FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

FTA National Fuel Cell Bus Program: Proterra HD 30 Fuel Cell Bus Demonstration

Addendum 1

SEPTEMBER 2020

FTA Report No. 0172
Federal Transit Administration

PREPARED BY
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Center for Transportation and the Environment

U.S. Department of Transportation
Federal Transit Administration

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U.S. Department of Transportation
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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Richmond Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY	2. REPORT DATE September 2020	3. REPORT TYPE AND DATES COVERED Project Report, 2020

4. TITLE AND SUBTITLE National Fuel Cell Bus Program: Proterra HD 30 Fuel Cell Bus Demonstration	5. FUNDING NUMBERS

6. AUTHOR(S)
Drew Turro, Alison Smyth, Erik Bigelow, Lauren Justice

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Center for Transportation and the Environment 730 Peachtree Street, Suite 450 Atlanta, GA 30308	8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0172
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration Office of Research, Demonstration and Innovation East Building 1200 New Jersey Avenue, SE Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER FTA Report No. 0172

11. SUPPLEMENTARY NOTES [https://www.transit.dot.gov/about/research-innovation] [https://doi.org/10.21949/1518344]
Suggested citation: Federal Transit Administration. National Fuel Cell Bus Program: Proterra HD 30 Fuel Cell Bus Demonstration. Washington, D.C.: United States Department of Transportation, 2020. https://doi.org/10.21949/1518344

12A. DISTRIBUTION/AVAILABILITY STATEMENT Available from: National Technical Information Service (NTIS), Springfield, VA 22161. Phone 703.605.6000, Fax 703.605.6900, email [orders@ntis.gov]	12B. DISTRIBUTION CODE TRI-30

13. ABSTRACT
This document is an addendum to the final report to the Federal Transit Administration (FTA) covering the project performance and results on the development, build, and demonstration of a next generation Proterra fuel cell hybrid bus. The bus was built using two Hydrogenics HD30 fuel cells and was demonstrated by Capital Metro in Austin, Texas. A second demonstration was planned for Flint, Michigan, but the program ended prior to the beginning of the scheduled demonstration period. By the end of the project, the bus was driven 5,788 miles over 84 service days. That work is reported in "FTA National Fuel Cell Bus Program: Proterra HD 30 Fuel Cell Bus Demonstration" (August 2017). This report covers the analyses of large-scale zero-emission bus fleet infrastructure costs conducted as part of this project and documents the coordination of communications and outreach work CTE conducted on behalf of FTA's National Fuel Cell Bus Program (NFCBP) as part of this same grant. This is the final report for the bus development, build, and demonstration project and the outreach and education work.

14. SUBJECT TERMS Fuel cell electric bus, transit, outreach	15. NUMBER OF PAGES 34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT None

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The authors thank the Federal Transit Administration for its support of this project. Thank you also to each transit agency that contributed data for this report—Duluth Transit Authority (DTA), Minnesota Valley Transit Authority (MVTA), and Tri-County Metropolitan Transportation District of Oregon (TriMet).

Abstract

This document is an addendum to the final report to the Federal Transit Administration (FTA) covering the project performance and results for the development, build, and demonstration of a next generation Proterra fuel cell hybrid bus. The bus was built using two Hydrogenics HD30 fuel cells and was demonstrated by Capital Metro in Austin, Texas. A second demonstration was planned for Flint, Michigan, but the program ended prior to the beginning of the scheduled demonstration period. By the end of the project, the bus was driven 5,788 miles over 84 service days. That work is reported in "FTA National Fuel Cell Bus Program: Proterra HD 30 Fuel Cell Bus Demonstration" (August 2017). This report covers the analyses of large-scale zero-emission bus fleet infrastructure costs conducted as part of this project and documents the coordination of communications and outreach work CTE conducted on behalf of FTA's National Fuel Cell Bus Program (NFCBP) as part of this same grant. This is the final report for the bus development, build, and demonstration project and the outreach and education work.

EXECUTIVE SUMMARY

The Center for Transportation and the Environment (CTE) managed the design, build, testing, and operation of a next generation Proterra fuel cell hybrid bus, which was demonstrated in Austin, Texas, by Capital Metro. The Federal Transit Administration (FTA) has sponsored this project since 2011 as part of the National Fuel Cell Bus Program.

This bus built on lessons learned from the original Proterra fuel cell bus build and Austin demonstration. The original project goal was to design and build a 35-ft fuel cell dominant hybrid using a Ballard fuel cell and then demonstrate the bus in Austin and Washington, DC. Due to various project challenges, the original scope was modified. Ultimately, Proterra built the bus using two HD30 Hydrogenics fuel cells, and the project team demonstrated the bus in Austin for one year. A second demonstration was planned for Flint, Michigan, but the program ended prior to the beginning of the scheduled demonstration period. By the end of the project, the bus was driven 5,788 miles over 84 service days.

As part of this grant, CTE led a number of outreach and education events from 2011 through 2019 to facilitate information-sharing on the status of zero-emission bus projects worldwide to advance the industry's commercialization. CTE's work under this grant met the following stated goals:

- Increase public awareness and acceptance of zero-emission vehicles.
- Facilitate stakeholder information-sharing through web-based and workshop tools.
- Educate and attract new transit agency partners to the zero-emission bus community.
- Share National Fuel Cell Bus Program (NFCBP) progress with the larger international community.
- Maintain an information-rich and up-to-date website for the fuel cell bus community.
- Explore the following key themes of interest (among others) at the workshops/conferences, and the website:
  - How lessons learned at demonstration sites are applied as fleet size increases
  - How demonstrations are advancing zero-emission propulsion technology
  - How configurations of regional partnerships and governmental support have assisted zero-emission bus introduction
  - What infrastructure challenges remain and how are they being addressed
  - Where the market for future demonstrations is and how communication tools could assist those potential partners
  - Responses of transit operators, riders, and the general public

These goals were achieved through execution of six national and international workshops/conferences, development and maintenance of the gofuelcellbus.com website, two rider surveys, two webinars, results dissemination at external events, and facilitation of the Zero Emission Bus Resource Alliance (ZEBRA). Completion of this work required deep collaboration across US and with international partners. This globally-engaged network of zero-emission bus stakeholders is a legacy of CTE and FTA's successful partnership.

