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Zero-Emission Bus Evaluation Results: Stark Area Regional Transit Authority Fuel Cell Electric Buses

OCTOBER 2019

FTA Report No. 0140
Federal Transit Administration

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U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

Image courtesy of L. Eudy, National Renewable Energy Laboratory

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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)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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Abstract

This report summarizes the experience and results from a demonstration of a fleet of five fuel cell electric buses (FCEBs) operated by the Stark Area Regional Transit Authority (SARTA). SARTA, based in Canton, Ohio, has been operating the FCEBs funded through the Federal Transit Administration's (FTA's) Low or No Emission Deployment program. The FCEBs were built by ElDorado National-California with a BAE Systems electric propulsion system and a Ballard Power Systems fuel cell. FTA is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory to conduct in-service evaluations of advanced technology buses developed under its programs. This report presents evaluation results for the FCEBs in comparison to baseline buses in similar service. The focus of the analysis is on the most recent year of service, from February 2018 through January 2019. SARTA is collaborating with CALSTART to analyze acceptance of the technology within the agency. CALSTART conducted surveys of the operators and maintenance technicians at SARTA; survey analysis results are presented in the report.

EXECUTIVE SUMMARY

The U.S. Department of Transportation's (DOT's) Federal Transit Administration (FTA) supports the research, development, and demonstration of low- and zero-emission technology for transit buses. FTA funds research projects with a goal of facilitating commercialization of advanced technologies for transit buses that will increase efficiency and improve transit operations. FTA is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to conduct in-service evaluations of advanced technology buses developed under its programs. NREL uses a standard evaluation protocol for evaluating the advanced technologies deployed under the FTA programs.

FTA seeks to provide results from new technologies being adopted by transit agencies. The eight evaluations selected to date include fuel cell electric buses (FCEBs) and battery electric buses (BEBs) from different manufacturers operating in fleets located in both cold and hot climates. This report presents the results from an evaluation of five FCEBs operated by Stark Area Regional Transit Authority (SARTA) in Canton, Ohio. SARTA has partnered with CALSTART to manage its FCEB projects. CALSTART is a non-profit consortium that works with transit agencies to plan and manage zero-emission bus projects around the United States. NREL and CALSTART have worked together to evaluate the buses in service at SARTA. The purpose of this report is twofold: (1) to present the results from the NREL FCEB performance and cost evaluation and (2) to present the results of the user acceptance survey conducted by CALSTART.

Performance and Cost Evaluation Results

SARTA provides public transit service to Stark County, Ohio. SARTA is committed to using clean-fuel buses in its service. It began investigating hydrogen-fueled buses in 2014 and has successfully competed for funding from two FTA programs that will add a total of ten 40-foot FCEBs to its fleet. The agency was awarded $8.877 million in the first round of FTA's Low or No Emission Deployment Program (Low-No) for five FCEBs (the focus of this evaluation). The FCEBs are 40-foot ElDorado National-California (ENC) buses with BAE Systems hybrid electric propulsion systems powered by Ballard's FCvelocity-HD6 150-kW fuel cells. NREL is collecting data on a fleet of four Gillig compressed natural gas (CNG) buses as the primary baseline comparison. Table ES-1 provides a summary of the results for the FCEB and CNG buses.

Table ES-1:

Summary of SARTA Evaluation Results

Data Item	FCEB	CNG
Number of buses	5	4
Total mileage in data period	130,798	230,144
Average monthly mileage per bus	2,180	4,795
Availability (85% is target)	68	76
Fuel economy (kg/mile or gge[a]/mile)	4.99	4.21
Fuel economy (mpdge[b])	5.63	4.70
Miles between roadcalls (MBRC) – bus[c]	3,737	7,936
MBRC – fuel cell system only[c]	26,160	–
Total maintenance cost ($/mile)	0.33	0.33
Maintenance cost – propulsion system only ($/mile)	0.15	0.12

[a] *Gasoline gallon equivalent.*
[b] *Miles per diesel gallon equivalent.*
[c] *MBRC data cumulative through January 2019.*

SARTA selected two routes for its first FCEBs, whereas the CNG buses are randomly dispatched on all routes, including commuter runs to Akron and Cleveland. The fuel economy for the FCEBs averaged 5.63 mpdge compared to 4.59 mpdge for the CNG buses.

The overall average availability for the FCEB fleet was 68%, and the overall availability for the CNG baseline fleet was 76%. Most unavailable days for the FCEBs were due to general bus issues, followed by preventive maintenance. The overall availability of the fuel cell system was 94%.

Bus reliability, measured as miles between roadcall (MBRC), for the FCEBs shows a slow but steady climb from the beginning of the demonstration to an overall bus MBRC of 3,737 at the end of the data period, nearing the ultimate target of 4,000. The overall fuel-cell-system-related MBRC, at more than 26,000, surpassed the DOE/DOT ultimate target.

During the data period, the maintenance cost for the FCEBs was essentially the same as that of the CNG buses. The systems with the highest percentage of maintenance costs for the FCEBs and CNG buses were the same. Propulsion-related maintenance costs were highest, followed by preventive maintenance costs and cab, body, and accessories.

Issues and lessons learned for SARTA include the following:

- **Maintenance manpower** – At the onset of the program, SARTA trained two maintenance technicians to handle preventive maintenance, general bus repairs, and troubleshooting and repair of propulsion system issues with help from the manufacturer partners. Occasionally, both technicians were away from work at the same time, resulting in a delay for repair of an FCEB. SARTA has a third technician currently in training who will help with the manpower issue. As its FCEB fleet grows, the agency plans to train an additional technician each year.

- **Technology issues** – There were a few issues with the fuel cell and hybrid drive systems during the data period. The fuel cell issues were not related to the stack itself, but rather to the peripheral components that supply hydrogen and air, including a failed hydrogen recirculation blower and an air compressor controller. Hybrid system issues included a problem with a low-voltage connector in the electronics that was not properly seated. Because the problem was intermittent, it took some time to diagnose. Once the connector was reseated, the system worked reliably and consistently.
- **Heating, ventilation, and air conditioning (HVAC)** – SARTA experienced some issues with the electrically-driven air conditioning on the FCEBs due to failing evaporative and condenser motors. The local technician for the component supplier was not familiar with the model, which added to the time to troubleshoot the issue. The failed part had quality issues in the manufacturing process, and the component supplier has addressed the issue. The buses also had early issues with interior heating during extreme cold days. SARTA reported that the heat would be insufficient on days when the temperature fell below -15 degrees Fahrenheit; the agency elected to keep the buses out of service on the coldest days. The manufacturer addressed this issue by widening the setpoint limits for heating and insulating the components of the HVAC system that were outside the cabin area. These changes have resulted in better heating inside the bus without affecting the bus efficiency.
- **Downtime for non-technology-related issues** – During the data period, there were two incidents in which a bus was out of service for an extended period that were not due to an issue with the technology. For one case, the internal process for SARTA to issue a part order took longer than expected. In the second case, a part request was not received by the supplier. These were extenuating circumstances that are not expected to reoccur.

Customer Acceptance Assessment

To assess customer perception for FCEB technology, CALSTART administered surveys to SARTA drivers and maintenance technicians in September 2017 and May 2018. The survey results provide insights into their impressions on measures of bus performance, operation, and maintenance. CALSTART identified key takeaways regarding what these stakeholders thought were the best and worst qualities of the fuel cell buses. The most cited positive responses are as follows:

- **Overall rating** – Drivers and technicians rated the buses as good overall, and their opinions improved on most metrics over time, indicating that more experience with the buses led to better perception of them.

- **Performance comparison with conventional bus** – Both drivers and technicians rated the FCEBs either the same or better than conventional buses on initial launch, acceleration, coasting/deceleration, and braking behavior.
- **Low noise levels** – Results from both groups indicate that of all metrics, the FCEBs performed best in terms of low inside and outside noise levels.

The survey respondents also had negative feedback and offered suggestions for improving the FCEBs:

- **Worse productivity** – Overall, the respondents expressed that the productivity of the FCEBs was worse than that of the conventional buses, indicating that they were pulled out for servicing more.
- **Commonly reported issues** – Respondents cited that the bus was often unable to reach highway speeds and had multiple component failures that had to be addressed.
- **HVAC and energy consumption** – Respondents stated that running heating and cooling systems in the buses limited the range of the buses due to the energy needed to run those systems.

SECTION

1

Introduction

The U.S. Department of Transportation's (DOT's) Federal Transit Administration (FTA) supports the research, development, and demonstration of low- and zero-emission technology for transit buses. FTA funds a number of research projects with a goal of facilitating commercialization of advanced technologies for transit buses that will increase efficiency and improve transit operations. These programs include the following:

- **National Fuel Cell Bus Program (NFCBP)** – $180 million, multi-year, cost-share research program for developing and demonstrating commercially-viable fuel cell technology for transit buses.
- **Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER)** – $225 million for capital investments that would reduce greenhouse gas (GHG) emissions and/or lower the energy use of public transportation systems.
- **Low or No Emission Vehicle Deployment Program (Low-No)** – $271.35 million in funding (FYs 2013–2018) to transit agencies for capital purchases of zero-emission and low-emission transit buses that have been largely proven in testing and demonstration efforts but are not yet widely deployed.

FTA understands the need to share early experience with advanced technologies with the transit industry and is funding evaluations of a selection of these projects to provide comprehensive, unbiased performance results from advanced technology bus development, operations, and implementation. These evaluations have proved useful for a variety of groups, including transit operators considering the technology for future procurements, manufacturers needing to understand the status of the technology for transit applications, and government agencies making policy decisions or determining future research needs. The evaluations include economic, performance, and safety factors. Data are collected on the operation, maintenance, and performance of each advanced technology fleet and a comparable baseline fleet operating at the same site (if available).

FTA is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to conduct in-service evaluations of advanced technology buses. For more than a decade, NREL has been evaluating advanced technology transit buses using a standard data collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations. Funding for these evaluations has come from several agencies, including FTA, DOE, and the California Air Resources Board. NREL has evaluated fuel cell electric buses (FCEBs) as well as battery electric buses (BEBs) following this standard protocol.

NREL uses a set of criteria to prioritize the available projects for selection. The criteria include number of buses deployed, record-keeping practices of the transit agency, commitment level of the bus original equipment manufacturer (OEM), and the availability of appropriate baseline buses for comparison. The criteria are not intended to be rigid; however, the determination of priority is based on how many criteria are met. In consultation with FTA, NREL selected several projects that are in the highest priority category. Other projects will be chosen as more information becomes available. Table 1-1 lists the projects selected for evaluation as of the publication date of this report.

Table 1-1

Selected Evaluation Projects

Site #	Transit Agency and Location	Project Description	Evaluation Status
1	King County Metro, Seattle, WA	3 Proterra 40-ft Catalyst buses and 1 fast-charge station	Completed
2	Long Beach Transit, Long Beach, CA	10 BYD 40-ft BEBs, overnight charging with 1 inductive charger on route	Completed
3	Central Contra Costa Transit Authority, Concord, CA	4 Gillig/BAE Systems 29-ft BEBs, overnight charging with 1 inductive charger on route	Completed
4	Orange County Transportation Authority, Santa Ana, CA	1 American Fuel Cell Bus (AFCB) – BAE Systems, Ballard Power Systems, and ElDorado National-California	Completed
5	Stark Area Regional Transit Authority, Canton, OH	5 AFCBs	Completed
6	Massachusetts Bay Transportation Authority, Boston, MA	1 AFCB with Nuvera PowerTap system fueling infrastructure	Completed
7	Duluth Transit, Duluth, MN	6 Proterra 40-ft Catalyst E2 BEBs	Initiated May 2018
8	Southeastern Pennsylvania Transportation Authority, Philadelphia, PA	25 Proterra 40-ft Catalyst E2 BEBs	Planned 2019

The focus of this report is on the Stark Area Regional Transit Authority (SARTA) in Canton, Ohio. As part of the NFCBP, SARTA was awarded $5.5 million in 2014, with an additional $500,000 from the Ohio Department of Transportation, to purchase and operate hydrogen fuel cell buses. The agency also received Low-No awards to add to its fleet of FCEBs. The NFCBP was established in 2016 to aid in commercializing FCEBs. CALSTART was one of the three non-profit consortia selected to develop and manage projects under the program. SARTA has partnered with CALSTART to manage its FCEB projects, and NREL and CALSTART have worked together to evaluate the buses in service at SARTA. The purpose of this report is twofold: (1) to present the results from the NREL FCEB performance and cost evaluation and (2) to present the results of the user acceptance survey conducted by CALSTART.

SECTION

2

SARTA FCEB Evaluation Results

SARTA began operating its first of the five Low-No-funded FCEBs in July 2017. The rest of the buses were phased in as they were prepped for service. This section summarizes the evaluation results for the FCEBs in comparison to a fleet of compressed natural gas (CNG) baseline buses. Data from three older hybrid electric buses is included for a selection of data elements. The focus of the analysis is on the most recent year of data, from February 2018 through January 2019.

Fleet Profile – SARTA

SARTA provides public transit service to Stark County, Ohio. Its service area covers 581 square miles and contains more than 372,000 residents. Its bus fleet operates on 34 fixed routes, with service focused in the cities of Canton, North Canton, Massillon, and Alliance, along with several commuter routes to Akron and Cleveland. As of 2017, the transit authority operated 50 fixed-route buses and 52 paratransit buses for customers with disabilities. Figure 2-1 is a map of SARTA's service area.

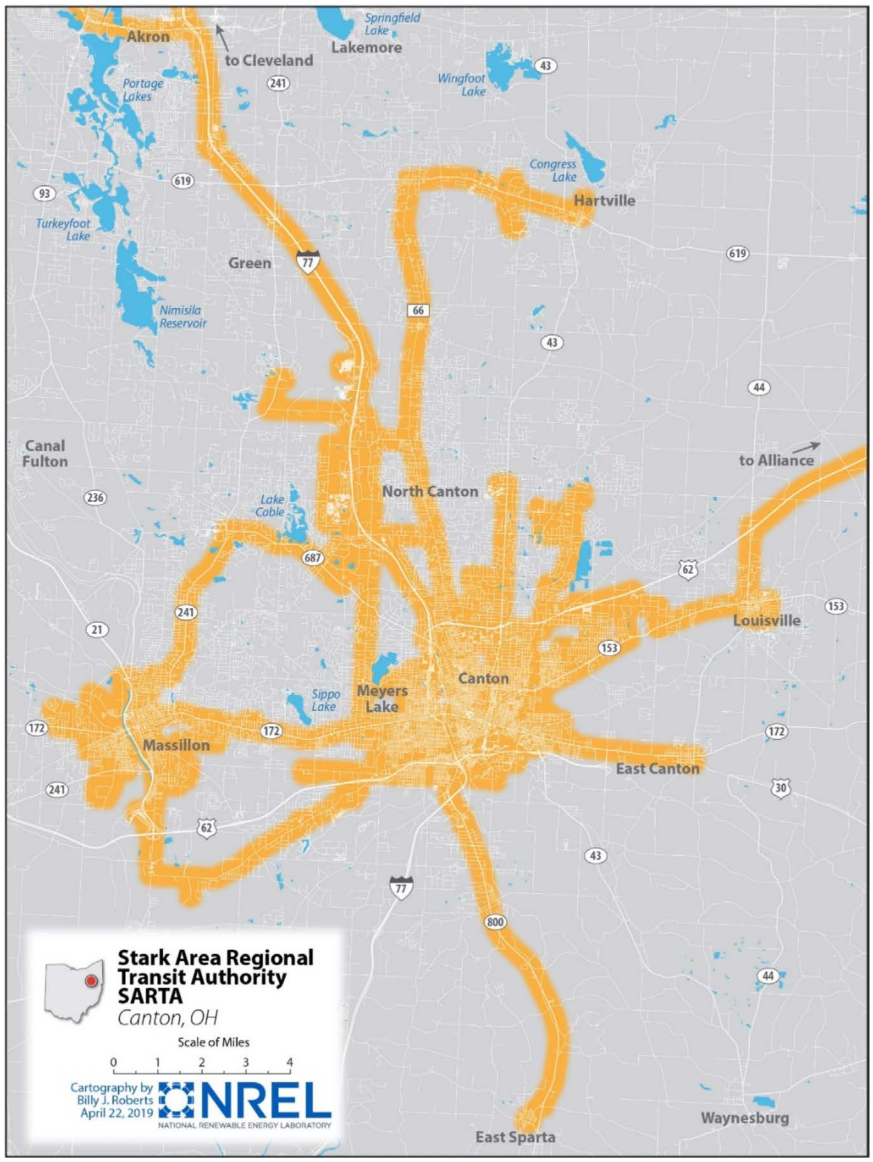
SARTA is committed to using clean-fuel buses in its service. The agency introduced diesel hybrid electric buses to its fleet in 2009 and CNG buses in 2012. It began investigating hydrogen-fueled buses and in 2014 received a grant from FTA to purchase its first FCEB. That bus, developed under the FTA NFCBP, would be operated by Ohio State University for a year prior to delivery to SARTA. Through the NFCBP, the agency received funding for a second bus that was tested at the Altoona Bus Research and Testing Center. This testing, which is required by FTA for buses to be purchased with Federal funds, is a major milestone for the technology. After the testing was complete, the bus was returned to the manufacturer to be prepped for service at SARTA. To add to its fleet of FCEBs, SARTA successfully competed for funding from the FTA Low-No Program. The agency was awarded $8.877 million in the first round of Low-No funding for five FCEBs (the focus of this evaluation) and additional awards of $4 million and $1.7 million in subsequent rounds for a total of five more. In addition to the 40-foot FCEBs, SARTA is procuring five paratransit vehicles fueled by hydrogen.

Promoting Hydrogen in the Region

To promote the use of hydrogen in Ohio and the surrounding states, SARTA collaborated with the Ohio State University Center for Automotive Research to establish the Renewable Hydrogen Fuel Cell Collaborative.[1] A key initiative of the Collaborative, the Midwest Hydrogen Center of Excellence is a regional ambassador for the advancement and adoption of hydrogen-powered, zero-emission vehicles in Midwestern public transit. In partnership with CALSTART, the Collaborative released a roadmap for deploying hydrogen vehicles into the Midwest region.[2] The roadmap is a 15-year plan to deploy 135,000 fuel cell electric vehicles in both light-duty and heavy-duty applications in the region. The plan projects that hydrogen vehicle deployment and renewable hydrogen production have the potential to add 65,000 new jobs in the region.

Figure 2-1

SARTA Service Area



[1] Renewable Hydrogen Fuel Cell Collaborative website, http://www.midwesthydrogen.org/.

[2] http://www.midwesthydrogen.org/site/assets/files/1252/hydrogen_roadmap_for_the_midwest_09152017.pdf.

Bus Technology Descriptions

SARTA's FCEBs are 40-foot ElDorado National-California (ENC) buses with a BAE Systems hybrid electric propulsion system powered by Ballard's FCvelocity-HD6 150-kW fuel cell. NREL is collecting data on two fleets of baseline buses for comparison. The primary comparison is with a fleet of four Gillig CNG buses that are similar in age. NREL is collecting data on a fleet of three Gillig diesel hybrid buses as a secondary comparison. These hybrid buses are much older and have accumulated significantly more miles than the FCEBs; therefore, the comparison is limited to mileage accumulation, fuel efficiency, and availability. Table 2-1 provides selected specifications for each bus type.

Table 2-1

System Descriptions for FCEB, CNG, and Diesel Hybrid Buses

Vehicle System	FCEB	CNG	Hybrid
Number of buses in evaluation	5	4	3
Bus manufacturer	ENC	Gillig	Gillig
Bus year and model	2016 Axess	2014, 2016 Low Floor	2009, 2010 Low Floor
Length (ft)	40	40	40
GVWR (lb)	43,420	41,600	39,600
Fuel cell or engine	Ballard FCvelocity[3]-HD6, 150 kW	Cummins ISL-G 280 hp @ 2,200 rpm	Cummins ISB
Hybrid system	BAE Systems, series hybrid propulsion system, HDS 200, 200 kW peak	N/A	Allison, parallel hybrid propulsion system, H40EP 209 kW continuous
Energy storage	A123, Nanophosphate Li-ion; 200 kW, 11 kWh	N/A	Allison ESS2; Nickel Metal Hydride
Accessories	Electric	Mechanical	
Fuel capacity	Gaseous hydrogen, 8 Luxfer-Dynetek cylinders, 50 kg at 350 bar	CNG, 8 SCI cylinders, 167 gge at 3,600 psi	125 gallon, diesel
Bus purchase cost	$2.04M	$533,037	$561,654

The FCEBs on order for SARTA will have an upgraded design powered by a smaller Ballard fuel cell. A detailed description of the upgrades is included in Section 3. Figure 2-2 is a photo of one of the FCEBs, and a CNG bus is pictured in Figure 2-3.

[3] FCvelocity is a registered trademark of Ballard Power Systems.

Figure 2-2
SARTA FCEB

Figure 2-3
SARTA CNG Bus

Fueling and Maintenance Facilities

SARTA's hydrogen station features liquid delivery, storage, and dispensing. This Air Products station stores 9,000 gallons of liquid hydrogen and uses liquid hydrogen pumping. Hydrogen is currently delivered from Sarnia, Ontario, in Canada, about 300 miles away. The station is designed to fuel up to 20 FCEBs but was built to allow upgrades for expansion and includes two compressors to reduce the chance of downtime. Air Products owns the hydrogen storage equipment and compressors; SARTA's contract with Air Products includes lease of the equipment, operations, and maintenance for about $10,000 per month plus fuel cost. The dispenser provides hydrogen at 350 bar pressure for the FCEBs and is in the fueling island that is part of a public access CNG station at the front of the property. SARTA plans to add a dispenser for light-duty FCEVs at 700 bar pressure. Figure 2-4 shows the station from two different angles. Cost of the station was approximately $2.9 million.

