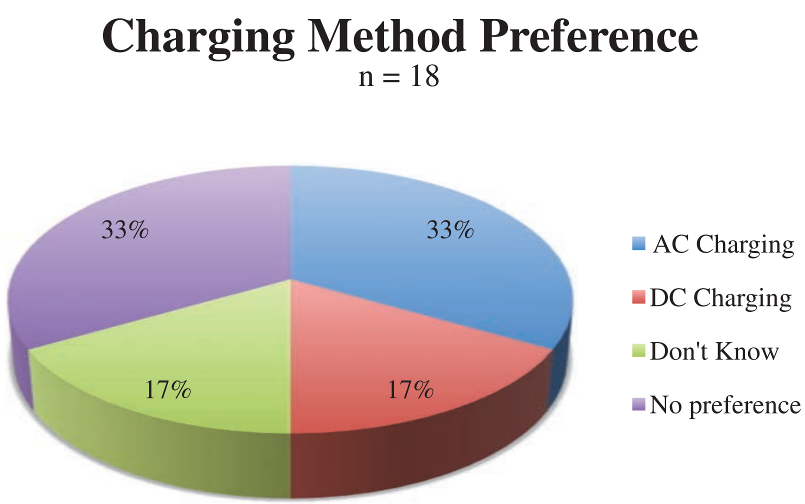
*All seven respondents also replied that they maintain the high voltage infrastructure

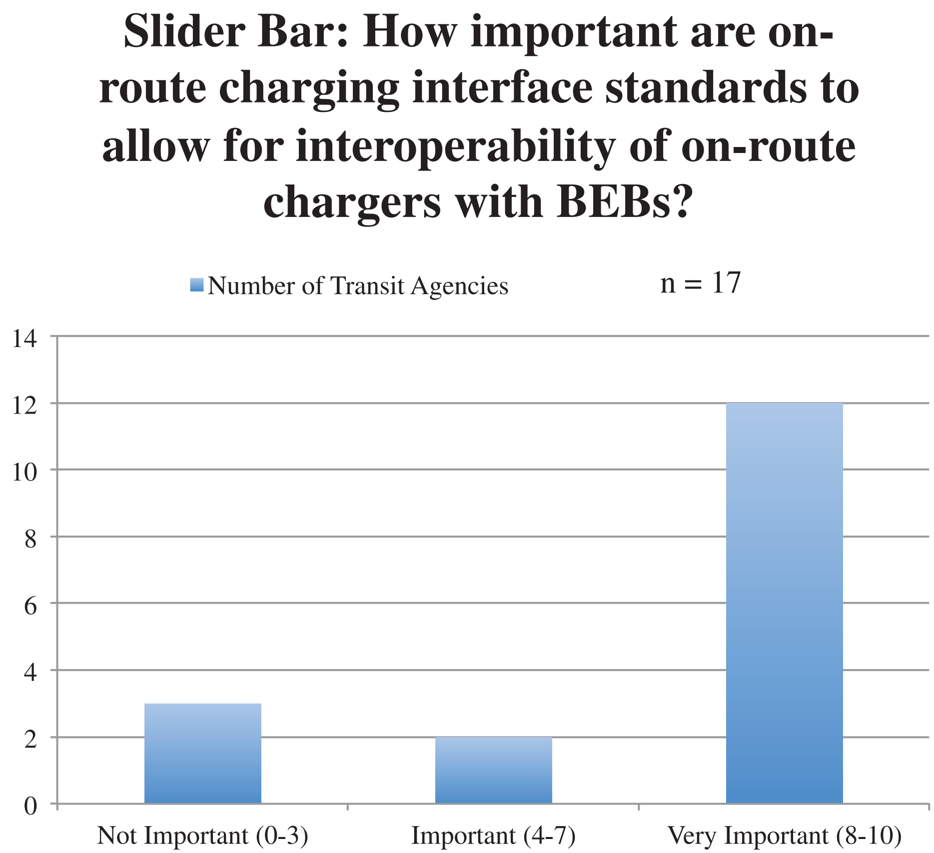


Other recommendations include:

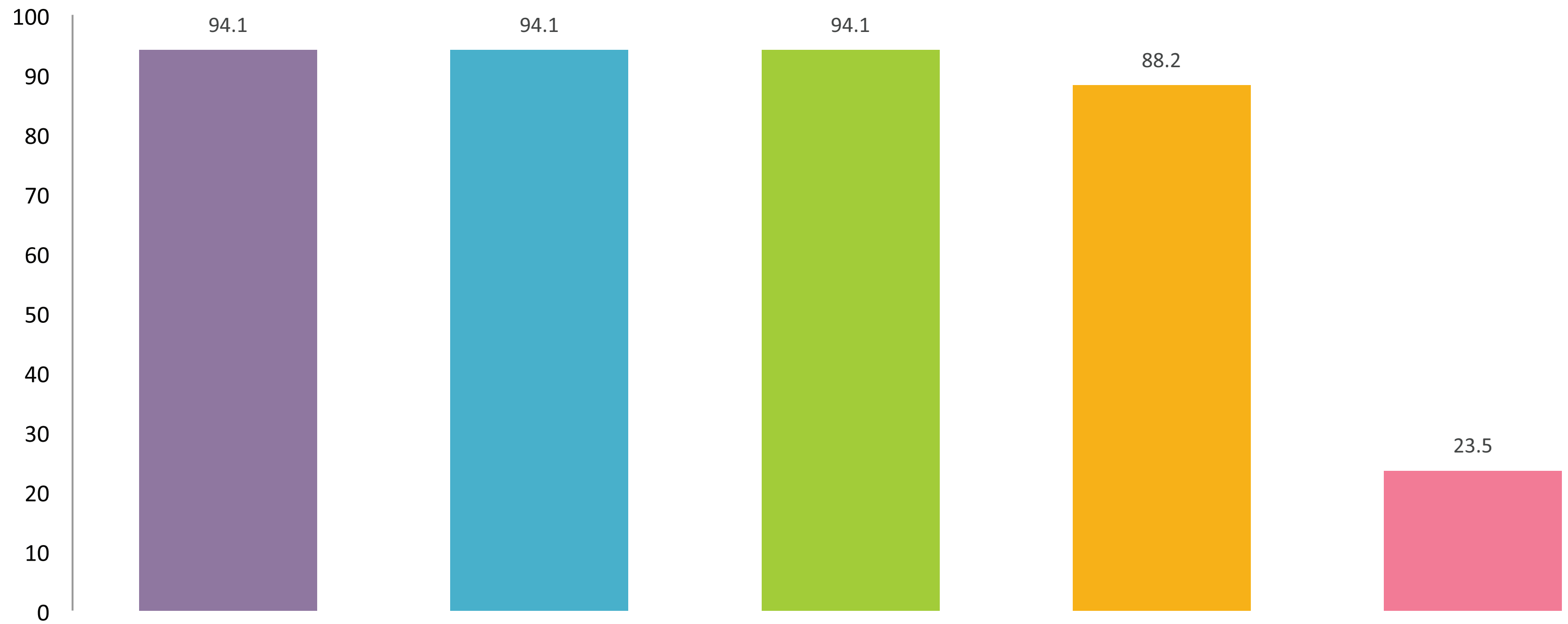
- Flashing light and audible horn
- Interactive signs and mobile application notifications
- External speakers, bus approaching or bus turning
- To provide a rocker switch so the driver can manually turn on/off the back-up alarm, and a front speaker
- Crowd alert alarm
- There are technologies that are available now that connect with bus IT systems which can monitor conditions that could communicate with pedestrians as the buses approach. I.e. - IO Controls

Agency Preferences





What type of data/telematics are you interested in? Select all that apply



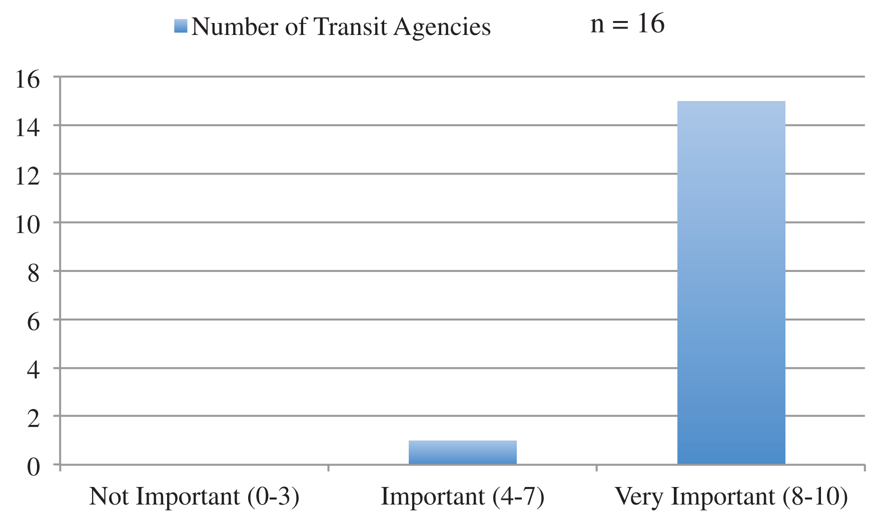
Legend	Value	Percent	Count
	Range anxiety related (state of charge, range to recharge, charger status, traffic status, etc.)	94.1%	16
	Operations (passengers counted, outside and inside temperatures, energy this cycle, energy over life, energy over vehicle life, drive cycle specifics like hard braking)	94.1%	16
	Maintenance (fault codes)	94.1%	16
	Safety	88.2%	15
	Other - Write In	23.5%	4

Planning and Procurement

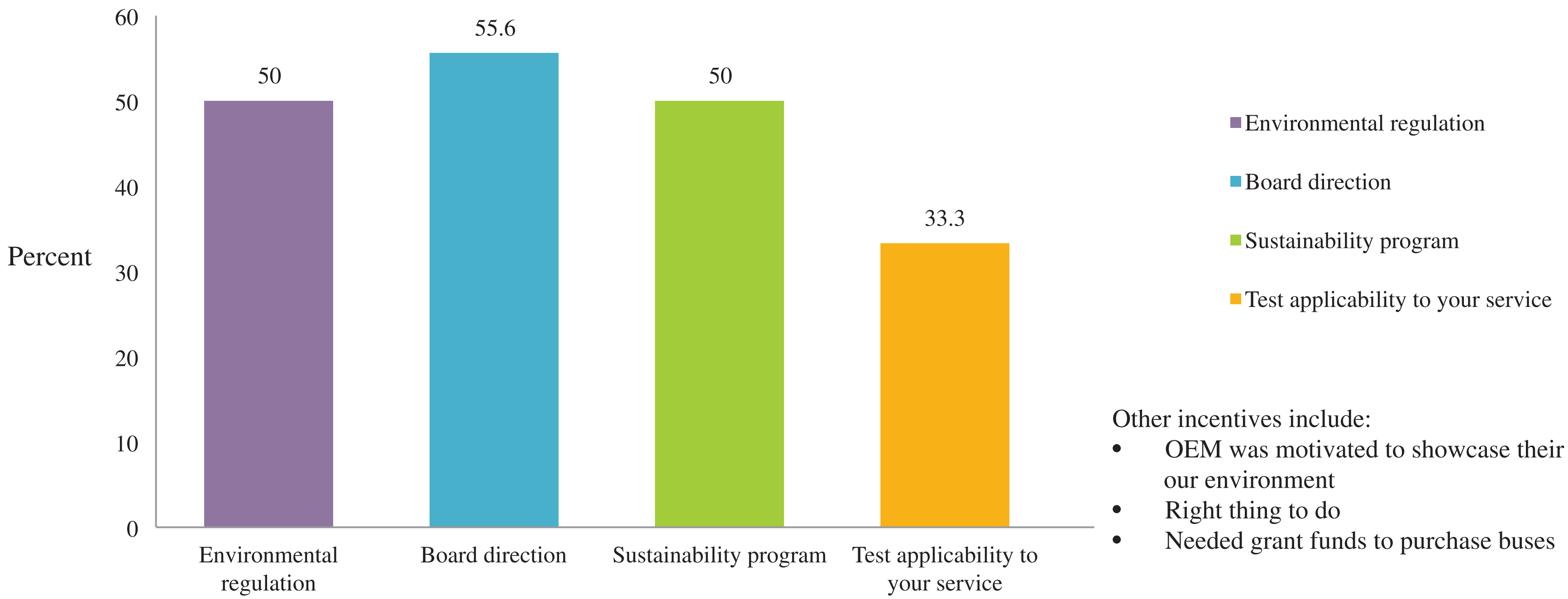
Planning – Procurement General

Deployment Costs	Minimum	Average	Maximum
Buses (avg per bus)	$579,000	$887,308	$1,200,000
Depot Charging Equipment (per charger)	$2,000	$50,000	$100,000
Depot Charging Installation (per charger)	$2,000	$17,050	$64,000
On-Route Charging Equipment (per charger)	$330,000	$495,636	$600,000
On-Route Charging Installation (per charger)	$50,000	$202,811	$400,000

Slider Bar: How important do you believe continued public investment is to the deployment of BEBs?



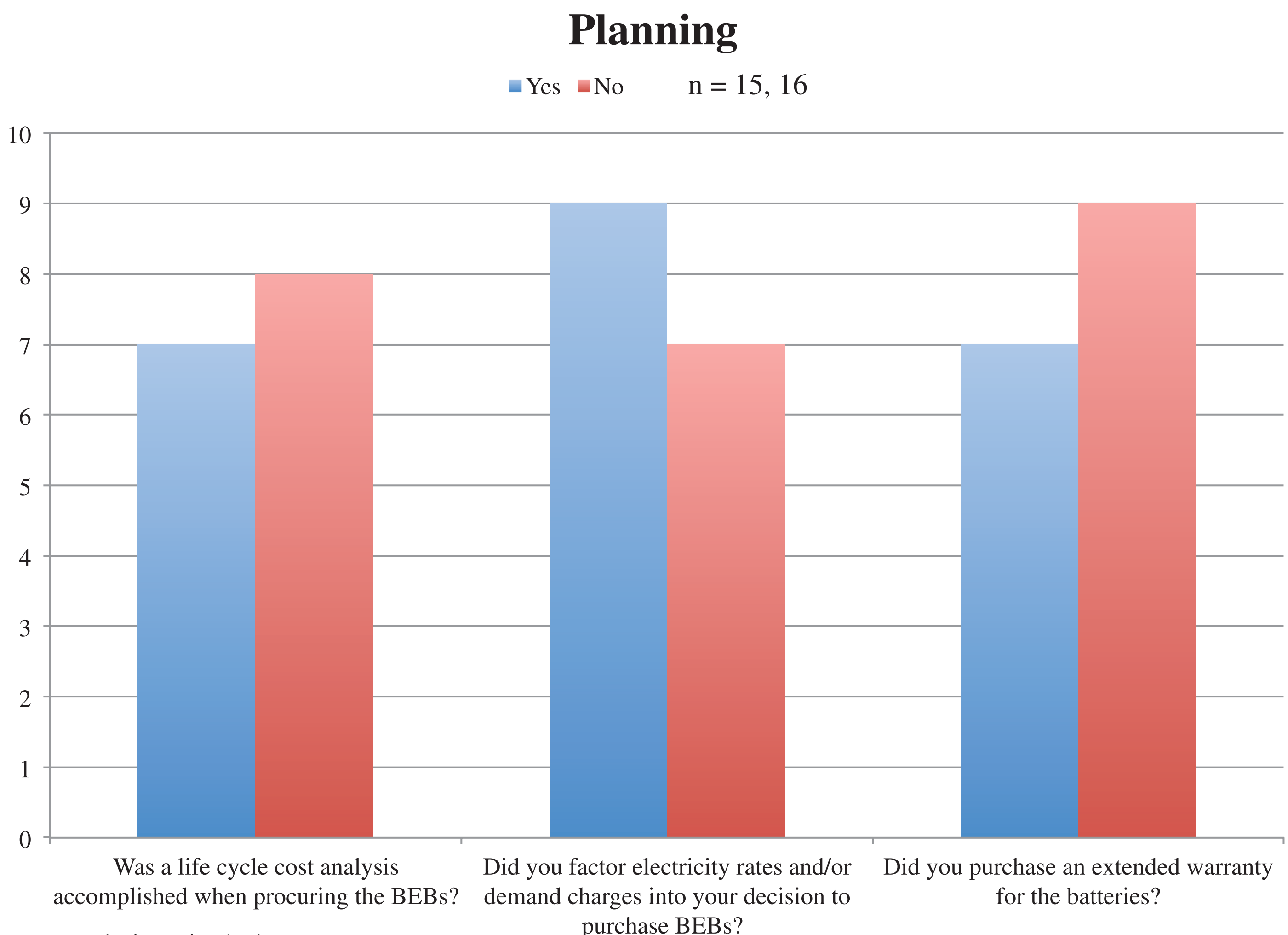
What incentives or drivers contributed to your agency's decision to purchase electric buses? Select all that apply.