At the end of the demonstration, the project scope was expanded to include an evaluation of the cost of large-scale infrastructure for zero-emission bus fleets. CTE established a methodology for determining infrastructure and operational costs for large-scale electric bus deployments with an eye toward evaluating the variables that impact cost-competitiveness between fuel cell electric bus (FCEB) and battery electric bus (BEB) fleets. This methodology, which evolved throughout the course of the project, was applied to the actual blocking schedules of three transit agencies to conduct case studies for evaluating costs. The Duluth Transit Authority (DTA), the Minnesota Valley Transit Authority (MVTA), and the Tri-County Metropolitan Transportation District of Oregon (TriMet) participated in this evaluation and were selected due to their fleet sizes and operational characteristics.

The initial evaluation found that infrastructure costs are a small portion of the overall costs for zero-emission bus fleets. However, site-specific constraints play a significant role in determining costs, with the cost differences between upgrading two similar size facilities for battery electric buses sometimes on the order of millions of dollars. Fuel costs are the biggest differentiator between FCEBs and BEBs. Even when comparing hydrogen costs of $4/kg and applying a rate structure from California, fuel costs for the BEBs are much lower than for FCEBs.

An updated analysis incorporated revised cost estimates for BEB infrastructure. These revised cost estimates, although subject to site-specific constraints, were based on a larger sample size of costs observed by CTE on BEB deployment projects. On average, these revised estimates increased infrastructure costs by 50%, and overall project costs increased 3–4%. These results aligned with the initial findings regarding the role of infrastructure in overall project costs.

CTE participated in a number of events throughout the course of this project, during which it shared results and lessons learned from this analysis and gathered feedback from industry stakeholders. In early 2019, CTE supported a presentation of preliminary results to the US Interagency Hydrogen Working Group. In Summer 2019, CTE facilitated a roundtable discussion with fleet managers at the 2019 APTA Sustainability Conference, at which it presented preliminary results and solicited feedback from participants to integrate into the analysis.

One of the key infrastructure costs for a BEB fleet is the charging equipment. As the number of charger manufacturers and options has increased, so has the number of ways an agency can choose to charge their fleet. CTE conducted an analysis of large-scale charging to evaluate how the number of chargers required for a fleet might decrease if a transit agency is willing to move buses around at night. The analysis examined TriMet's 179 blocks operating from its Powell Garage under two operational scenarios and found that numerous options existed for agencies to charge buses while controlling for various factors.

SECTION

1

Introduction

The Center for Transportation and the Environment (CTE) led a team in the development of a fuel cell hybrid bus for demonstration as a part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP). CTE, Proterra, and Hydrogenics designed and built a bus powered by two 30 kW fuel cell modules. The technology is being evaluated by the National Renewable Energy Laboratory (NREL), one of the US Department of Energy's (DOE) national laboratories, as part of the NFCBP. This addendum to the final report summarizes the outreach efforts conducted under this project and the efforts to evaluate the costs of large-scale infrastructure for zero-emission buses.

SECTION

2

Coordination of Communications & Outreach

Importance of Work

The primary objective of FTA's NFCBP in 2011 was to compile and maintain information on the state of fuel cell bus technologies development and needs. NFCBP used four key mechanisms to accomplish this objective—1) publication of FTA's 2009 *Report on Worldwide Hydrogen Bus Demonstrations 2002–2007*, which details lessons learned by key stakeholders involved in fuel cell buses worldwide, 2) facilitation of the National Fuel Cell Bus Working Group, 3) facilitation of the International Fuel Cell Bus Working Group, and 4) maintenance of the International Fuel Cell Bus website.

Under this grant, CTE began coordinating these four data-sharing forums in addition to identifying and developing additional enhanced platforms. These mechanisms were designed to help decision-makers better understand progress made in zero-emission bus demonstrations, what challenges remained, and how best to leverage limited resources to commercialize FCEBs and BEBs and their supporting infrastructure.

CTE's coordination of the NFCBP's communication and outreach activities brought harmony to the zero-emission bus industry's group conscience on the state of the technology. The project activities resulted in a generally-shared understanding of the key barriers and best practices for zero-emission bus commercialization amongst industry stakeholders.

CTE cultivated an industry knowledge base around the following:

- How lessons learned at "evolutionary" demonstration sites are being applied as fleet size increases.
- How "clean slate" demonstrations are advancing fuel cell propulsion technology.
- How configurations of regional partnerships and governmental support have assisted fuel cell bus introduction.
- What communication mechanisms are most beneficial to current stakeholders.
- Where the market for future demonstrations is and how communication tools could assist those potential partners.
- Transit operators' experience with the buses.

- Infrastructure issues encountered during the demonstrations.
- Response of transit riders and the general public.

Project Milestones

From 2011 to 2019, CTE led the coordination of complementary information-gathering and outreach activities designed to maintain and increase awareness on the state of zero-emission transit bus commercialization. Following are the major milestones CTE completed as part of this project:

- **Milestone 1: Project Kick-Off and Planning** – CTE worked with FTA to finalize priorities and goals of the coordination program.
- **Milestone 2: Conduct Background Research** – CTE conducted a review of existing resources related to current demonstrations, past working group activities, and the working group website.
- **Milestone 3: Complete Stakeholder Interviews for Worldwide Report**[1] – CTE identified and interviewed leaders in global fuel cell bus deployments, noting the biggest hurdles and lessons learned for commercialization.
- **Milestone 4: 2011 National Workshop & 2012 Webinar Planning and Completion** – CTE coordinated the event logistics of the 2011 Workshop in New Orleans in partnership with the American Public Transportation Association (APTA), including scheduling, securing the venue, organizing travel, and inviting speakers, using information gathered from research and interviews to ensure that the workshops were efficient and effective. CTE also hosted a 2012 fuel cell bus-focused webinar targeting transit agencies.
- **Milestone 5: International Fuel Cell Bus Working Group Website Redesign and Maintenance** – Based on stakeholder and FTA website recommendations, CTE developed a new International Fuel Cell Bus Website. CTE purchased and housed the domain http://www.gofuelcellbus.com as the NFCBP International working group website. Grant funds allowed CTE to maintain responsibility for website from 2011 through 2015.
- **Milestone 6: Conduct Rider Survey(s)** – CTE designed, administered, and analyzed two fuel cell bus rider surveys.
- **Milestone 7: Complete Worldwide Repor**t – CTE compiled details of current global fuel cell bus deployments, noting the biggest hurdles and lessons learned for commercialization.

[1] In 2015, Milestones 3 and 7 were removed from the scope under FTA approval.