Figure 2-4 *SARTA Hydrogen Station*

The dispenser is shown in Figure 2-5. Fueling a bus at the SARTA station takes about 20 minutes. The agency uses a lower fueling rate to avoid the need to top off the tanks before putting the FCEBs into service in the morning. Other agencies have reported issues in getting a full fill when the station fill rate is high because the hydrogen heats up in the process and reaches the setpoint pressure of 350 bar. After the tank cools, the tank pressure is less than 350 bar. Agencies report that this can result in the buses running low on fuel before completing scheduled service. To avoid the need for fueling twice or sending out a bus with less fuel than needed, SARTA uses a slower fueling rate.

Figure 2-5

Hydrogen Dispenser at SARTA Hydrogen Station

The dispenser does not have a flow meter for measuring the kilograms dispensed, so the amount dispensed is calculated using pressure, temperature, and volume. The volume is consistent for all buses and is the internal volume capacity of the on-board hydrogen cylinders. An initial pressure reading is recorded before fueling as is an ambient temperature reading. After fueling, the pressure is recorded again. The temperature of the compressed hydrogen in the cylinders heats up during the fueling process, but because there is no temperature measurement inside the hydrogen cylinders, the final mass of hydrogen cannot be calculated at this point. The final settled pressure and ambient temperature readings are recorded at 4:30 AM after the gas temperature has cooled and before service. SARTA uses a lookup table to determine the mass before fueling and after settling and then subtracts the initial mass from the final mass to calculate the kilograms dispensed. NREL uses the National Institute of Standards and Technology Reference Fluid Thermodynamic and Transport Properties (REFPROP) database[4] to apply the equations of state calculations for hydrogen[5] to the same pressure and temperature readings for the analysis.

SARTA's maintenance facility was purpose-built in 2012 for maintaining gaseous-fueled CNG buses. Because of this, it was easily upgraded to allow maintenance of hydrogen-fueled buses. Upgrades included new sensors for detecting hydrogen leaks and increased air flow rate. Four air handlers can change the air in the facility every 15 minutes with the help of auxiliary fans on the roof. The doors open automatically in an emergency event. Cost to upgrade the facility was around $100,000. SARTA stores all its buses inside the facility overnight. The agency installed plug-in connections for the FCEBs to protect the fuel cell from freezing. The newer-design buses on order will have freeze protection.

In-Service Operations Evaluation Results

This section focuses on a full year of operation from February 2018 through January 2019 (the evaluation period). SARTA put its first fuel cell bus into service in October 2017; all five buses were in service by the end of 2017.

Route Assignments

SARTA's service is planned to operate six days each week, Monday through Saturday. The CNG and hybrid buses are randomly dispatched. SARTA selected two routes for FCEB operation—routes 102 and 105. Route 102 is a 10-mile loop that travels from downtown Canton to downtown Massillon, and Route

[4] Lemmon, E. W., Bell, I. H., Huber, M. L., McLinden, M. O., NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2018.

[5] Leachman, J. W., Jacobsen, R. T, Penoncello, S. G., and Lemmon, E. W., "Fundamental Equations of State for Parahydrogen, Normal Hydrogen, and Orthohydrogen," *J. Phys. Chem. Ref. Data* 38(3): 721-748, 2009.

105 is a 12-mile loop that travels between downtown Canton and the Beldin Village Mall area. These two routes are heavily used, with around 35,000 riders each month. During the data period, the FCEBs were operated 74% of the time on Route 102 and 24% of the time on Route 105. SARTA occasionally used the buses for special service, such as shuttles during Enshrinement Week for the Pro Football Hall of Fame. The CNG buses were operated on 14 different routes, with the most service on Route 81 (32%) followed by Route 105 (17%).

The hybrid buses were also operated on 14 different routes, with the most service on Route 102 (43%), followed by Route 105 (17%) and Route 110 (16%). The average speed for all operations is 18–20 mph; the average speed for the FCEBs on routes 102 and 105 is slightly higher, at 22 mph.

Bus Use

Figure 2-6 tracks the accumulated mileage and operating hours of the fuel cell buses for the data period. Since being placed into service, the FCEBs have accumulated more than 152,000 miles and more than 10,700 hours on the fuel cells.

Figure 2-6

Cumulative Miles and Hours for FCEBs

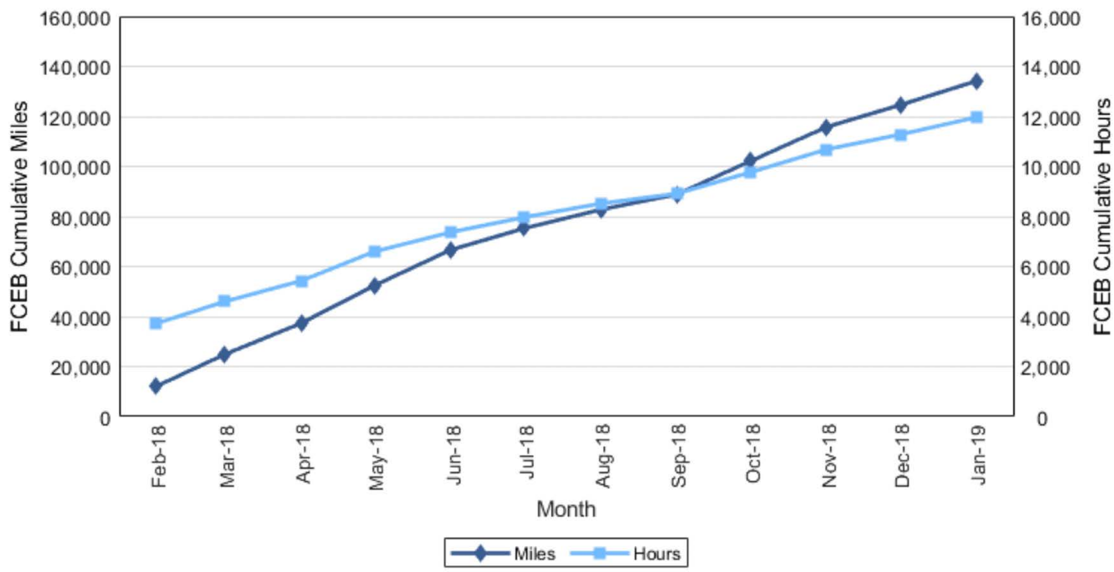


Table 2-2 provides the data period mileage for each bus and the average monthly mileage by bus type, which is also displayed in Figure 2-7. The fuel cell bus fleet averaged 2,180 miles per month, the CNG bus fleet averaged 4,795 miles per month, and the hybrid bus fleet averaged 3,698 miles per month. During the initial stage of deployment, SARTA is operating the FCEBs primarily on weekdays. Both the CNG and the hybrid bus fleet are typically operated six days per week. One of the hybrid buses (0976) was removed from service during the data period.

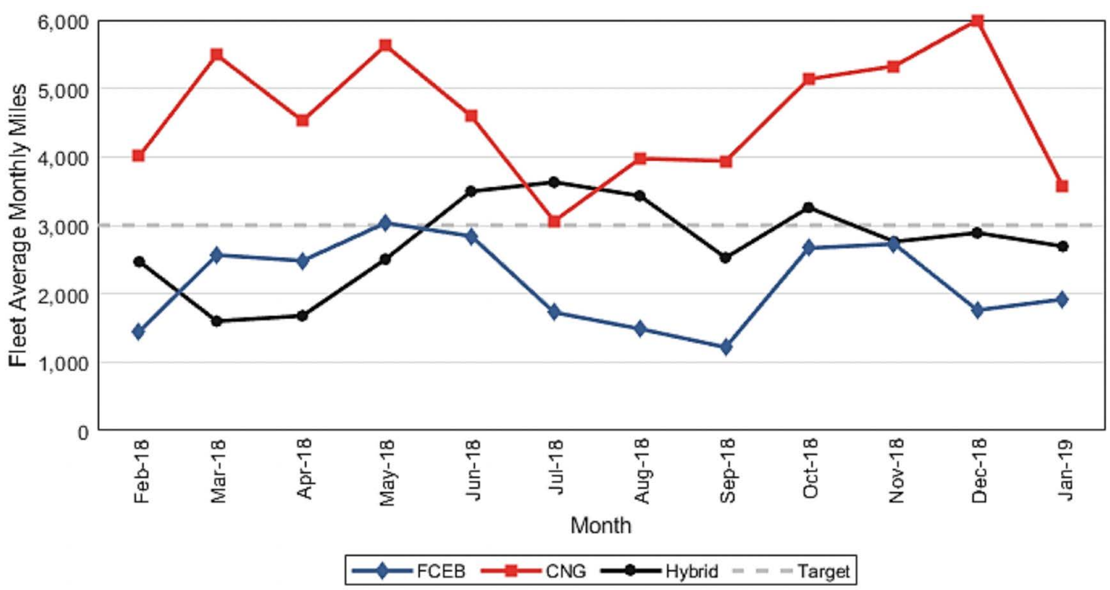
Table 2-2

Average Monthly Mileage (Evaluation Period)

Bus #	Total Mileage	Months	Average Monthly Mileage
1712	19,414	12	1,618
1713	32,016	12	2,668
1714	26,094	12	2,175
1715	26,564	12	2,214
1716	26,710	12	2,226
FCEB Fleet	**130,798**	**60**	**2,180**
1402	68,873	12	5,323
1404	41,656	12	3,471
1608	68,354	12	5,696
1609	56,261	12	4,688
CNG Fleet	**230,144**	**48**	**4,795**
0976	14,167	5	2,833
0977	44,288	12	3,691
1079	41,378	10	4,138
Hybrid Fleet	**99,833**	**27**	**3,698**

Figure 2-7

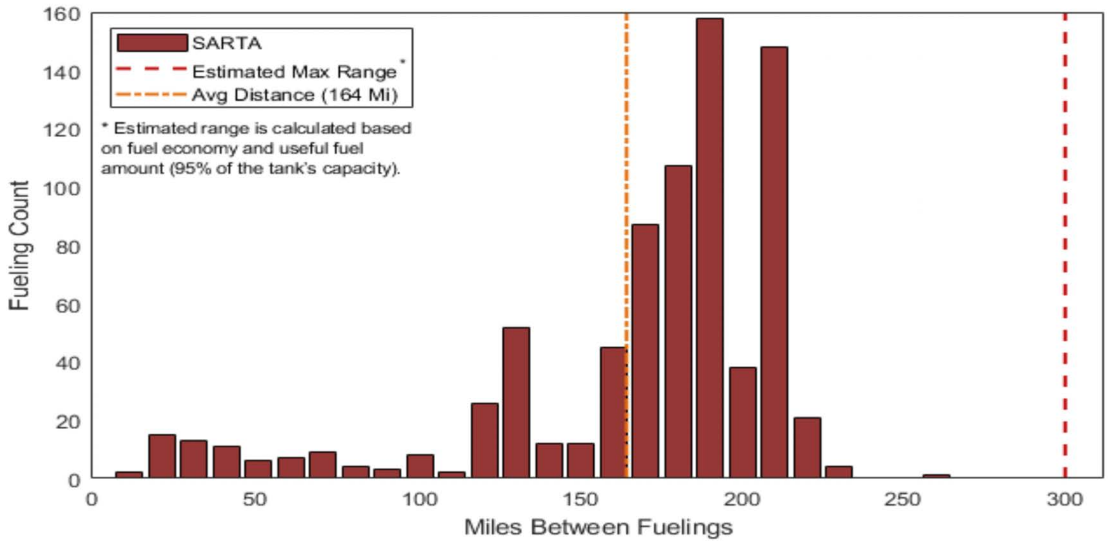
Average Monthly Miles for SARTA FCEB and Baseline Bus Fleets



SARTA has reported some concerns about the range of the FCEBs. NREL does not conduct range tests on buses; however, data can be used to show the typical use of a bus in service. Figure 2-8 provides a histogram of miles traveled between hydrogen fueling events over the past year. Although this is a measure of how the buses were used and not a specific range, some inferences can be drawn from the results. The average miles driven for the fleet (dashed orange line) was 164 miles. The estimated range, calculated using the average fuel economy and the useful fuel amount in the tanks at 95% of capacity, is shown as a dashed red line. These data show that the SARTA FCEBs regularly travel 150–225 miles between fueling events.

Figure 2-8

Histogram of Miles between Fueling Events



Availability

The availability analysis covers 12 months of data collection and evaluation. Planned service for SARTA is six days per week (no Sunday service provided). During this early deployment, the FCEBs are operated primarily on weekdays. The data presented are based on availability at morning pull-out and do not necessarily reflect all-day operation. Table 2-3 summarizes the availability and reasons for unavailability for each of the three bus fleets. The overall average availability for the FCEB fleet was 68%, and the overall availability for the CNG and hybrid baseline fleets were 77% and 83%, respectively. Most unavailable days for the FCEBs were due to general bus issues, followed by preventive maintenance (PM). The CNG and hybrid bus fleets also had issues primarily due to general bus problems, followed by time for PM. During the data period, there were two incidents during which an FCEB repair was delayed due to issues that were not related to the technology. One was due to a delay in completing paperwork within the agency to submit a purchase request for a part. The second delay occurred when an online part order was not received at the warehouse. Because these situations are not typical and not due to technology issues, the bus was considered unplanned during that timeframe.

Table 2-3

Summary of Availability and Unavailability by Category

Category	FCEB # Days	FCEB %	CNG # Days	CNG %	Hybrid # Days	Hybrid %
Planned days	1,427		1,158		698	
Days available	967	68	881	76	561	80
Unavailable	460		277		137	
Fuel cell system/engine	85	6	63	5	—	—
Hybrid propulsion	66	5	—	—	38	5
Traction battery	0	0	—	—	0	0
PM	96	7	93	8	47	7
General bus	213	15	121	10	52	7

Figure 2-9 tracks the monthly average availability for the FCEB, CNG, and hybrid bus fleets as lines along the top of the chart. The stacked columns in the figure show the number of days that the FCEB fleet was unavailable, organized into five categories. The light blue line tracks the availability of the fuel cell system, which averages 94% availability over the full-year data period.

Figure 2-9

Monthly Availability for All Fleets and Reasons for Unavailability for FCEB Fleet

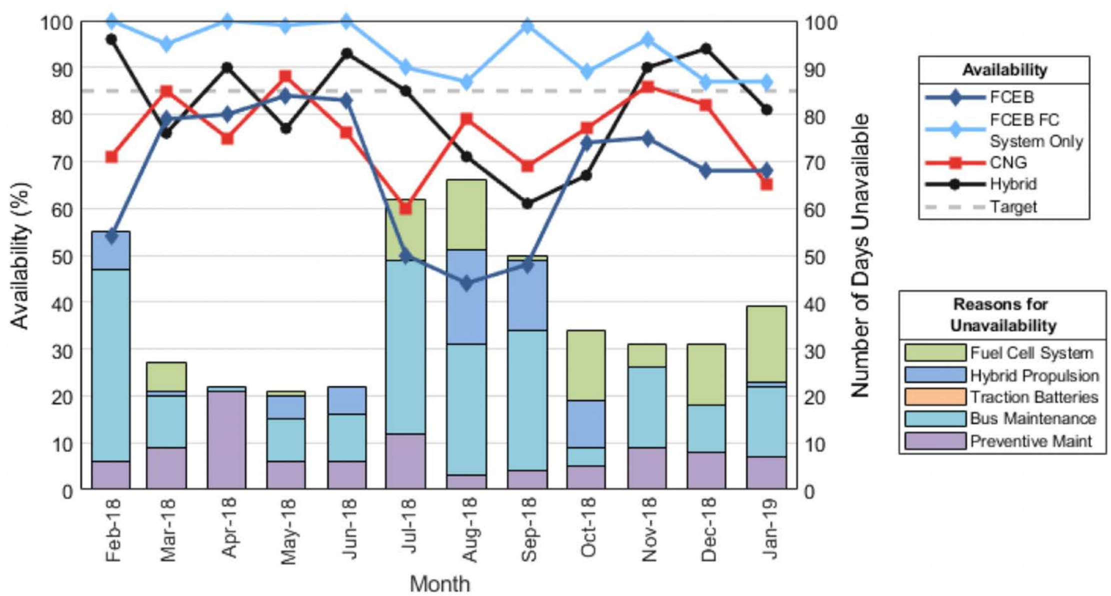
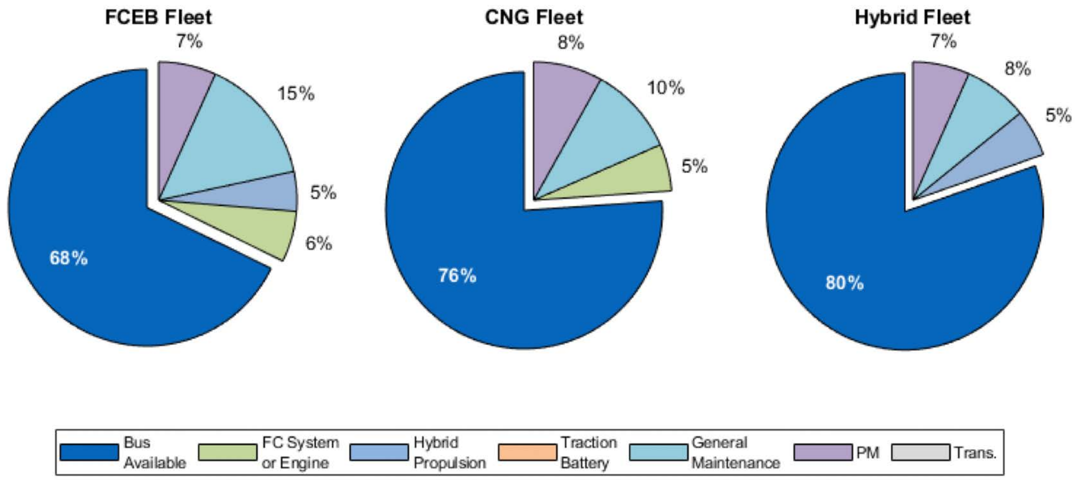


Figure 2-10 shows the overall percentage of days each bus fleet was available for service, the percentage of days buses were out of service, and the reasons for unavailability during the data period. The majority of issues with the FCEBs were due to time for PM or for general bus repairs, which included issues with the air conditioning system, kneeler valves, and a water leak.

Figure 2-10

Overall Availability for FCEB, CNG, and Hybrid Bus Fleets during Evaluation Period



Fuel Economy

Table 2-4 lists the per-bus mileage, fuel use, and fuel economy along with the fleet averages. Figure 2-11 shows the monthly average fuel economy in miles per diesel gallon equivalent (mpdge) for the FCEB, CNG, and hybrid bus fleets. Also plotted in Figure 2-11 is the average daily high temperature recorded at Akron/Canton Airport.[6] The fuel economies for all three fleets follow a seasonal trend with the lowest fuel economies during high- and low-temperature months when the HVAC system would be used. At an average of 5.63 mpdge, the FCEB fleet has a fuel economy that is 20% higher than the CNG bus fuel economy and 23% higher than the hybrid bus fuel economy.

Table 2-4

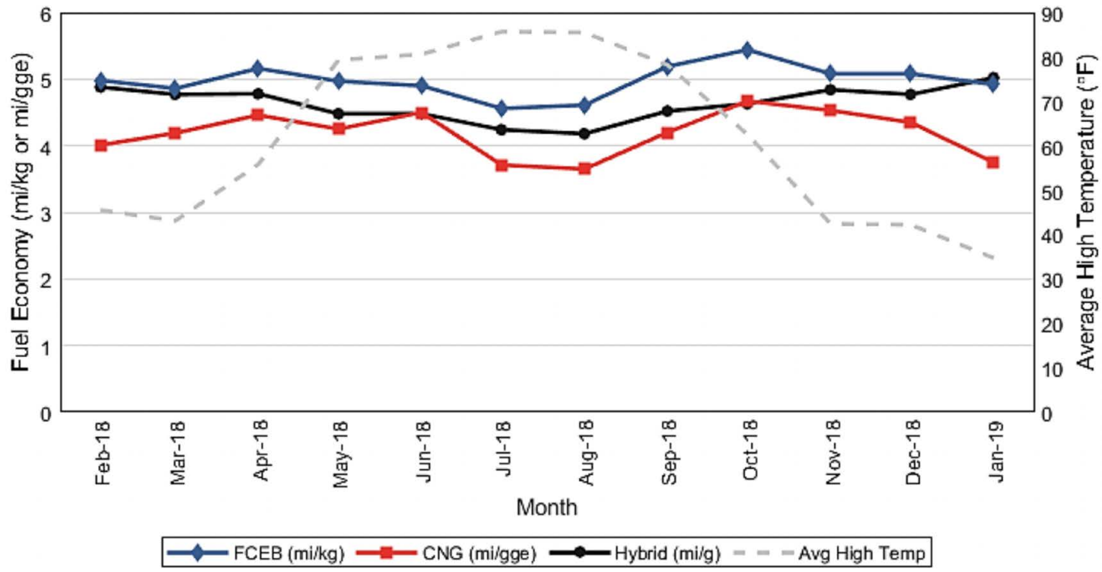
Mileage, Fuel Use, and Fuel Economy

Bus	Mileage (fuel base)	Fuel Consumption (kg/gge)	Fuel Consumption (dge)	Fuel Economy (mi/kg or gge)	Fuel Economy (mpdge)
1712	19,268	3,788.6	3,352.7	5.09	5.75
1713	32,016	6,345.4	5,615.4	5.05	5.70
1714	25,838	5,089.8	4,504.2	5.08	5.74
1715	25,816	5,255.5	4,650.9	4.91	5.55
1716	26,399	5,461.4	4,833.1	4.83	5.46
FCEB Fleet	**129,337**	**25,940.7**	**22,956.3**	**4.99**	**5.63**
1402	62,661	15,011.6	13,435.4	4.17	4.66
1404	39,524	10,950.7	9,800.9	3.61	4.03
1608	66,443	14,868.0	13,306.9	4.47	4.99
1609	52,350	11,699.7	10,444.4	4.49	5.01
CNG Fleet	**220,978**	**52,500.0**	**46,987.5**	**4.21**	**4.70**
0976	13,977	—	3,145.7	—	4.44
0977	43,627	—	9,602.1	—	4.54
1079	41,183	—	8,792.7	—	4.68
Hybrid Fleet	**98,787**	**—**	**21,540.5**	**—**	**4.59**

[6] NOAA National Centers for Environmental Information – Climate Data Online, https://www.ncdc.noaa.gov/cdo-web/.