Other incentives include:

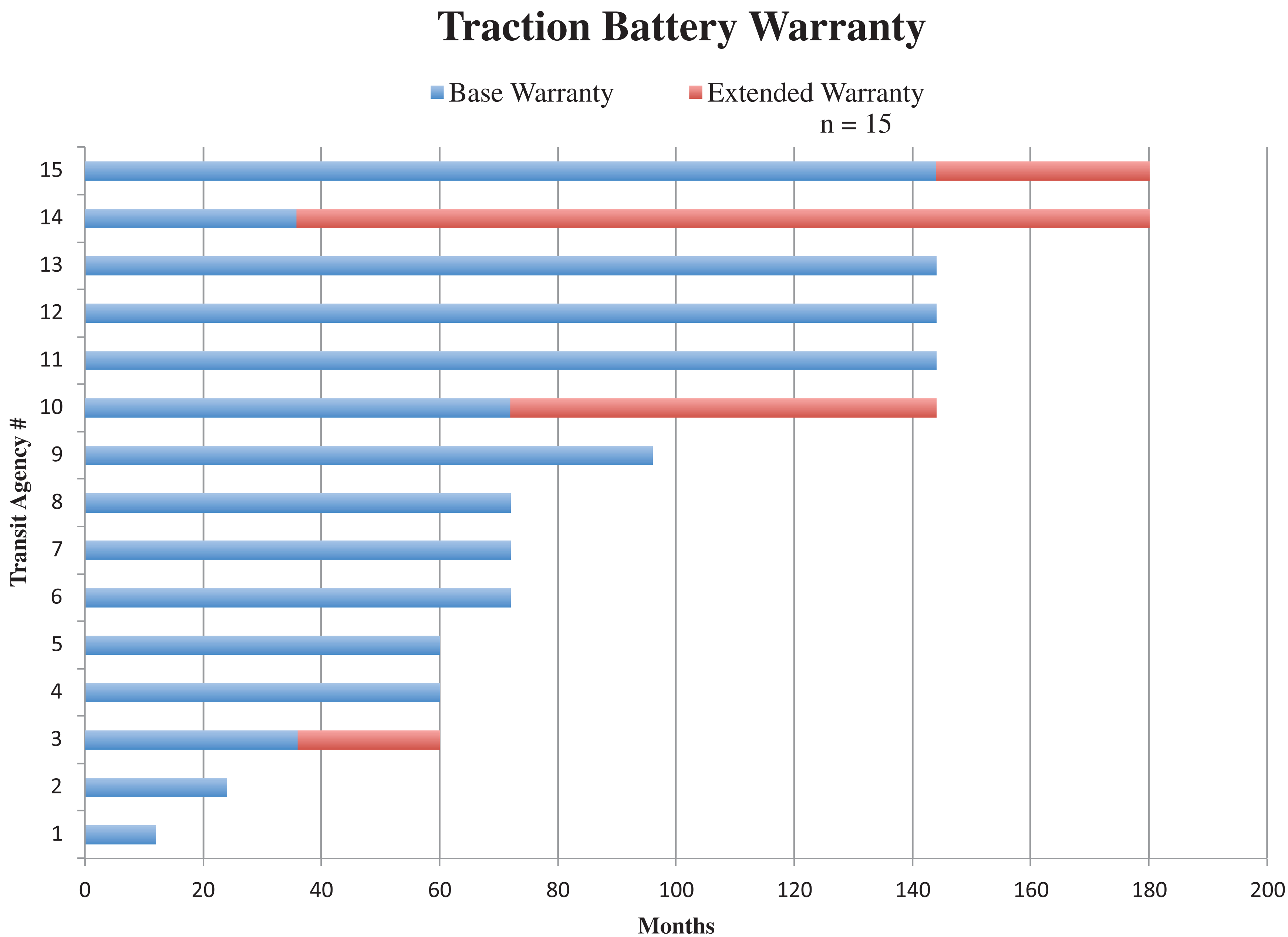
- OEM was motivated to showcase their bus in our environment
- Right thing to do
- Needed grant funds to purchase buses

Value	Percent	Count
Environmental regulation	50.0%	9
Board direction	55.6%	10
Sustainability program	50.0%	9
Test applicability to your service	33.3%	6



Other recommendations include:

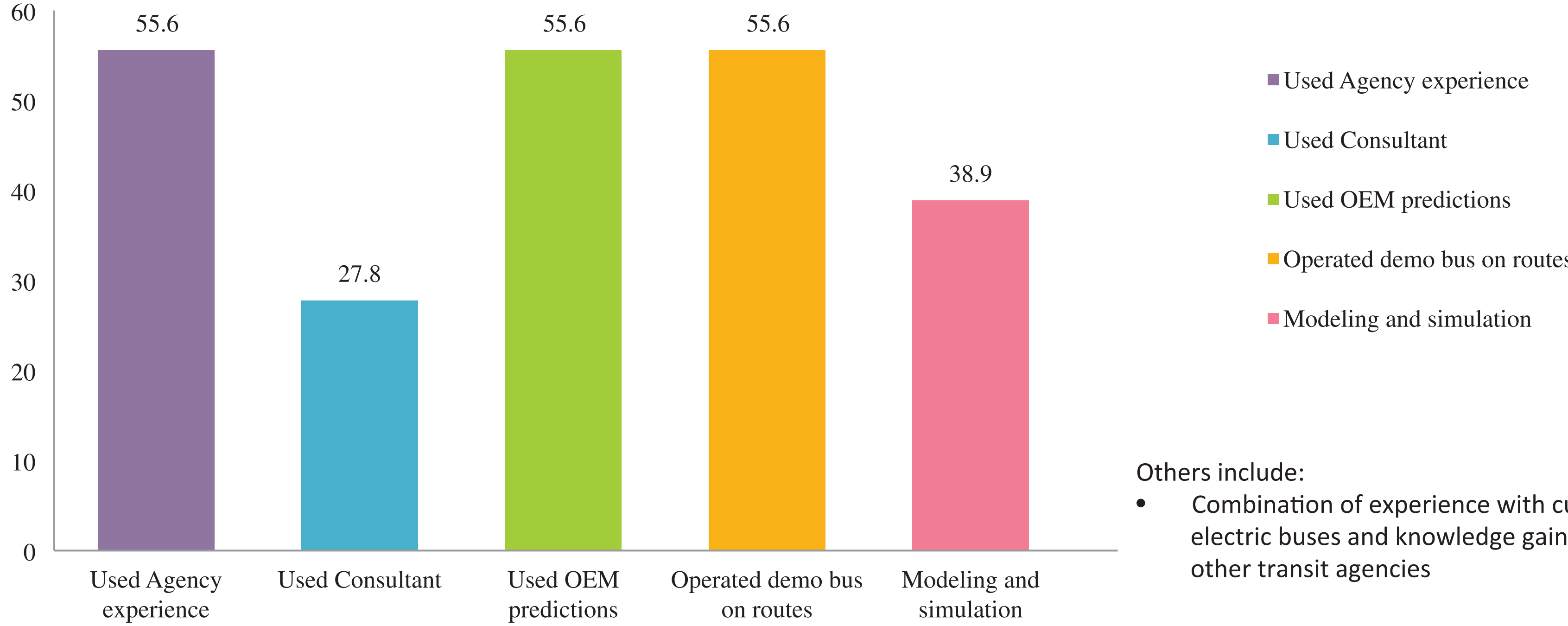
- Vehicle weight, nominal/maximum passenger load, auxiliary energy demands, motor outputs and energy demands, battery energy and energy capacity
- Battery life
- Completed by CTE
- We mainly reviewed the cost based on our hybrid experience. (e.g. benefits of removing engine + additional risk of replacing more batteries)
- body, motor, batteries
- controllers, motors, batteries, electrical rates


Traction Battery Warranty
Base Warranty
Extended Warranty
n = 15
Transit Agency #
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
140
160
180
200
Months

Evaluation Methods Utilized by Agencies to Determine Vehicle Specifications, Operational Requirements, and Route Selection

Method Used	Evaluation of range with respect to route needs	Account for variables when verifying range	Determination of charge method
Used Agency Experience	56%	50%	50%
Used Consultant	28%	33%	6%
Used OEM Predictions	56%	50%	44%
Operated demo bus on routes	56%	50%	11%
Modeling and simulation	39%	33%	22%

How did you evaluate vehicle range with respect to your route needs? Check all that apply

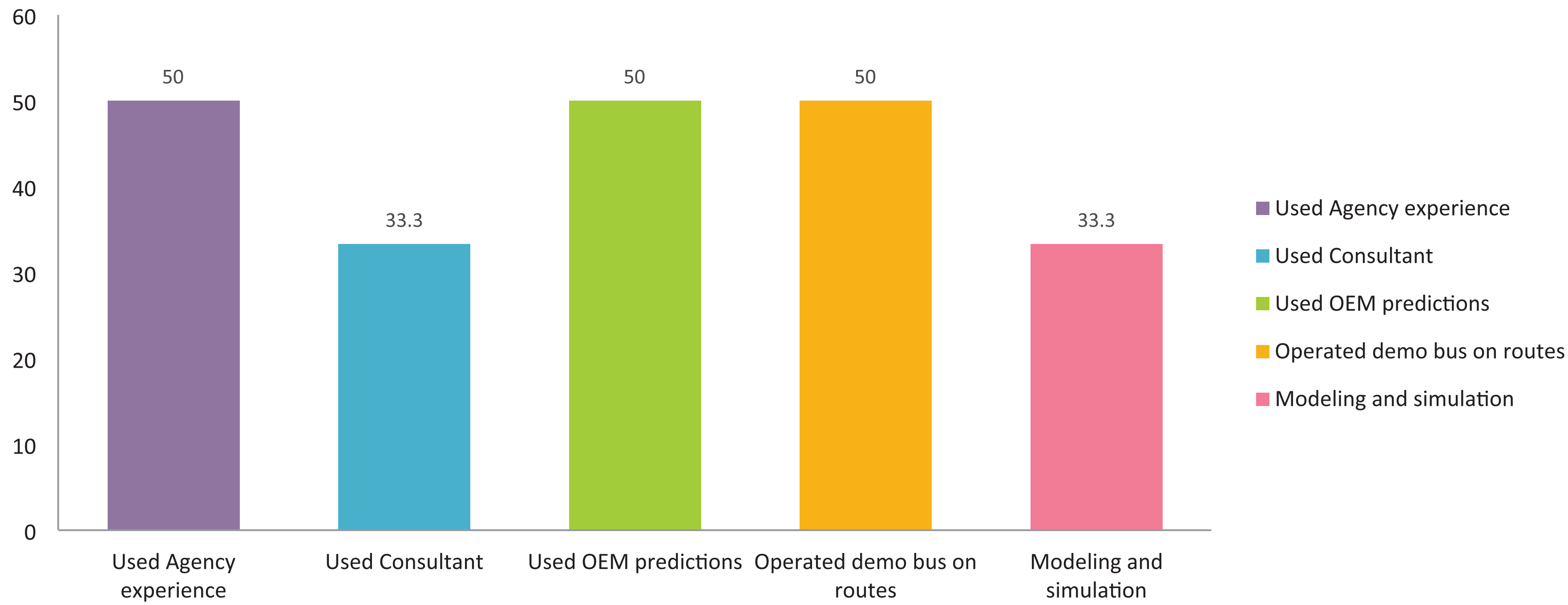


Others include:

- Combination of experience with current electric buses and knowledge gained from other transit agencies

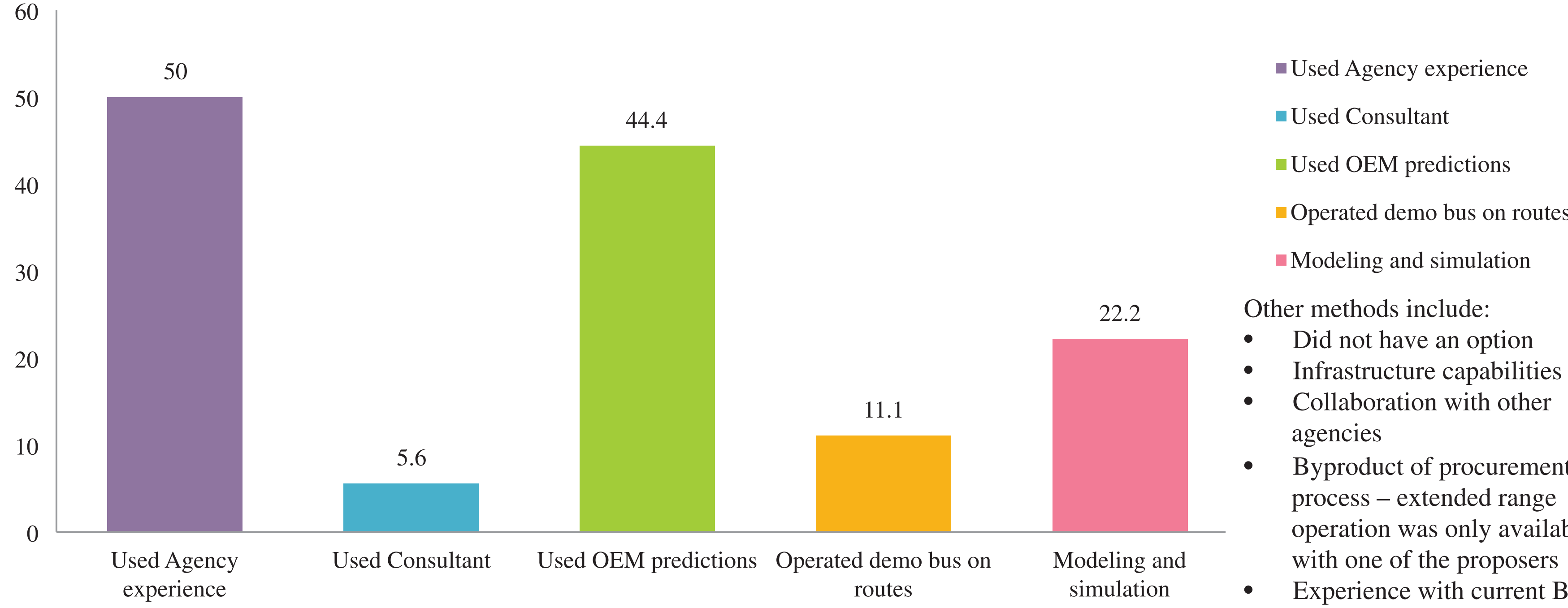
Value	Percent	Count
Used Agency experience	55.6%	10
Used Consultant	27.8%	5
Used OEM predictions	55.6%	10
Operated demo bus on routes	55.6%	10
Modeling and simulation	38.9%	7

How did you account for variables (such as ambient temperatures, battery degradation, bus loading, grades) when verifying range capabilities?
Check all that apply



Value	Percent	Count
Used Agency experience	50.0%	9
Used Consultant	33.3%	6
Used OEM predictions	50.0%	9
Operated demo bus on routes	50.0%	9
Modeling and simulation	33.3%	6

How did you determine which charge method was right for your needs (depot, on-route - overhead conductive, on-route - wireless)? Check all that apply

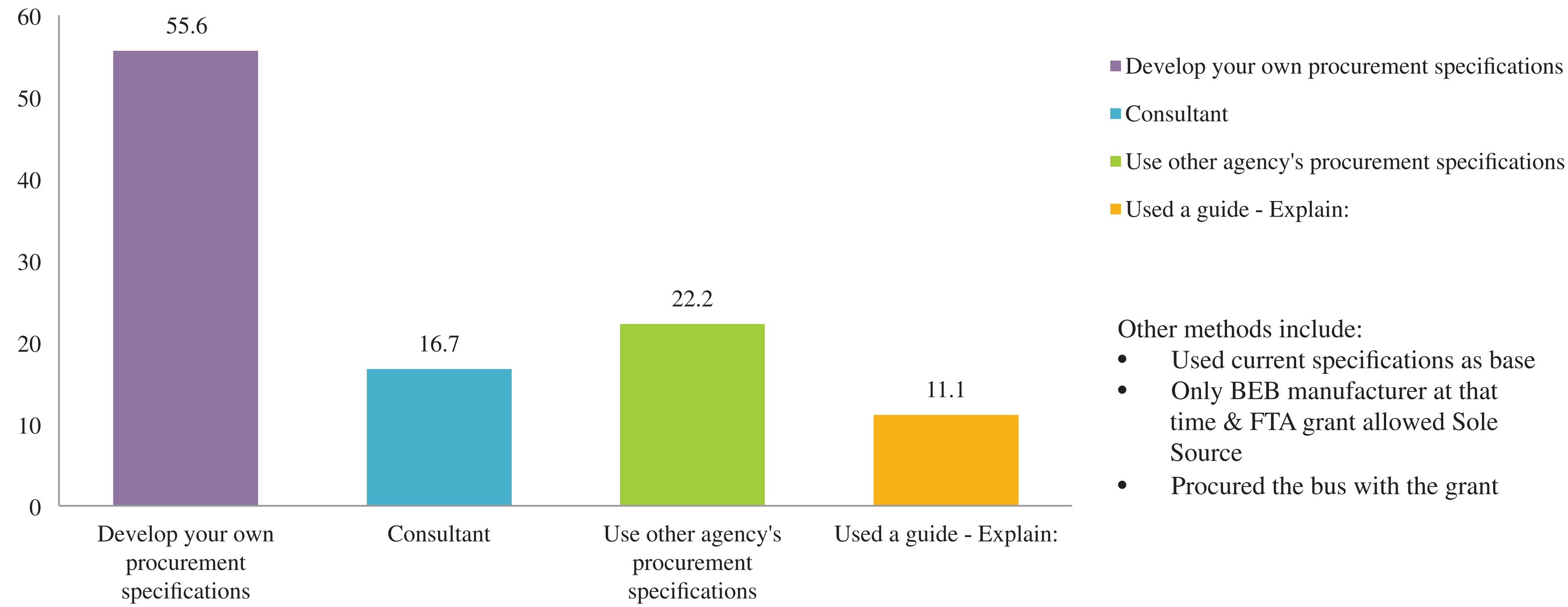


Other methods include:

- Did not have an option
- Infrastructure capabilities
- Collaboration with other agencies
- Byproduct of procurement process – extended range operation was only available with one of the proposers
- Experience with current BEBs

Value	Percent	Count
Used Agency experience	50.0%	9
Used Consultant	5.6%	1
Used OEM predictions	44.4%	8
Operated demo bus on routes	11.1%	2
Modeling and simulation	22.2%	4

How did you develop your electric bus specifications? Check all that apply



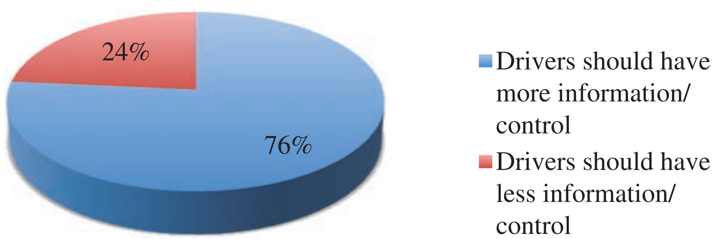
Other methods include:
- Used current specifications as base
- Only BEB manufacturer at that time & FTA grant allowed Sole Source
- Procured the bus with the grant