- **Milestone 8: 2013/2014 International Workshops Planning and Completion** – CTE coordinated the event logistics of the 2013 International Workshop in Hamburg, Germany, including scheduling, securing a venue, organizing travel, and inviting speakers.
- **Milestone 9: Present Results at Relevant Industry Events** – CTE presented the results of this project at relevant industry events.
- **Milestone 10: Facilitate 2015/2016 National and International Workshops** – The Outreach I grant (2011) supported the 2011 National FCB Workshop, the 2012 Webinar, and the 2013 International Working Group Meeting in Hamburg, Germany. The addition of Milestone 10 (2012) allowed CTE to continue management of the 2015 and 2016 Working Groups/Conferences through 2016, adding continuity and stability to the program.
- **Milestone 11: Project Management** – CTE worked closely with FTA project sponsors to ensure that project activities continued to meet their goals. CTE was responsible for project management, including managing invoices, tracking schedule and budget, and submitting required reports.
- **Milestone 12: ZEB Operator Resource Development** – CTE partnered with the Zero Emission Bus Resource Alliance (ZEBRA) to support its mission. ZEBRA is a self-organized coalition of US transit operators working to grow their capacity to deploy fuel cell and battery electric buses.
- **Milestone 13: National & International Zero Emission Bus Conferences** – Capitalizing on the success of the previous fuel cell and battery electric bus conferences, CTE organized an International ZEB Conference in Fall 2019.

Table 2-1 *Coordination of Outreach & Education Project Schedule*

Milestone	2011	2012	2013	2014	2015	2016	2017	2018	2019
Milestone 1: Project Kick-off and planning									
Milestone 2: Conduct background research									
Milestone 4: 2011/2012 National Workshop and Webinar									
2011 National Workshop	•								
2012 Fuel Cell Bus Webinar		•							
Milestone 5: International Fuel Cell Bus website									
Milestone 6: Conduct rider survey(s)									
Milestone 8: 2013/2014 National and International Workshops									
2013 International Workshop			•						
2013 Fuel Cell Bus Webinar			•						
Milestone 9: Present results at relevant industry events									
Milestone 10: 2015/2016 National & International Workshops									
2015 International Workshop					•				
2016 International Workshop						•			
Milestone 11: Project Management									
Milestone 12: ZEB Operator Resource Development									
Milestone 13: National and International Zero Emission Bus Conference									
2019 International Workshop									•