Figure 2-11

Monthly Fuel Economy for FCEB, CNG, and Hybrid Buses



Roadcall Analysis

Table 2-5 provides the MBRC for the FCEB and CNG buses categorized by bus roadcalls, propulsion-related roadcalls, and fuel-cell-system-related roadcalls.

Table 2-5

Roadcalls and MBRC

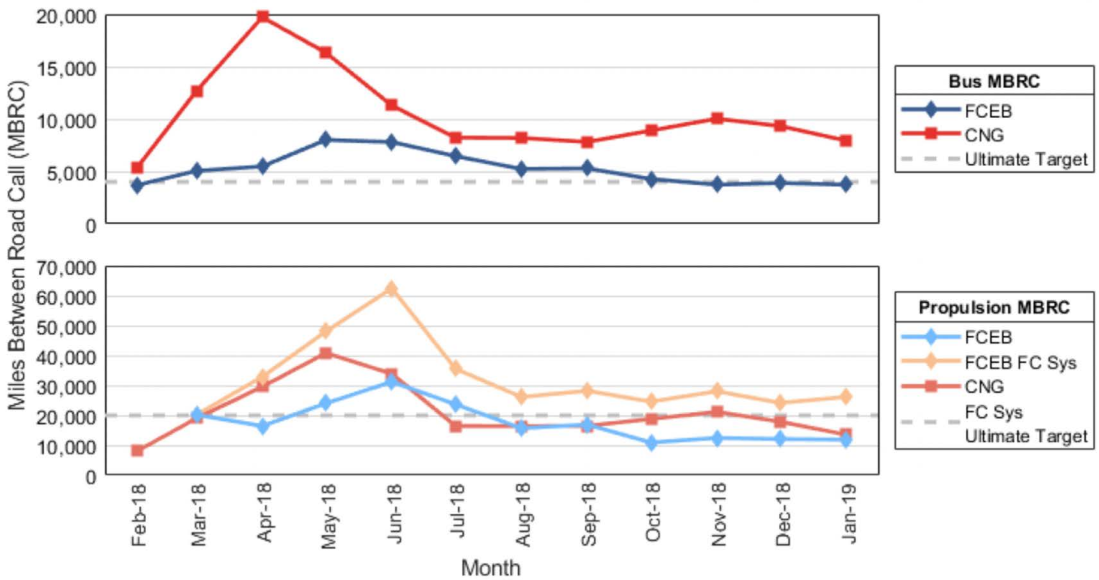
	FCEB	CNG
Dates	2/18–1/19	2/18–1/19
Mileage	130,798	230,144
Bus roadcalls	35	29
Bus MBRC	3,737	7,936
Propulsion-related roadcalls	11	17
Propulsion-related MBRC	11,891	13,538
Fuel-cell-system-related roadcalls	5	
Fuel-cell-system-related MBRC	26,160	

Figure 2-12 plots the cumulative MBRC for the FCEB and CNG buses, with total bus roadcalls on the upper chart and propulsion-related roadcalls and fuel-cell-system-related roadcalls on the lower chart. Propulsion-related roadcalls are a subset of bus roadcalls for all bus fleets. Fuel-cell-system-related roadcalls are a subset of the propulsion-related roadcalls, specific to the fuel cell of the FCEB. The DOE/FTA targets of 4,000 overall MBRC and 20,000 fuel-cell-system-related MBRC are included in the graph as dashed lines.

The bus MBRC for the FCEBs shows a slow but steady climb since the beginning of the demonstration to an overall bus MBRC of 3,737 at the end of the data period, nearing the ultimate target of 4,000. A few fuel cell system roadcalls midway through the data period resulted in a downward trend in July 2018, which then stabilized. The overall fuel-cell-system-related MBRC at more than 26,000 has surpassed the DOE/DOT ultimate target.

Figure 2-12

Cumulative Bus MBRC and Propulsion-Related MBRC



Maintenance Analysis

SARTA has two technicians trained to service the FCEBs, and a third technician is being trained. The agency reports that introducing FCEBs to maintenance staff was facilitated by their early experience with hybrid electric and CNG propulsion systems; the technicians became familiar with high-voltage electric systems of the hybrid buses and with high-pressure gas in the CNG buses.

This section covers total maintenance costs and maintenance costs by bus system. NREL excludes accident data and warranty repairs from the calculations. The FCEBs were under warranty support by the OEMs during the data period; the CNG buses were out of the warranty period. Any work covered under warranty is considered to be part of the purchase price of the bus and was removed from the data set.

Total Work Order Maintenance Costs

Table 2-6 shows maintenance costs per mile for the FCEBs and CNG buses and includes scheduled cost, unscheduled cost, and total cost. Scheduled costs include PM based on OEM recommendations; all other maintenance is included in unscheduled costs. During the data period, the maintenance cost for the FCEB fleet was essentially the same as that of the CNG buses.

Table 2-6

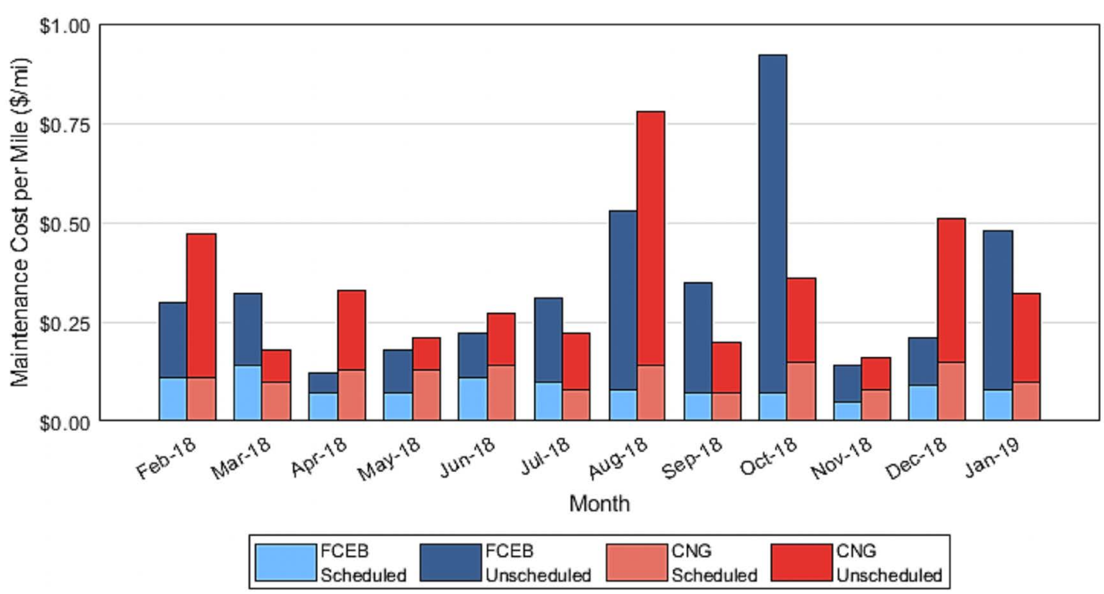
Total Work Order Maintenance Costs

Bus Fleet	Mileage	Parts ($)	Labor Hours	Scheduled Cost per Mile ($)	Unscheduled Cost per Mile ($)	Total Cost per Mile ($)
1712	19,414	295.63	167.5	0.079	0.368	0.446
1713	32,016	469.07	132.7	0.080	0.141	0.222
1714	26,094	10,133.74	103.8	0.092	0.495	0.587
1715	26,564	156.27	115.4	0.093	0.130	0.223
1716	26,710	213.12	127.2	0.085	0.161	0.246
FCEB Fleet	**130,798**	**11,267.83**	**646.5**	**0.086**	**0.247**	**0.333**
1402	63,873	8,680.41	230.7	0.116	0.201	0.316
1404	41,656	9,860.36	179.5	0.134	0.318	0.452
1608	68,354	6,970.88	198.7	0.098	0.150	0.247
1609	56,261	10,485.15	184.9	0.127	0.223	0.351
CNG Fleet	**230,144**	**35,996.80**	**793.7**	**0.117**	**0.212**	**0.329**

The monthly scheduled and unscheduled maintenance costs per mile for the buses are shown as stacked columns in Figure 2-13. The higher cost for the FCEBs during August 2018 was a result of lower mileage, labor for troubleshooting issues, and replacement of several low-voltage batteries. The high cost in October 2018 was due to a high-cost part (air compressor controller) that was not covered under warranty.

Figure 2-13

Monthly Scheduled and Unscheduled Maintenance Cost per Mile



Work Order Maintenance Costs Categorized by System

Table 2-7 shows maintenance costs per mile by vehicle system and bus fleet (without warranty costs). The color shading denotes the systems with the highest percentage of maintenance costs: orange for the highest, green for the second highest, and purple for the third highest. The vehicle systems shown in the table include the following:

- Cab, body, and accessories – includes body, glass, cab and sheet metal, seats and doors, and accessory repairs such as hubodometers and radios
- Propulsion-related systems – repairs for exhaust, fuel, engine, electric motors, battery modules, propulsion control, non-lighting electrical (charging, cranking and ignition), air intake, cooling, and transmission
- PMI – labor for inspections during preventive maintenance
- Brakes – includes brake pads, disks, calipers, anti-lock braking system, and brake chambers
- Frame, steering, and suspension
- HVAC
- Lighting
- Air system (general)
- Axles, wheels, and drive shaft
- Tires

Table 2-7

Work Order Maintenance Cost per Mile by System[a]

System	FCEB Cost per Mile ($)	FCEB Percent of Total (%)	CNG Cost per Mile ($)	CNG Percent of Total (%)
Propulsion-related	0.154	46	0.116	35
Cab, body, and accessories	0.058	17	0.048	15
PMI	0.075	22	0.059	18
Brakes	0.001	0	0.023	7
Frame, steering, and suspension	0.015	5	0.011	3
HVAC	0.016	5	0.045	14
Lighting	0.002	1	0.006	2
General air system repairs	0.002	1	0.004	1
Axles, wheels, and drive shaft	0.005	1	0.012	4
Tires	0.005	1	0.004	1
Total	0.333	100	0.329	100

[a] *Top three categories for maintenance for each fleet are color coded as follows: orange – highest, green – second highest, and purple – third highest.*

The systems with the highest percentage of maintenance costs for the FCEBs and CNG buses were the same: (1) propulsion-related, (2) PMI, and (3) cab, body, and accessories. Figure 2-14 shows the monthly cost per mile by system for the FCEBs, and Figure 2-15 shows the monthly cost per mile by system for the CNG fleet.

Figure 2-14

Monthly Maintenance Cost per Mile by System for FCEBs

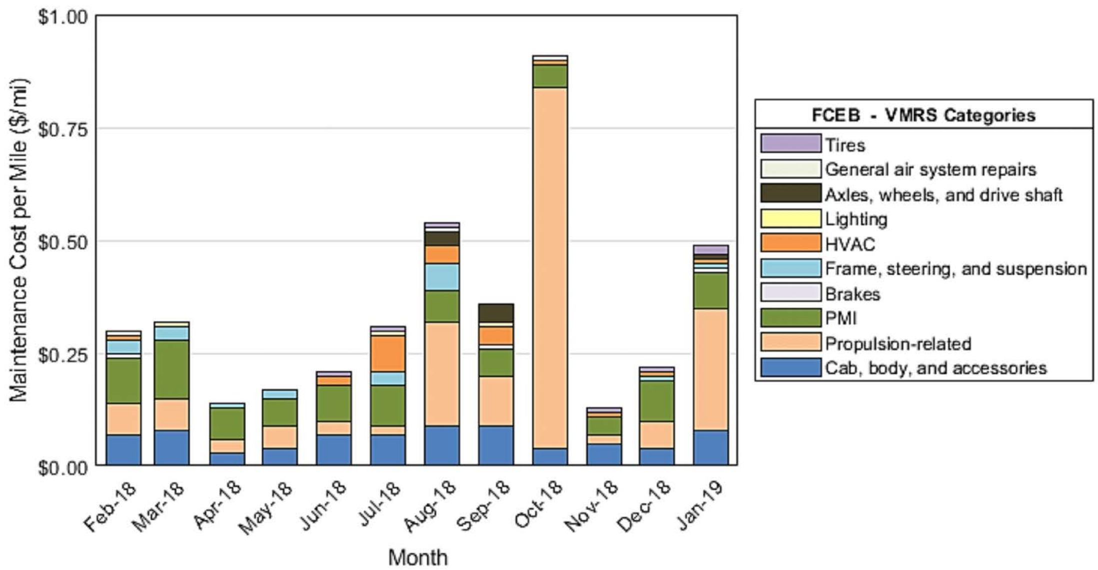
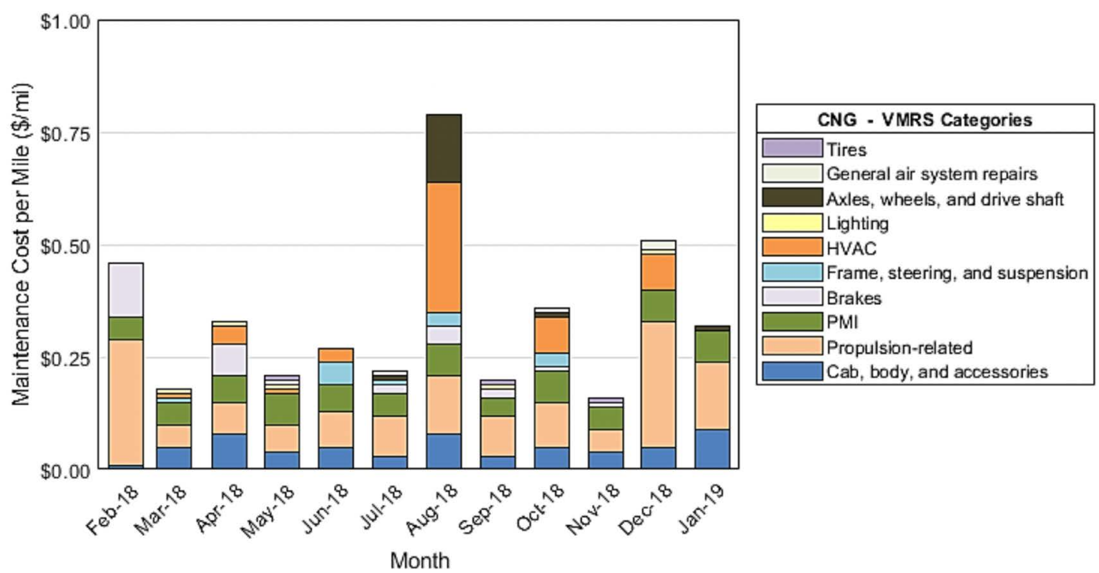


Figure 2-15

Monthly Maintenance Cost per Mile by System for CNG Buses



Propulsion-Related Work Order Maintenance Costs

Propulsion-related vehicle systems include the exhaust, fuel, engine, fuel cell system, battery modules, electric propulsion, air intake, cooling, non-lighting electrical, transmission, and hydraulic systems. These vehicle subsystems have been separated to highlight how maintenance costs for the propulsion system are affected by the change from conventional technology (CNG) to advanced technology (FCEB). Table 2-8 shows the propulsion-related system maintenance costs by category for the two fleets during the data period. Figure 2-16 shows the monthly propulsion-system-only costs for the FCEBs, and Figure 2-17 provides the same for the CNG buses. Parts for scheduled maintenance, such as filters and fluids, are included in the specific system categories. For example, oil and oil filters are included in the power plant (engine) subsystem parts costs, and air filters are included in the air intake subsystem parts costs.

- **Total propulsion-related** – total propulsion-related maintenance cost for the FCEBs was 32% higher than that of the CNG buses.
- **Exhaust system** – costs for the FCEBs and CNG buses were low or zero.
- **Fuel system** – costs for the CNG buses made up 15% of the total propulsions system costs; costs were low for the FCEBs.
- **Power plant and electric propulsion** – for the FCEBs, the costs for the electric propulsion system and fuel cell power plant accounted for 93% of the total propulsion system costs, primarily driven by one high-cost part for the fuel cell system (air compressor controller) that was not covered under warranty. Power plant repairs made up 23% of the total propulsion system costs for the CNG buses; there are no electric propulsion costs for the CNG buses.
- **Non-lighting electrical (charging, cranking, and ignition)** – costs made up only 5% of the propulsion system costs for the FCEBs and 35% of the total propulsion costs for the CNG buses.
- **Air intake** – costs were low for the FCEBs and CNG buses.
- **Cooling** – costs for this system were low for the FCEBs and made up 15% of the total cost of the CNG buses.
- **Transmission** – costs were low for the CNG buses; FCEBs do not have a transmission.
- **Hydraulic** – costs were low for the FCEBs and CNG buses.

Table 2-8

Propulsion-Related Work Order Maintenance Costs by System

Maintenance System	Maintenance Costs	FCEB	CNG
Mileage		130,798	230,144
Total Propulsion-Related Systems (Roll-up)	Parts cost ($)	10,873	18,931
	Labor hours	184.5	157.0
	Total cost ($)	20,098	26,781
	Total cost ($) per mile	***0.154***	***0.116***
Exhaust System Repairs	Parts cost ($)	0	354
	Labor hours	0.0	2.1
	Total cost ($)	0	459
	Total cost ($) per mile	***0.000***	***0.002***
Fuel System Repairs	Parts cost ($)	0	2,910
	Labor hours	3.5	20.6
	Total cost ($)	175	3,940
	Total cost ($) per mile	***0.001***	***0.017***

Maintenance System	Maintenance Costs	FCEB	CNG
Power Plant System Repairs	Parts cost ($)	10,070	4,871
	Labor hours	118.5	23.7
	Total cost ($)	15,995	6,056
	Total cost ($) per mile	***0.122***	***0.026***
Electric Propulsion System Repairs	Parts cost ($)	248	0
	Labor hours	45.5	0.0
	Total cost ($)	2,523	0
	Total cost ($) per mile	***0.019***	***0.000***
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)	Parts cost ($)	510	6,444
	Labor hours	14.0	59.6
	Total cost ($)	1,210	9,421
	Total cost ($) per mile	***0.009***	***0.041***
Air Intake System Repairs	Parts cost ($)	35	125
	Labor hours	0.0	2.0
	Total cost ($)	35	225
	Total cost ($) per mile	***0.000***	***0.001***
Cooling System Repairs	Parts cost ($)	0	2,453
	Labor hours	2.5	31.6
	Total cost ($)	125	4,033
	Total cost ($) per mile	***0.001***	***0.018***
Transmission System Repairs	Parts cost ($)	0	1,037
	Labor hours	0.0	16.7
	Total cost ($)	0	1,869
	Total cost ($) per mile	***0.000***	***0.008***
Hydraulic System Repairs	Parts cost ($)	10	737
	Labor hours	0.5	0.8
	Total cost ($)	35	777
	Total cost ($) per mile	***0.000***	***0.003***

Figure 2-16

Monthly Propulsion Maintenance Cost per Mile by Subsystem for FCEBs

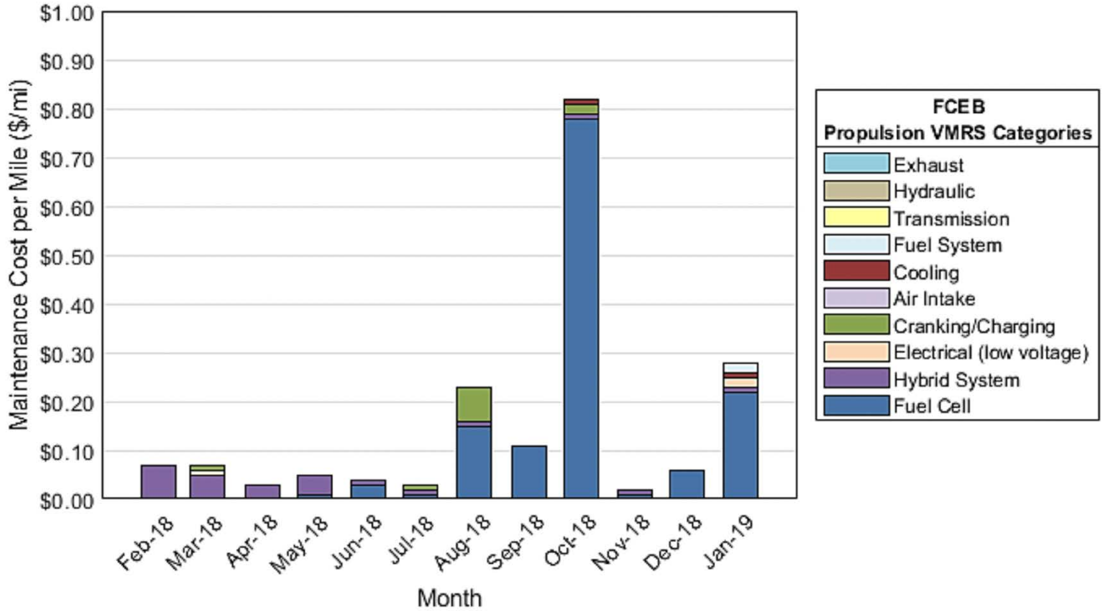
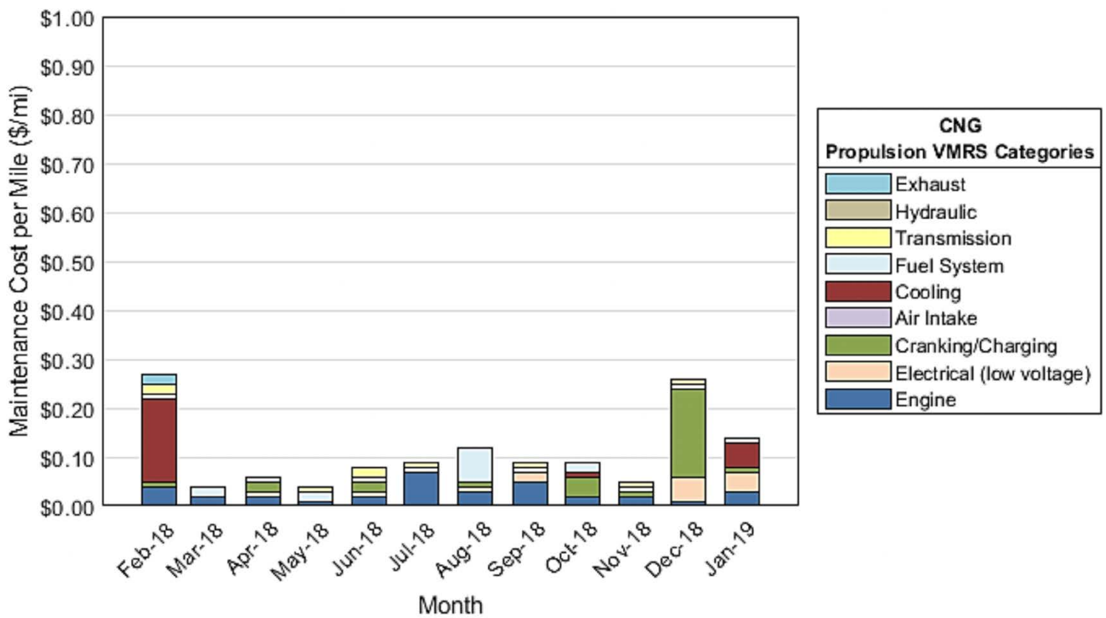


Figure 2-17

Monthly Propulsion Maintenance Cost per Mile by Subsystem for CNG Buses



Total Cost per Mile

The fuel costs per mile for the evaluation period were $1.06/mi for the FCEBs and $0.45/mi for the CNG buses. During the data period, SARTA's average cost of hydrogen was $5.27/kg. The agency paid an average cost of $1.89/gge for CNG. Totaling both fuel and maintenance costs, the cost per mile for the FCEBs was $1.39 and the cost per mile for the CNG buses was $0.78 for the data period. Table 2-9 is a summary of the costs per mile to operate the FCEB and CNG fleets over the data period.