Value	Percent	Count
Develop your own procurement specifications	55.6%	10
Consultant	16.7%	3
Use other agency's procurement specifications	22.2%	4
Used a guide - Explain:	11.1%	2
Other - Write In	22.2%	4

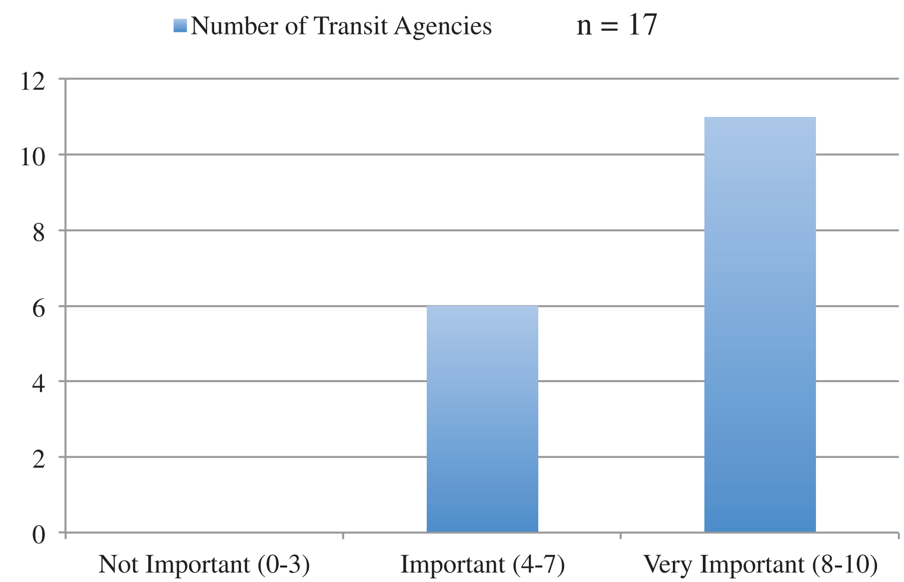
Driver Information

Driver information and control over managing remaining range and battery SOC

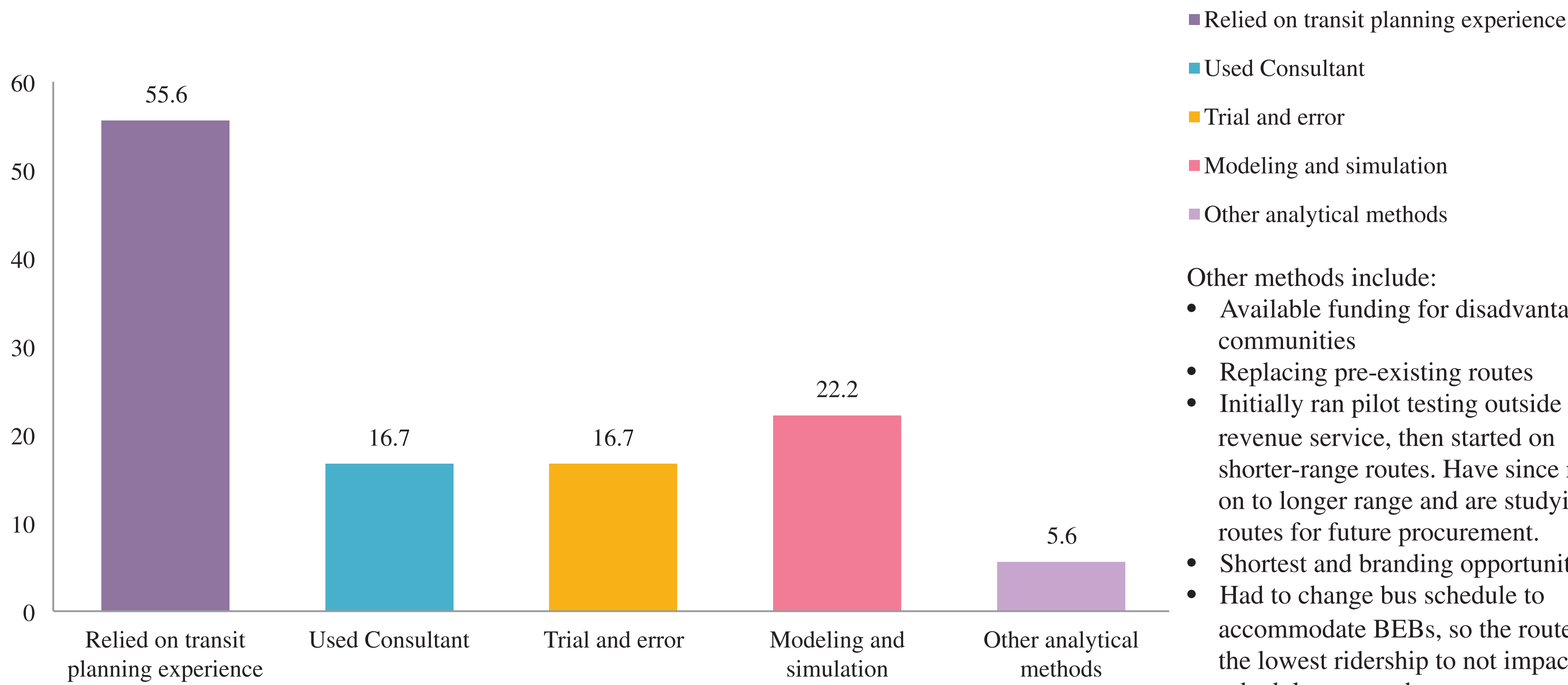
n = 17



Slider Bar: How important is the forthcoming APTA Zero Emission Bus Standard Bus Procurement Guideline?



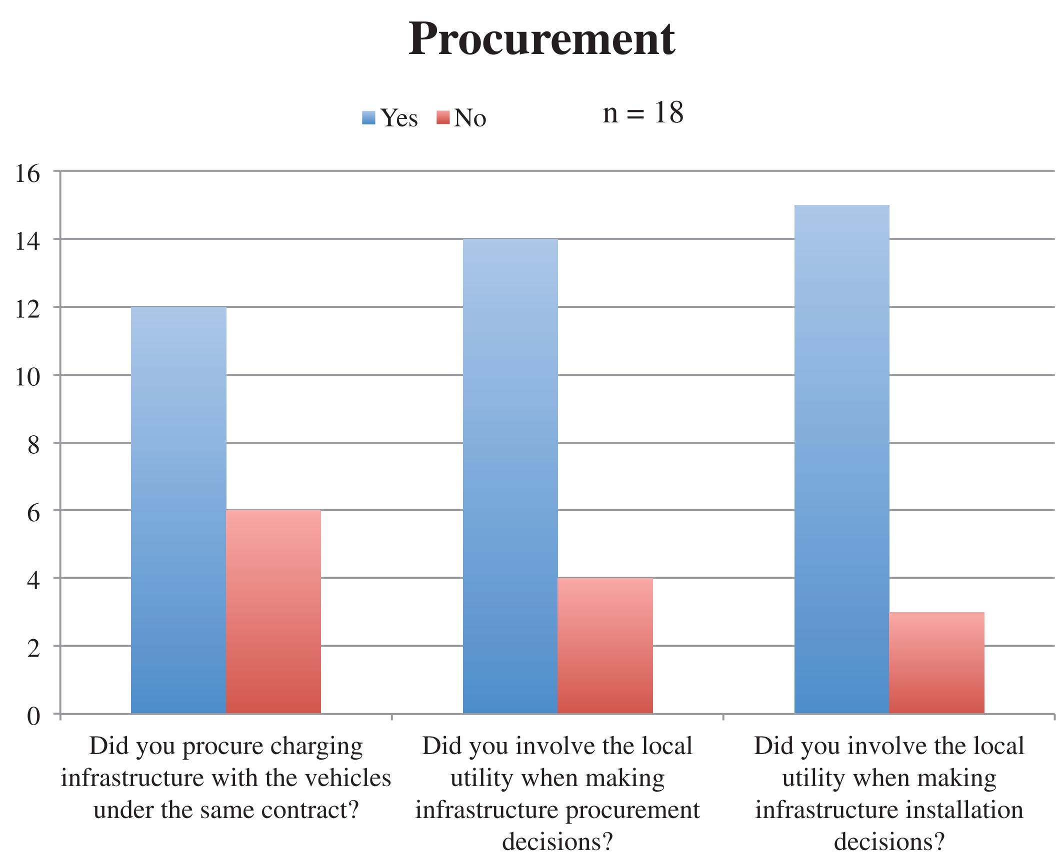
How did you select the routes to place the BEBs on? Select all that apply

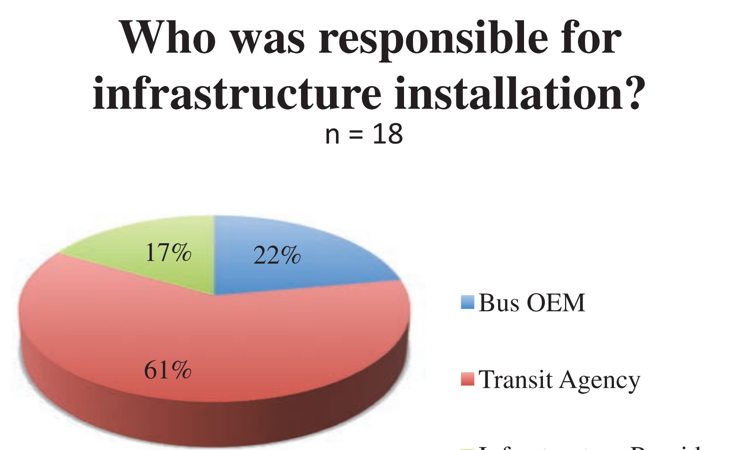


Other methods include:
- Available funding for disadvantaged communities
- Replacing pre-existing routes
- Initially ran pilot testing outside of revenue service, then started on shorter-range routes. Have since moved on to longer range and are studying all routes for future procurement.
- Shortest and branding opportunity
- Had to change bus schedule to accommodate BEBs, so the route with the lowest ridership to not impact schedule too much

Value	Percent	Count
Relied on transit planning experience	55.6%	10
Used Consultant	16.7%	3
Trial and error	16.7%	3
Modeling and simulation	22.2%	4
Other analytical methods	5.6%	1

Procurement Infrastructure





How did you coordinate deployment of infrastructure in conjunction with arrival of the BEBs?

- Charger was installed before bus delivery
- Scheduled construction milestones to coordinate with the BEB delivery schedule.
- Timing was interrupted by regulations
- Ensured infrastructure was in place prior to bus arrival as soon as PO was awarded for buses, the facility upgrade started.
- Infrastructure had to be in place prior to delivery of the BEBs
- Unfortunately BEBs arrived before infrastructure was established.
- Worked with OEM to install fast charger prior to bus deployment.
- Lots of meetings
- We worked with New Flyer to ensure the chargers were provided and UL certified by the time of the arrival of the buses.
- Our project manager worked closely with both OEMs to ensure that the deployment went smoothly.
- Gantt chart developed at beginning of process to determine that chargers would be in place before buses arrived.
- Upgraded charging infrastructure prior to new bus deliveries

Please describe what worked well and what didn’t work well form your experience procuring infrastructure.

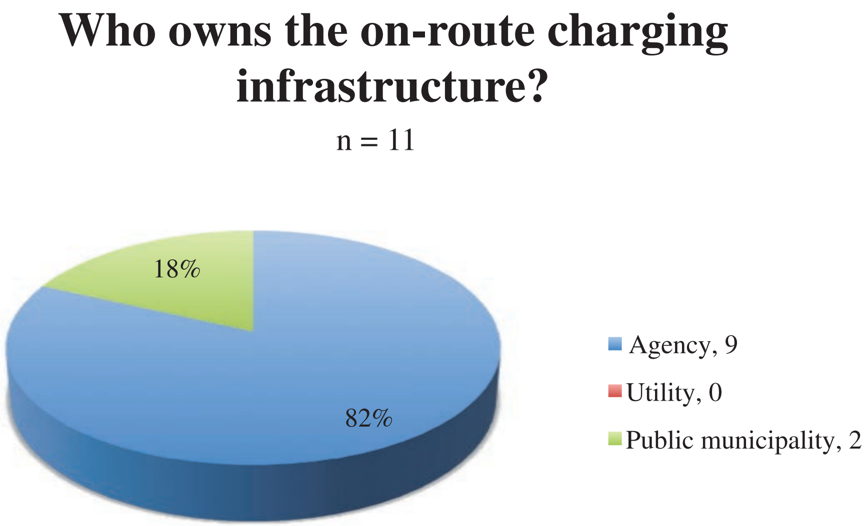
Worked well:

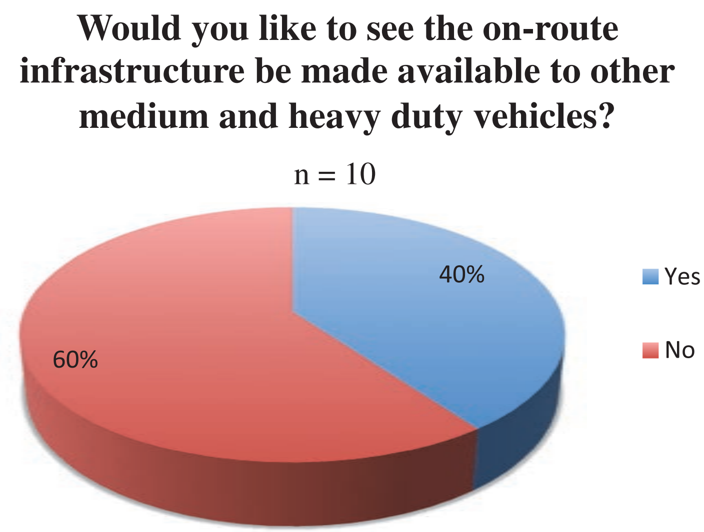
- Charger installation was smooth. Power requirements must be well understood by all
- Partnering with OEM, local utility and our A&E (accident and emergency) worked very well in design and construction of the charging infrastructure.
- Communication with local utility company and learning curve of agency
- Involvement of all stakeholders to determine locations (utility, public works, local and state DOTs, OEM, local planners)
- For the previous e-bus installation, we didn't have to involve the local utility due to the depot chargers. However for the future en-route chargers, we are involving well in advance of any RFP.
- Worked with same electrical engineer we have used for years.

Didn’t work well:

- We should have done a better job of determining our ultimate goal for BEBs. We had two restarts.
- Still working with our Utility company. Full infrastructure has not begun.
- Procuring property and ancillaries along with knowledge of systems are challenges.
- Working with the local utility company became trying at times as well as agreeing on the actual installation of the equipment.
- It was VERY expensive with unforeseen additional costs, the utilities and OEM were not as helpful.

Planning – Deployment of On-Route Infrastructure





Explain: Would you like to see the on-route infrastructure be made available to other medium and heavy duty vehicles?

No:

- Making them available to other users will interfere with bus operations. In addition it will complicate the responsibility for electric bills.
- We need the available time for the transit vehicles.
- TI is on restricted access authority property

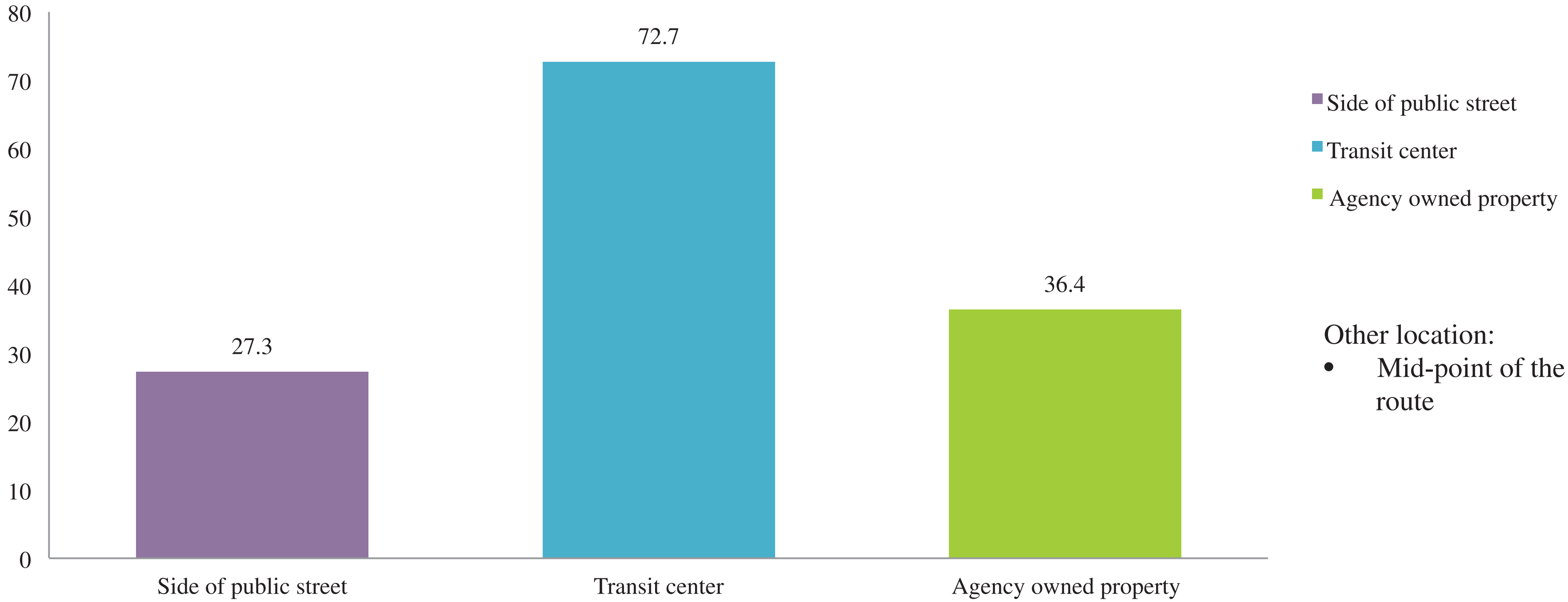
Yes:

- It is possible, but there are significant barriers. Shared use cannot jeopardize the ability of buses to dock, charge and run on schedule. A transparent method to segregate and assign charging costs to multiple entities would also be very important.
- As we expand, on-route infrastructure could be a great option for the public to use.
- Other city vehicles could go electric

How did you select the location of your on-route charging stations?