Project Showcase

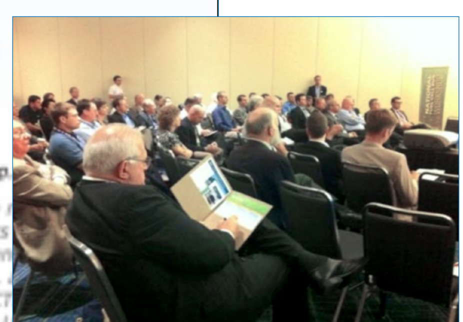


Figure 2-1 *2011 National Fuel Cell Bus Workshop in New Orleans*

Figure 2-2 *2012 FCEB Webinar Ad on APTA Website*

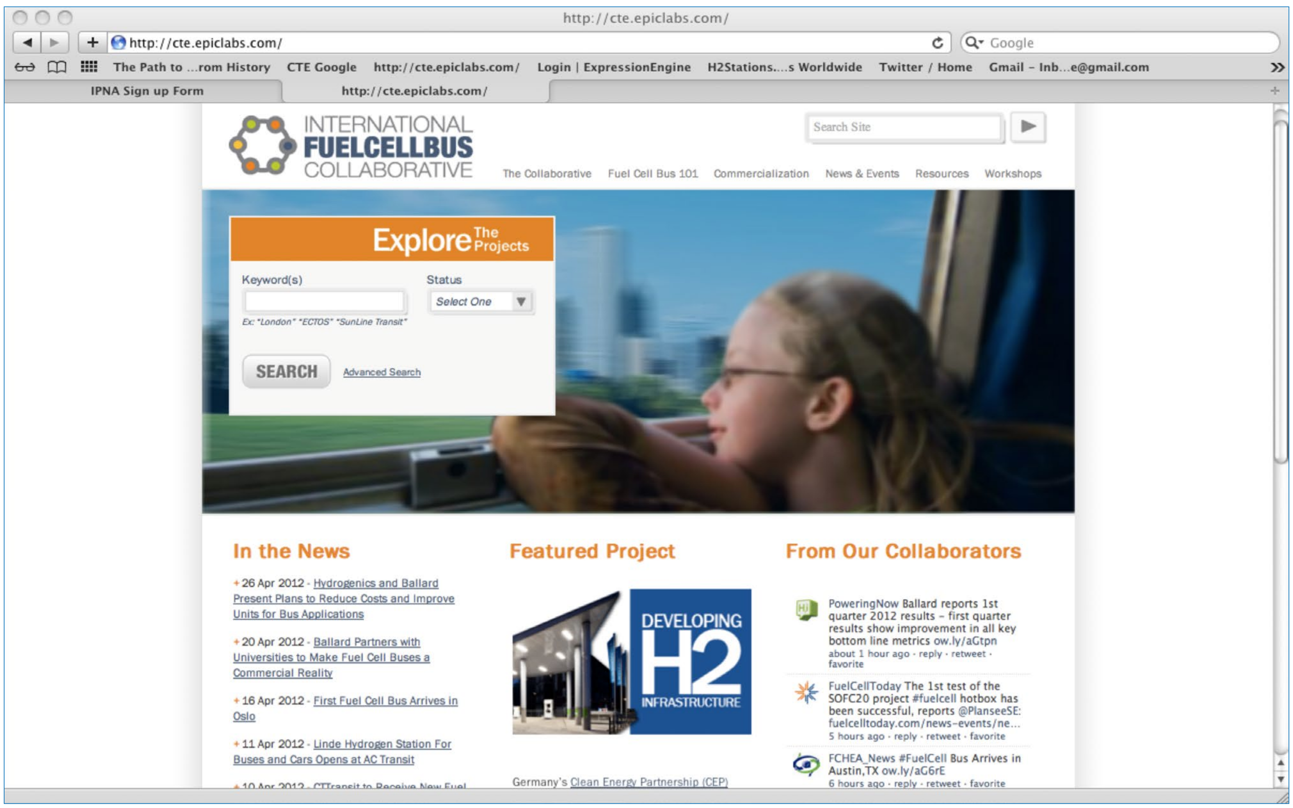


Figure 2-3 *GoFuelCellBus.com Homepage*

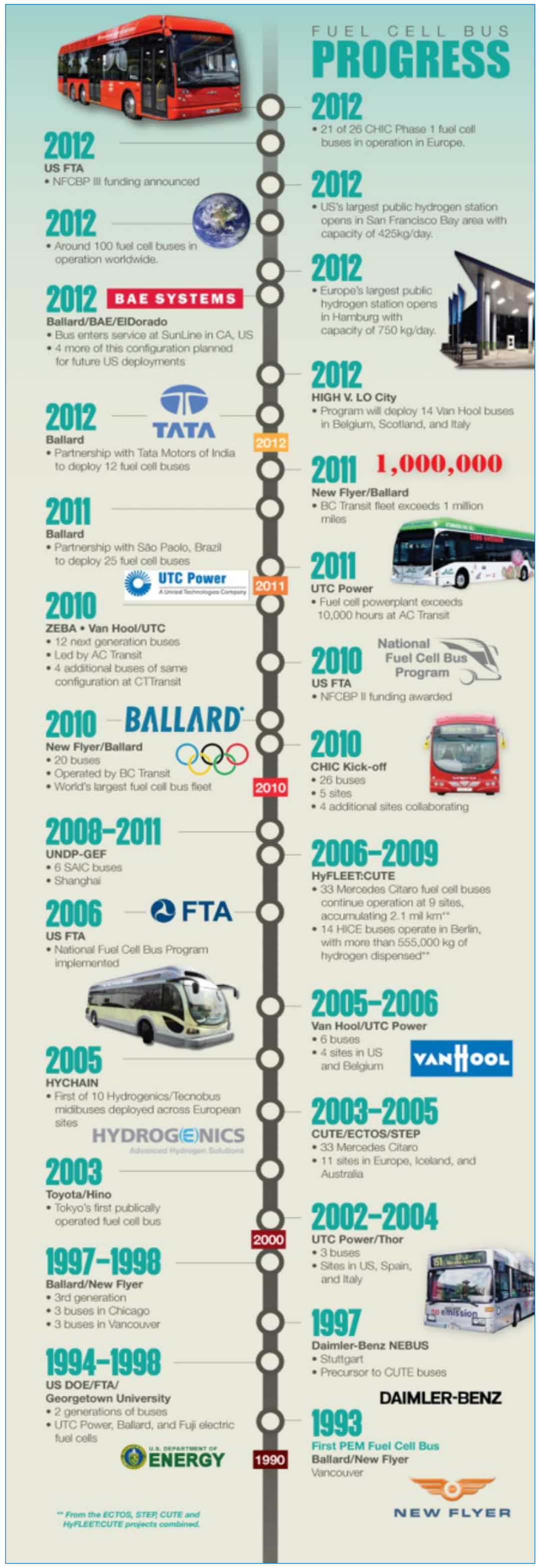


Figure 2-4 *FCEB Commercialization Timeline Page*

Figure 2-5 *2013 International Fuel Cell Bus Workshop in Hamburg, Germany*

Figure 2-6

International Fuel Cell Bus Workshop in Thousand Palms, CA

Figure 2-7

International Fuel Cell Bus Workshop in Thousand Palms, CA

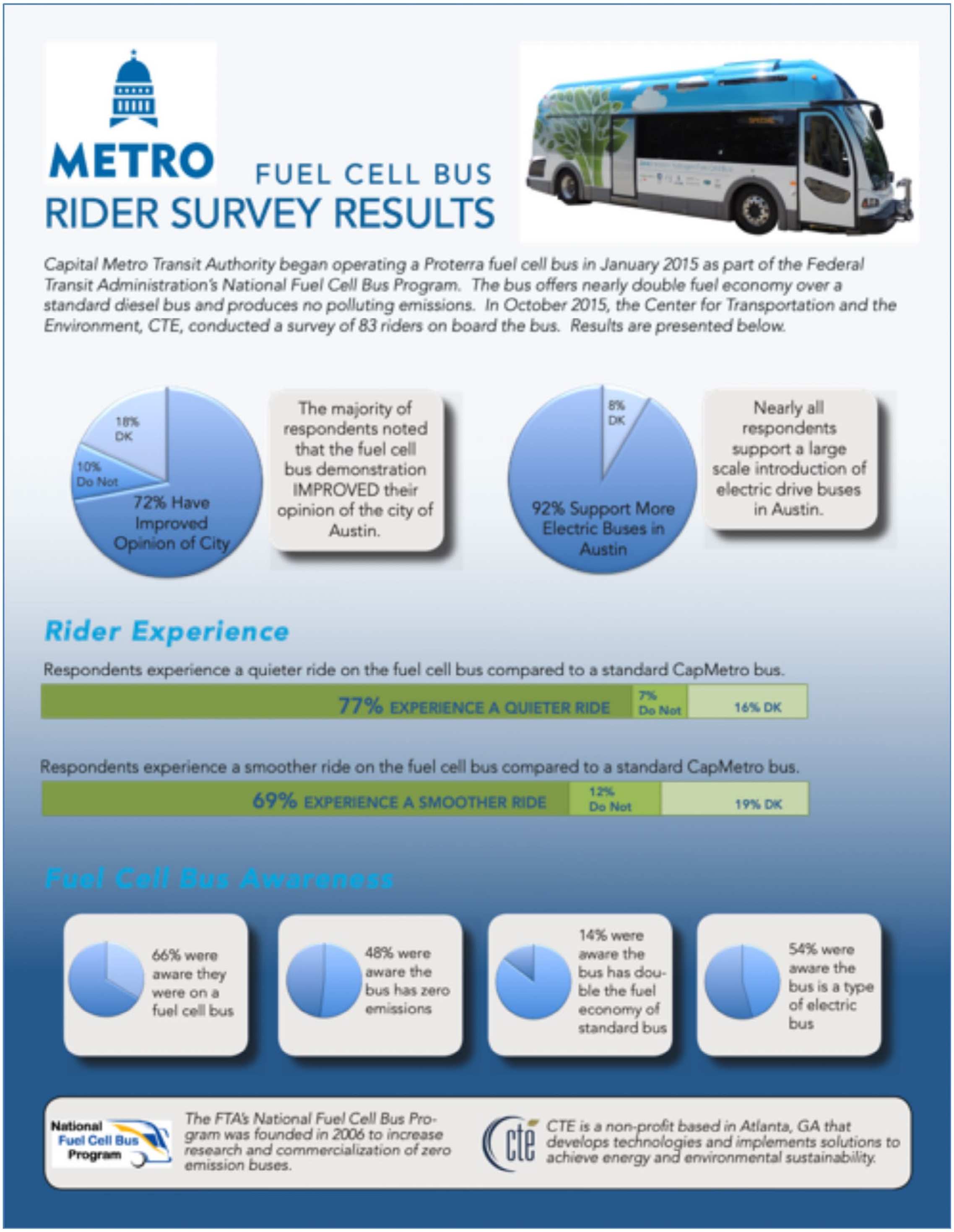


Figure 2-8 *Capitol Metro Fuel Cell Bus Rider Survey Results*

Figure 2-9 *2016 International Zero Emission Bus Conference in London (300+ attendees)*

Figure 2-10 *2018 US Zero Emission Bus Conference in Los Angeles (300 attendees)*

Figure 2-11 *2019 International Zero Emission Bus Conference in San Francisco (500+ attendees, 40% representing transit agencies)*

SECTION 3

Large-Scale Zero-Emission Bus Fleet Infrastructure

During the course of this project, both FCEBs and BEBs moved toward becoming fully commercial products. The industry began asking questions about the costs of large-scale zero-emission bus (ZEB) fleets and how FCEB fleets with their high initial investment requirements compare to BEB fleets in the long term.

