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Using the Birmingham National Fuel Cell Bus Program Bus for Regional Outreach in Ohio

MAY 2020

FTA Report No. 0165
Federal Transit Administration

PREPARED BY
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David Higgs
Erik Bigelow
Center for Transportation and the Environment

U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

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U.S. Department of Transportation
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Metric Conversion Table

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

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

1. AGENCY USE ONLY	2. REPORT DATE May 2020	3. REPORT TYPE AND DATES COVERED Project Report, November 2016–June 2019
4. TITLE AND SUBTITLE Using the Birmingham National Fuel Cell Bus Program for Regional Outreach in Ohio		5. FUNDING NUMBERS
6. AUTHOR(S) Alison Smyth, David Higgs, Erik Bigelow		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Center for Transportation and the Environment 730 Peachtree Street, Suite 760 Atlanta, GA 30308		8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0165
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration Office of Research, Demonstration and Innovation East Building 1200 New Jersey Avenue, SE Washington, DC 20590		10. SPONSORING/MONITORING AGENCY REPORT NUMBER FTA Report No. 0165
11. SUPPLEMENTARY NOTES [https://www.transit.dot.gov/about/research-innovation] [https://doi.org/10.21949/1518337] Suggested citation: Federal Transit Administration. Using the Birmingham National Fuel Cell Bus Program for Regional Outreach in Ohio. Washington, D.C.: United States Department of Transportation, 2020. https://doi.org/10.21949/1518337		
12A. DISTRIBUTION/AVAILABILITY STATEMENT Available from: National Technical Information Service (NTIS), Springfield, VA 22161. Phone 703.605.6000, Fax 703.605.6900, email [orders@ntis.gov]		12B. DISTRIBUTION CODE TRI-30
13. ABSTRACT This report is an addendum to the final report to the Federal Transit Administration (FTA) covering the project performance and results for the development, build, and demonstration of a fuel cell electric bus in Birmingham, Alabama. Following that demonstration, the bus was shipped to the Stark Area Regional Transit Authority (SARTA) in Canton, Ohio. SARTA staff were trained on and repaired the bus, which was then used in educational outreach to middle schoolers in Ohio. This project also included a study evaluating the performance of hydrogen fuel cell buses in comparison to conventional fuel technologies.		
14. SUBJECT TERMS Fuel cell electric bus, transit, outreach		15. NUMBER OF PAGES 28
16. PRICE CODE		

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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Acknowledgments

The authors would like to thank the Federal Transit Administration for its support of this project. Thank you to each of the project partners—Stark Area Regional Transit Authority, Midwest Hydrogen Center of Excellence, The Ohio State University Center for Automotive Research, and Columbus State Community College—for their diligence and hard work in executing this project.

Abstract

This report is an addendum to the final report to the Federal Transit Administration (FTA) covering the project performance and results for the development, build, and demonstration of a fuel cell electric bus in Birmingham, Alabama. Following that demonstration, the bus was shipped to the Stark Area Regional Transit Authority (SARTA) in Canton, Ohio. SARTA staff were trained on and repaired the bus, which was then used in educational outreach to middle schoolers in Ohio. This project also included a study evaluating the performance of hydrogen fuel cell buses in comparison to conventional fuel technologies.

EXECUTIVE SUMMARY

The Center for Transportation and the Environment (CTE) managed the design, build, testing, and demonstration of a fuel cell electric bus, which was demonstrated at the University of Alabama–Birmingham (UAB). The Federal Transit Administration (FTA) sponsored this project as part of the National Fuel Cell Bus Program. The original project goal was to design, build, and demonstrate a fuel cell electric bus at UAB. At the end of the demonstration, the project scope was expanded to include using the bus to conduct educational outreach to middle school students in Ohio.

This report covers the efforts conducted following the bus demonstration at UAB. The bus was shipped from UAB to Canton after the end of a demonstration in Birmingham, and CTE worked to finalize the disposition plan for the vehicle. The fuel cell stack was in danger of freezing at UAB, so the Stark Area Regional Transit Authority (SARTA) agreed to house the bus while disposition was finalized. The bus arrived in Canton in 2016. Following delivery, CTE worked with the Midwest Hydrogen Center of Excellence (MHCoE), Columbus State Community College (CSCC), and SARTA to develop plans to use the bus for outreach in Ohio. Once these plans were finalized, CTE formally dispositioned the bus to SARTA.