- We determined the transit center was the perfect location for the charging station since it was mid-point of the route. In addition, it provided us with a safe location to install the chargers considering its height limitations.
- They are located at the 2 main transit centers/park & ride facilities in the Antelope Valley.
- Selection was made based on route structure, recovery areas and demands.
- Proximity to layover points on existing routes, availability of low-cost real estate, availability of adequate utility infrastructure, adequate right-of-way for safe docking
- Our Central Hub is the transfer station for all WRTA routes
- End of the line of a route.
- Real-estate availability
- This was based off of the need of the agency as well as took into consideration future expansion options.
- As utility owner, we looked for locations on separate parts of grid for redundancy. Locations are at existing stops. One is located at planned service expansion location.
- It was the only location that we could make work
- Route analysis, available transit owned property, availability of power, and ease of installation

Where is the on-route charging infrastructure located? Select all that apply

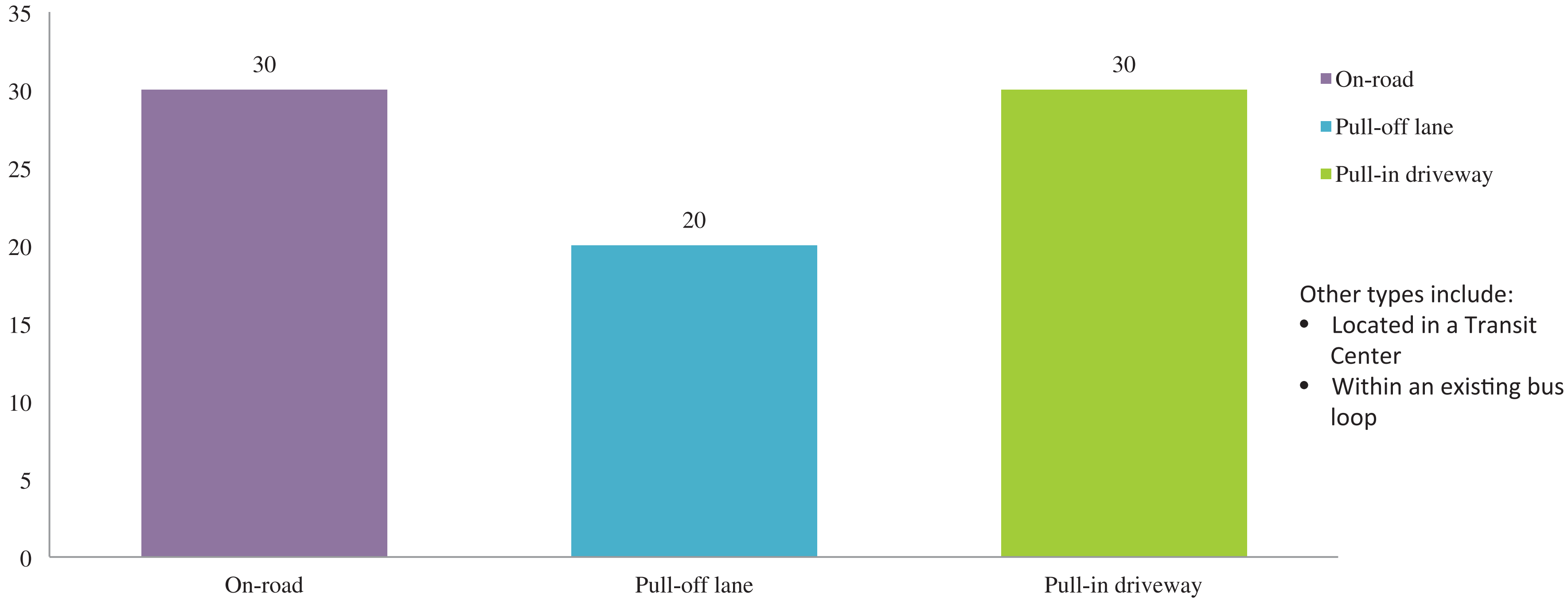


Other location:

- Mid-point of the route

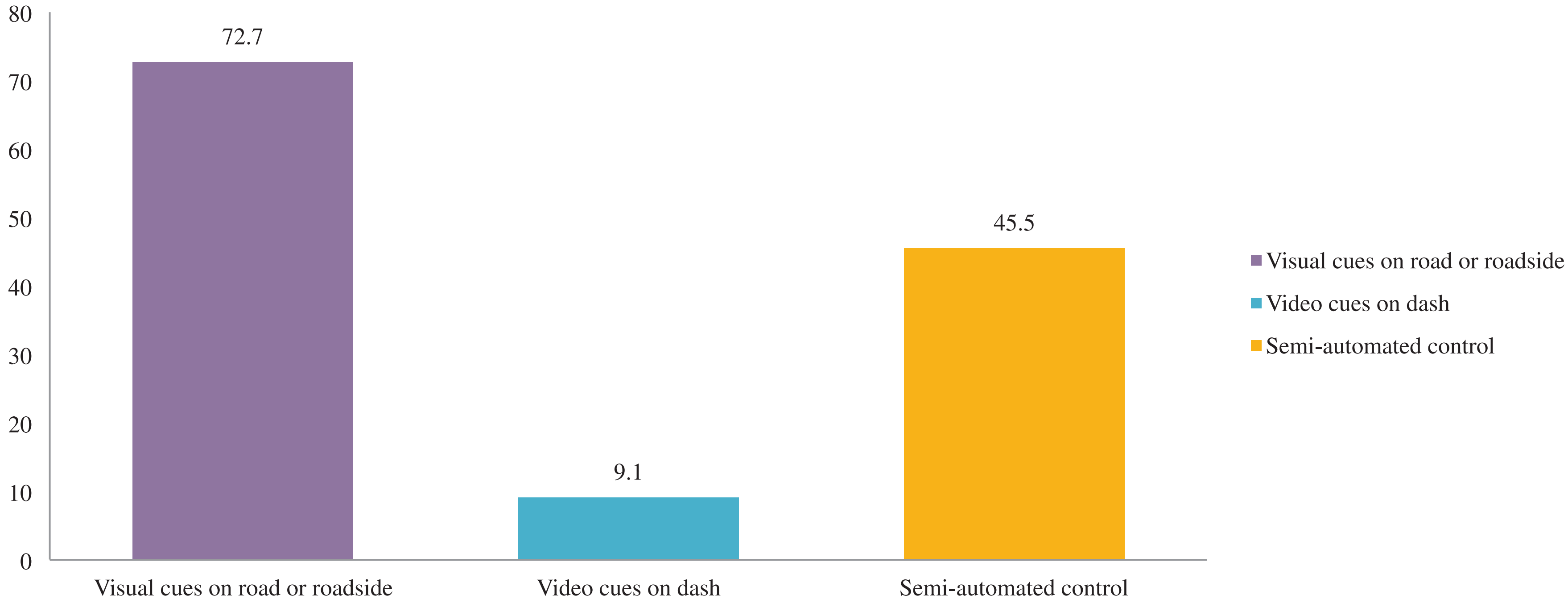
Value	Percent	Count
Side of public street	27.3%	3
Transit center	72.7%	8
Agency owned property	36.4%	4

What type of entrance/exit do you use for on-route infrastructure? Select all that apply



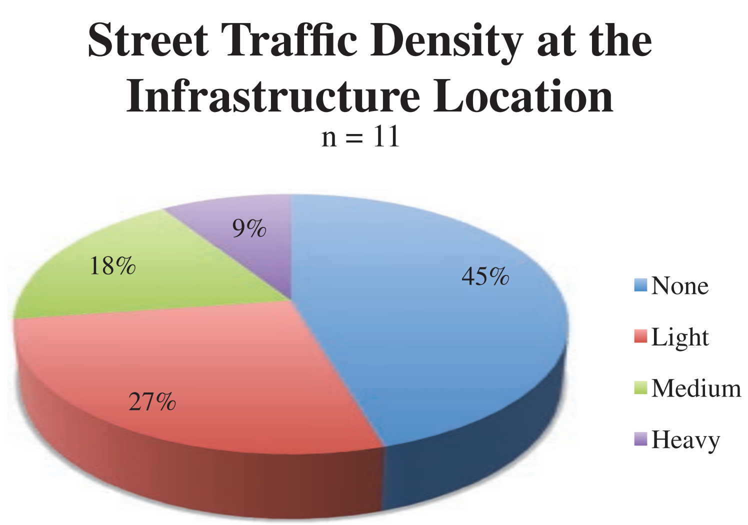
Value	Percent	Count
On-road	30.0%	3
Pull-off lane	20.0%	2
Pull-in driveway	30.0%	3

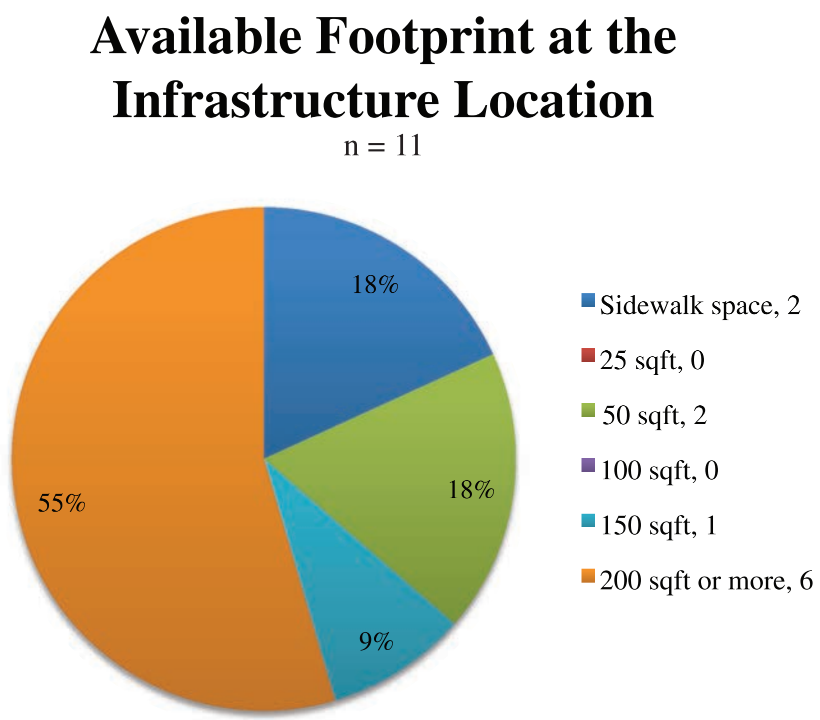
What alignment method for charging is used?

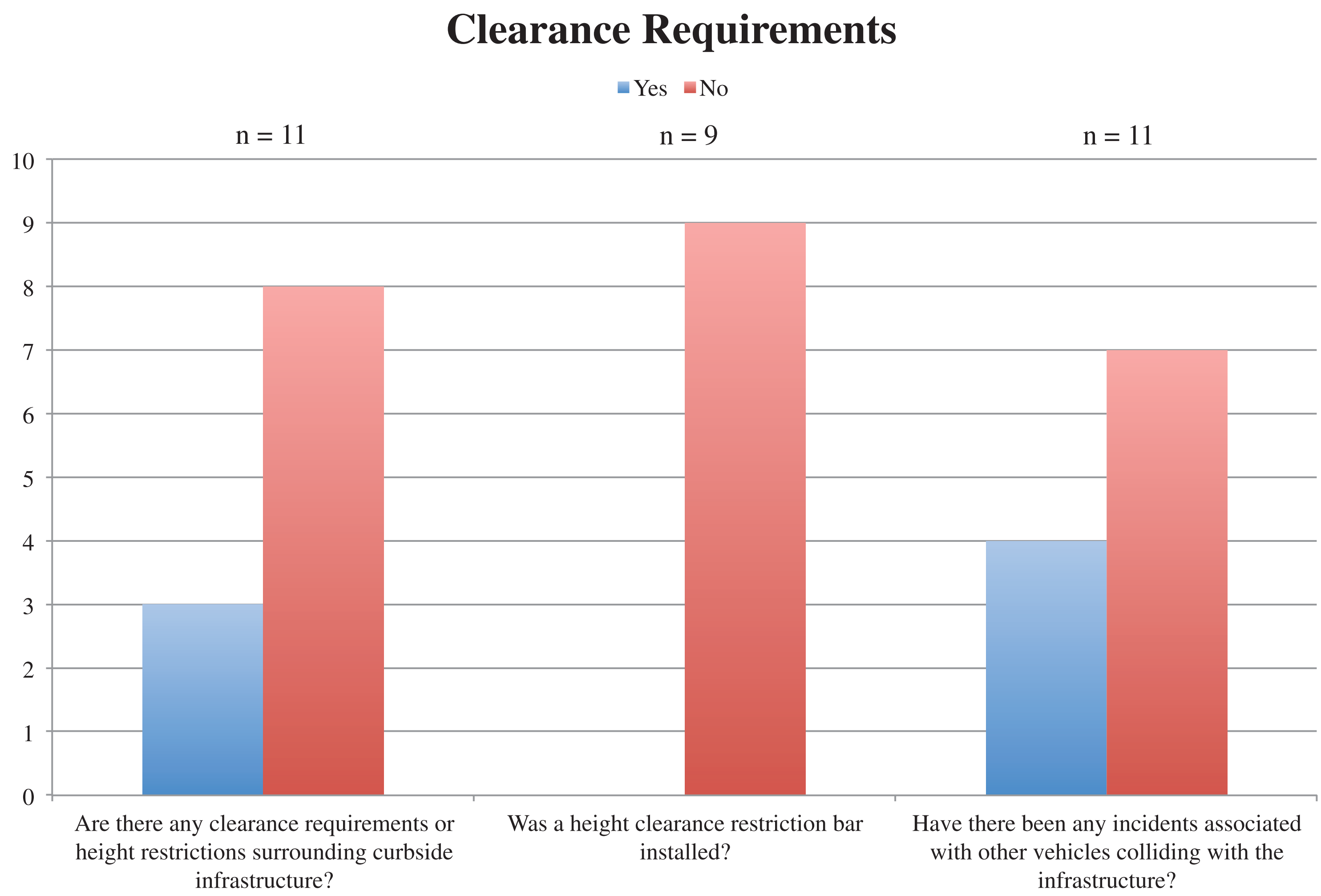


Value	Percent	Count
Visual cues on road or roadside	72.7%	8
Video cues on dash	9.1%	1
Semi-automated control	45.5%	5
Other - Write In	18.2%	2

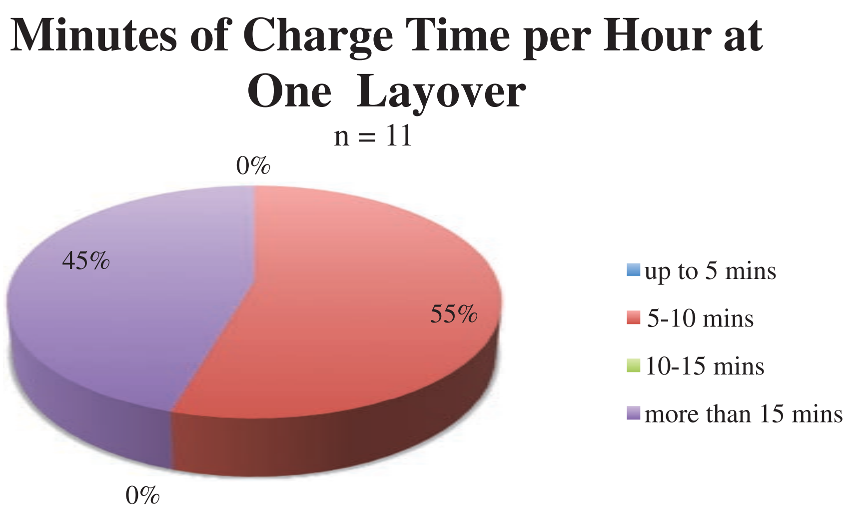
Planning – Deployment of On-Route Infrastructure