CTE established a methodology for determining infrastructure and operational costs for large-scale electric bus deployments with an eye toward evaluating the variables that impact cost-competitiveness between FCEB and BEB fleets. This methodology, which evolved throughout the course of the project, was applied to the actual blocking schedules of three transit agencies to conduct case studies for evaluating costs.

Methodology

CTE began approaching the problem of determining large-scale infrastructure costs for ZEB fleets by constructing a theoretical framework for the analysis (Figure 3-1). This analysis starts from the assumption that transit agency service requirements are the fundamental building blocks for fleet operation. Vehicle and fueling needs are driven by the service requirements.

As such, the first input to any analysis of ZEB fleets is a transit agency's blocking schedule. Route assignments and the specific characteristics of each block (vehicle type, average speed, block length, topography, climate, etc.) determine the energy requirements for that service. The energy requirements, in turn, determine the number of vehicles required and amount of fuel needed. Having determined how much fuel is needed per bus, the agency's fueling speed requirements can be known. This information is needed to determining infrastructure sizing and costs.

CTE also identified other costs associated with ZEB fleets, such as maintenance, labor for fueling, charge management, land for the fueling station or chargers, backup power, etc.

To truly evaluate a fleet using this framework was beyond the scope of this project given the complexity and site-specific nature of the outcomes of this detailed analysis. As such, CTE decided to focus on three large categories of cost—40-ft buses, infrastructure, and fuel.

Since service requirements are critical to determining the number of vehicles and the infrastructure requirements for a fleet, CTE decided it was necessary to conduct this analysis using an actual fleet blocking schedule. CTE reached out to multiple fleets to obtain blocking information. The Duluth Transit Authority (DTA) shared its routing assignments, and CTE started the analysis using DTA's data. The Minnesota Valley Transit Authority (MVTA) and the Tri-County Metropolitan Transportation District of Oregon (TriMet) subsequently provided blocking information and were incorporated into the analysis.

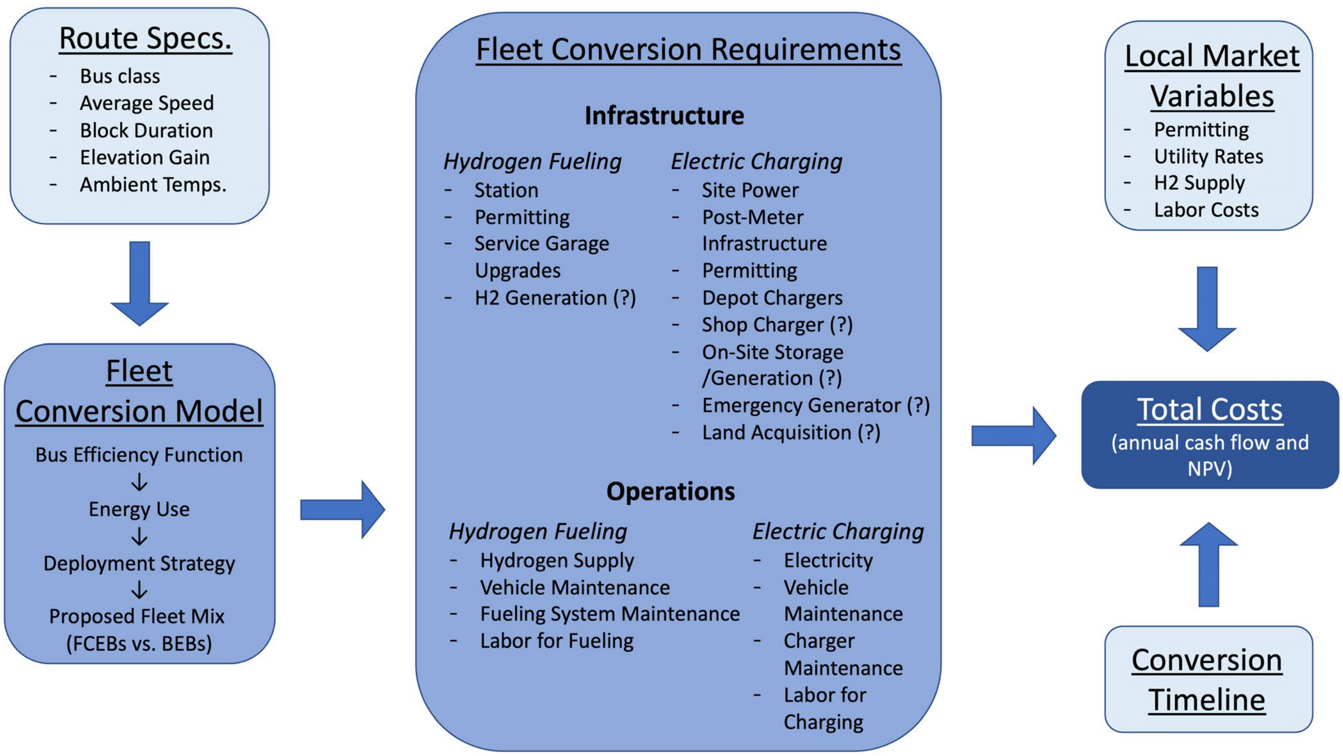


Figure 3-1 *Theoretical Framework for Evaluating Large-scale ZEB Fleet Capital and Operational Costs*

Preliminary Analysis

CTE's initial analysis of DTA's blocking information started by examining vehicle costs. The cost of BEBs used in the analysis was $800,000; two different costs were used for FCEBs—$1.2 million for current buses and $850,000 for future buses. CTE's first estimate assumed that DTA's blocking schedule would be identical to its current schedule and that if a BEB could not meet the range requirements of a block, an additional vehicle would be needed.