Table 2-9

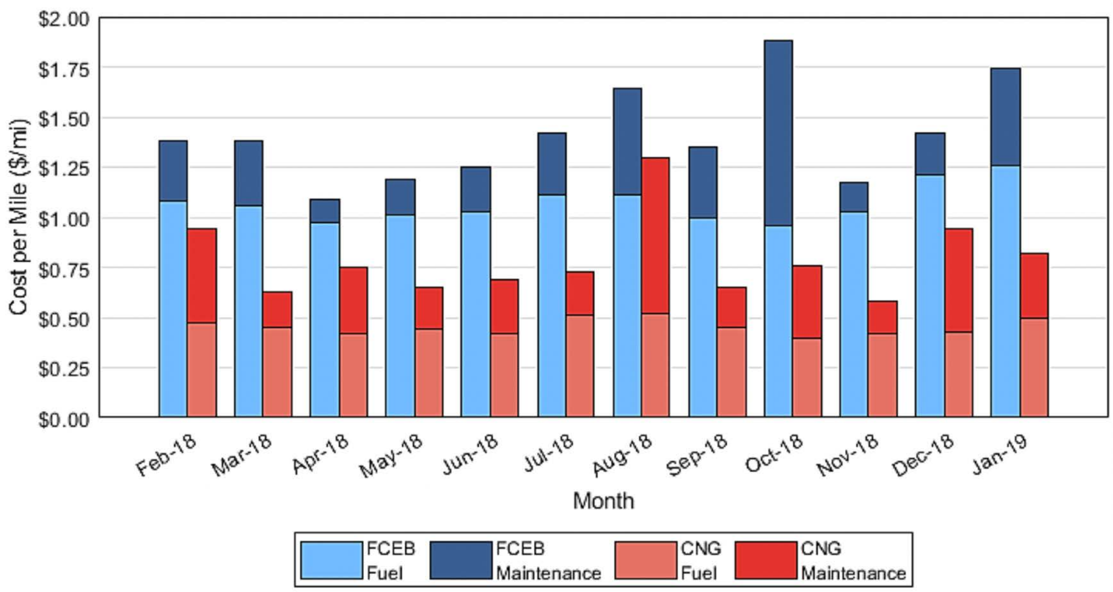
Total Cost Per Mile

Cost Source	FCEB Cost per Mile ($)	FCEB Percent of Total (%)	CNG Cost per Mile ($)	CNG Percent of Total (%)
Maintenance	0.333	24	0.329	42
Fuel	1.06	76	0.45	58
Total	***1.39***	*100*	***0.78***	*100*

The total monthly cost per mile, as seen in Figure 2-18, combines the maintenance and fuel costs per mile for each month over the data period.

Figure 2-18

Total Monthly Costs for FCEBs and CNG Buses



Summary of Achievements and Challenges

As with all new technology development, lessons learned during this project could aid other agencies considering FCEB technology. SARTA reports that it has had a positive experience with the technology and that its manufacturer partners have provided excellent support for the buses. The agency's maintenance technicians have embraced the technology, and customers have provided positive feedback on the FCEBs. The team reports a number of successes that include the following:

- Implemented the agency's first FCEBs
- Accumulated more than 152,000 miles on the FCEBs since first placed in service
- Installed a hydrogen station that has proven to be reliable, with no loss of service due to station downtime
- Introduced FCEB technology to maintenance and operations staff

- Teamed with Ohio State University to form the Renewable Hydrogen Fuel Cell Collaborative and Midwest Hydrogen Center of Excellence and develop a hydrogen roadmap for the Midwest region of the U.S.
- Initiated a "Borrow-a-Bus" program to allow interested transit agencies to try the technology risk-free

Summary of Challenges

Advanced-technology demonstrations typically experience challenges and issues that need to be resolved. Issues and lessons learned for SARTA include the following:

- **Maintenance manpower** – At the onset of the program, SARTA trained two maintenance technicians to support the buses, senior-level technicians who had a strong interest in learning the new technology. These technicians handle preventive maintenance, general bus repairs, and troubleshooting and repair of propulsion system issues with help from the manufacturer partners. SARTA's manufacturer partners are available for troubleshooting issues over the phone and travel to the site for repairs as needed. Occasionally, both technicians were away from work at the same time, resulting in a delay for repair of an FCEB. SARTA has a third technician currently in training who will help with the manpower issue. As its FCEB fleet grows, the agency plans to train an additional technician each year.
- **Technology issues** – There were a few issues with the fuel cell and hybrid drive systems during the data period. The fuel cell issues were not related to the stack itself but rather to the peripheral components that supply hydrogen and air; those included a failed hydrogen recirculation blower and an air compressor controller. Hybrid system issues included a problem with a low-voltage connector in the electronics that was not properly seated. Because the problem was intermittent, it took some time to diagnose; once the connector was reseated, the system worked reliably and consistently.
- **Air filter quality** – SARTA replaced an air filter with one from a manufacturer that was different from the OEM-specified part for the FCEB. The new filter was listed as a substitute for the original part. Although the non-OEM filter fit, the quality was not the same—the filter allowed water to enter the vent air filter housing, which corroded the wiring for the vent fan, causing premature failure of the fan.
- **HVAC** – SARTA experienced some issues with the electrically-driven air conditioning on the buses due to failing evaporative and condenser motors. The local technician for the component supplier was not familiar with the model, which added to the time to troubleshoot the issue. The failed part had quality issues in the manufacturing process. The component supplier has addressed the issue. The buses also had early issues with interior heating during extreme cold days. SARTA reports that the heat would be insufficient

on days when the temperature fell below -15 degrees Fahrenheit. The agency elected to keep the buses out of service on the coldest days. The manufacturer addressed this issue by widening the setpoint limits for heating and insulating the components of the HVAC system that were outside the cabin area. These changes have resulted in better heating inside the bus without affecting the bus efficiency.

- **Downtime for non-technology-related issues** – During the data period, there were two incidents during which a bus was out of service for an extended period that was not due to an issue with the technology. In one case, the internal process for SARTA to issue a part order took longer than expected. In the second case, the delay was due to a part request that was not received by the supplier. These were extenuating circumstances that are not expected to reoccur. During this downtime, the buses were considered as not planned for service.

SECTION 3

User Acceptance Results

This section details the results of surveys that CALSTART administered to SARTA drivers and maintenance technicians in September 2017 and May 2018 to assess their perceptions of the fuel cell buses. Overall, this study provides insights into their impressions on measures of bus performance, operation, and maintenance. Through these surveys, CALSTART identified key takeaways regarding what these stakeholders thought were the best and worst qualities of the fuel cell buses. Although they do not represent all feedback collected from this study, the most cited positive responses were as follows:

- **Overall rating** – Drivers and technicians rated the buses as good overall, and their opinions improved on most metrics over time, indicating that more experience with the buses led to better perception of them.
- **Performance comparison with conventional bus** – Both drivers and technicians rated the fuel cell buses either the same as or better than conventional buses on initial launch, acceleration, coasting/deceleration, and braking behavior.
- **Low noise levels** – Results from both groups indicate that of all metrics the buses performed best in terms of low inside and outside noise levels.

The survey respondents also offered negative feedback and suggestions for improving the fuel cell buses:

- **Worse productivity** – Overall, the respondents expressed that the productivity of the fuel cell buses was worse than that of the conventional buses, indicating that the fuel cell buses were pulled out for servicing more.
- **Commonly reported issues** – Respondents cited that the bus was often unable to reach highways speeds and had multiple component failures that had to be addressed.
- **HVAC and energy consumption** – Respondents stated that running heating and cooling systems in the fuel cell buses limited the range of the bus due to the energy needed to run those systems.

The remainder of this section elaborates further on these results and provides other impressions shared by bus drivers and maintenance technicians.

User Acceptance Data

The purpose of the user acceptance evaluation was to assess impressions of the fuel cell bus from both bus drivers and maintenance technicians. Comparisons were made between the fuel cell bus and a baseline bus with conventional gasoline or natural gas fuel to determine the advantages and disadvantages during everyday use. Driver surveys assessed the performance and operation of the fuel cell bus, as well as customer feedback and complaints. Maintenance technician surveys also assessed performance and operation measures of the bus and measures of bus maintainability and serviceability.

Methodology

Survey Administration and Data Gathered

To obtain insights into user acceptance of the fuel cell bus, CALSTART distributed written surveys to drivers and maintenance technicians at SARTA. Table 3-1 outlines the survey distribution and responses. Both the drivers and the maintenance technicians were surveyed twice, once in September 2017 and again in May 2018. In September 2017, CALSTART received responses from six drivers and five maintenance technicians; in May 2018, it received responses from five drivers and five maintenance technicians. The responses from technicians came from the same five people in 2018 as in 2017; likewise, the five driver responses in 2018 came from drivers who also responded in 2017, with one driver who responded in 2017 not responding in 2018. As the survey questions remained largely the same in 2017 and 2018, these responses provide before-and-after impressions from respondents who worked with the fuel cell bus for nearly one year.

In the survey, the drivers were asked to describe their route, provide an overall rating for and comments on training to use the fuel cell bus, compare various measures of bus performance to a conventional bus, compare various measures of bus operation to a conventional bus, share customer complaints, share issues with the bus as it operated at low speeds, share issues related to regenerative braking, provide an overall rating for the fuel cell bus in general, and provide comments and suggestions for improving the bus. In 2018, drivers were also asked to describe how their opinions changed after driving the bus. The maintenance technicians were also asked to compare various measures of bus performance and operation to a conventional bus, describe any problems with the fuel cell bus at early stages of development that were corrected by the manufacturer, rate various measures of bus maintenance, provide an overall rating for the bus, and provide any comments and suggestions for improving the bus. Like the drivers, technicians were asked to describe how their opinions changed after spending time working on the bus.

Table 3-1

Survey Distribution and Response Breakdown

Role of Person Surveyed	No. of Responses Collected
First Round of Surveys – September 2017	
Driver	6
Maintenance Technician	5
Second Round of Surveys – May 2018	
Driver	5
Maintenance Technician	5

Data Analysis

Both drivers and maintenance technicians were asked questions with two forms of response: Likert scale response and short answer response. To analyze questions with Likert scale responses, the investigator counted the frequency of each response per question, and the frequency of each response was graphed using a bar chart. To analyze questions with short answer responses, the investigator used a method called thematic coding, in which the investigator read all responses for each question, focusing on one question at a time. After reading all responses for one question, the investigator developed short phrases (codes) based on common themes recurring in the responses. For example, a common theme in responses to a question posed to maintenance technicians regarding operational problems with the fuel cell bus was ongoing component issues, so a code entitled "Component issues" was created. After codes were created for a given question, the investigator read responses to the questions and assigned codes to each where appropriate. All codes were then counted for frequency and graphed using a bar chart. This process was repeated for every question with a short answer response individually.

Results

Drivers

Drivers were asked to rank the fuel cell buses in terms of performance and operation and to provide comments on driver training, how the bus performed at low speeds, issues related to regenerative braking, and comments on the fuel cell bus in general. Drivers were asked to rate training on a scale from "Very poor" to "Excellent"; Figure 3-1 takes that scale and quantifies it from 1 to 5, respectively, showing the average rating across all drivers in 2017 and 2018. In 2017, most drivers rated their training "Good" or "Very good," for an average of 3.7. In 2018, however, perceptions of training worsened after time had passed and the drivers had gained more experience with the buses. When asked to comment on training, drivers were split in their responses, with half saying it was "Completely sufficient" and half stating that they would have liked "More time" to complete training, as shown in Figure 3-2.

Figure 3-1

Overall Rating for Driver Training

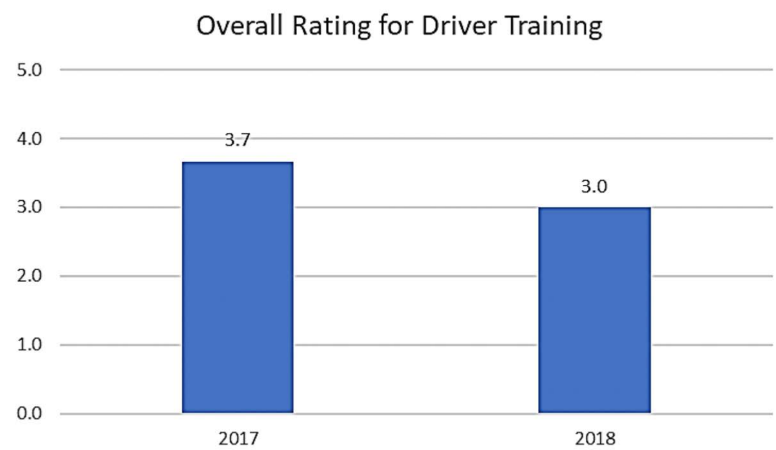
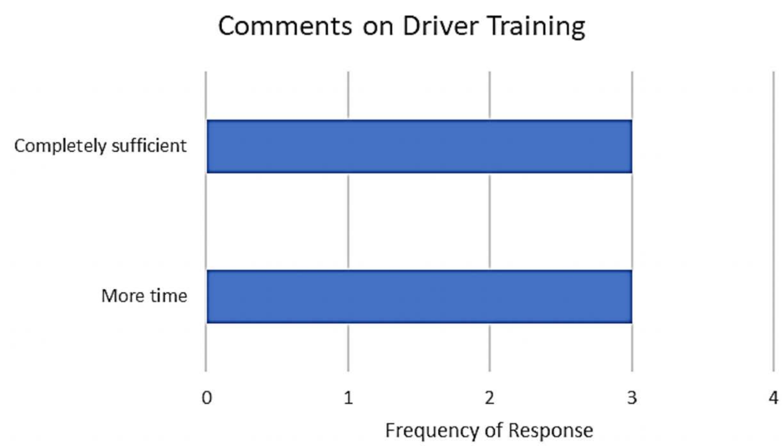


Figure 3-2

Comments on Driver Training



There were six performance metrics on which drivers compared the fuel cell bus to the conventional bus on a scale from "Much worse" to "Much better":

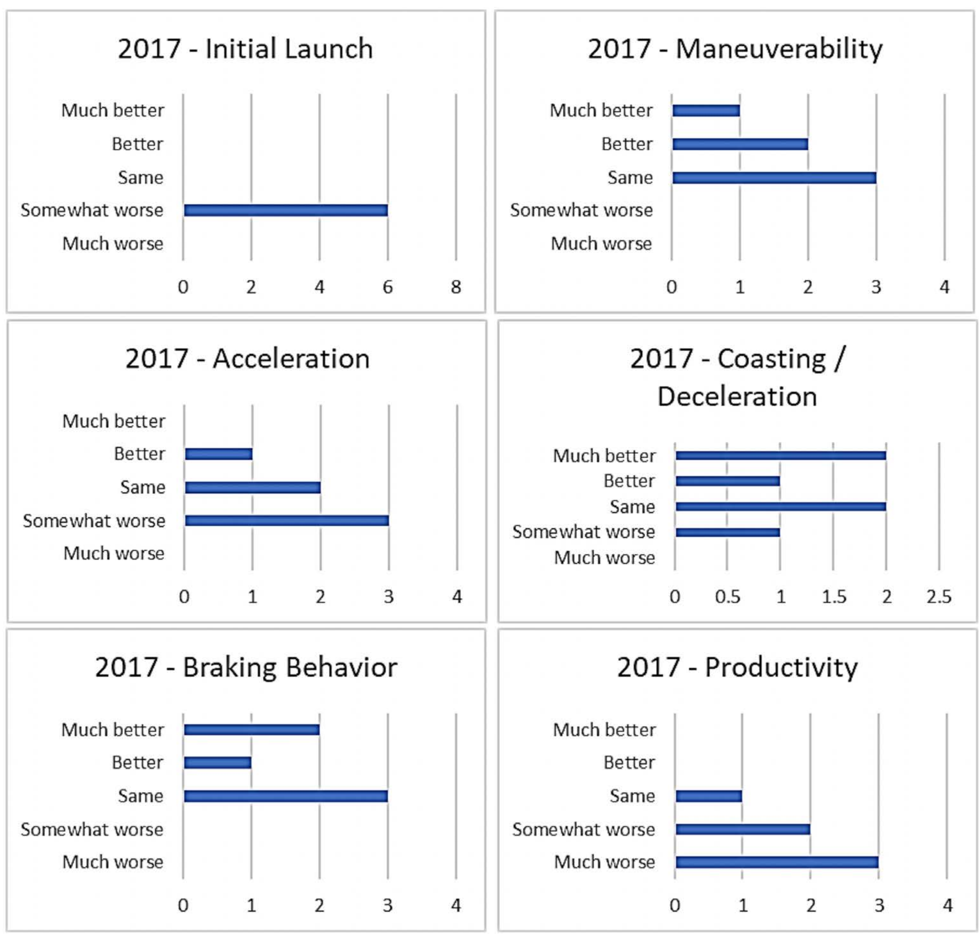
- **Initial launch from standstill** – Conventional buses are typically most inefficient when launching from standstill. Fuel cell buses have an advantage due to the torque provided during startup. This metric captures driver perceptions of the quality of launch with the fuel cell drive system.
- **Maneuverability at slow speeds** – This metric measures how well the fuel cell bus maneuvered at slow speeds since it travels through neighborhoods on route.
- **Acceleration** – This metric gauges driver perceptions of how well the fuel cell bus accelerates in general, similar to initial launch from standstill.
- **Coasting/deceleration** – The drive system uses regenerative braking to convert the vehicle's kinetic energy into stored energy in the battery. This metric seeks to measure driver perceptions on the feel of this different form of coasting.

- **Overall braking behavior** – This metric seeks to capture driver perceptions on braking behavior overall, including its feel and effectiveness.
- **Productivity** – This metric seeks to capture driver perceptions on how the different requirements coming with the fuel cell powertrain (e.g., different fueling system than conventional, regenerative braking) affected the drivers' abilities to cover their routes productively.

For performance, drivers had mixed responses when surveyed in 2017 (see Figure 3-3). In that year, all drivers stated that initial launch of the fuel cell bus was somewhat worse than for a conventional bus. A majority of respondents stated that maneuverability was the same as or better than that of the conventional bus, with no one stating that it was worse. Most said that acceleration was somewhat worse, followed closely by those stating that it was the same, and one saying that it was better. The ratings for coasting and deceleration were mixed, with every answer choice represented except "Much worse." Most drivers said that braking behavior was the same, with some stating that it was better than that of the conventional bus. Finally, most drivers were dissatisfied with productivity, stating that it was worse than with the conventional bus.