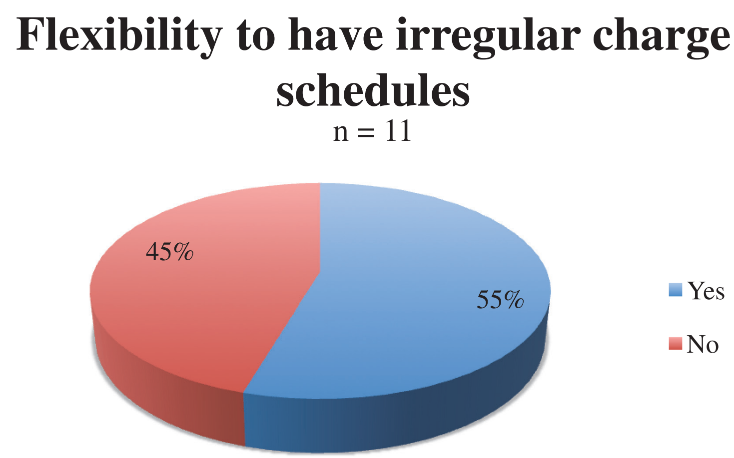


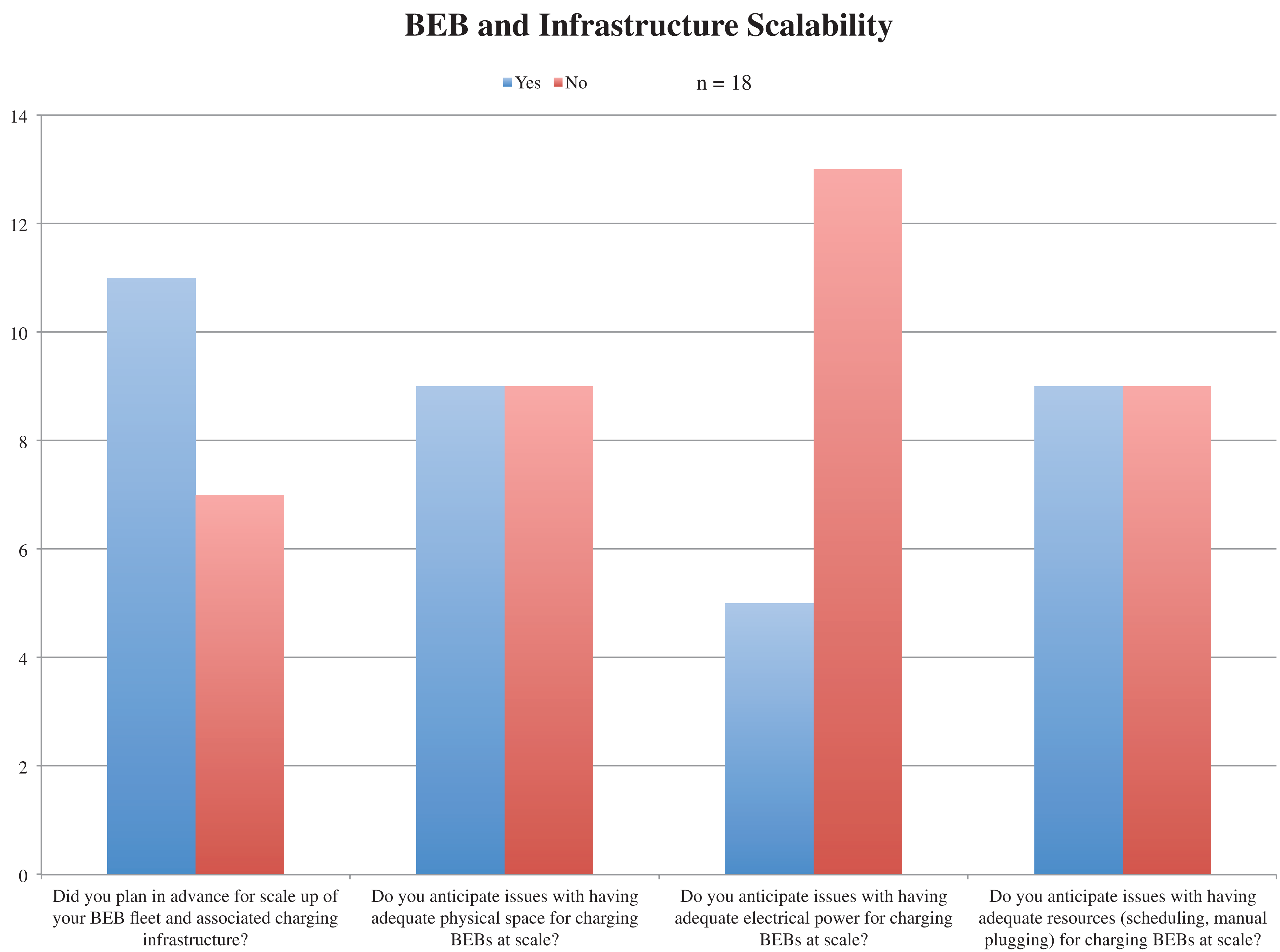



Clearance Requirements
Yes
No
n = 11
n = 9
n = 11
10
9
8
7
6
5
4
3
2
1
0
Are there any clearance requirements or height restrictions surrounding curbside infrastructure?
Was a height clearance restriction bar installed?
Have there been any incidents associated with other vehicles colliding with the infrastructure?

Scheduling


Minutes of Charge Time per Hour at One Layover
n = 11
0%
45%
55%
0%
up to 5 mins
5-10 mins
10-15 mins
more than 15 mins


Flexibility to have irregular charge schedules
n = 11
45%
55%
Yes
No


BEB and Infrastructure Scalability
Yes
No
n = 18
0
2
4
6
8
10
12
14
Did you plan in advance for scale up of your BEB fleet and associated charging infrastructure?
Do you anticipate issues with having adequate physical space for charging BEBs at scale?
Do you anticipate issues with having adequate electrical power for charging BEBs at scale?
Do you anticipate issues with having adequate resources (scheduling, manual plugging) for charging BEBs at scale?

How did you plan in advance for scale up of your BEB fleet and associated charging infrastructure?

- Parking location and distance from utility service.
- We started with 3 BEBs as a demo program knowing in advance that electrifying line 291 will require 7 buses during peak periods.
- We had two restarts as we went from 16 to 50 to 85
- 24 year roadmap and model simulations were produced
- City's agreement to provide more service for increased demand.
- Planned on doing as much underground work as possible. Take advantage of the open trench and concrete work to lay electric foundation.
- We are planning future routes and locations based on maximum scalability based on the real estate and number of potential buses.
- adding one more on route charger
- Recently we were awarded a Low-No grant to procure four (4) more electric buses and one (1) additional in route charge.
- location of chargers to serve existing and planned routes. Development of bus maintenance facility to accommodate fleet expansion.
- Our site was constructed fifteen years ago with excess electrical capacity in expectation of BEB growth

Do you anticipate issues with having adequate electrical power for charging BEBs at scale?

Yes:

- Depot charging is limiting in terms of space if a charger is needed for each bus
- As we move forward with our initiative of 100% fleet electrification by 2030, we are faced with depot space availability to accommodate a bank of charging stations necessary to charge our fleet.
- As fleet increases, we'll have to look into induction and on-route charging options.
- Adequate space for charging is a significant issue for on-route charging because we don't own any appropriate real estate.
- We already know sites where charging will be an issue if we scale.
- All charging infrastructure is on perimeter of yard, and agency does not have any other available land and will need to pay for ROW.
- Many reasons. Impact to maintenance and dispatch operations, footprint requirements, power requirements, time to upgrade power distribution infrastructure to name a few

No:

- We are a tier 2 fleet with over 10 acres of property
- We are installing the full system at the beginning
- Bus barn capacity is large enough to upgrade
- Adequate planning in OEM contract for increased fleet size
- Planned on expanding solar panels to provide post for depot chargers to be mounted on.

Do you anticipate issues with having adequate electrical power for charging BEBs at scale?

Yes:

- At this time we are not sure if we have the appropriate electrical infrastructure at our bus depots.
- There is a clear capacity limit for extended range bus charging at our single depot.

No:

- We know how much power the ultimate system needs, that how much we are starting with
- Adequate planning with provider
- No, we worked with Utility Company, to size correctly.
- COMED has indicated that providing the power will not be an issue. The issue is the cost to bring the power.
- We have adequate power
- Up to 30% of our fleet could be charged using current facilities
- Adequate power is available from our two utility companies

Do you anticipate issues with having adequate resources (scheduling, manual plugging) for charging BEBs at scale?

Yes:

- Securing funds are limited and require commitment to renewal
- There are clear capital and operating costs associated with charging. The question has to do with the trade-off with costs associated with diesel use.
- We expect to have some issues. However, we are trying to plan around them based on our technical specs.
- Impacts to footprint, maintenance process, etc.

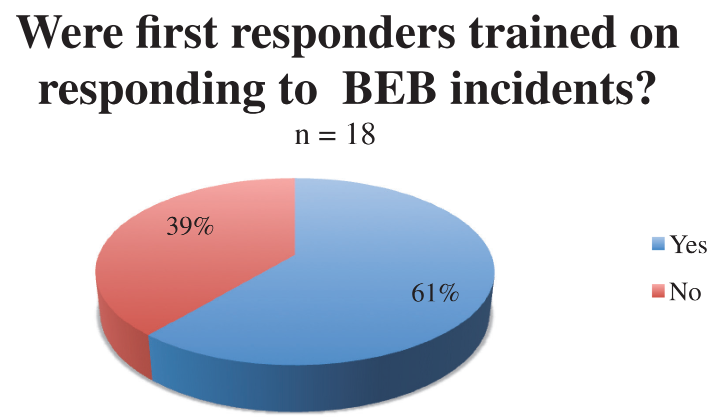
No:

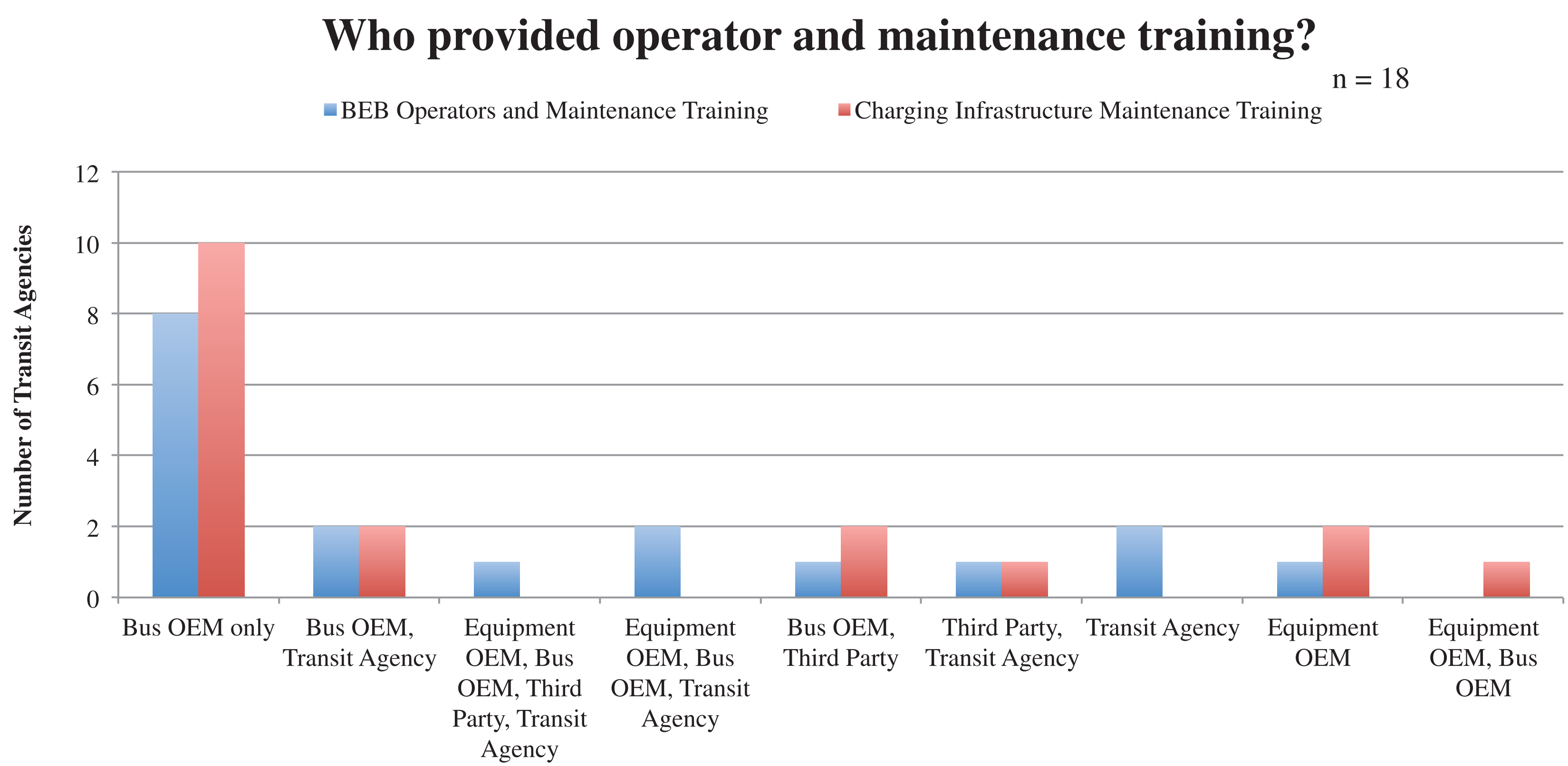
- Utility staff are trained how to manage the charging cycle
- With depot charging on route charging and long range buses we will be able to operate without issue
- already worked into standard SOP
- Adequate planning
- Easier process to plug in than to fill with gasoline pumps.
- we have adequate resources
- Connectors do wear out

Training

What percentage of your personnel has been trained on the BEB fleet?

- Drivers: average 70%
- Maintenance workers: average 58%





Training

What worked well and didn't work well when training for BEBs?

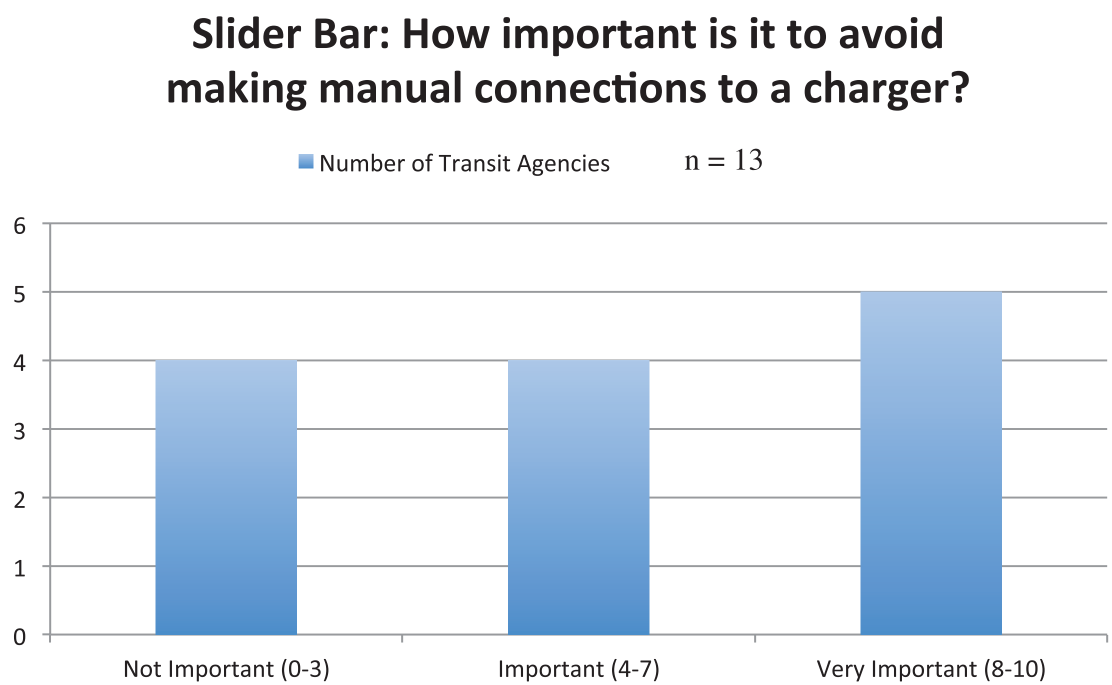
- Working with third party trainers worked well. Initially Bus OEM trainer needed help
- training first responders was most important and went very well.
- OEM was well prepared and trained all areas well and in groups, for more one on one time.
- The biggest issue is the unknown nature of the SOC for new operators. It would be best to have an estimated range (time of operation remaining) for the operators.   Additionally, the bus is top-heavy due to the batteries.
- Train the trainer went well and training material was well organized
- Shadowing the service gave us the flexibility to pull BEB's offline to train personnel.
- training sessions for drivers and first responders together worked well.
- Range capacities of different battery chemistries
- Hands on with bus on site worked well. Having factory technical rep on site worked well. Covering all shifts since we operate 24/7 was challenging. The training manuals were not ideal

Other

- We are still in the process of expanding our maintenance training. More detailed diagnostic training is still required.
- We are currently in the process of completing our training for our recently delivered BEB; presently, we cannot provide an accurate assessment of our training until the training has completed.
- No issues with driver training on BEBs

Operations Experience

State of Charge	Minimum	Average	Maximum
Depart for service (%)	83	93	98
Return from service (%)	45	60	73



Reasons:

Not Important:

- It is much easier to plug in a BEB than fuel a CNG bus.
- Redundant system, hasn't been used.

Important:

- It is much less of an issue for depot charging.
- Easier to have connections be automated. Reliance on humans for manual connections generally introduces higher risk of error or oversight.