Although the initial analysis did not optimize the use of BEBs and strategies such as mid-day charging, CTE refined its analysis to optimize the use of BEBs throughout DTA's service, incorporating required re-charging times into the analysis. This did not account for any change in required spare ratio due to expected reduced downtime on BEBs compared to diesel buses.

In the optimized schedule scenario, the total vehicle cost of a BEB fleet was comparable to the vehicle cost of an FCEB fleet with current prices. In that scenario, fuel costs became the main differentiator between a BEB and an FCEB fleet.

With hydrogen costs estimated at $7/kg, fuel costs for an FCEB far exceeded those for a BEB fleet, provided that DTA's electricity rate structure remained constant. CTE also looked at the impact of having a different rate structure on fuel costs. CTE used Pacific Gas & Electric's (PG&E) E20S rate for comparison. Under the PG&E rate, DTA's fuel costs were roughly double compared to DTA's current electricity rates and brought the fuel costs closer to those of hydrogen.

Infrastructure costs were relatively minor compared to bus and fuel costs, accounting for only 4% of total costs. The cost of the hydrogen refueling infrastructure was estimated using Argonne National Laboratory's HDRSAM model, and the electrical infrastructure costs were approximated based on CTE's industry knowledge.

The preliminary findings from this analysis indicated that the lifecycle costs of BEB and FCEB fleets could be comparable, but the allocation between capital and operational costs could vary greatly between the two technologies. However, site-specific factors such as local utility rates significantly influenced an agency's overall project costs.

Expanded Analysis

During the first quarter of 2019, CTE collected additional information on different transit agency electrical infrastructure costs. Using data collected from agencies, manufacturers, and engineering firms, CTE found that depot charging infrastructure installation and construction costs, from design through commissioning, costs approximately $60,000–$80,000 per bus (including charging hardware). This was seen for a number of agencies in different geographical locations with varying equipment and fleet sizes and configurations.

The six scenarios examined for this analysis are outlined in Table 3-1. Vehicle costs remained consistent from the preliminary analysis, as did the comparison of fuel costs for an agency using a standard electricity rate in California to a standard electricity rate in Minnesota. This was done to highlight the importance of regional variations in electricity rate in determining fuel costs.

Table 3-1
ZEB Transition Analysis Scenarios

Scenario	Bus Type	Electricity Rate	Price (per kWh or kg)	Price (per kW)	Price (per bus)	Facility Upgrade
1	BEB	Minnesota	$0.06	$10.50	$800,000	NA
2	BEB	California	$0.11	$17.87	$800,000	NA
3	FCEB	NA	$7.00	NA	$1,200,000	$1,000,000
4	FCEB	NA	$4.00	NA	$1,200,000	$1,000,000
5	FCEB	NA	$7.00	NA	$850,000	$1,000,000
6	FCEB	NA	$4.00	NA	$850,000	$1,000,000

CTE included four FCEB scenarios in the cost analysis, varying the bus and fuel costs. The station costs were generated using Argonne National Laboratory's Heavy-Duty Vehicle Refueling Cost models, and CTE added $1 million for infrastructure upgrades. Table 3-2 shows the inputs used when station costs were generated for the three transit agencies included in the analysis. Overall, the fueling station infrastructure costs were the smallest component of the fleet costs.

Table 3-2 *Hydrogen Fueling Inputs Used for Analysis (by Agency)*

Agency	Production Volume	Avg Fill (kg)	Fueling Rate (kg/min)	Tank Type	# of Dispensers)	Fueling Window (hr)	Fuel	Fueling Pressure
DTA	Low	19	7.2	IV	2	6	Liquid	350 bar
MVTA	Low	16	7.2	IV	2	7	Liquid	350 bar
TriMet	Low	23	7.2	IV	2	11	Liquid	350 bar

During the first quarter of 2020, CTE revisited the cost assumptions for BEB charging infrastructure. The updated analysis incorporated revised cost estimates for BEB infrastructure, which, although subject to site-specific constraints, were based on a larger sample size of costs observed by CTE on BEB deployment and fleet transition projects. On average, these revised estimates increased infrastructure costs by 50%, and overall project costs increased 3–4%. These results aligned with the initial findings regarding the role of infrastructure in overall project costs.

Blocking Methodology

CTE analyzed the number of BEBs needed to fulfill TriMet's blocks that operate more than 85 miles daily. The 119 blocks were analyzed under two blocking scenarios and three service energy scenarios:

- **Energy Depleting** – buses used all available service energy before returning to the depot to charge, minus reserve energy and necessary deadhead energy; buses could be redeployed after recharging.
- **Block Halving** – buses used half of their available service energy before returning to the depot to charge, minus reserve energy and necessary deadhead energy.
- **No Re-blocking** – buses were deployed under existing service schedules, with blocks split based on estimated energy consumption and one bus used per resulting block

Table 3-3 shows the results of the modeled blocking scenarios under the three service energy scenarios. These scenarios were determined based on expected energy for new, mid-life, and end-of-life batteries. The number of buses needed to complete service under these blocking scenarios is shown along with the number of buses needed to fulfill block requirements with no block modeling performed.

Table 3-3

TriMet Block Splitting Results

Service Energy Capacity	Required Buses Energy-Depleting Scenario	Required Buses Block-Halving Scenario	Required Buses No Reblocking Scenario
280 kWh	185	163	201
307 kWh	176	148	196
350 kWh	163	139	182

It appears that the block splitting strategy and age of the batteries can have a significant impact on fleet size. Both block splitting strategies, which plan for mid-day charging and optimizing bus utilization, reduce the fleet size required to complete service when compared to a blocking strategy that does not optimize bus utilization. The two strategies also result in different answers. The energy-depleting scenario requires 176 buses in a mid-life battery scenario ,but the block-halving strategy requires only 148 buses in the same scenario. Further work will need to be done to optimize the block-splitting strategy and minimize the number of buses needed to provide service, which is beyond that scope of this project. For the purposes of this analysis, CTE will use this information to inform infrastructure sizing and costs.

Results

The results for each transit agency under the three scenarios outlined in Table 3-3 are included in Table 3-4 and Figures 3-2, 3-3, and 3-4.