Figure 3-3

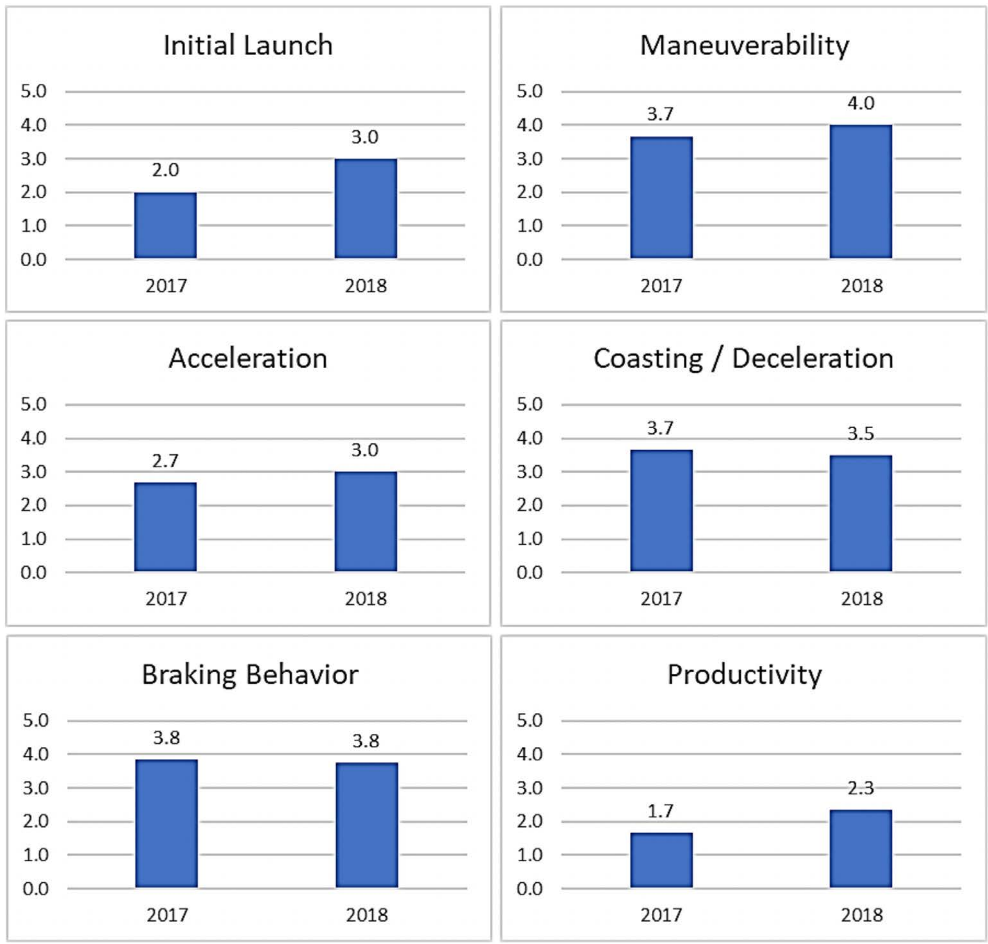
2017 Driver Performance Ratings



Drivers were surveyed again in 2018. To see how impressions of bus performance changed over time, Figure 3-4 shows the average rating that the drivers gave each metric in 2017 and 2018. In this figure, the rating scale of "Much worse" to "Much better" is quantified from 1 to 5, respectively. Ratings for initial launch at startup, maneuverability, acceleration, and productivity all improved during that time. Ratings for coasting and deceleration decreased slightly, and impressions of braking behavior stayed the same.

Figure 3-4

Average Driver Performance Ratings in 2017 and 2018



In terms of vehicle operation, drivers were asked to compare the following metrics on the fuel cell bus to conventional buses:

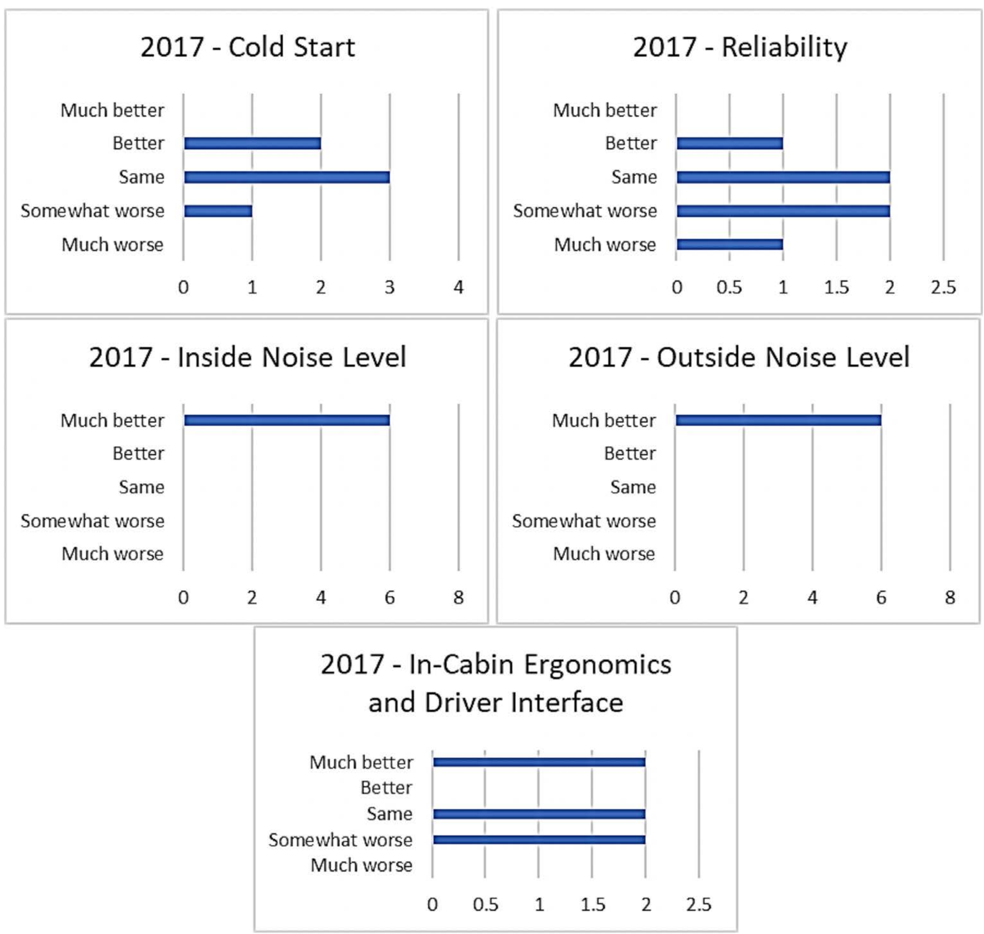
- **Cold start** – as the buses were demonstrated in Ohio, cold weather conditions may have an impact on their performance; this assesses driver perceptions of how easily the fuel cell buses started in cold weather.
- **Reliability** – measures how frequently the fuel cell buses required servicing, thus making them unavailable for operation; also covers other general comments on bus reliability, such as reliability of the buses in cold and hot weather.

- **Inside noise level** – captures driver perceptions of the noise level inside the bus, which can vary significantly from conventional buses.
- **Outside noise level** – captures driver perceptions of the noise level outside the bus; if it is loud, may indicate poor integration of the drive components with other vehicle systems.
- **In-cabin ergonomics and driver interface** – captures driver perceptions of the ergonomics and interface within the driver cab space.

When surveyed in 2017, drivers indicated that cold start was mostly the same as or better than that of the conventional bus, with one respondent stating that it was "Somewhat worse." Driver ratings for reliability were mixed, with most stating that it was "Same "or "Somewhat worse," and all answer options were represented except "Much better." Both inside and outside noise levels scored very well, with all drivers stating that noise levels were "Much better" in the fuel cell bus. Finally, ratings for in-cabin ergonomics and the driver interface were mixed, with all responses evenly spread among somewhat "Worse," "Same," and "Much better."

Figure 3-5

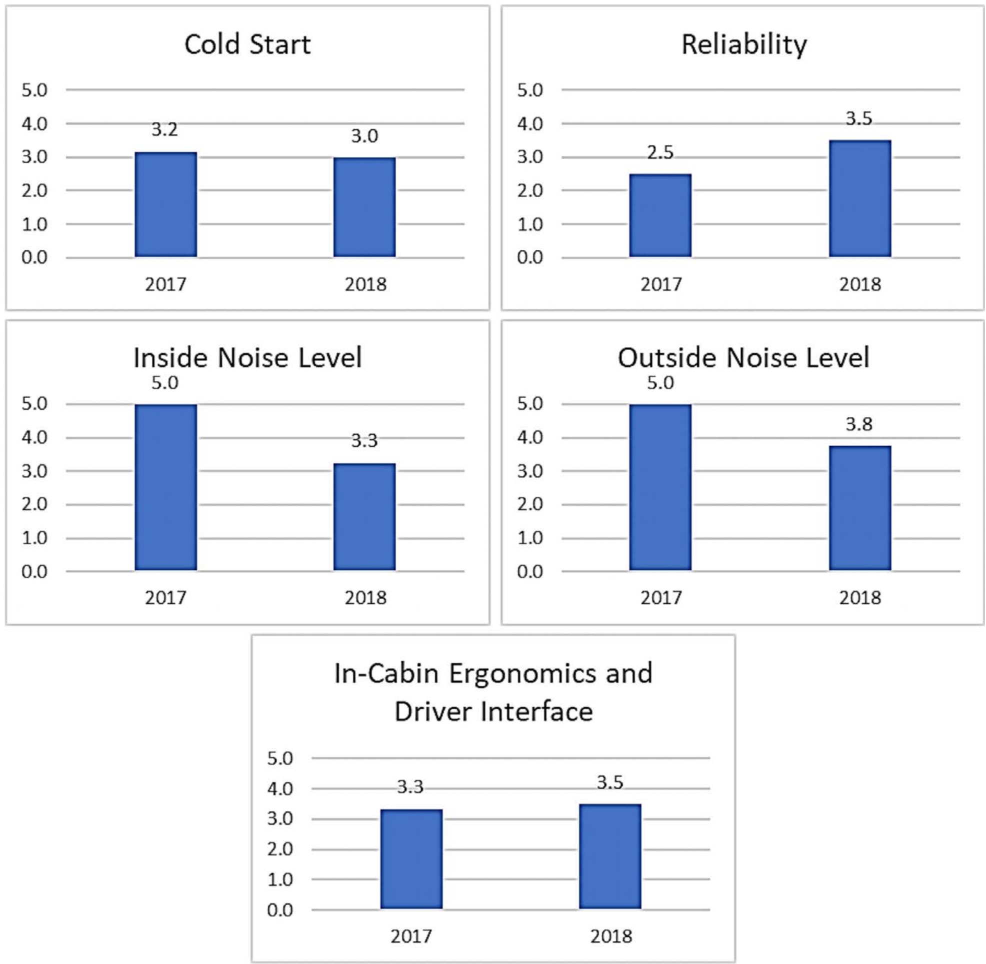
2017 Driver Operational Ratings



Using the same quantified scale as in Figure 3-4, Figure 3-6 shows the average ratings for each operational metric in 2017 and 2018. Impressions of fuel cell bus reliability and in-cabin ergonomics and driver interface both improved in 2018. Driver impressions of cold start, inside noise level, and outside noise level all worsened during that time period.

Figure 3-6

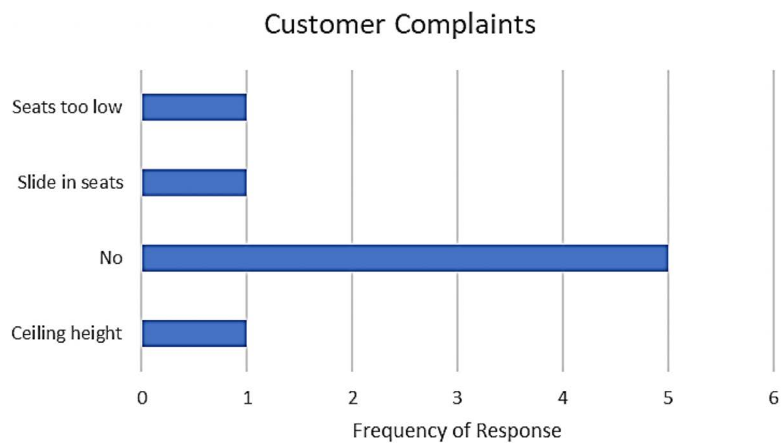
Average Driver Operational Ratings in 2017 and 2018



When the drivers were asked to inform CALSTART of any customer complaints they collected about the fuel cell bus, most stated that they did not hear any. However, they did share three complaints (Figure 3-7). One complaint regarded the ceiling height above the last seat in the bus; the driver did not elaborate on whether the ceiling was believed to be too high or too low, but it is likely that the complaint meant it was too low. Two other drivers shared complaints about the seats; one stated that customers found them uncomfortable due to sliding while the bus was driving, and another shared a comment that the seats were low enough to require a passenger to stand to pull the stop request.

Figure 3-7

Driver-Reported Customer Complaints



In 2017, drivers reported no issues with the fuel cell bus at low speeds; however, in 2018, two drivers each shared an issue—one stated that the bus accelerates very slowly on startup, and the other expressed that the kneeler raises and lowers very slowly, a common complaint that is seen in other responses to this survey (Figure 3-8). Additionally, as seen in Figure 3-9, no drivers expressed any issues or concerns with regenerative braking on the fuel cell bus.

Figure 3-8

Driver-Reported Issues at Low Speed

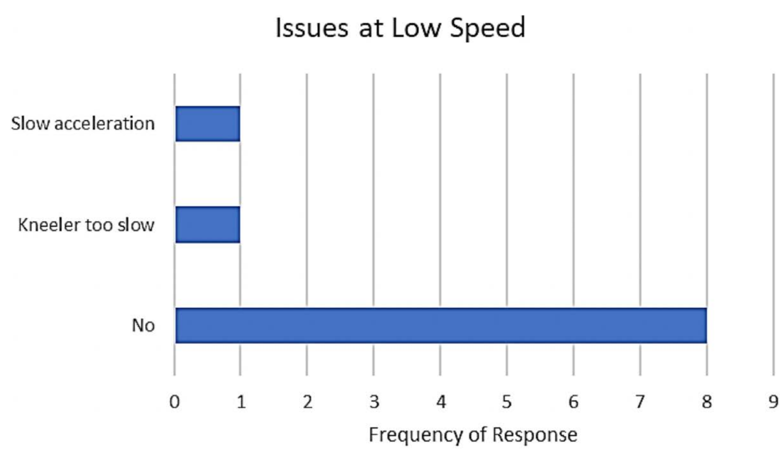
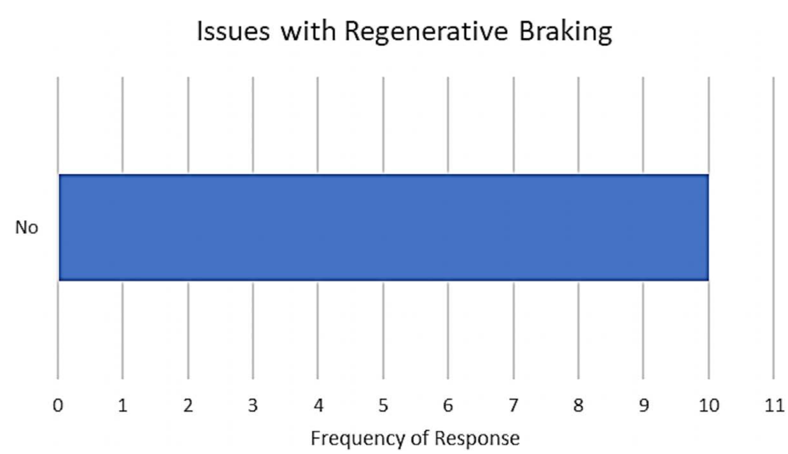


Figure 3-9

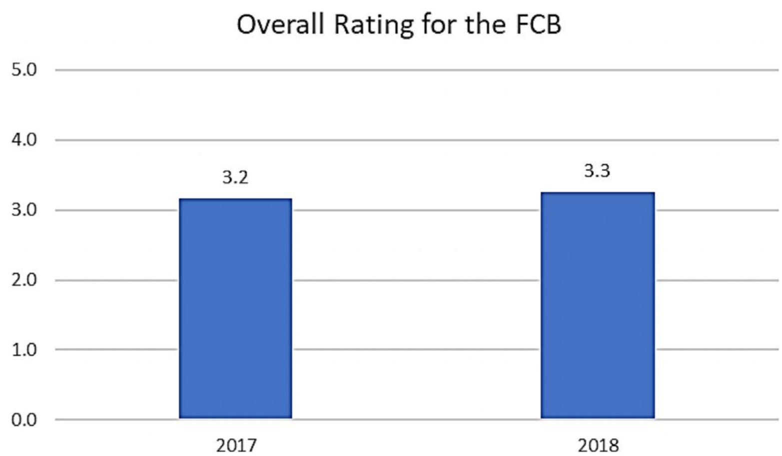
Driver-Reported Issues with Regenerative Braking



On average, the drivers rated the fuel cell bus as "Good." In 2017, all drivers rated the bus either "Good" or "Very good." In 2018, most drivers rated the bus either "Good," "Very good," or "Excellent," with only one driver rating the bus "Very poor" (Figure 3-10).

Figure 3-10

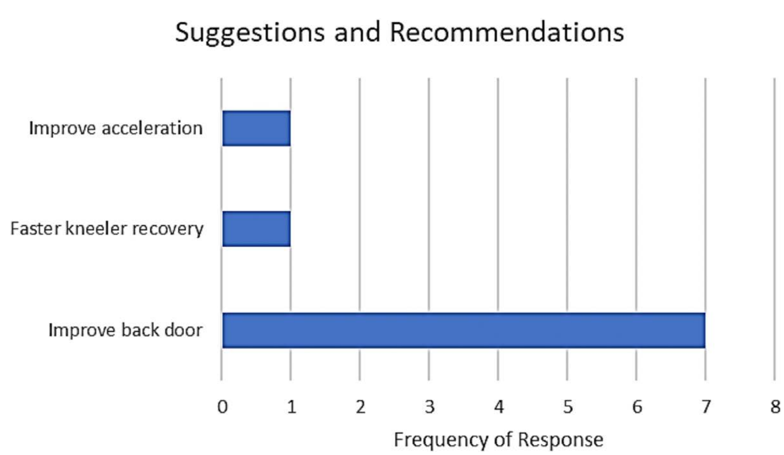
Average Overall Rating for the Fuel Cell Bus by Drivers



Drivers shared comments and suggestions for improving the fuel cell bus, as shown in Figure 3-11. The most common suggestion was to improve the functionality of the back door. According to drivers, the back door opens and closes very slowly and sometimes opens while the bus is in route and must be shut manually; other times, it opens when passengers lean or push on it. Also, one driver echoed sentiments about the speed of the kneeler, as noted previously. Another stated that the stop request gets stuck occasionally. One driver mentioned that the number of steps in the rear of the bus created a tripping hazard for passengers. One stated that the mileage of the bus was too low, requiring refueling too often. Another expressed concern for the bus's ability to reach highway speeds and to accelerate quickly.

Figure 3-11

Suggestions and Recommendations by Drivers



In 2018, drivers were asked if their opinions of the fuel cell bus changed as they spent more time driving it and to explain why. As can be seen in Figure 3-12, the responses were evenly split between "Yes" and "No," with only one driver elaborating, saying his/her opinion did change on the bus and highlighting a problem with the heating and air conditioning for the customer cabin, stating that it was ineffective.

Figure 3-12

Driver Opinion Change Over Time

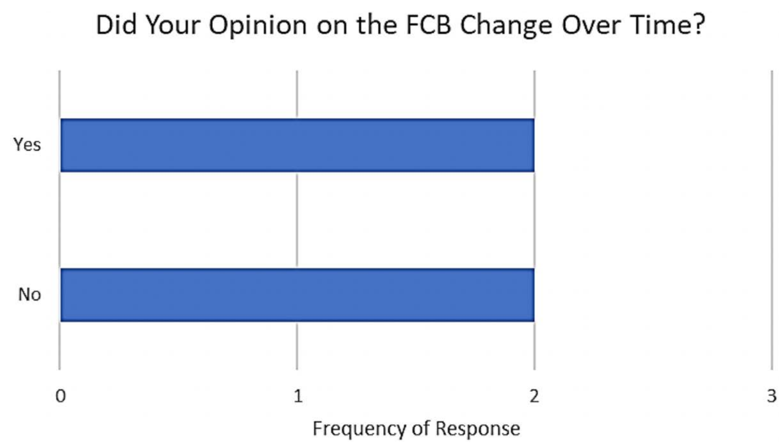
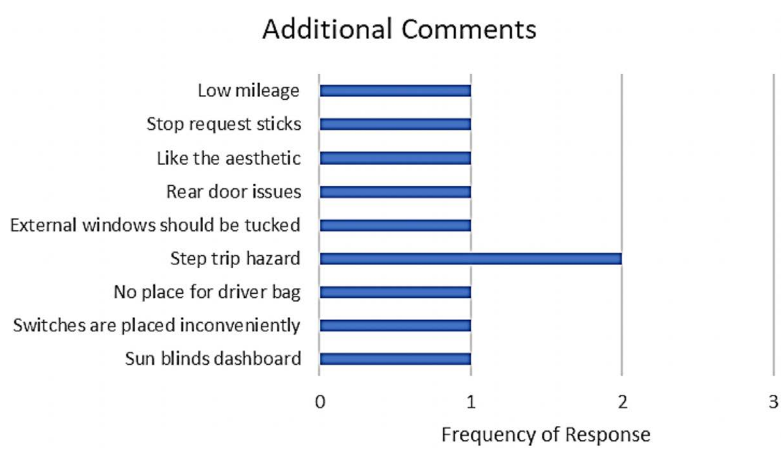


Figure 3-13 shows extra comments drivers shared in the survey. One driver expressed concerns about the sun blinding out the driver's dashboard, noted that switches are placed too far back on the left side of the driver's cabin, stated that no secure compartment for the driver's bag exists, was concerned (echoing that from another driver) about steps creating a tripping hazard in the rear of the bus, and provided a suggestion to tuck in the external windows to prevent an accident with the bus. A second driver shared the same concerns about the rear doors.