CTE organized a kickoff meeting for the project in October 2017, at which bus ownership, manual development, and bus repair plans were discussed. All needed to be completed prior to conducting outreach and education with the vehicle.

CTE arranged for two members of the original bus build to provide training to SARTA staff on the vehicle, who also assisted in diagnosing and repairing some issues on the bus and helped SARTA with installing a diagnostic maintenance computer on the vehicle and resolving an issue identified at the end of the demonstration in which the traction motor and air conditioning would not run simultaneously. Feedback was provided to CSCC on the draft comprehensive manual for the vehicle, and the manual was provided to SARTA for use in maintaining and operating the vehicle.

SARTA conducted minor repairs on the bus, such as replacing the tires and fuses, and developed a new bus wrap and interior placards for the vehicle for use in outreach events. CSCC and MHCoE conducted outreach to middle school students by presenting to nearly 1,000 students from four middle schools in Canton, Massillon, Cleveland, and Alliance, conducted a continuing education program for middle school teachers, and visited Cleveland State University to present on alternative energy sources and hydrogen fuel cells and take students on bus rides.

CTE contracted with The Ohio State University's Center for Automotive Research (CAR) to collect speed profile data on multiple SARTA buses. CAR investigated appropriate loggers, eventually selecting one that could collect 10

Hz speed data, and ordered 10 loggers, The loggers were installed on three hydrogen fuel cell electric vehicles, three CNG vehicles, one diesel hybrid vehicle, and two diesel vehicles. Overall, CAR collected more than 5,000 hours of 10 Hz data that was parsed into individual blocks to compare the performance of SARTA's buses with different propulsion types, for which CTE developed a Matlab program.

CTE compared observed data points to identify patterns in vehicle behavior. The hydrogen buses did not travel on SARTA's highest mileage routes or routes with the highest average speeds; its hydrogen fuel cell bus rarely exceeded 200 miles per day. CTE also compared fuel economies of different propulsion types. Analysis showed that the hydrogen buses experienced fuel consumption similar to the diesel buses but had less relative fuel consumption than the CNG vehicles. The remaining comparisons focused on vehicle acceleration metrics; the hydrogen fuel cell buses experienced much greater positive acceleration values than the diesel and CNG buses, even though the average acceleration was similar when controlling for different routes.

SECTION 1

Introduction

The Center for Transportation and the Environment (CTE) led a team in the development and demonstration of a fuel cell electric bus (FCEB) at the University of Alabama–Birmingham (UAB) as part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP). That effort is described in more detail in the report titled "National Fuel Cell Bus Program: Birmingham Fuel Cell Hybrid Bus Demonstration."

Following completion of the demonstration, the bus was shipped to the Stark Area Regional Transit Authority (SARTA) in Canton, Ohio, and prepared for a second phase of the project that consisted of conducting training for SARTA staff on the bus, repairing the bus to a workable condition, and coordinating educational outreach at middle schools in Ohio using the bus.

SARTA repaired and managed the bus during the project. Columbus State Community College (CSCC) developed a manual for maintenance of the bus and developed materials for and participated in the educational events, with the Midwest Hydrogen Center of Excellence (MHCoE) organizing and participating in the events.

CTE worked with the Ohio State University Center for Automotive Research (CAR) to collect speed profile data on SARTA's buses with different propulsion types to evaluate whether or not FCEBs are driven differently from compressed natural gas (CNG) or diesel vehicles.

SECTION

2

Bus Tasks

The FCEB was shipped from UAB to Canton after the end of the demonstration in Birmingham, and CTE worked to finalize the disposition plan for the vehicle. The fuel cell stack was in danger of freezing at UAB, so SARTA agreed to house the bus while disposition was finalized. The bus arrived in Canton in November 2016. CTE organized a kickoff meeting for the project in October 2017, at which bus ownership, manual development, and bus repair plans were discussed.