Table 3-4

ZEB Transition Analysis Results

Scenario	Transit Agency	# of Buses	Infrastructure ($)	Buses ($)	Fuel ($)	Total ($)
1	DTA	74	7,810,000	59,200,000	8,007,652	75,017,652
	MVTA	82	8,630,000	65,600,000	11,273,904	85,503,904
	TriMet	139	14,575,000	111,200,000	13,169,350	138,944,350
2	DTA	74	7,810,000	59,200,000	14,445,275	81,455,275
	MVTA	82	8,630,000	65,600,000	20,286,722	94,516,722
	TriMet	139	14,575,000	111,200,000	23,881,534	149,554,034
3	DTA	53	4,183,131	63,600,000	33,772,284	101,555,415
	MVTA	74	4,106,768	88,800,000	45,453,845	138,360,613
	TriMet	127	5,565,503	152,400,000	79,179,864	237,145,367
4	DTA	53	4,183,131	63,600,000	19,298,448	83,005,415
	MVTA	74	4,106,768	88,800,000	25,973,626	118,880,394
	TriMet	127	5,565,503	152,400,000	45,245,637	203,211,140
5	DTA	53	4,183,131	45,050,000	33,772,284	87,081,579
	MVTA	74	4,106,768	62,900,000	45,453,845	112,460,613
	TriMet	127	5,565,503	107,950,000	79,179,864	192,695,367
6	DTA	53	4,183,131	45,050,000	19,298,448	68,531,579
	MVTA	74	4,106,768	62,900,000	25,973,626	92,980,394
	TriMet	127	5,565,503	107,950,000	45,245,637	158,761,140

Figure 3-2

ZEB Transition Analysis – DTA Results

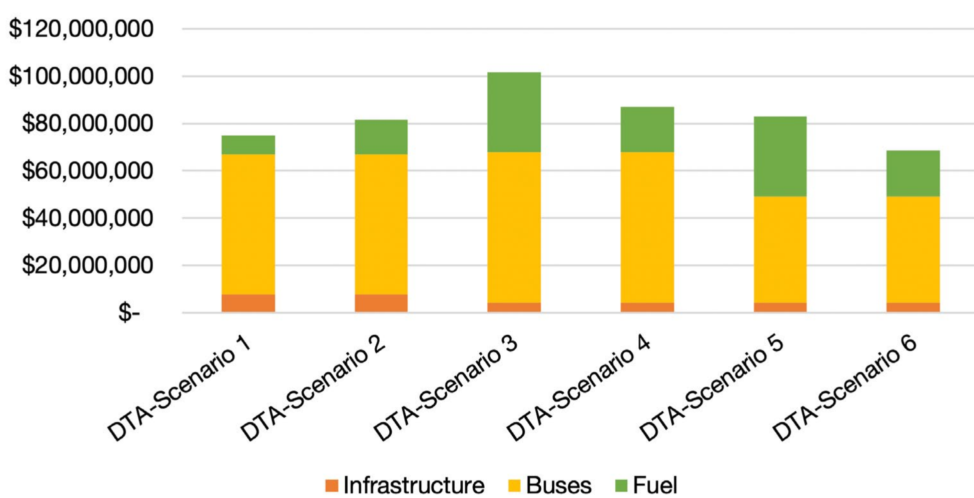


Figure 3-3

ZEB Transition Analysis – MVTA Results

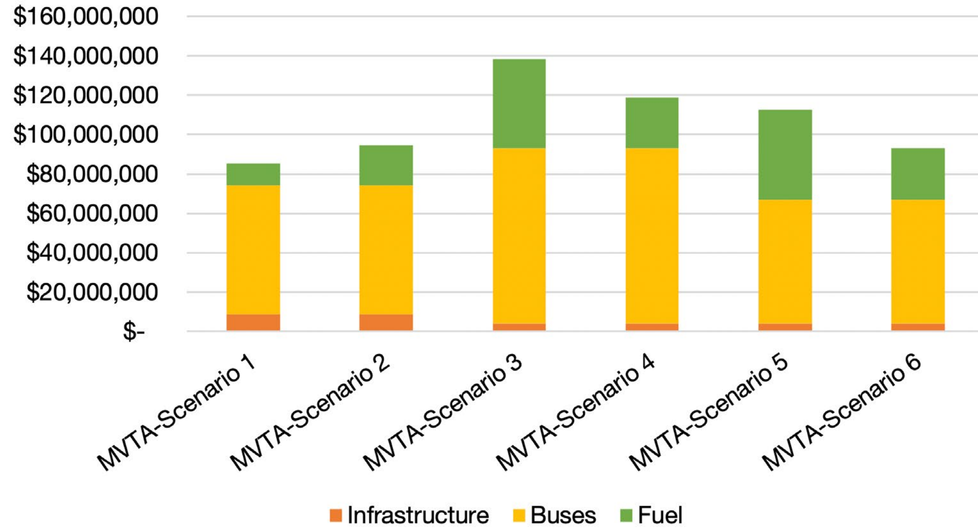
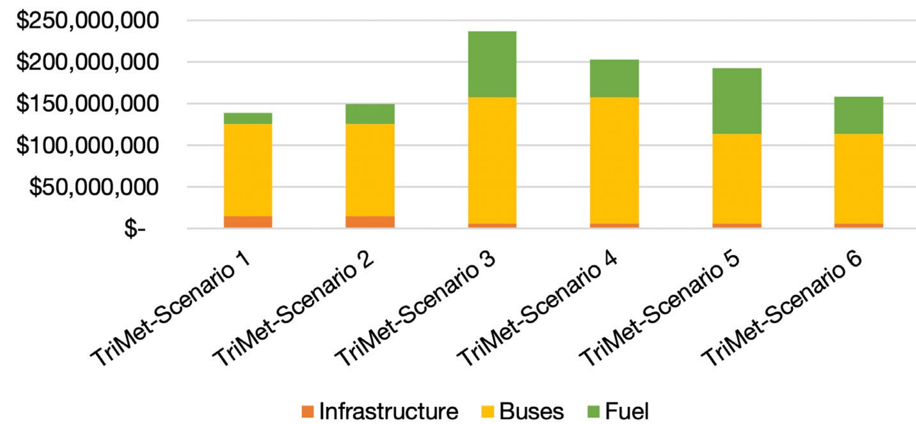


Figure 3-4

ZEB Transition Analysis – TriMet Results



The total bus cost for an FCEB fleet and a BEB fleet varied across the transit agencies analyzed in this study. In DTA's case, for which a significant increase in BEBs was needed to meet service requirements, the overall cost of buses was similar to the FCEB fleet, with current bus prices of $1.2 million per bus.