Figure 3-13

Additional Comments from Drivers

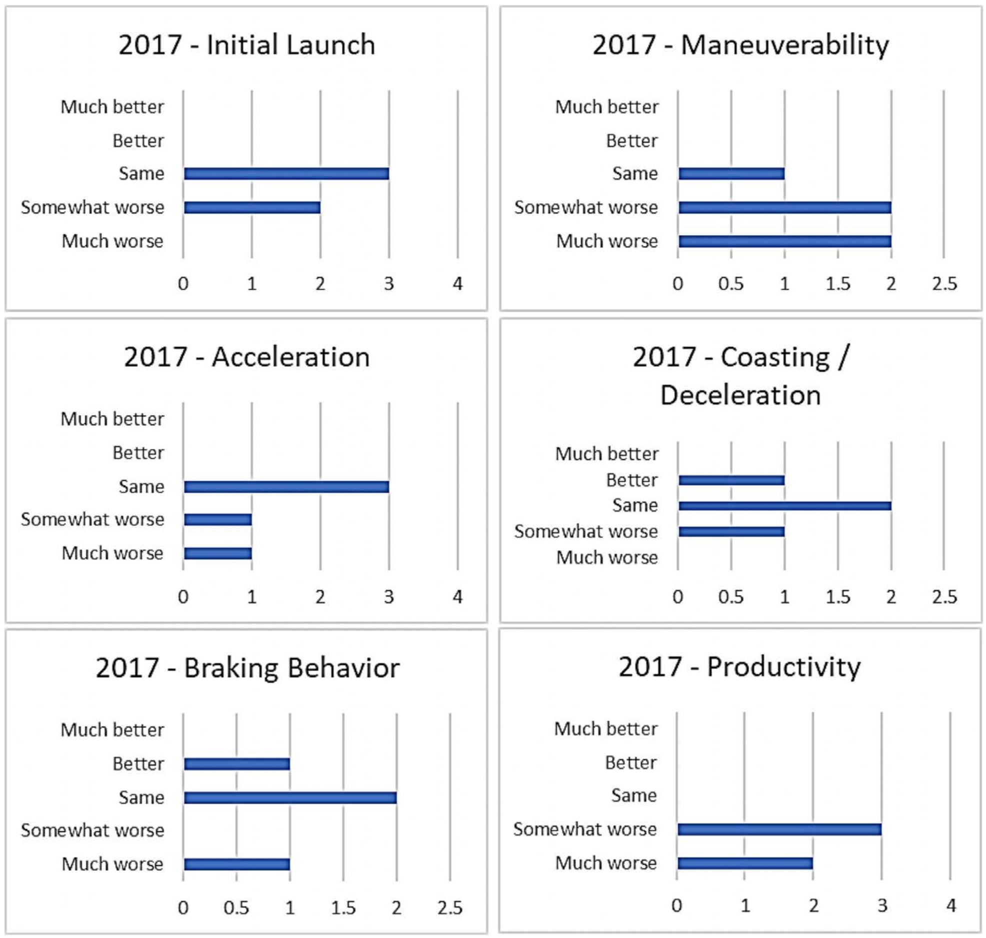


Technicians

Like the drivers, maintenance technicians were asked to rank the fuel cell bus on the same measures of performance and operation. Results of these surveys are provided in Figure 3-14. When surveyed in 2017, technicians rated initial launch of the fuel cell bus as either the "Same" as or "Somewhat worse" than that of a conventional bus. Most of them stated that maneuverability was either "Much worse" or "Somewhat worse" than that of a conventional bus. For acceleration, coasting and deceleration, and braking behavior, most stated that fuel cell buses performed the "Same" as a conventional bus. For productivity, all technicians stated that the fuel cell bus performed either "Much worse" or "Somewhat worse."

Figure 3-14

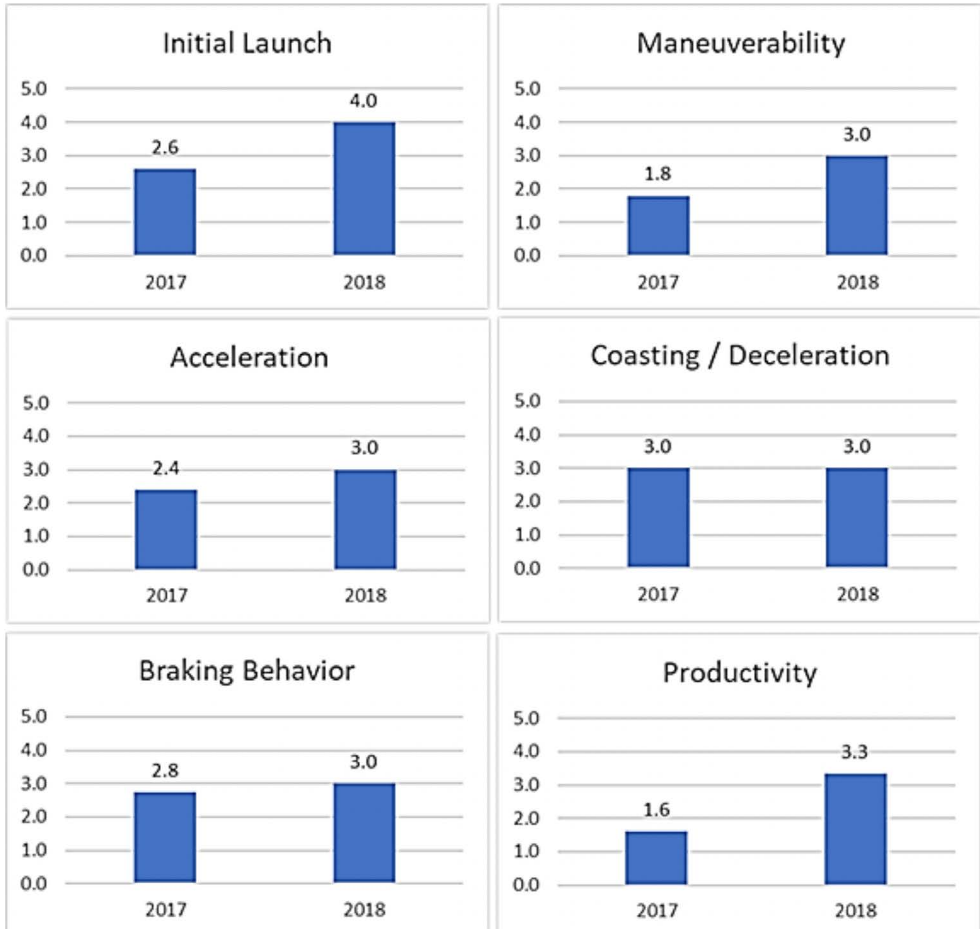
2017 Technician Performance Ratings



As was done for driver responses, the rating scale was quantified from 1 to 5, and the average rating for each metric in both years was recorded (Figure 3-15). Average ratings for all metrics except coasting/deceleration improved in 2018. Technician impressions of initial launch from startup improved significantly, from 2.6 to 4, maneuverability increased from 1.8 to 3, and productivity increased from 1.6 to 3.3. Acceleration and braking behavior improved moderately, from 2.4 to 3.0 and 2.8 to 3.0, respectively.

Figure 3-15

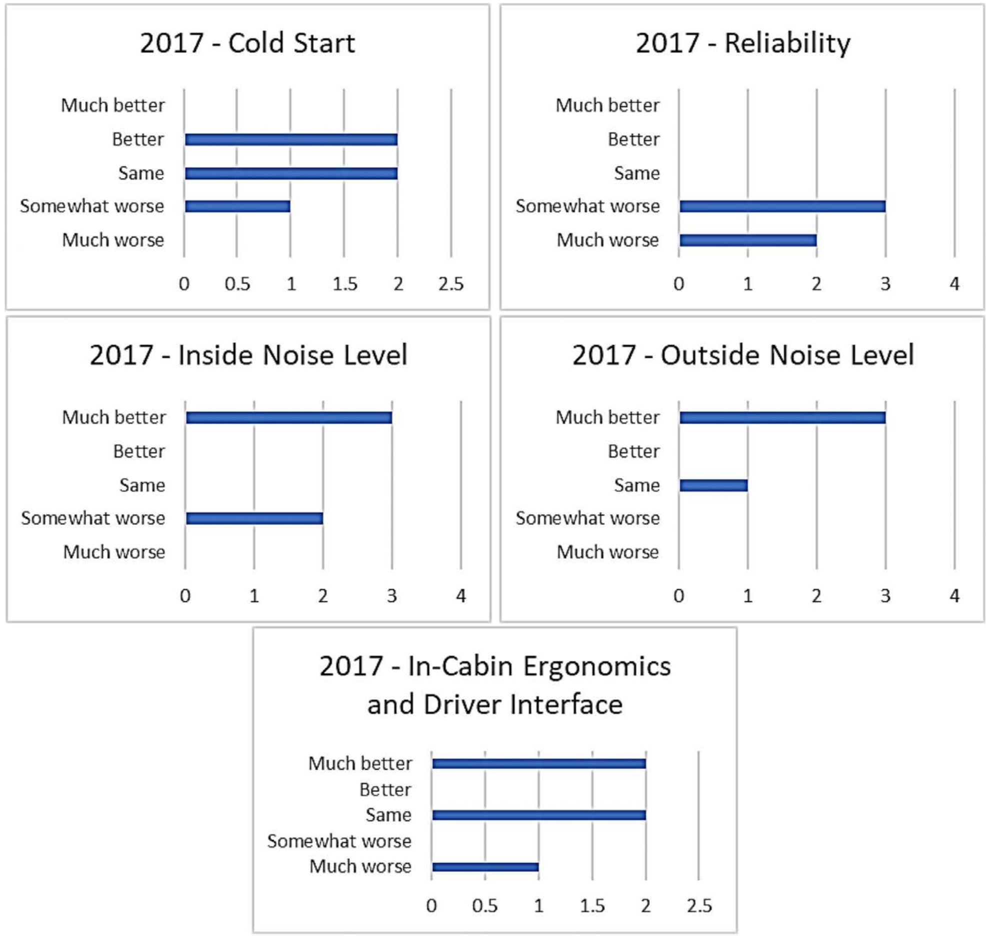
Average Technician Performance Ratings in 2017 and 2018



For operational measures (Figure 3-16), technicians rated the fuel cell bus favorably for cold start in 2017, with a majority stating that it was the "Same" as or "Better" than a conventional bus. However, all technicians agreed that reliability was "Worse." A majority stated that both inside and outside noise levels were "Much better" than for conventional buses. Finally, most rated in-cabin ergonomics and driver interface either the "Same" or "Much better."

Figure 3-16

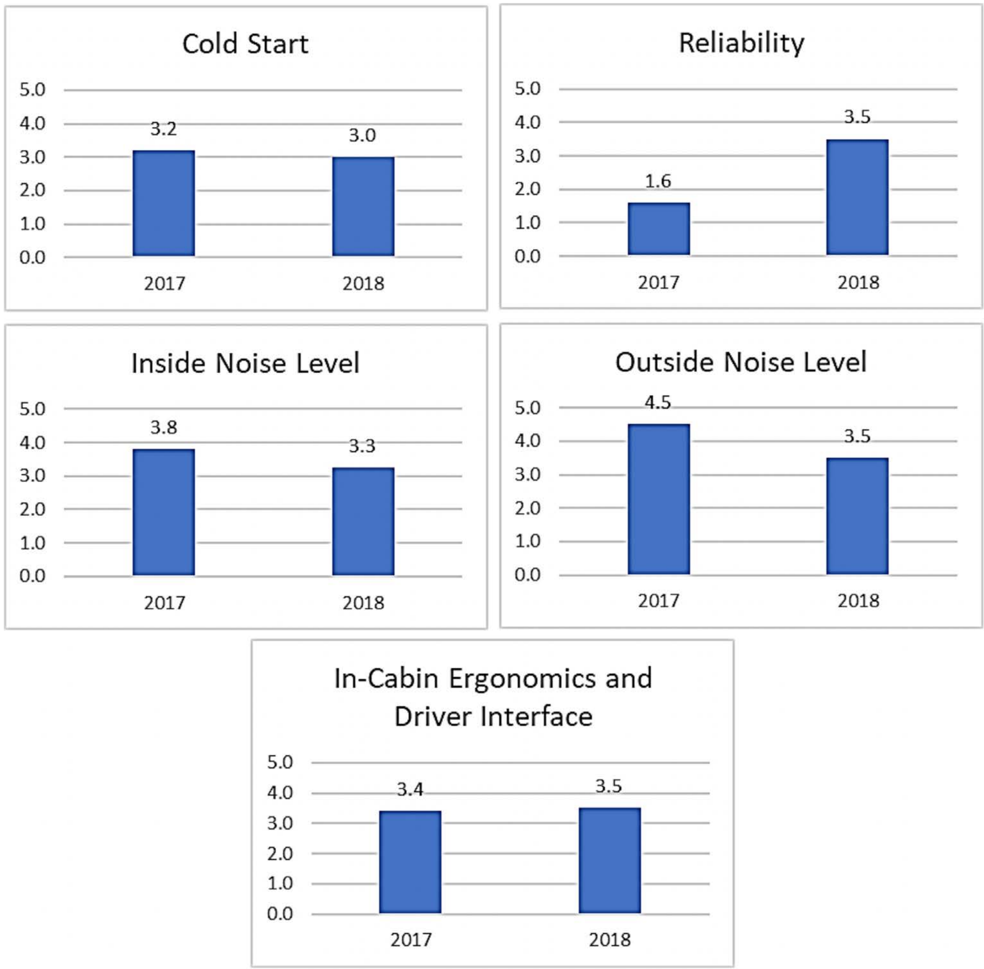
2017 Technician Operational Ratings



In 2018, average ratings changed on all measures at least slightly. Reliability and in-cabin ergonomics and driver interface both improved, and cold start, inside noise level, and outside noise level all worsened.

Figure 3-17

Average Technician Operational Ratings in 2017 and 2018



In addition to rating performance and operation, technicians were asked to rank the fuel cell bus on six metrics of maintenance and to provide any other comments on maintenance issues and general suggestions for improvement. The six maintenance metrics were ranked on a numeric scale from 1 (Unacceptable) to 5 (Excellent) and were as follows:

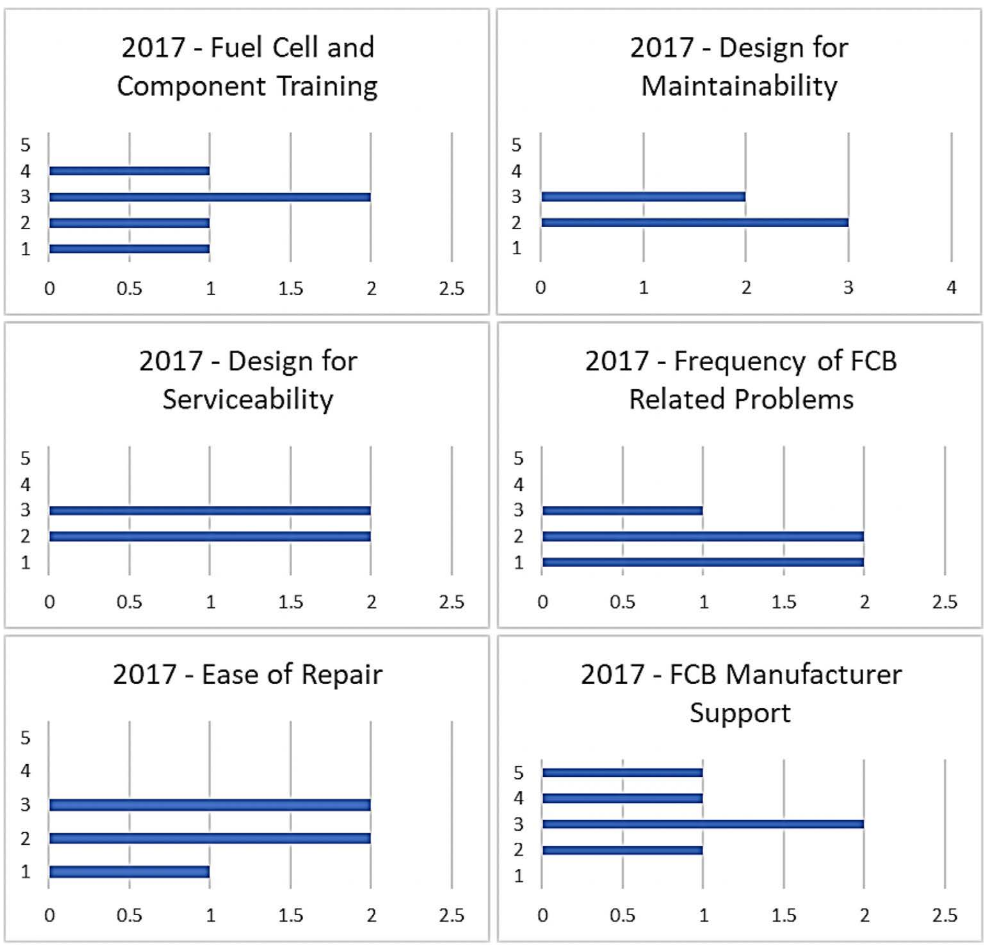
- **Fuel cell system and component training** – assesses maintenance staff perceptions on whether maintenance and service for fuel cell system and component training was adequate.
- **Design for maintainability** – assesses maintenance staff perceptions on how easily the bus can be maintained to minimize downtime and maximize availability.
- **Design for serviceability** – assesses maintenance staff perceptions on how easily the bus and its components can be serviced when maintenance is required.

- **Overall frequency of fuel cell bus-related problems** – assesses maintenance staff perceptions on how frequently the fuel cell bus must be removed from service for unplanned maintenance or roadcalls.
- **Ease of repair of fuel cell bus-related problems** – assesses maintenance staff perceptions of overall ease of repair for unplanned maintenance issues.
- **Fuel cell bus system manufacturer support** – assesses maintenance staff perceptions on how adequate the manufacturer's efforts to provide support were during the bus demonstration.

Figure 3-18 provides the technician's responses. In 2017, their ratings for fuel cell and component training were evenly split, from 1 to 4 out of 5. Most were displeased with both design for maintainability and design for serviceability on the fuel cell bus, rating both metrics as 2 or 3 out of 5. Most rated the frequency of fuel cell bus-related problems as 1 or 2 out of 5. Ease of repair was rated primarily as 2 or 3 out of 5, and fuel cell bus manufacturer support was rated evenly between 2 and 5, with a plurality rating it as 3.

Figure 3-18

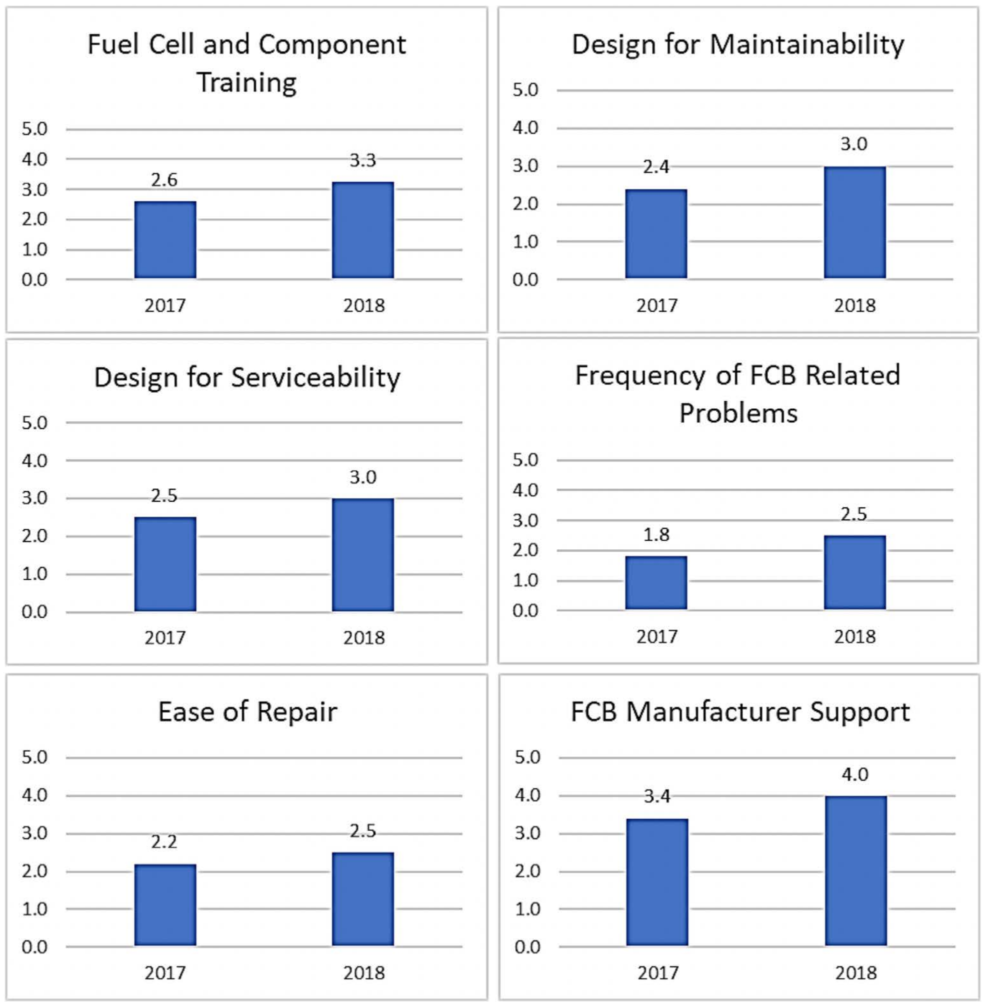
2017 Technician Maintenance Ratings



Average ratings for each metric improved slightly in 2018 (Figure 3-19). Fuel cell and component training rose from 2.6 to 3.3, design for maintainability improved from 2.4 to 3.0, design for serviceability improved from 2.5 to 3.0, frequency of fuel cell bus-related problems improved from 1.8 to 2.5, ease of repair improved from 2.2 to 2.5, and fuel cell bus manufacturer support, the highest-rated metric on average, improved from 3.4 to 4.0.