Before SARTA could conduct repair work on the bus, SARTA staff needed to be trained. Dick Boothe of EPC and Mark Morgan, both of whom worked on the original bus build, conducted training for SARTA staff in January 2018, that focused on high-voltage systems and mechanical systems of the bus.

The following sections describe the inspections, testing, training, and repairs conducted upon receipt of the bus.

Inspection, Testing, and Training

Charger

The UAB charger enclosure and hardware were inspected for shipping and handling damage. Other than one loose connection, no damage was found. The power wiring was inspected, and it was found that the ground connection from the source transformer had not been terminated to the enclosure, which was corrected. An additional #1 cable ground from the chassis to a nearby building column was added for increased safety. Before powering the charger for the first time, it was verified with a meter that the incoming power configuration was 208VAC, 3-phase, with the neutral grounded.

The charger cooling air filters were inspected and were found to be very dirty. The need to inspect and regularly change the filters was made known to SARTA and CSCC. A maintenance schedule for the bus and charger was sent to CSCC, and EPC provided written and verbal instructions for charging the bus traction battery. The charger connections were made, and the bus was charged for about an hour as a test without issues. This also verified operation of the Altairnano traction battery BMS, since the charger must communicate over the CAN network with the BMS for safe charging to take place. As part of the exercise, verbal instructions were provided on the proper method for removing the traction battery for maintenance or other reasons.

Fueling

After completing a one-hour test charge, a SARTA driver started the bus, including the fuel cell, and drove it several hundred yards to the hydrogen fueling station while receiving instructions on the hydrogen fueling procedure. The hydrogen tanks were fully filled.

Maintenance PC Computer

The maintenance PC (Nitro-3600 from Industrial PC) arrived at EPC one day before the scheduled trip to SARTA, which did not allow enough time for checking out and loading software before installation; however, EPC had a computer. The team reviewed the location for the computer and the necessary wiring additions to add the computer into the traction system. While reviewing the wiring, it was found that the antennas for the wireless modem were no longer mounted on the bus. EPC later ordered and shipped the antennas to SARTA and planned to install them during the May training.

Bus Cooling Systems

The operation and maintenance of each bus cooling system were reviewed in detail. These systems require scheduled maintenance for proper operation, including filter changes and level checks. The location of each system was pointed out, including those on top of the bus. The separate systems include:

- Chiller for traction battery cooling
- EMP cooling system for traction components
- Fuel cell cooling loops (main cooling loop and condensate cooling loop)

EPC discussed the small inverter drives associated with each loop and their known failures, including seal failures in the Tuthill pump, motor and drive failures of the condensate pump, and EMP pump failures in the traction cooling system.

SARTA put the UAB bus on a lift so details of the suspension system could be observed. The important components of the system and the necessary maintenance were pointed out. In addition, how to properly remove the traction motor if the need arises was discussed.

Fuel Cell Bus Primer

Each component of the electric traction propulsion system was labeled, and the team discussed its use in the overall system and the need for opening the high voltage battery disconnect (Andersen Connector) before servicing any of the modules attached to the traction system. A copy of the EPC traction system drawing was provided to SARTA and CSCC, and time was spent reviewing how to read the document.

In two cases, the programmable parameters had not been captured on the system diagram (condensate pump and stack coolant pump). EPC instructed CSCC personnel in the methods necessary for reading and programming parameters, and CSCC was able to access these parameters using the ABB display and record them for possible future use if necessary to replace one of the drives. Also provided was a copy of the standard ABB reference manual for this type of drive.

Air Conditioner Troubleshooting

SARTA noted that the bus would not be placed into service unless the air conditioner was operational and reliable, so its status was investigated. The air conditioner operated without any of the traction system operational (no fuel cell, no traction inverter). After the fuel cell DC- DC converter was added, the air conditioner continued to operate properly. Although the testing was not conclusive, the air conditioner appeared to operate properly with the fuel cell DC-DC converter operating but not when the traction inverter was operating. Most of the time, the air conditioner tripped (fault 42) as soon as the bus was shifted into forward or reverse; occasionally, it would continue to operate. The transient of turning on the traction inverter seemed to be the trigger. The fault code generated was not helpful in diagnosing the issue.