However, although the overall bus costs could be lower for a FCEB fleet, the fueling costs are higher. CTE used $7/kg and $4/kg for hydrogen fuel costs in the analysis. Even in the lowest-cost case, hydrogen fuel would cost a transit agency $20 million over 12 years compared to $14 million for an agency with the California rate scenario. Conversely, BEB infrastructure costs were higher than FCEB infrastructure costs in each scenario. The highest-cost FCEB infrastructure (TriMet, 127 buses) was lower than the lowest cost BEB infrastructure (Duluth, 74 buses).

Despite these major cost discrepancies, the overall cost picture for BEB and FCEB fleets was similar in certain scenarios, especially if the cost of an FCEB decreases to the projected future cost of $850,000 per bus. The most expensive scenario overall was an FCEB fleet, with buses priced at $1.2 million per bus and fuel priced at $7/kg. The least expensive scenario overall was also an FCEB fleet but with buses priced at $850,000 and fuel priced at $4/kg.

Minimizing Charging Infrastructure – Fleet Infrastructure Simulation

One of the key infrastructure costs for a BEB fleet is charging equipment. As the number of charger manufacturers and options has increased, so has the number of ways an agency can choose to charge its fleet. Many agencies are interested in pursuing a depot-charging-only strategy for refueling their electric buses, and there is a question regarding how many chargers are needed to refuel. In small-scale deployments, transit agencies often deploy one charger per bus, but this may not be necessary at larger scales.

CTE conducted an analysis of large-scale charging to evaluate how the number of chargers required for a fleet might decrease if a transit agency was willing to move buses around at night. The analysis examined TriMet's 179 blocks operating from its Powell Garage. CTE accounted for estimated bus cleaning time when determining time available to charge and set up the framework to evaluate different charger layouts.

Analysis

To evaluate resources needed for large fleets, two scenarios were compared:

- **A total of 24 120-kW chargers (4 rows of 6 chargers)** – when returning from route service, buses park in charging rows first and then fill in from closer to further from chargers; once a full row is done charging, all buses are moved to new parking spots and a new line of six buses fills the spots.
- **All parking spots have a 120-kW charger to serve buses to left or right of dispenser** – in this scenario, buses do not need to be moved to begin charging, although it is possible to control the number of chargers being used at one time by limiting the peak and off-peak demand.

The analysis examined 179 blocks coming from the Powell Garage in TriMet's service area. This number included any block over 150 miles being split in half by time, with 30 minutes of deadhead added to each half block. These blocks were consistent for all iterations of the analysis, and a combination of factors was considered successful only if it completed all blocks.

The variables tested were on-peak and off-peak demand and number of buses available to be used in service. To minimize cost, it was important to find the fewest number of buses within the demand constraints that would still meet the service needs of all 179 blocks.

Scenario 1

In this scenario, the demand never exceeded 2880 kW due to the number of charger constraints. Table 3-5 shows the results of varying limits to on-peak charging; the values were selected because they represent 0, 1, 2, 3, and all 4 charger rows turned on.

Table 3-5

Scenario 1 Successful Results

On-Peak Limit (kW)	Off-Peak Limit (kW)	Buses Used	kW On-Peak	kW Off-Peak
2880	2880	124	2876	2872
2160	2880	124	2040	2872
1440	2880	130	1320	2880
720	2880	142	720	2880
0	2880	160	0	2880

Scenario 2

Given the increased number of chargers, there were more options to limit on and off-peak demand, thus allowing the number of buses to also be limited. In each of the cases shown in Table 3-6, the on-peak limit was set first and increased by the use of six chargers. The analysis found that 118 buses was the lowest number needed to meet the service needs of 179 blocks, even when the on- and off-peak limits were increased. In this scenario, there were half the number of chargers as there were buses. This was due to the ability of the chargers to be used on either the right or left side of the dispenser.

Table 3-6

Scenario 2 Successful Results

On-Peak Limit (kW)	Off-Peak Limit (kW)	Buses Used	kW On-Peak	kW Off-Peak
0	1440	139	0	1440
720	1440	124	720	1440
720	2160	124	720	2160
1440	1440	118	1440	1448
2160	2160	118	2160	2168
2880	2880	118	2820	2880
6480	6480	118	2836	3672

Sharing Findings

CTE participated in a number of events throughout the course of this project, during which they shared results and lessons learned from this analysis. A summary of these events is shown in Table 3-7.

Table 3-7

CTE Outreach Event Summaries

Date/ Quarter	Event/Group	Summary
Q1 2019	US Interagency Hydrogen Working Group	CTE supported a presentation on findings of this research. And compiled current findings into a presentation.
July 29–31, 2019	2019 APTA Sustainability Conference	CTE presented MVTA and Duluth fleet analyses to roundtable participants for feedback, with particular interest in operational constraints. CTE asked participants to comment on specific topics and collected feedback, which was incorporated into subsequent analyses.

The CTE-led roundtable discussions at the 2019 APTA Sustainability Conference included 19 participants across two sessions. Participants were nearly evenly split between transit agencies and other stakeholders (e.g., OEMs). The discussion title was "Large Scale Zero-Emission Bus Fleet Infrastructure and Operational Costs."

CTE presented the MVTA and Duluth fleet analyses that had been completed at that point in the study. Feedback was solicited from participants, with a particular interest in operational constraints. CTE asked participants to comment on a range of topics, including (but not limited to) schedule redesign based on new technology constraints, space and/or land constraints, capital vs. operating costs, maintenance uncertainty, and facility modifications.

Comments shared by participants highlighted the site-specific nature of fleet transition costs. Real estate, operator time, and infrastructure upgrade costs are determined by several factors. The location and size of an agency's depot(s) play a role, as do the number of on-route chargers in the system, which is driven by service requirements and the characteristics of an agency's blocks.

SECTION 4

Conclusions

This analysis explored several different facets of ZEB fleet costs, including fleet sizing, vehicle cost, infrastructure sizing, infrastructure cost, and regional variations in fuel costs. At today's prices, BEB fleets appear to be less expensive overall than FCEB fleets, depending on agency characteristics. If FCEB-related costs drop more rapidly than BEB costs, FCEB fleets may be cost-competitive, if not less expensive than BEB fleets. Part of this is because FCEB fleet infrastructure, even at today's prices, may be less expensive than BEB infrastructure. Many early reports of electrical charging infrastructure costs are for small-scale installations, and the costs do not scale linearly with size. However, these costs are very difficult to predict in the rapidly-evolving ZEB industry.

Ultimately, a key finding from this analysis was that operational decisions can have a tremendous impact on fleet size and infrastructure costs. This is true for both BEBs and FCEBs, although the impacts may be more dramatic for BEBs, as they have limited range compared to FCEBs.

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