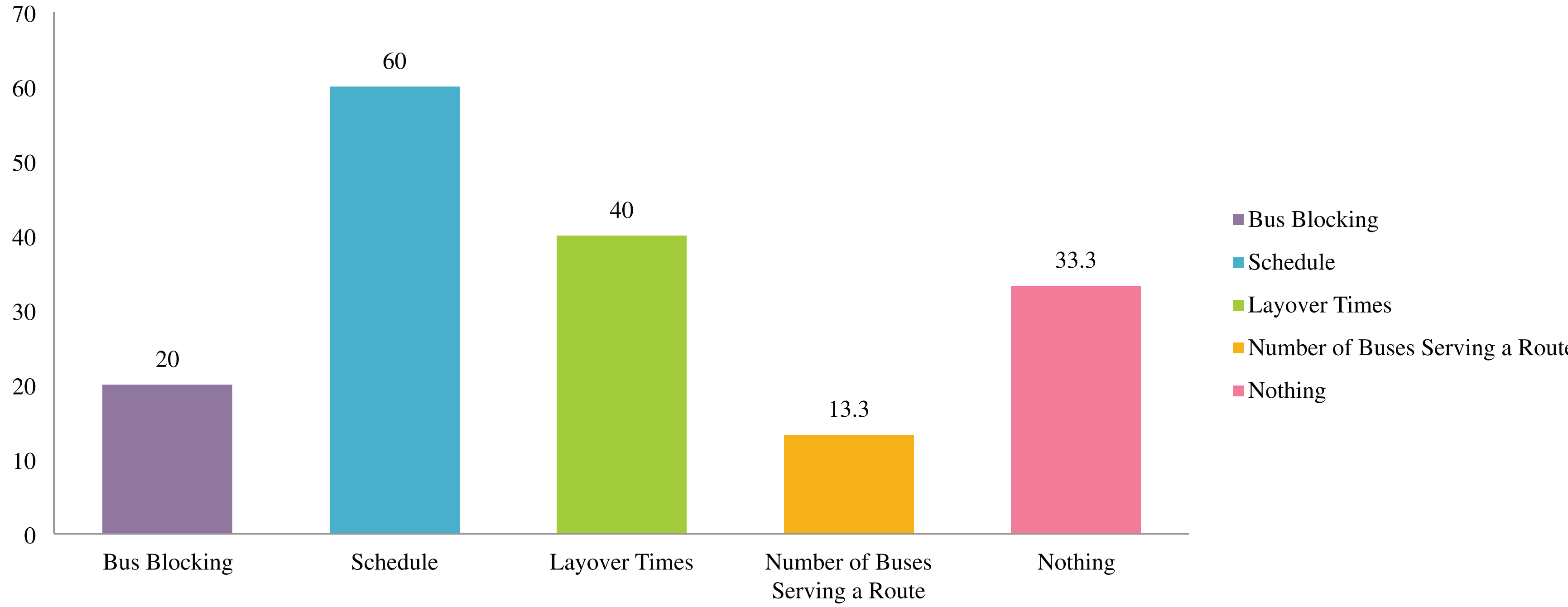
Very Important:

- Avoid injury and errors
- Needs a good connection to charge, trained employees on what to look for.
- Route timing & safety concerns

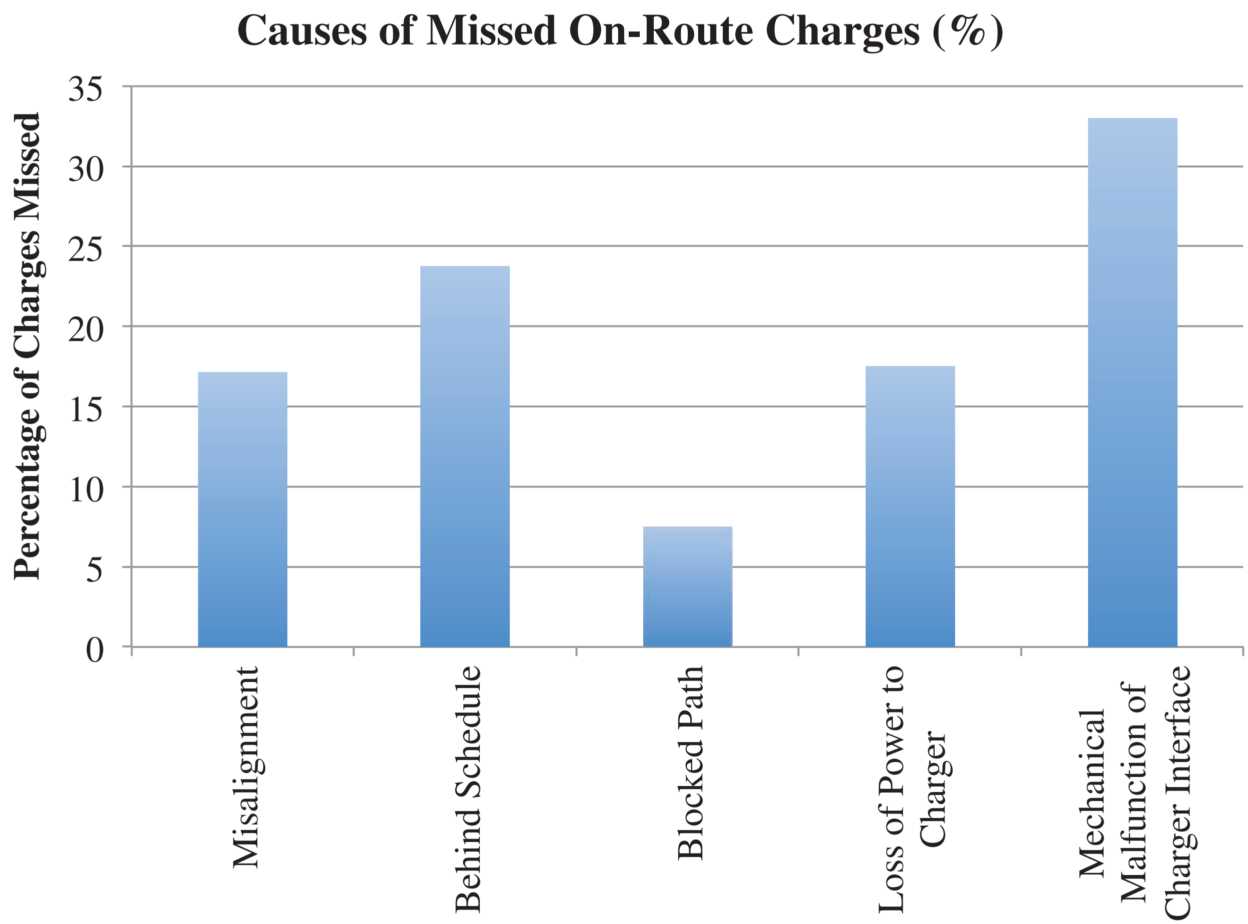
Other:

- We want to minimize Manual connections (e.g. plug-in depot chargers) as much as possible.
- Manual charging is fine. We have used it for years
- We will have depot charging for all buses

Which of the following, if anything, did you have to change to accommodate the BEBs? Select all that apply



Value	Percent	Count
Bus Blocking	20.0%	3
Schedule	60.0%	9
Layover Times	40.0%	6
Number of Buses Serving a Route	13.3%	2
Other - Write In	13.3%	2
Nothing	33.3%	5



How did you manage continued operations during missed charges?

- They returned for a second attempt to dock and charge.
- Used alternate charger
- In some cases, we re-route to alternate charger. On circulator routes, where the issue is that the charger is occupied or the bus is behind schedule, we simply perform another loop. In extreme cases, we operate diesel buses.
- We didn't and had to wait for repair
- The routes are short so the buses can miss a charge and not impact service
- We shadowed our service until we felt the reliability of the buses and infrastructure was stable.
- Express bus has priority, other buses have another charging opportunity at second fast charger 2.5 miles away.
- Send out fossil fuel bus

Please describe what worked well and what didn’t work well when operating BEBs.

- The good buses are very reliable, over 92% availability rate. The not so good - operator training. on board monitoring of consumption rate would help.
- The buses can operate on route 24 hours 7 days a week. We have not experienced any major operational issues. Driver training related to the docking as an early issue.
- winter is a small issue. Need additional heat requirements for cold weather areas.
- We have had minimum problems.
- Our inability to locate on-route charging equipment where it would be most efficient is a significant issue. Driver's configuration was not to our typical specification and was challenging
- The issues are ensuring you have ample time to charge when various factors happen (e.g. late pull-in) and also ensuring charging is occurring when it should be. (e.g. charging operation may stop)
- We sometimes have issues with making pull out when the charger is down or when we loose access during special events.
- Inability to avoid layover time has affected route schedules when traffic or other delays occur.
- Worked well—passenger experience Didn't work, long term support from component manufacturers

Please describe what worked well and what didn’t work well for charging with on-route infrastructure.

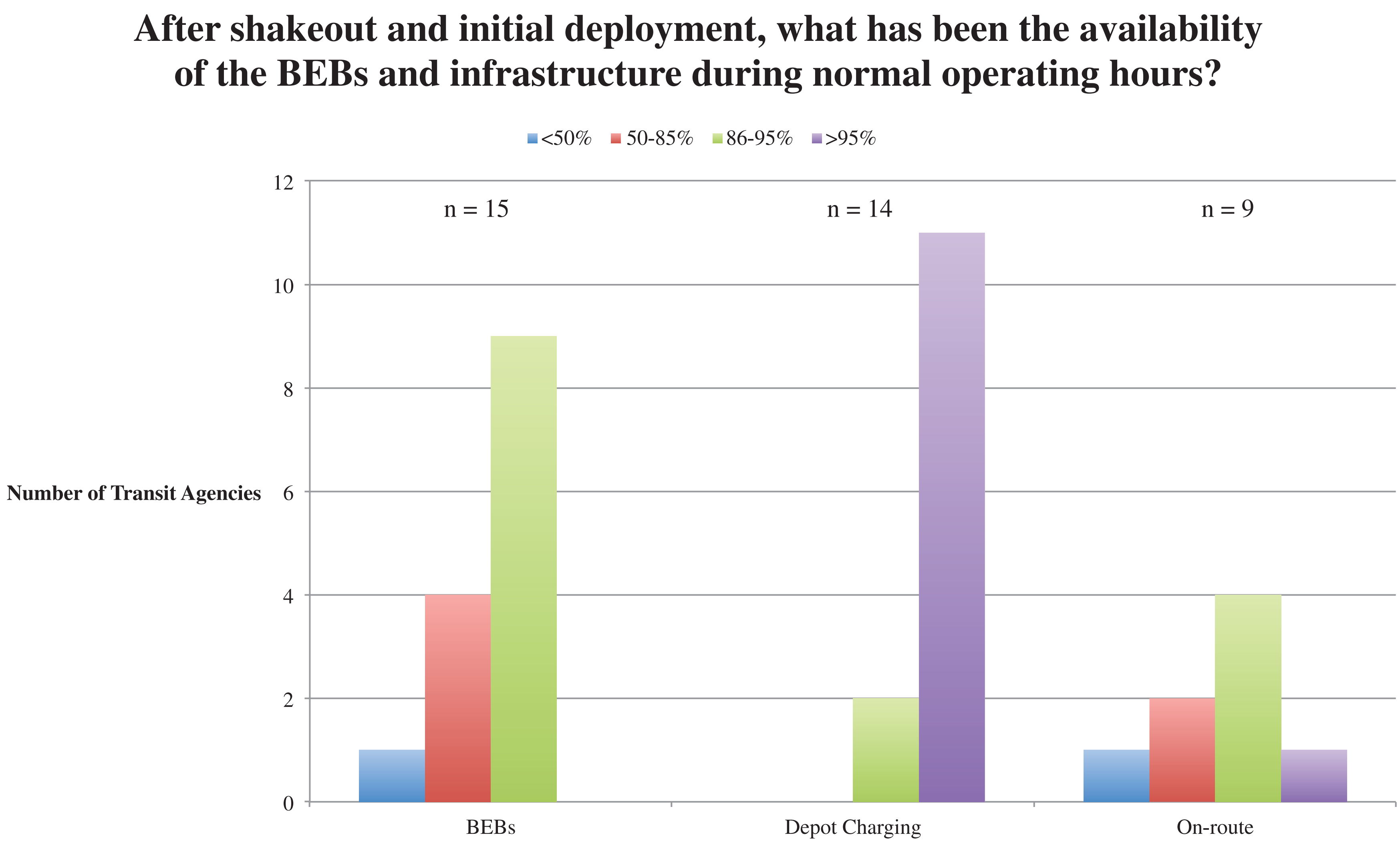
- With in-route charging we can practically operate the BEBs 24 hours a day 7 days a week. The BEBs are always charged without having to return to the depot. What didn't work well is a single point of failure. If the chargers go down, it impacts delivery of service. If one of the two chargers goes down, charging of buses is impacted and on-time performance.
- We are just now putting on-route chargers in service
- The system generally works well.
- Adequate testing, training and PRACTICE docking.
- On route charging works well; buses are able to charge quickly and not cause long layovers
- Managing the unknown issues that arose during the implementation of our service.
- Electrical demand costs caused transit managers to instruct drivers to avoid using the second charger in order to save money. Non-demand pricing fixed that.
- Getting operators trained worked well. When operators forget the procedures it was a challenge

Explain how the availability of the BEBs has affected operations.

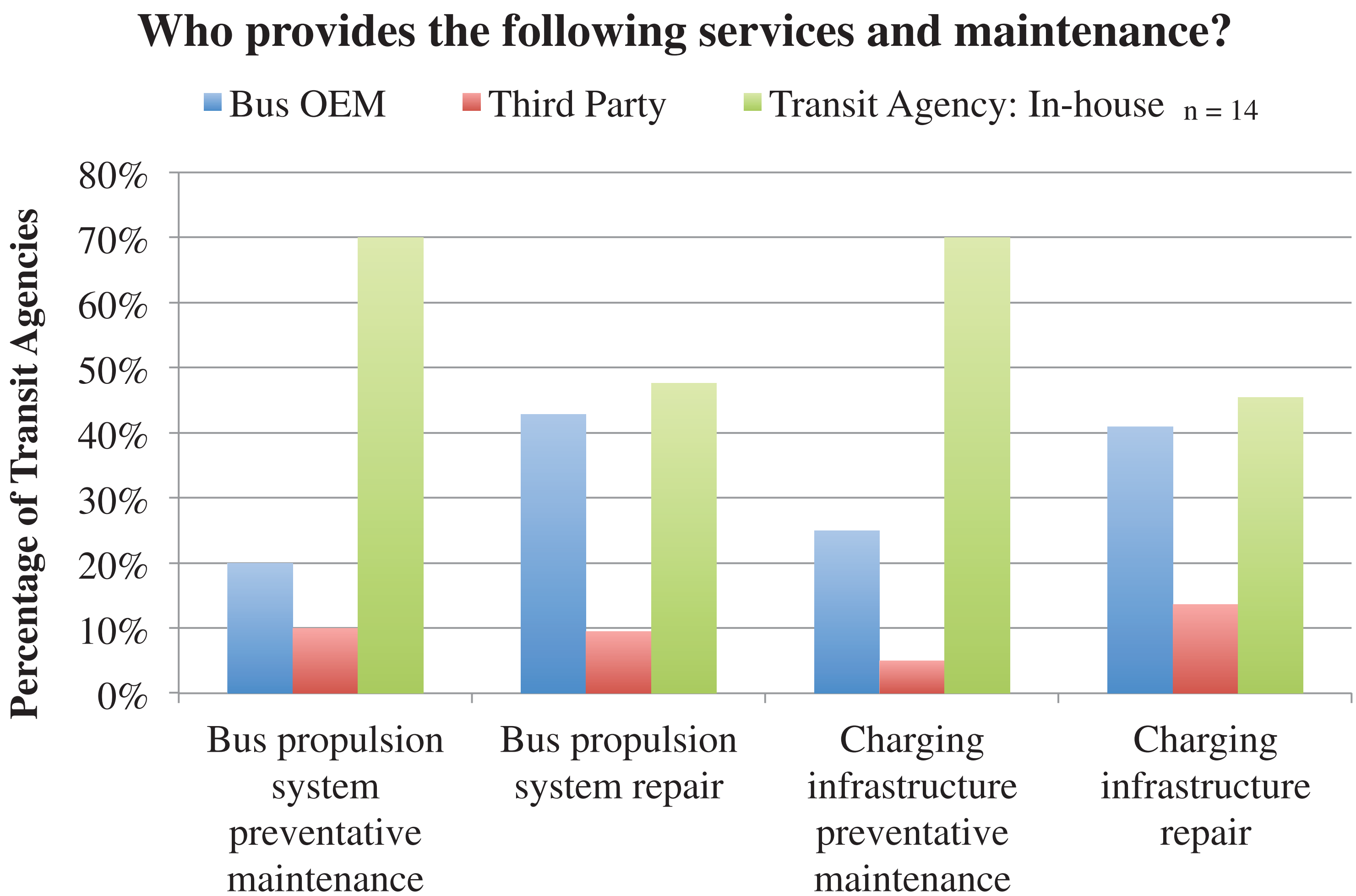
- High availability has been positive for ops.
- The BEBs replaced the CNG buses that were initially operated on Line 291. We have sufficient spare ratio to supplement service when BEBS are going through PMIs.
- We had issues with one rear wheel hub
- Great, they're available and more reliable than the diesel buses
- In general, reduced maintenance cost and increased reliability. Where used for local service, it has also increased operating cost due to the alteration in scheduling.
- Has caused service delays, as we often need to swap bus out when it has a low SOC.
- Missed trips and spare fleet vehicle availability
- When the bus\charging isn't available, we will operate normal buses
- There has not been any impact because we still are able to use our older diesels buses when the BEB's are not available.
- Spare factor=no effect
- when we add the remaining buses to the fleet we will have to change the schedule of the route

Explain how the availability of the charging infrastructure has affected operations.

- Vehicles operate 95 miles in the AM peak and return to facility at 10am. buses are topped up and do 95 miles in the PM peak.
- The charging infrastructure did not have any impact on operations. Buses charge at the charging station at the Transit Center while passengers board and alight.
- Location of the infrastructure has increased route length for local (non-circulator) service
- Missed trips and spare fleet vehicle availability
- When the bus\charging isn't available, we will operate normal buses
- Increased our number of missed trips.
- Redundancy=no effect
- Only minor charging problems


After shakeout and initial deployment, what has been the availability of the BEBs and infrastructure during normal operating hours?
<50%
50-85%
86-95%
>95%
n = 15
n = 14
n = 9
Number of Transit Agencies
0
2
4
6
8
10
12
BEBs
Depot Charging
On-route

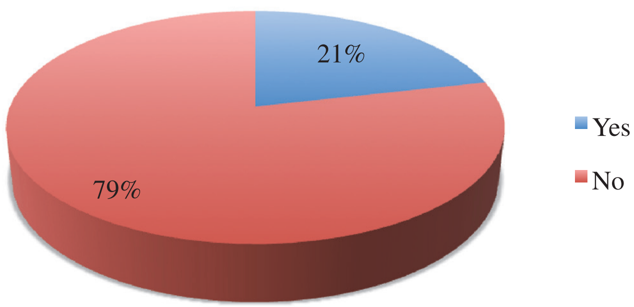
Maintenance Experience



Traction Battery Experience

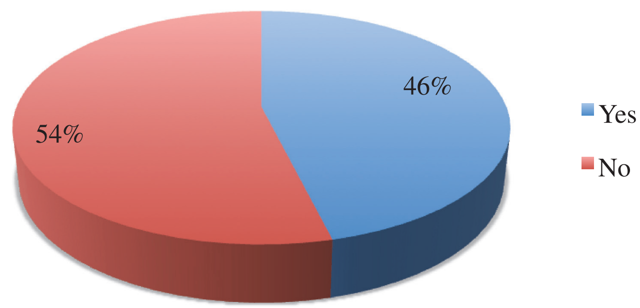
Have you had any issues with the traction battery?

n = 14



Do you track battery degradation/ end of life?