Figure 3-19

Average Technician Maintenance Ratings in 2017 and 2018



In 2017, when asked to elaborate on issues with the fuel cell bus at early stages of development, technicians shared comments on a variety of issues, mostly concerning component issues (Figure 3-20). Numerous technicians cited examples of failures and repairs required on a variety of components, including circulation fan, smoke detector, speed sensor, interior lighting module, rear door module, horn, cooling fan, diagnostics gear hardware, air pressure module, and fuel gauge module. One technician also stated that the buses could not be operated on the highway, echoing sentiments from driver surveys, and another stated that the bus did not start up on initial delivery from the manufacturer. In

2018, technicians expressed additional concerns about sensors and pumps, as well as heating issues (Figure 3-20).

Figure 3-20

Technician-Reported Fuel Cell Bus Problems at Early Stages of Deployment

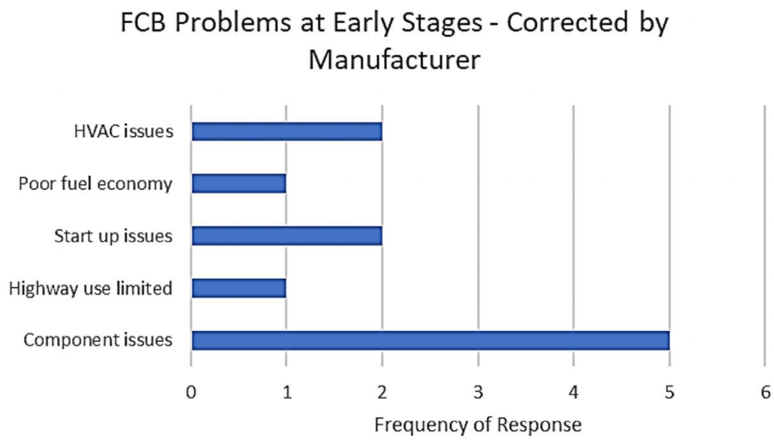
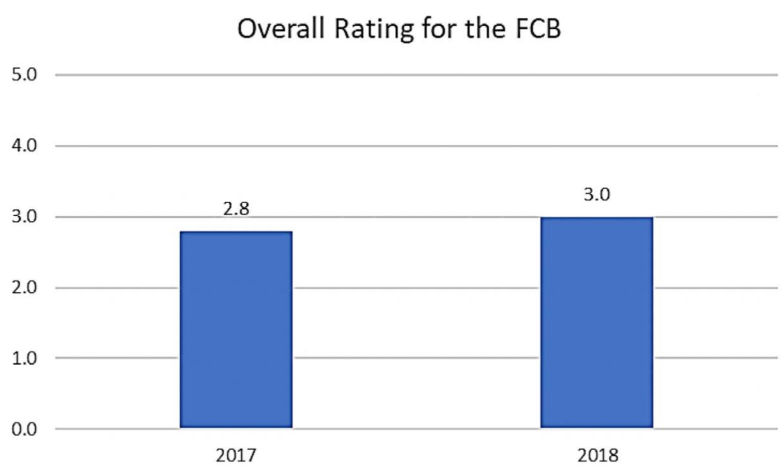


Figure 3-21 shows the average overall rating for the fuel cell bus by technicians. The original rating scale of "Very poor" to "Excellent" was quantified from 1 to 5, respectively. Overall, the technicians rated the bus "Good" on average. Whereas in 2017, two technicians rated the bus "Poor," all five technicians rated the bus "Good" in 2018, indicating some perception of overall improvement.

Figure 3-21

Average Overall Rating for Fuel Cell Bus by Technicians



Technicians also shared several suggestions on improving the operation of the fuel cell bus. A plurality suggested improving bus component lifetimes in general, but some were more specific, citing the HVAC system and the fuel cell itself and describing their impact on fuel economy. Technicians also stated that no two buses have been built consistently, causing quality control issues and challenges for maintenance. One technician suggested that the buses should be test-driven before delivery to the customer, the manufacturer should send someone to the site to inspect bus problems, and technician training was not adequate. Another technician echoed earlier sentiments about the ability of the bus to drive at highway speeds. One technician cited issues with startup, stating that if the bus sat more than three days without being charged it was difficult to start. Another stated that the public enjoyed the aesthetics of the bus (Figure 3-22 and Figure 3-23). Like the drivers, the technicians were asked in 2018 if their opinions on the fuel cell buses changed after working on them for a while.

Figure 3-22

Suggestions and Recommendations from Technicians

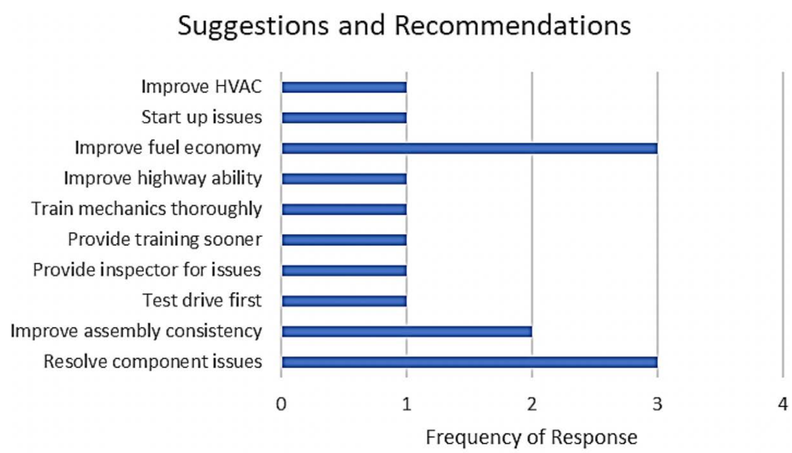
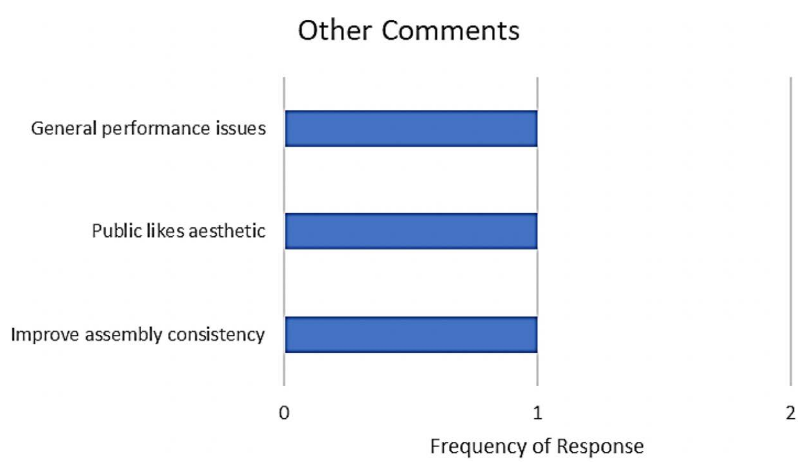


Figure 3-23

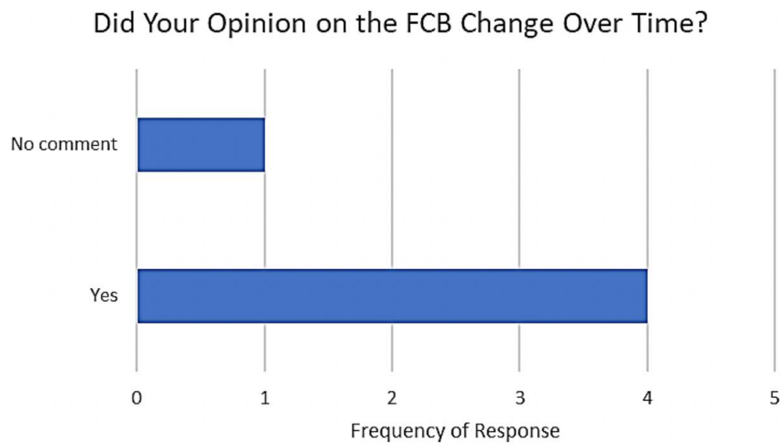
Other Comments Shared by Technicians



As shown in Figure 3-24, most said "Yes" and elaborated that working on them over time caused them to learn more about the bus and the fuel cell. One technician also said that he/she saw the bus in service more often over time, leading to an improved opinion on the bus.

Figure 3-24

Technician Opinion Change Over Time



Interview with Operations Lead

CALSTART also interviewed the operations lead at SARTA. This interview was conducted after all survey results were collected and analyzed, and it was intended to obtain additional perspective on the benefits and challenges associated with deployment of the fuel cell bus. By interviewing this individual, CALSTART was able to corroborate some driver and technician survey results while also gaining new insights from a higher-level view on SARTA's operations.

First, this interview confirmed that SARTA did indeed experience issues with the heating and cooling system as it relates to energy consumption in the fuel cell bus. The operations lead indicated that running the HVAC system in cold months caused the fuel cell to deplete, limiting the range of the bus. He indicated that two Thermo-King heating units went out during the demonstration; thus, as a precaution, drivers turned heating off when possible to maximize mileage. This dovetails with a second, related point on mileage. He stated that some drivers obtained better mileage than other drivers did and that experience through driving the same route routinely helped in this regard. Ultimately, the operations lead indicated that although the range for the bus was originally forecasted for 250 miles, in reality it was closer to 215 miles.

The operations lead stated that drivers experienced range anxiety; because there was no indication of the distance remaining until the fuel cell was depleted on the bus's dashboard, drivers acted cautiously with mileage and refueling. Anxious about the prospect of running out of fuel, drivers would often drive less than the bus could manage and refueled more than necessary. As a recommendation for improving this issue, the operations lead suggested that the bus be redesigned to include instrumentation indicating the distance to an empty fuel cell.

The operations lead made a few other key observations about the fuel cell bus. He stated that there were generally no safety issues associated with the bus, except that it was so quiet that pedestrians could not hear the bus coming at times. Additionally, although the demonstration was largely a success, the largest obstacle was getting buy-in from drivers and maintenance technicians. The new fuel cell technology took drivers and maintenance technicians out of their comfort zones, but continued daily use and exposure to the bus alleviated this problem.

Overall, the operations lead was pleased with the fuel cell bus and considers himself to be a champion of fuel cell technology as an application for transit buses. To date, SARTA has 8 fuel cell buses, and by the end of 2019 the agency expects to acquire 10 more (5 40-foot buses and 5 paratransit buses) for a total of 18 fuel cell buses. Although the operations lead wants to continue converting the fleet to alternative fuel buses, he is wary of the lack of fueling and charging infrastructure available to do so, stating that it is a significant obstacle to adoption.

Design Changes for Next Generation of American Fuel Cell Bus

As SARTA plans to purchase 10 more fuel cell buses, it will need to be mindful of the design and operational changes taking place to the next generation of the AFCB.

Tables 3-2 and 3-3 show the specifications for both generations of the AFCB, integrated by BAE Systems. The changes coming to the next generation of fuel cell buses include a lower-power fuel cell, more electrical energy storage, slightly less hydrogen fuel storage, and a decrease in the expected range that the bus can travel. The next generation will come equipped with the Ballard Power Systems FCveloCity-HD85 fuel cell at 85 kW rather than the HD6 fuel cell at 150 kW; 50 kWh of electrical energy storage compared to the previous 11.2 kWh of energy storage; 40 kg of hydrogen fuel storage compared to 50 kg in the first-generation bus; and an expected range of 210 miles compared to the previously stated 260 miles. These changes will need to be considered by SARTA as it plans to further integrate fuel cell buses into its transit operations.

Table 3-2

Specifications for AFCB Generation 1

Hybrid Electric Fuel Cell Bus Specifications – Generation 1	
Manufacturer	ElDorado National-California 40-ft Axess
Curb weight	~34,800 lb (15,785 kg)
Seats/stands	34 plus driver/17 standees
Power plant	Ballard Power Systems FCvelocity-HD6, 150 kW fuel cell
Hybrid propulsion system	BAE Systems HybriDrive Series-E propulsion system
Electrical energy storage	200 kW, 11.2 kWh nanophosphate Li-ion energy storage
Accessories	Electronic alternator, electrically driven cooling systems, HVAC, power steering, and air compressor
Fuel storage	Gaseous hydrogen: 50 kg at 350 bar
Range	260 miles (418 km) under typical urban transit cycle and loads
Length (L), width (W), height (H)	493.5 in. (12.5 m) L; 102 in. (2.6 m) W; 139 in. (3.5 m) H

Table 3-3

Specifications for AFCB Generation 2

Hybrid Electric Fuel Cell Bus Specifications – Generation 2	
Manufacturer	ElDorado National-California
Curb weight	~34,800 lb (15,785 kg)
Seats/stands	34 plus driver/17 standees
Power plant	Ballard Power Systems FCveloCity-HD85 fuel cell (85 kW)
Hybrid propulsion system	BAE Systems HybriDrive Series E propulsion system
Electrical energy storage	186 kW, 50kWh nanophosphate Li-ion energy storage
Accessories	Electronic alternator, electrically driven cooling system, HVAC, power steering and air compressor
Fuel storage	Gaseous hydrogen: 40 kg at 350 bar
Range	210 miles (338 km) under typical urban transit cycle and loads
Length (L), width (W), height (H)	493.5 in. (12.5 m) L; 102 in. (2.6 m) W; 139 in. (3.5 m) H

Conclusion

Overall at SARTA, the fuel cell bus received a generally good rating from both drivers and maintenance technicians. Although both drivers and technicians reported several issues with the bus, most stated that their opinions of the bus improved over time as they gained more experience driving and working on it. This suggests that drivers and maintenance technicians are more likely to accept the fuel cell bus and adopt it over time if the manufacturer works with them to resolve issues quickly and to improve bus design as feedback is provided.

As noted, common issues with the fuel cell bus included a reportedly faulty back door, a slow kneeler, uncomfortable and low seats, slow acceleration, an inability to reach highway speeds, multiple component failures, inconsistencies in the manufacturing quality of buses delivered to SARTA, and poor fuel economy. One-off issues were also mentioned, including ineffective heating and cooling in the passenger cabin and problems starting the bus, especially after days without refueling. In terms of vehicle performance, both drivers and technicians agreed on how the bus performed in terms of initial launch, acceleration, coasting/deceleration, and braking behavior. In 2018, both groups rated the fuel cell bus either the same or better on these measures when compared to a conventional bus. Drivers and technicians also agreed on their operational ratings for cold start and inside and outside noise level. In 2018, both rated these measures the same as or better than that of conventional buses. All in all, the fuel cell bus seemed to perform best on the measures of inside and outside noise level, reportedly much quieter than conventional buses, and it seemed to perform worst in terms of productivity.

Additionally, insights from the operations lead indicated that both the HVAC system and the lack of indication for range remaining on the bus deserve attention by the manufacturer. Results from this interview also provided tips for driving adoption of new fuel cell technology that may be intimidating to drivers, technicians, and other staff who are not used to it—that gaining buy-in through training and continued exposure is key.

The results of this survey provided useful insights into the acceptance of new fuel cell bus technology, using SARTA's experience as a case study. These results are helpful for other transit authorities seeking to transition their fleets toward low- or no-emission vehicles. Likewise, they are also helpful to the manufacturers looking to improve the design and performance of the AFCB, which is currently on its second generation. As the AFCB goes into further generations of design, ongoing feedback from drivers and maintenance technicians is helpful in communicating the benefits of its design changes as well as opportunities for further improvement.

APPENDIX

A

SARTA Fleet Summary Statistics

Table A-1 *SARTA – Fleet Operations and Economics*

	FCEB	CNG	Hybrid
Number of vehicles	5	4	3
Period used for fuel and oil analysis	2/18–1/19	2/18–1/19	2/18–1/19
Total number of months in period	12	12	12
Fuel and oil analysis base fleet mileage	129,337	220,978	98,787
Period used for maintenance analysis	2/18–1/19	2/18–1/19	2/18–1/19
Total number of months in period	12	12	12
Maintenance analysis base fleet mileage	130,798	230,144	99,833
Average monthly mileage per vehicle	2,180	4,795	3,698
Availability	65	77	83
Fleet fuel usage (kg, gge, gal)	25,940.7	52,500.0	21,540.5
Roadcalls	35	29	25
Total MBRC	3,737	7,936	3,993
Propulsion roadcalls	12	17	8
Propulsion MBRC	10,900	13,538	12,479
Fleet mileage (mi/kg, mi/gge, mi/gal)	4.99	4.21	4.59
Representative fleet mpg (energy equivalent)	5.63	4.70	4.59
Fuel cost per unit (kg, gge, gal)	5.27	1.89	2.30
Fuel cost per mile	1.06	0.45	–
Total scheduled repair cost per mile	0.09	0.12	–
Total unscheduled repair cost per mile	0.25	0.21	–
Total maintenance cost per mile	0.33	0.33	–
Total operating cost per mile	***1.39***	***0.78***	**–**

Table A-2 *SARTA – Maintenance Costs*

	FCEB	CNG
Fleet mileage	130,798	230,144
Total parts cost	$11,267.83	$35,996.80
Total labor hours	646.5	793.7
Labor cost (@ $50 per hour)	$32,322.50	$39,685.00
Total maintenance cost	$43,590.33	$75,681.80
Total maintenance cost per bus	$8,718.07	$18,920.45
Total maintenance cost per mile	***$0.333***	***$0.329***

Table A-3 *SARTA – Breakdown of Maintenance Costs by System*

	FCEB	CNG
Fleet mileage	130,798	230,144
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts cost	$10,872.75	$18,931.28
Labor hours	184.5	157.0
Labor cost	$9,225.00	$7,850.00
Total cost (for system)	$20,097.75	$26,781.28
Total cost (for system) per bus	$4,019.55	$6,695.32
Total cost (for system) per mile	*$0.154*	*$0.116*
Exhaust System Repairs (ATA VMRS 43)		
Parts cost	0.00	353.68
Labor hours	0	2.1
Labor cost	$0.00	$105.00
Total cost (for system)	$0.00	$458.68
Total cost (for system) per bus	$0.00	$114.67
Total cost (for system) per mile	*$0.000*	*$0.002*
Fuel System Repairs (ATA VMRS 44)		
Parts cost	0.31	2,909.90
Labor hours	3.5	20.6
Labor cost	$175.00	$1,030.00
Total cost (for system)	$175.31	$3,939.90
Total cost (for system) per bus	$35.06	$984.98
Total cost (for system) per mile	*$0.001*	*$0.017*
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts cost	10,070.00	4,871.39
Labor hours	118.5	23.7
Labor cost	$5,925.00	$1,185.00
Total cost (for system)	$15,995.00	$6,056.39
Total cost (for system) per bus	$3,199.00	$1,514.10
Total cost (for system) per mile	*$0.122*	*$0.026*
Electric Propulsion Repairs (ATA VMRS 46)		
Parts cost	247.64	0.00
Labor hours	45.5	0
Labor cost	$2,275.00	$0.00
Total cost (for system)	$2,522.64	$0.00
Total cost (for system) per bus	$504.53	$0.00
Total cost (for system) per mile	*$0.019*	*$0.000*

Table A-3 *SARTA – Breakdown of Maintenance Costs by System (cont'd)*

	FCEB	CNG
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts cost	510.48	6,443.84
Labor hours	14	59.55
Labor cost	$700.00	$2,977.50
Total cost (for system)	$1,210.48	$9,421.34
Total cost (for system) per bus	$242.10	$2,355.34
Total cost (for system) per mile	*$0.009*	*$0.041*
Air Intake System Repairs (ATA VMRS 41)		
Parts cost	34.74	125.43
Labor hours	0	2
Labor cost	$0.00	$100.00
Total cost (for system)	$34.74	$225.43
Total cost (for system) per bus	$6.95	$56.36
Total cost (for system) per mile	*$0.000*	*$0.001*
Cooling System Repairs (ATA VMRS 42)		
Parts cost	0.00	2,453.40
Labor hours	2.5	31.6
Labor cost	$125.00	$1,580.00
Total cost (for system)	$125.00	$4,033.40
Total cost (for system) per bus	$25.00	$1,008.35
Total cost (for system) per mile	*$0.001*	*$0.018*
Hydraulic System Repairs (ATA VMRS 65)		
Parts cost	9.58	736.96
Labor hours	0.5	0.8
Labor cost	$25.00	$40.00
Total cost (for system)	$34.58	$776.96
Total cost (for system) per bus	$6.92	$194.24
Total cost (for system) per mile	*$0.000*	*$0.003*
General Air System Repairs (ATA VMRS 10)		
Parts cost	42.42	256.87
Labor hours	5.5	14.75
Labor cost	$275.00	$737.50
Total cost (for system)	$317.42	$994.37
Total cost (for system) per bus	$63.48	$248.59
Total cost (for system) per mile	*$0.002*	*$0.004*
Brake System Repairs (ATA VMRS 13)		
Parts cost	0.00	2,968.28
Labor hours	3.9	44.5
Labor cost	$195.00	$2,225.00
Total cost (for system)	$195.00	$5,193.28
Total cost (for system) per bus	$39.00	$1,298.32
Total cost (for system) per mile	*$0.001*	*$0.023*