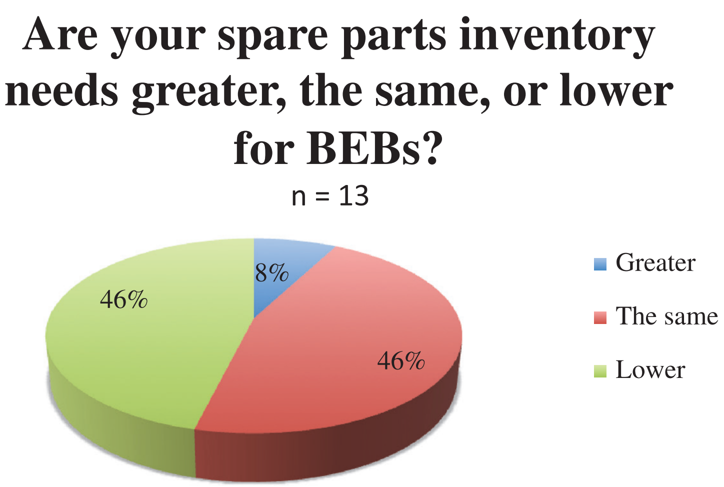
n = 13



How do you track the degradation?

- OEM tracks
- OEM software/report
- We have asked New Flyer to review recently; and they provide the current capacity vs. initial capacity.
- comparing battery data with expected 6 year battery life.
- Fleet maintenance software

Spare Parts Requirements



Explain

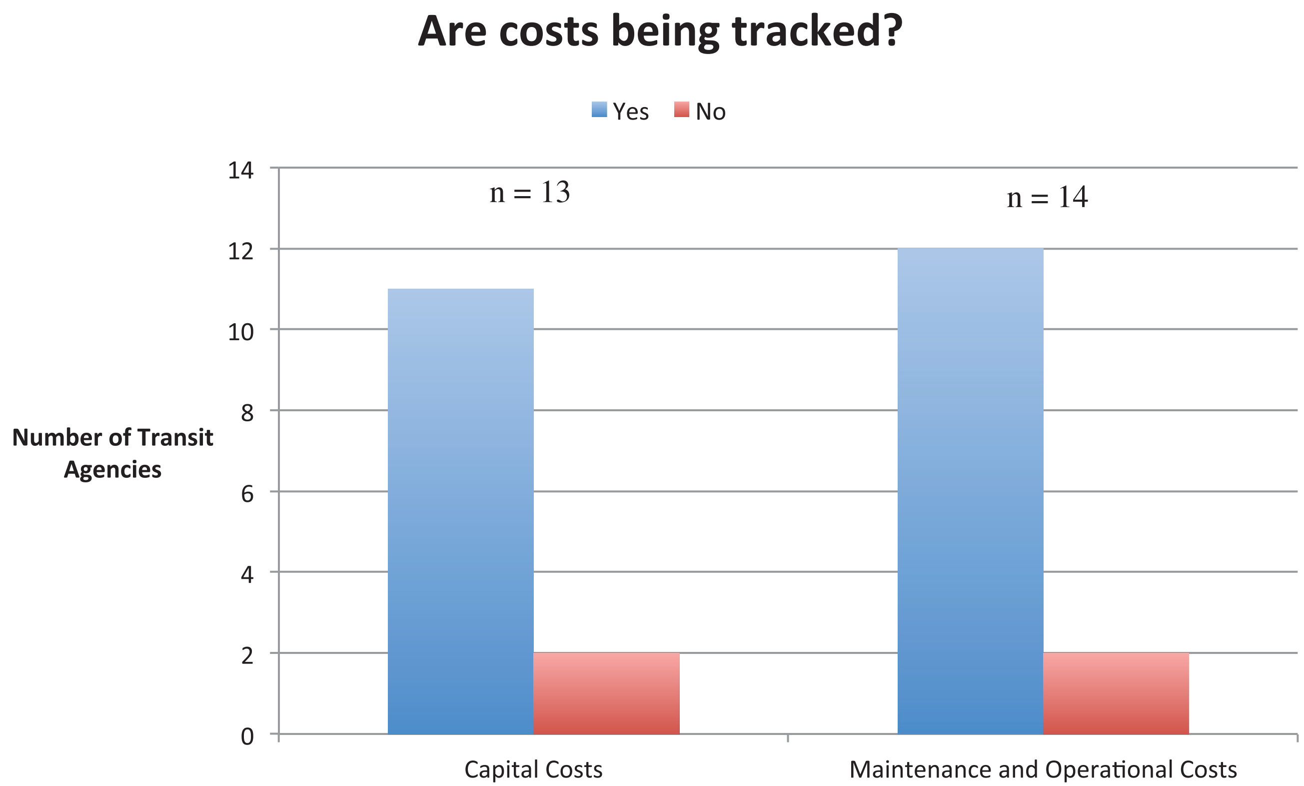
- No transmission (for instance), and brake life is longer with BEBs
- already have same model year buses
- No transmission or engine spare parts are needed.
- Far fewer parts to stock
- Parts availability is an issue
- This is hard to perfectly evaluate since we only have 2 buses vs. a much larger fleet.
- Too early to determine.
- Fewer moving/wearing parts means lower need for propulsion inventory, however bus body discontinuation means having more body parts available for 12 year bus life.
- Long lead times, smaller manufacturers
- Fewer parts needed for BEBs

Please describe what worked well and what didn't work well when maintaining BEBs.

- We had initial issues with the low voltage side of the system. This required programming changes to ensure the low voltage batteries remained charged
- BEBs PMIs are labor intensive similar to other vehicles. BEBs do not require consumables such as oil, transmission fluid, filters, belts, etc. So, maintenance costs are cheaper around 9 cents per mile versus 12 cents per mile on CNG buses. This is based on scheduled maintenance and does not account for any unscheduled maintenance costs.
- We have not had any significant issues with the buses, so all is going well.
- All went well
- Working very well, operating at a 98% rate. Down time is usually due to issues other than maintenance. Also, maintenance costs are down significantly.
- We didn't train early enough, relying on OEM tech support. Techs with electrical engineering backgrounds would be helpful, which we don't have.
- Parts availability is an issue; change in technology and associated training
- For the most part, there hasn't been any issue in maintaining them.
- BEB have been very reliable and good customer service
- Parts availability for discontinued body design, including windshields, doors.
- No established maintenance parameters. Had to create them.
- We have only had the buses in service for less than a month
- Well: simpler to work on; not as well: new technology is a challenge

Cost Experience

Cost Tracking

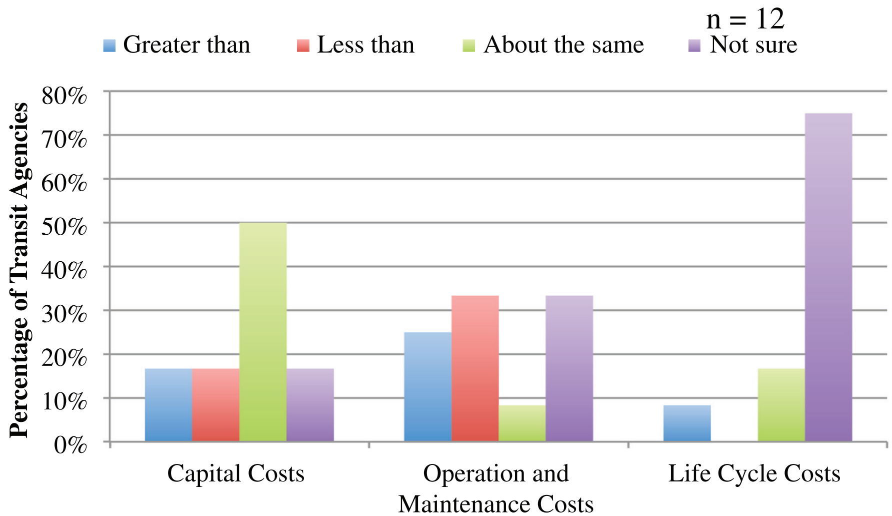


Costs ($/mile)	Minimum	Average	Maximum
Scheduled Maintenance	$0.09	$0.36	$0.92
Unscheduled Maintenance	$0.09	$0.28	$0.55
Fuel/electricity for BEB Fleet	$0.27	$1.52	$0.47

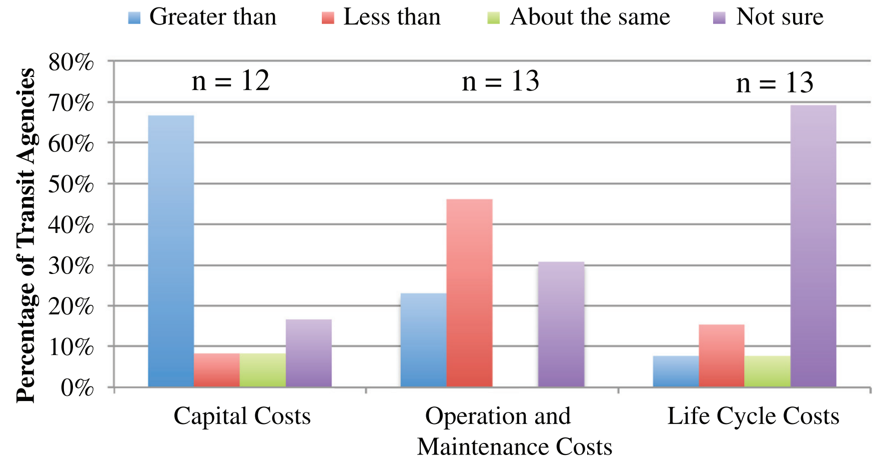
Explain costs and benefits

- Electric bus maintenance and "fuel" costs are less than diesel.
- The capital cost has to date been about 2:1 for BEBs. The maintenance costs are lower due to the elimination of standard diesel PMs and less frequent brake maintenance. There is not yet enough data to validate life cycle cost savings.
- Capital costs: charging and other infrastructure upgrade costs are not included. Ops and Maint costs: Not enough data to know yet. Life cycle costs: not enough data to know yet
- We did a very high level analysis of the BEB's cost. However, we are trying to fine tune that as we implemented sub-meters to take data more accurately.
- Budgets were based on diesel bus operation and have not yet been modified. More operation time with BEBs is needed to ensure that costs will continue to be lower.

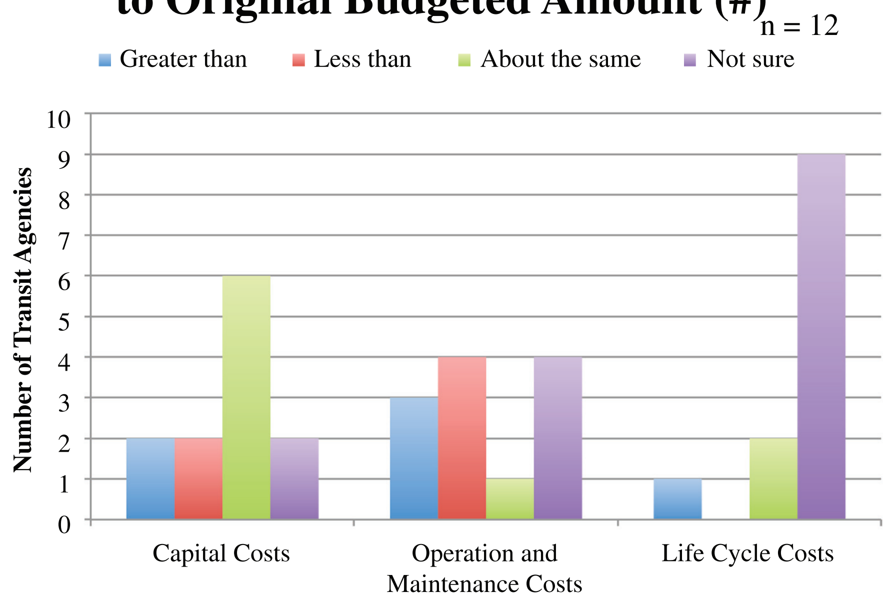
Cost Comparison: Actual BEB Cost to Original Budgeted Amount (%)



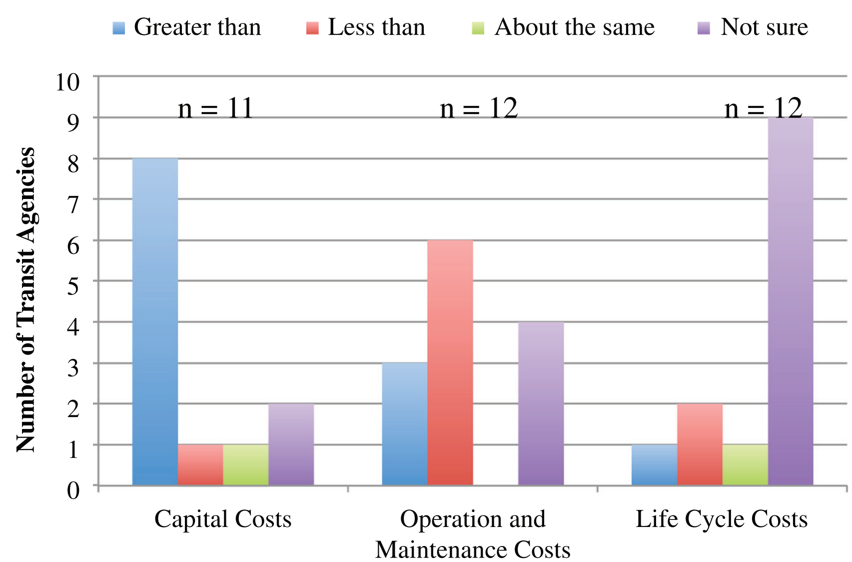
Cost Comparison: BEBs to Existing Diesel/CNG Buses (%)

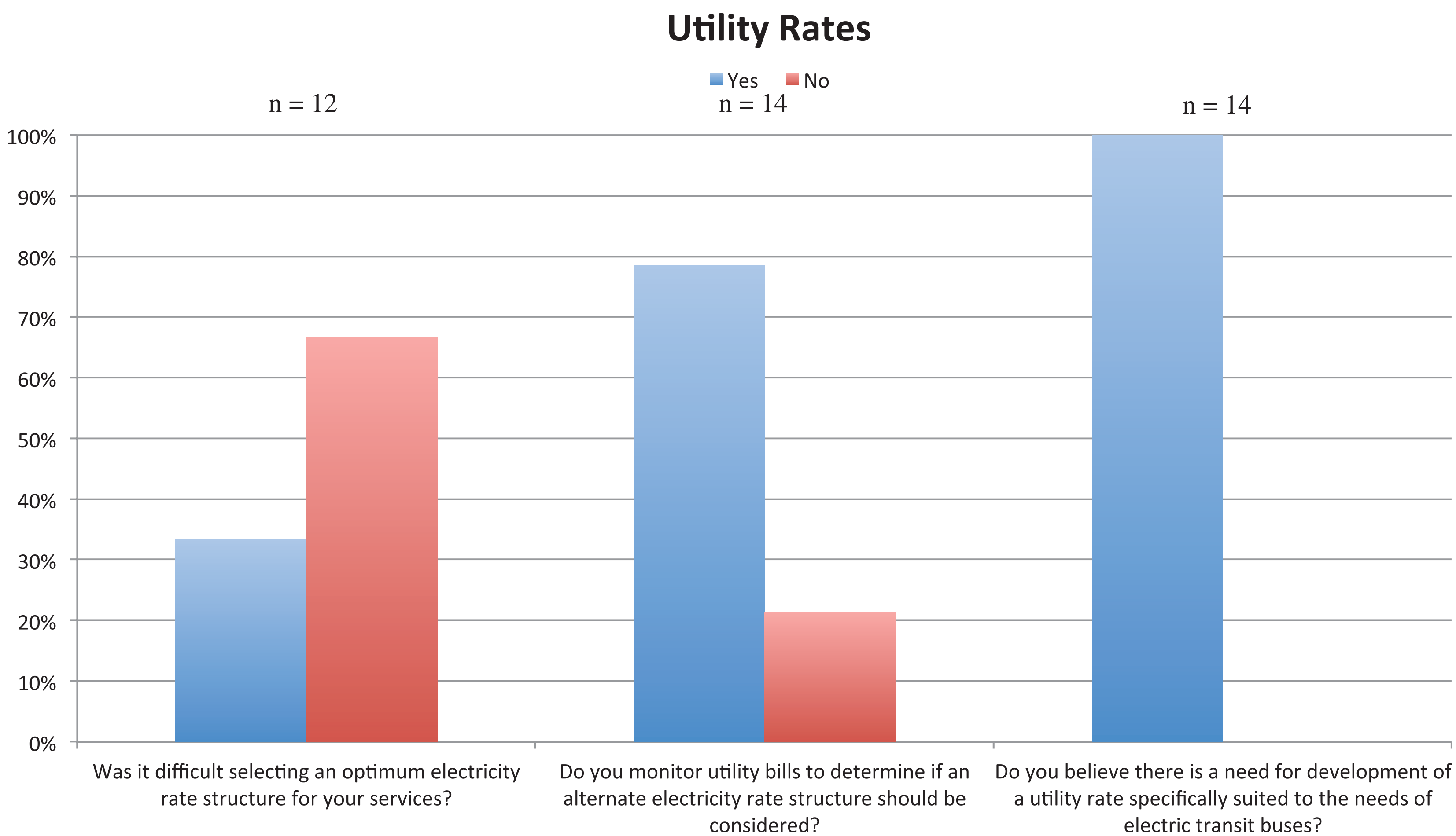


Cost Comparison: Actual BEB Cost to Original Budgeted Amount (#)



Cost Comparison: BEBs to Existing Diesel/CNG Buses (#)





Explain: Was it difficult selecting an optimum electricity rate structure for your services?

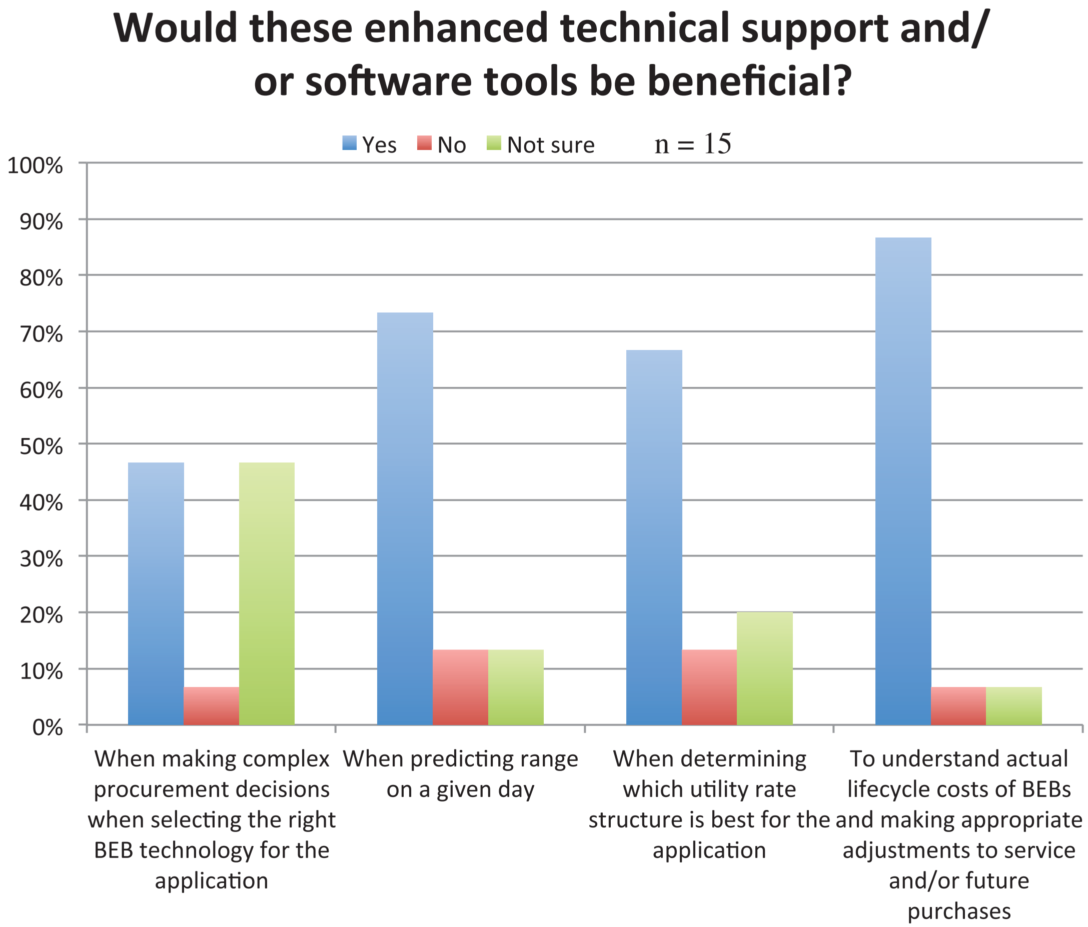
Yes

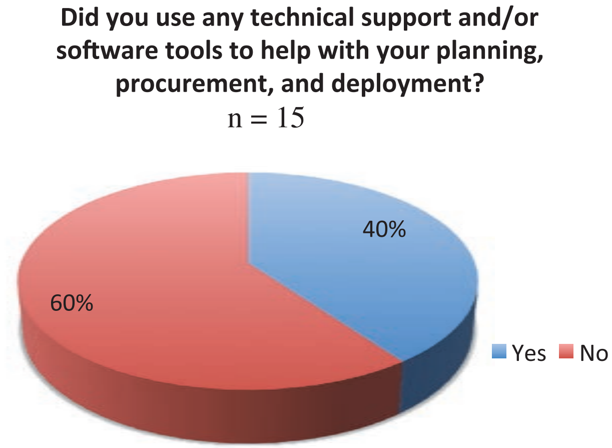
- We do not select our electric rate structure. That is developed and determined by So. Cal. Edison. We have been working with Edison for the past 4 years to determine a suitable and lowest possible rate for our EBs.
- Worked with local utility
- The optimum rate still has to be determined.
- Demand vs. non-demand charge

No

- We have fantastic support from the two utilities we work with
- Had to negotiate with the City.
- We were given a very limited choice, which made very little difference.
- We have nighttime TOU metering

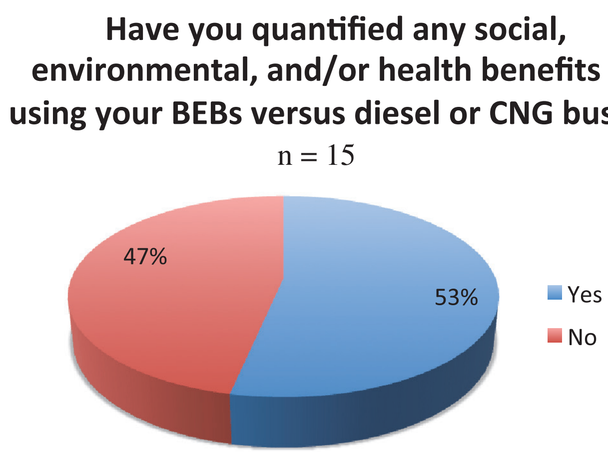
Technical Support Tools





What did you use?

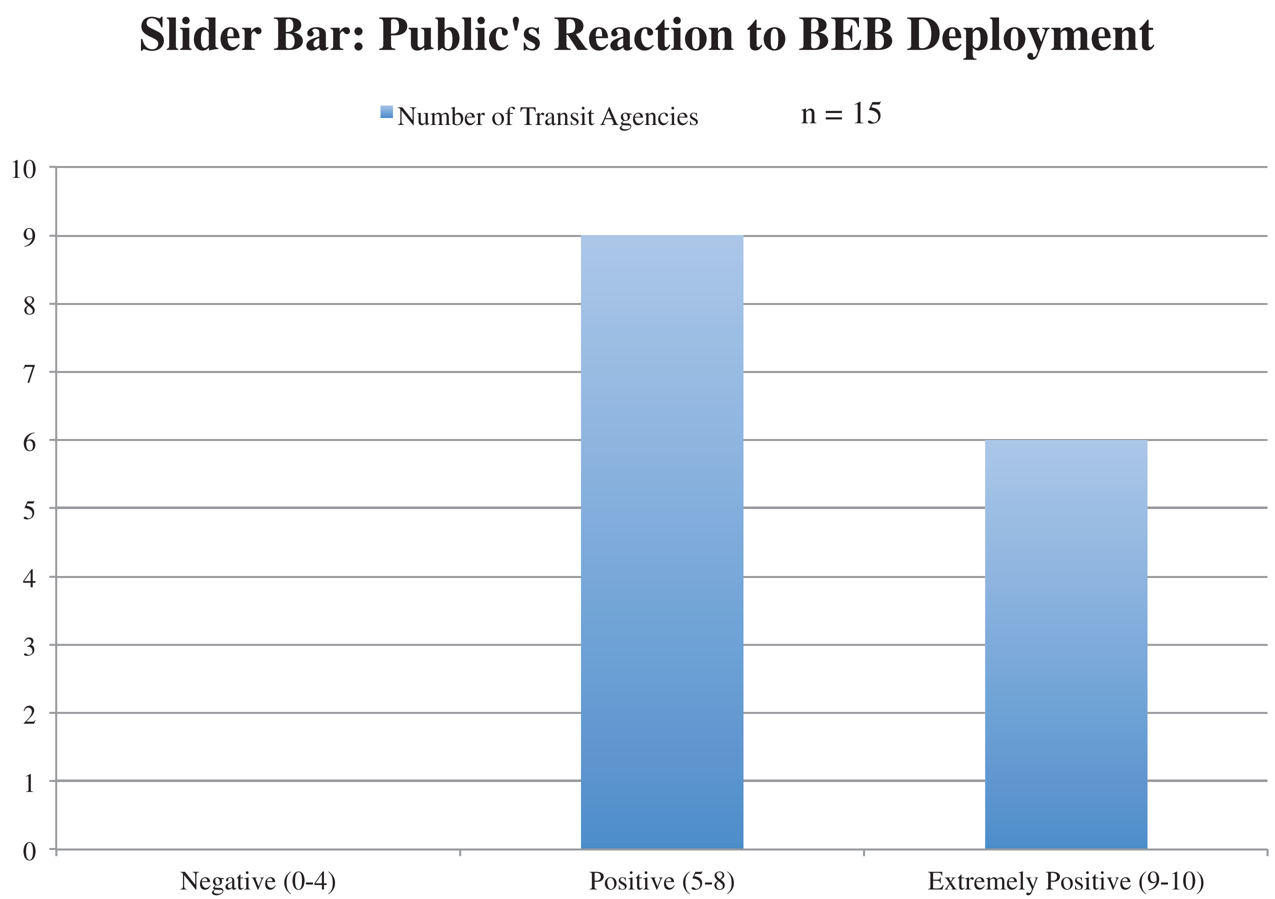
- OEM support and staff support.
- We used CTE (Center for Transportation and Environment)
- We used a software called Viricity. It records and provides real time electric data, SOW, speed, miles, Kwh etc...
- We worked with the OEM using their route projection information software. This looked at speed, grade, average speed to determine a safe range of travel.
- We utilized our route data in order to make an informed decision.
- Proterra supplied software



Please describe those benefits.

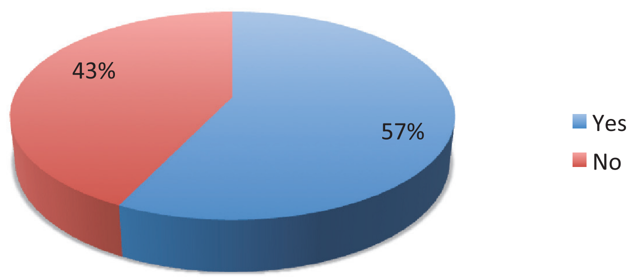
- We calculated the GHG emission reductions in utilizing BEBs in fully electrifying Line 291.
- Because most of our funds for the project have come from the State of California, we have had to calculate GHG reductions.
- Environmental & Health benefits: Decreased the CO2 emissions and other Greenhouse Gases.
- We know that compared to the buses they replaced we are avoiding over 3,000 lbs/year of criteria air pollutants, depending on miles in service per year.
- 504 tons of carbon monoxide saved in 40 months
- We have put this both in advertising on bus, press, and web. We utilized EPA's DEQ calculator for this. http://www.transitchicago.com/electricbus/ What are some of the environmental benefits? The new electric buses will replace two 6400-series Nova buses purchased in 2001. When comparing these two different model buses, each electric bus is expected to yield significant reductions in harmful emissions and air-borne pollutants. Reduced emissions lead to reduced occurrences of illness, such as respiratory diseases. According to the EPA's Diesel Emissions Quantifier Health Benefits Methodology, the reduction in particulate matter from just one electric bus is equivalent to about $55,000 in health benefits savings annually; and over the anticipated 12 year lifetime of the bus, annual health benefit savings are estimated at about $660,000 in health benefits. Reductions in other harmful emissions include: Carbon dioxide (CO2): a 121-ton reduction per year, per electric bus. Over the anticipated 12 year lifetime of the bus, this equates to 1,452 tons per bus. Hydrocarbons (HC): reduced by 0.0428 tons per year or 0.5136 tons over the 12 year lifespan of each bus. Carbon monoxide (CO): reduced 0.310 tons annually or 3.72 tons over the lifetime of the bus. Nitrogen Oxides (NOx): less 0.5938 tons per year, or 7.1256 tons over the lifetime of the bus. Particulate matter (PM): reduced by 0.0274 tons per year, or 0.3288 tons over the 12 year lifespan of each electric bus.
- Merchants and residents like the quiet buses

Public Relations

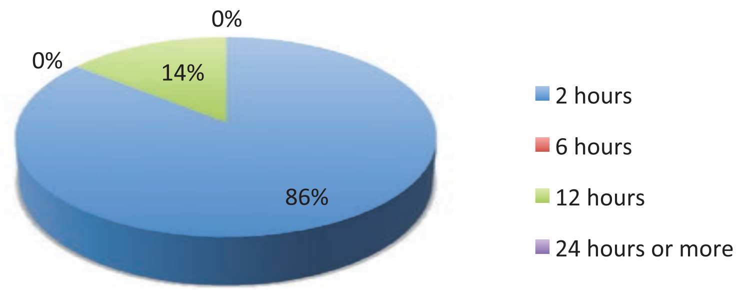


Resiliency and Emergencies

Do you provide any assistance for community critical functions that may require you to consider back-up power generation or additional battery storage capacity?
n = 14



How long after an event or outage would you expect to have some assistance in place?
n = 7



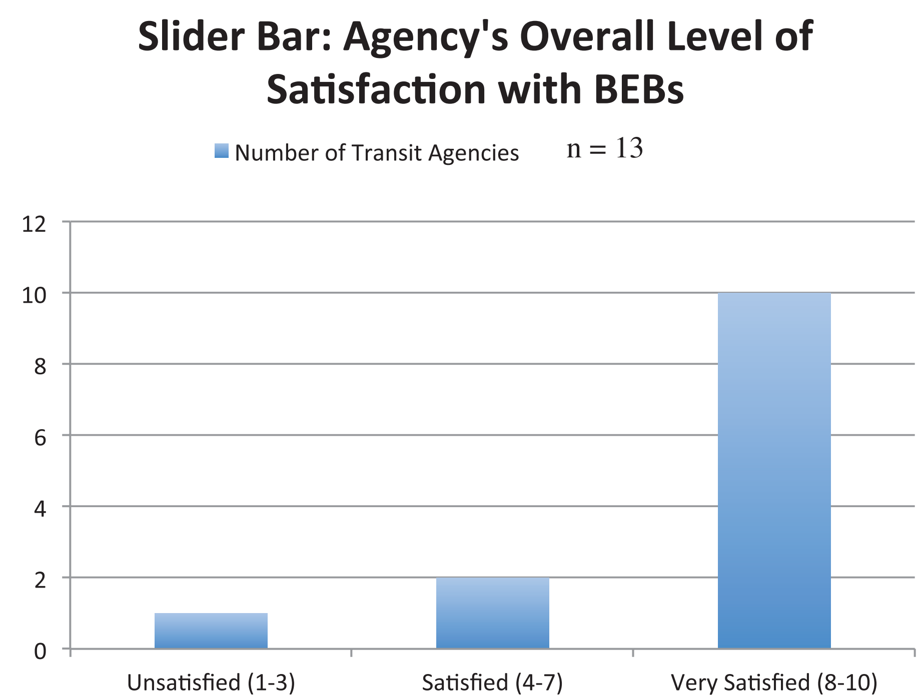
Explain
Yes:

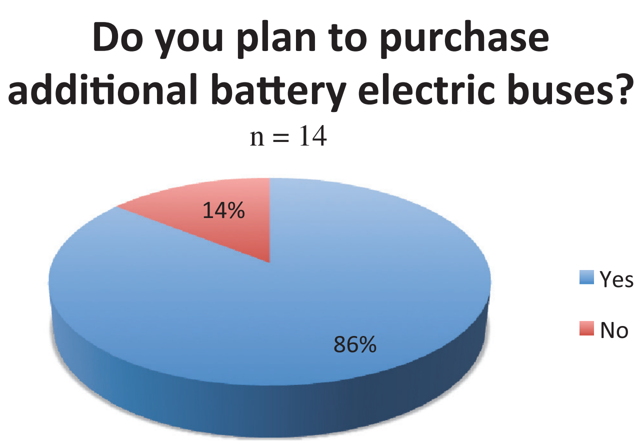
- We will be able to charge up to 25 buses at a time. Our BEB can be used in the case of an emergency as a power source VGI: V2B, V2L, V2G.
- We have immediate assistance in place...with another charger on a separate part of the grid and additional assistance with a local facility that has generators that can handle the load.
- Within two hours, I would hope to have some buses available to assist in any manner.
- We provide shelter and evacuation service. With a fleet of BEBs we would need back-up power regardless of these services but to keep regular service running.
- We provide buses for special events, for emergencies (e.g. warming/cooling buses), and for evacuation.
- We have back up generators for EV's in place

No:

- The current and near term BEB percentage of the fleet is far too small to require planning of that nature.
- We have contracts to provide assistance but have not considered additional power provision to accommodate long distance evac.
- We would not use the BEB in these situations, and likely would not go to a 100% fleet for that reason.

Conclusion





Explain: Do you plan to purchase additional BEBs?

Yes:

- Foothill Transit has an order for 13 more 40 ft. Catalyst buses with Proterra slated for delivery between June 2017 and October 2017. Foothill Transit won State and Local grants for 20 Proterra electric buses and for demonstration of 2 Alexander Dennis double-decker electric buses. Foothill Transit's Executive Board approved an initiative to fully electrify by 2030.
- The goal is to be 100% BEB fleet by the end of 2018 -- a fleet of 79 buses.
- Annual replacement moving forward
- We have currently won a Low-No Grant to purchase additional BEBs...and our long range goal is to make our fleet entirely BEB by the year 2025.
- Dependent on availability of additional discretionary funds and budgetary exigencies, increasing the size of the BEB fleet is definitely being considered.
- Between 2-6 over the next 5 years
- We just ordered 70 more BEBs. Twenty of those will be fast charge and the additional may be fast or slow charge. In addition we plan on buying up to 9 long range buses to help determine if the slow charge long range bus would be a better option for our type of service.
- 2017/2018 purchase of 4 additional BEBs
- experience and savings are positives
- We plan to replace our 17 year old BEBs with new BEBs soon
- As grant funds allow

No:

- Fleet at capacity for BEBs
- Not at present time

Final Comments

Are there any lessons learned for management or motivation of the various stakeholder groups (utilities, operators, unions, communities, executive boards, regulatory agencies, etc.) to engage in BEB procurement and deployment?

- It is recommended for agencies to early on engage the utilities, executive boards, and regulatory agencies to engage in BEB procurement and deployment. We had fantastic Board Support. It is easy if you demonstrate the savings
- Engaging operators
- The use of environmental effects and cost savings. Implementation of BEBs, especially when considering taking it to scale, requires strategic planning to determine type of BEB (FC or ER), as well as most effective placement of charging stations.
- You have to work very closely with the BEB manufacturers during the entire build process. Hold them accountable to the specs they agreed to provide.
- don't know
- There needs to be help with demand charges and infrastructure costs.
- Not everyone is for these vehicles, and many question their value and that they are not really reducing emissions because of increased use at power plant. The initial costs are too high to justify without any real success—would not have gone in this direction without grant funds

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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