Table A-3 *SARTA – Breakdown of Maintenance Costs by System (cont'd)*

	FCEB	CNG
Transmission Repairs (ATA VMRS 27)		
Parts cost	0.00	1,036.68
Labor hours	0	16.65
Labor cost	$0.00	$832.50
Total cost (for system)	$0.00	$1,869.18
Total cost (for system) per bus	$0.00	$467.30
Total cost (for system) per mile	*$0.000*	*$0.008*
Inspections Only – No Parts Replacements (101)		
Parts cost	0.00	0.00
Labor hours	195.8	272.45
Labor cost	$9,790.00	$13,622.50
Total cost (for system)	$9,790.00	$13,622.50
Total cost (for system) per bus	$1,958.00	$3,405.63
Total cost (for system) per mile	*$0.075*	*$0.059*
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts cost	272.26	1,966.14
Labor hours	146.5	183.35
Labor cost	$7,325.00	$9,167.50
Total cost (for system)	$7,597.26	$11,133.64
Total cost (for system) per bus	$1,519.45	$2,783.41
Total cost (for system) per mile	*$0.058*	*$0.048*
HVAC System Repairs (ATA VMRS 01)		
Parts cost	5.79	7,119.97
Labor hours	42.7	64.8
Labor cost	$2,135.00	$3,240.00
Total cost (for system)	$2,140.79	$10,359.97
Total cost (for system) per bus	$428.16	$2,589.99
Total cost (for system) per mile	*$0.016*	*$0.045*
Lighting System Repairs (ATA VMRS 34)		
Parts cost	63.53	788.53
Labor hours	4.5	9.55
Labor cost	$225.00	$477.50
Total cost (for system)	$288.53	$1,266.03
Total cost (for system) per bus	$57.71	$316.51
Total cost (for system) per mile	*$0.002*	*$0.006*
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts cost	0.00	1,480.39
Labor hours	39.3	22.4
Labor cost	$1,965.00	$1,120.00
Total cost (for system)	$1,965.00	$2,600.39
Total cost (for system) per bus	$393.00	$650.10
Total cost (for system) per mile	*$0.015*	*$0.011*

Table A-3 *SARTA – Breakdown of Maintenance Costs by System (cont'd)*

	FCEB	CNG
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts cost	11.08	2,474.48
Labor hours	11.7	7.9
Labor cost	$585.00	$395.00
Total cost (for system)	$596.08	$2,869.48
Total cost (for system) per bus	$119.22	$717.37
Total cost (for system) per mile	*$0.005*	*$0.012*
Tire Repairs (ATA VMRS 17)		
Parts cost	0.00	10.86
Labor hours	12.05	17
Labor cost	$602.50	$850.00
Total cost (for system)	$602.50	$860.86
Total cost (for system) per bus	$120.50	$215.22
Total cost (for system) per mile	*$0.005*	*$0.004*

Fleet Summary Statistics – SI Units

Table A-4 *SARTA – Fleet Operations and Economics (SI)*

	FCEB	CNG	Hybrid
Number of vehicles	5	4	3
Period used for fuel and oil analysis	2/18–1/19	2/18–1/19	2/18–1/19
Total number of months in period	12	12	12
Fuel and oil analysis base fleet kilometers	208,142	355,620	158,978
Period used for maintenance analysis	2/18–1/19	2/18–1/19	2/18–1/19
Total number of months in period	12	12	0
Maintenance analysis base fleet kilometers	210,493	370,371	160,661
Average monthly kilometers per vehicle	3,508	7,717	5,951
Availability	65	77	83
Fleet fuel usage in hydrogen kg/liter equivalent	25,940.7	198,734.1	81,539.7
Roadcalls	35	29	25
Total KMBRC	6,014	12,771	6,426
Propulsion roadcalls	12	17	8
Propulsion KMBRC	17,541	21,787	20,083
Fleet kg hydrogen/100 km (1.13 kg H_2/gal diesel fuel)	12.46	–	–
Rep. fleet fuel consumption (L/100 km)	41.75	55.88	51.29
Fuel cost per unit (kg, liter)	5.27	0.50	0.61
Fuel cost per kilometer	0.66	0.28	–
Total scheduled repair cost per kilometer	0.06	0.10	–
Total unscheduled repair cost per kilometer	0.18	0.16	–
Total maintenance cost per kilometer	0.24	0.27	–
Total operating cost per kilometer	***0.90***	***0.55***	–

Table A-5 *SARTA – Maintenance Costs (SI)*

	FCEB	CNG
Fleet mileage	210,493	370,371
Total parts cost	$11,267.83	$35,996.80
Total labor hours	646.5	793.7
Average labor cost (@ $50 per hour)	$32,322.50	$39,685.00
Total maintenance cost	$43,590.33	$75,681.80
Total maintenance cost per bus	$8,718.07	$18,920.45
Total maintenance cost per kilometer	$0.042	$0.053

APPENDIX

B

First Driver Survey

SARTA Bus Driver Operation Evaluation Survey

As part of the hydrogen fuel cell bus (FCB) deployment and testing period, we would like to hear your input and evaluation of the FCB. It will help us evaluate the performance of the FCB and identify areas that need improvement. Please take 15 minutes to provide your evaluation of the FCB by answering the following questions. For each question, check the box that best fits your rating. We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Steven Sokolsky at (626) 744-5604 or at ssokolsky@calstart.org.

First Name: ____

Last Name: ____

Work schedule (days, hours): __________________________________

Today's Date: ____

Please provide a brief description of the route on which the HEB is operating:

Average miles / Number of stops / Hours of operation / Type of customers / Traffic / Other

____

____

Please provide an overall rating for driver training:

Very Poor Poor Good Very Good Excellent

Comments on driver training:

____

____

Performance

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Initial launch from stand still					
Maneuverability at low speeds					
Acceleration					
Coasting/deceleration					
Overall braking behavior					
Productivity (ability to cover routes quicker)					

Operation

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Cold start					
Reliability					
Inside noise level					
Outside noise level					
In-cabin ergonomics and driver interface					
Productivity (ability to cover routes quicker)					

Questions

Did you have any customer complaints related to the hydrogen fuel cell system (noise, vibrations, uncomfortable ride)? Y N

If yes, please explain: ____

____

Did you have any issues at low speed (noise, vibrations, system unresponsive)? Y N

If yes, please explain: ____

____

Did you have any issues related to regenerative braking? Y N

If yes, please explain: ____

____

Please provide an overall rating for the FCB:

Very Poor Poor Good Very Good Excellent

Please provide any suggestions or recommendations of performance areas that need improvement in the FCB:

____
____

Please share any other comments you have concerning the FCB:

____
____

Thank you for your participation!

APPENDIX

C

Second Driver Survey

SARTA Bus Driver Operation Evaluation – Follow-Up Survey

As part of the hydrogen fuel cell bus (FCB) deployment and testing period, we would like to hear your input and evaluation of the FCB. It will help us evaluate the performance of the FCB and identify areas that need improvement. Back in September, you participated in an initial survey; we would like to see if your opinions of the technology have changed as you've had more experience with the fuel cell buses. Please take 15 minutes to provide your evaluation of the FCB by answering the following questions. For each question, check the box that best fits your rating. We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Mark Finnicum or Steven Sokolsky at (626) 744-5604 or at ssokolsky@calstart.org.

First Name: ____

Last Name: ____

Work schedule (days, hours): ___________________________________

Today's Date: ____

Please provide a brief description of the route on which the HEB is operating:

Average miles / Number of stops / Hours of operation / Type of customers / Traffic / Other

____

____

Please provide an overall rating for driver training:

Very Poor Poor Good Very Good Excellent

Comments on driver training:

____

____

Performance

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Initial launch from stand still					
Maneuverability at low speeds					
Acceleration					
Coasting/deceleration					
Overall braking behavior					
Productivity (ability to cover routes quicker)					

Operation

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Cold start					
Reliability					
Inside noise level					
Outside noise level					
In-cabin ergonomics and driver interface					
Productivity (ability to cover routes quicker)					

Questions

Did you have any customer complaints related to the hydrogen fuel cell system (noise, vibrations, uncomfortable ride)? Y N

If yes, please explain: ____

____

Did you have any issues at low speed (noise, vibrations, system unresponsive)? Y N

If yes, please explain: ____

____

Did you have any issues related to regenerative braking? Y N

If yes, please explain: ____

____

Please provide an overall rating for the FCB:

Very Poor Poor Good Very Good Excellent

Please provide any suggestions or recommendations of performance areas that need improvement in the FCB:

____
____

Did your opinions about the FCB change as you spent more time operating it? If so, why?

____
____

Thank you for your participation!

APPENDIX

D

First Maintenance Technician Survey

SARTA Maintenance Technician Evaluation Survey

As part of the hydrogen fuel cell bus (FCB) deployment and testing period, we would like to hear your input and evaluation of the FCB. It will help us evaluate the performance of the FCB and identify areas that need improvement. Please take 10 minutes to provide your evaluation of the FCB by answering the following questions. For each question, check the box that best fits your rating. We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Steven Sokolsky at (626) 744-5604 or at ssokolsky@calstart.org.

First Name: ____

Last Name: ____

Work schedule (days, hours): ________________________________

Today's Date: ____

Performance

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Initial launch from stand still					
Maneuverability at low speeds					
Acceleration					
Coasting/deceleration					
Overall braking behavior					
Productivity (ability to cover routes quicker)					

Operation

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Cold start					
Reliability					
Inside noise level					
Outside noise level					
In-cabin ergonomics and driver interface					
Productivity (ability to cover routes quicker)					

Please describe any FCB problems observed during the early stages of the deployment period that were subsequently corrected by the manufacturer/supplier:

____
____

Maintenance

Please rate the following issues related to FCB maintenance on a scale of 1 to 5, where 1 means unacceptable and 5 means excellent (circle the appropriate number):

	Unacceptable			Excellent	
Fuel cell system and component training:	1	2	3	4	5
Design for maintainability:	1	2	3	4	5
Design for serviceability:	1	2	3	4	5
Overall frequency of FCB related problems:	1	2	3	4	5
Ease of repair of FCB related problems:	1	2	3	4	5
FCB system manufacturer support:	1	2	3	4	5

Please provide an overall rating for the FCB:

Very Poor Poor Good Very Good Excellent

Suggestions and Comments

Please provide any suggestions or recommendations of performance areas that need improvement in the FCB:

____
____

Please share any other comments you have concerning the FCB:

____
____

Thank you for your participation!

APPENDIX

E

Second Maintenance Technician Survey

SARTA Maintenance Technician Evaluation – Follow-Up Survey

As part of the hydrogen fuel cell bus (FCB) deployment and testing period, we would like to hear your input and evaluation of the FCB. It will help us evaluate the performance of the FCB and identify areas that need improvement. Back in September, you participated in an initial survey; we would like to see if your opinions of the technology have changed as you've had more experience with the fuel cell buses. Please take 10 minutes to provide your evaluation of the FCB by answering the following questions. For each question, check the box that best fits your rating. We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Mark Finnicum or Steven Sokolsky at (626) 744-5604 or at ssokolsky@calstart.org.

First Name: ____

Last Name: ____

Work schedule (days, hours): ___________________________________

Today's Date: ____

Performance

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Initial launch from stand still					
Maneuverability at low speeds					
Acceleration					
Coasting/deceleration					
Overall braking behavior					
Productivity (ability to cover routes quicker)					

Operation

Property of FCB compared to conventional diesel or natural gas bus	Much worse	Somewhat worse	Same	Better	Much better
Cold start					
Reliability					
Inside noise level					
Outside noise level					
In-cabin ergonomics and driver interface					

Please describe any FCB problems observed during the early stages of the deployment period that were subsequently corrected by the manufacturer/supplier:

____
____

Maintenance

Please rate the following issues related to FCB maintenance on a scale of 1 to 5, where 1 means unacceptable and 5 means excellent (circle the appropriate number):

	Unacceptable			Excellent	
Fuel cell system and component training:	1	2	3	4	5
Design for maintainability:	1	2	3	4	5
Design for serviceability:	1	2	3	4	5
Overall frequency of FCB related problems:	1	2	3	4	5
Ease of repair of FCB related problems:	1	2	3	4	5
FCB system manufacturer support:	1	2	3	4	5

Please provide an overall rating for the FCB:

Very Poor Poor Good Very Good Excellent

Suggestions and Comments

Please provide any suggestions or recommendations of performance areas that need improvement in the FCB:

____
____

Did your opinions about the FCB change as you spent more time working on it? If so, why?

____
____

Thank you for your participation!

APPENDIX

F

Outreach to Outside Entities

Outreach to Outside Entities

The Midwest Hydrogen Center of Excellence conducted two workshops that highlighted the benefits associated with the deployment of hydrogen fuel cell transit buses. The one-day workshops (with a reception the previous evening) were held July 26–27 and September 13–14, 2017, in Canton, Ohio. The content of the two workshops was nearly identical. The primary objective of these workshops was to educate potential purchasers of fuel cell transit buses so they could make better informed decisions.

The July workshop was attended by 23 participants, 7 of whom were affiliated with transit agencies. The September workshop was attended by 33 participants, 18 of whom were affiliated with transit agencies. The workshops were also attended by regulators, educators, and suppliers. Each included panel discussions and a tour of the SARTA hydrogen refueling facility.

The session topics of both workshops were as follows:

- Features and Benefits of Hydrogen-Powered Transit
- Refueling Systems and Infrastructure Requirements
- Real Life Experiences of Transit Users
- The Hydrogen Roadmap for the Midwest
- Cost of Ownership and Reliability
- Helping Agencies Plan and Find Funding

At the end of each session, the fleet attendees were asked about what they learned from the workshop. Typical responses included the following:

- "I learned how to approach management about this topic."
- "This confirmed earlier knowledge."
- "The state of bus technology seems to be ahead of infrastructure technology."
- "This workshop filled in many of the knowledge gaps."
- "Infrastructure seems to be the most difficult topic."
- "The issues are the same across agencies, especially the need for education."
- "We already use CNG so transitioning to hydrogen won't be as difficult since we've learned so much. We'd like to leverage the CNG infrastructure if we can."

- "We're concerned about the availability of grants to help us fund the deployment."

Surveys of workshop attendees were conducted both before and after the event. Many fleet attendees had some experience with alternatively-powered buses, most notably compressed gas and hybrid-electric models. Most expected paybacks in the 6–9-year period, and the zero-emission bus attributes they found the most important were better fuel economy, elimination of tailpipe greenhouse gases, and improved reliability when compared to a diesel bus. Initial purchase price was seen as the biggest barrier to the adoption of zero-emission buses. Follow-up on post-workshop attitudes is still being conducted.

Attendees

The following people attended the July workshop (*fleet attendee in italics*):

- Erik Bigelow, Senior Project Manager, Center for Transportation and the Environment
- *Larry Braun, Regional Manager, Pace Suburban Bus Service*
- Don Butler, Administrative Manager, Midwest Hydrogen Center of Excellence
- Andrew Conley, Program Director, Clean Fuels Ohio
- *Kirt Conrad, Executive Director/CEO, Stark Area Regional Transit Authority (SARTA)*
- David Cooke, Research Specialist, Ohio State University Center for Automotive Research
- Jim Durand, Director, Renewable Hydrogen Fuel Cell Collaborative
- *Mark Finnicum, Chief Operations Officer, SARTA*
- *Alice Fuchs, Alternative Fueling Center Manager, Mass Transportation Authority*
- Yann Guezennec, Professor Emeritus, The Ohio State University
- David Kiefer, Candidate for Governor of Ohio
- Jaimie Levin, Director of West Coast Operations, Center for Transportation and the Environment
- Jim Maloney, Faculty Member, Stark State College
- Oscar Pardinas, Regional Sales Manager, ElDorado National
- Andrew Rezin, Director, Midwest Hydrogen Center of Excellence
- Fred Silver, Vice President, CALSTART
- *Bryan Smith, Deputy CEO, Ann Arbor Area Transportation Authority*
- Alison Smyth, Project Manager, Center for Transportation and the Environment
- *Adam Snyder, IT Administrator, SARTA*

- Steven Sokolsky, Program Manager, CALSTART
- *Jane Sullivan, Grant Manager/Sustainability Planner, Champaign-Urbana Mass Transit District*
- *Debbie Swickard, Grants Manager, SARTA*
- Pat Valente, Executive Director, Ohio Fuel Cell Coalition

The September workshop attendees were (*fleet attendees in italics*):

- Brian Bonner, Global Product Manager-Hydrogen Energy Systems, Air Products
- *Larry Buckel, Office of Transit Manager, Indiana DOT*
- Don Butler, Administrative Manager, Midwest Hydrogen Center of Excellence
- Andrew Conley, Program Director, Clean Fuels Ohio
- *Kirt Conrad, Executive Director/CEO, SARTA*
- *Chris Craves, Technical Assistance Review Coordinator, Ohio DOT*
- Jim Durand, Director, Renewable Hydrogen Fuel Cell Collaborative
- *Karl Gnadt, Managing Director, Champaign-Urbana Mass Transit*
- Abas Goodarzi, President and CEO, US Hybrid Corporation
- Yann Guezennec, Professor Emeritus, Center for Automotive Research
- *Jarrod Hampshire, Director of Maintenance, Akron Metro RTA*
- *Michael Hollibaugh, Director Dept. of Community Services, City of Carmel, Indiana Mayor's Office*
- *Juana Hostin, Urban Transit Coordinator, Ohio DOT*
- Jerrold Hutton, Manager, Energy Consulting Services
- George Judson, Adjunct Instructor, Stark State College
- Jaimie Levin, Director of West Coast Operations, Center for Transportation and the Environment
- *Mike Lively, Manager of Intelligent Transportation Systems, Greater Cleveland RTA*
- Guy Oliver, CEO, Alternative PowerMatrix
- Zhenmeng Peng, Assistant Professor, University of Akron
- Yeshwanth Premkumar, Program Manager, BAE Systems
- *Kelly Reagan, Fleet Administrator, City of Columbus*
- Andrew Rezin, Director, Midwest Hydrogen Center of Excellence
- *Philip Roth, Mobility Manager, Central Indiana RTA*
- *Tim Rowe, Director of Maintenance, Toledo Area RTA*
- *Eric Scott, Maintenance Trainer, Akron Metro RTA*

- Alison Smyth, Project Manager, Center for Transportation and the Environment
- Steven Sokolsky, Program Manager, CALSTART
- *John Sutherland, Assistant Director of Maintenance, Akron Metro RTA*
- *Debbie Swickard, Grants Manager, SARTA*
- Pat Valente, Executive Director, Ohio Fuel Cell Coalition
- *Jeff Vosler, CFO, Central Ohio Transit Authority*
- *Emille Williams,VP of Operations, Central Ohio Transit Authority*
- *Jim Williams, Quality Assurance/Quality Control Specialist, Southwest Ohio RTA*

Follow-Up

The fleet attendees were informed about funding opportunities to enable the purchase of zero-emission and fuel cell buses. In particular, FTA's Low or No Emission Vehicle Deployment Program provides funding to cover most of the incremental costs associated with the purchase of fuel cell and battery electric buses. The Midwest Hydrogen Center of Excellence, CALSTART, and the Center for Transportation and the Environment are available to assist transit agencies with the specification, procurement, and deployment of advanced technology buses and the associated infrastructure. Resources to help fleets in this area were identified at the workshops.

Acronyms and Abbreviations

ATA VMRS	American Trucking Association Vehicle Maintenance Reporting Standards
BEB	battery electric bus
CNG	compressed natural gas
dge	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ENC	Eldorado National-California
FCB	fuel cell bus
FCEB	fuel cell electric bus
FTA	Federal Transit Administration
gge	gasoline gallon equivalent
HVAC	heating, ventilation, and air conditioning
KMBRC	kilometers between roadcall
kW	kilowatt
kWh	kilowatt hour
Low-No	Low or No Emission Vehicle Deployment Program
MBRC	miles between roadcall
mpdge	miles per diesel gallon equivalent
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PM/PMI	preventive maintenance inspections
RC	roadcall
rpm	revolutions per minute
SARTA	Stark Area Regional Transit Authority
SI	International System of Units

Glossary

Availability: The number of days the buses are actually available compared to the days that the buses are planned for operation, expressed as percent availability.

Clean point: For each evaluation, NREL works with the project partners to determine a starting point—or clean point—for the data analysis period. The clean point is chosen to avoid some of the early and expected operations problems with a new vehicle going into service, such as early maintenance campaigns. In some cases, reaching the clean point may require 3–6 months of operation before the evaluation can start. This applies to new technology buses as well as conventional buses.

Deadhead: The miles and hours that a vehicle travels when out of revenue service with no expectation of carrying revenue passengers; includes leaving or returning to the garage or yard facility and changing routes.

Miles between roadcalls (MBRC): A measure of reliability calculated by dividing the number of miles traveled by the total number of roadcalls, also known as mean distance between failures. MBRC results in the report are categorized as follows:

- ***Bus MBRC:*** Includes all chargeable roadcalls. Includes propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires.
- ***Propulsion-related MBRC:*** Includes roadcalls that are attributed to the propulsion system. Propulsion-related roadcalls can be caused by issues with the transmission, batteries, and electric drive.
- ***Energy storage system-related MBRC:*** Includes roadcalls attributed to the energy storage system only (specific to BEBs).
- ***Fuel cell system-related MBRC:*** Includes roadcalls attributed to the fuel cell and balance of plant only (specific to FCEBs).

Revenue service: The time when a vehicle is available to the general public with an expectation of carrying fare-paying passengers; vehicles operated in a fare-free service are also considered revenue service.

Roadcall: A failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule; analysis includes chargeable roadcalls that affect the operation of the bus or may cause a safety hazard. Non-chargeable roadcalls can be passenger incidents that require the bus to be cleaned before going back into service, or problems with an accessory such as a farebox or radio.

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