EPC conducted limited troubleshooting. Upon measuring the voltage at the terminals of the air conditioner, it found that the differential voltage, P to N, remained constant at 681V DC when the traction inverter started up. However, the AC voltage from either terminal to chassis spiked from about 10VAC to > 100VAC during the start of the traction inverter. It was presumed that this "ground" electrical noise was confusing the circuitry of the air conditioner. The air conditioner has sophisticated electronics controlling several small inverters in its enclosure. It was possible to provide a small differential and common mode filter that would be added in the high voltage power lines (L1, L2) going into the air conditioner. This would remove the transients that occur due to the traction inverter starting up. This solution was implemented during the May training.

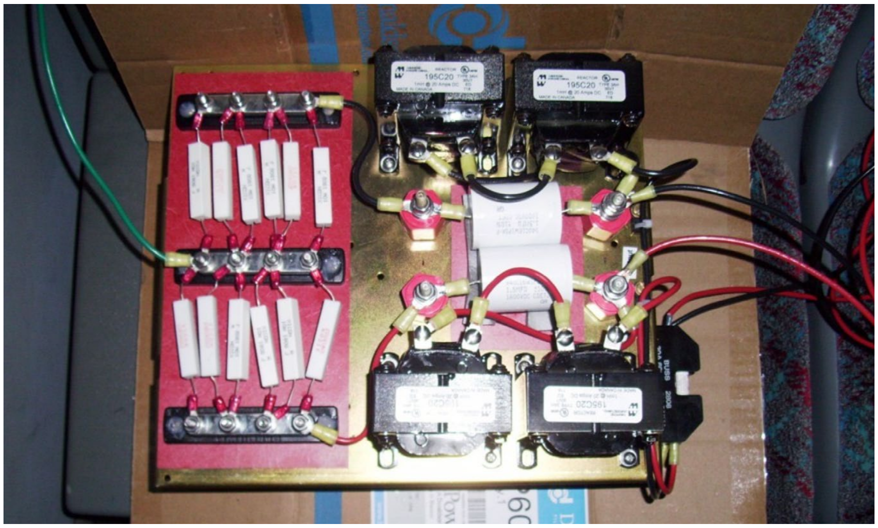
The switch labeled "Main Disconnect" in the rear of the bus in the EBox provided the high voltage power to the air conditioner unit on the roof. The team used the switch to access the power, allowing the filter to be located in the high voltage compartment in the rear of the bus (not on the roof).

The simpler common mode filter was tested first. SARTA technicians conducted the power wiring to the "Main Disconnect" switch, and the air conditioning unit was tested and operated normally until the IMC for bus propulsion was enabled, when the air conditioning unit quickly shut down. Testing showed that the noise voltage on each power terminal to the air conditioning was attenuated by about 30%, but this was not sufficient for operation.

The second, more sophisticated (but larger), filter was installed (Figure 2-1) on the bus. The air conditioner was tried again and operated normally with the filter installed. The IMC traction inverter was enabled. This time the air conditioning unit continued to operate.

Figure 2-1

Air conditioning power filter



The operation of the filter was tested further with a 10-minute drive around the SARTA parking lot. No problems were noted. During the testing, thermal measures were made on the filter to confirm the design.

It should be noted that the filter was not permanently mounted during the testing; SARTA technicians later completed this task. The filter was located in the EBox high-voltage compartment above the DC-DC inductors using an aluminum plate and all-thread rods. The filter size was approximately 12” × 12” × 6”. Measurements of voltage to ground before and after the filter was added and indicated an attenuation factor between 10:1 and 20:1.

Before bus arrival at SARTA, an air conditioning unit power filter was designed to allow the air conditioner to operate while the bus was driving. Two versions of the power filter were designed. There was no access to the bus for testing until the May training. Each version was to be tried on site, but only one would be installed even if both worked. The first filter is known as a common mode filter, which typically is installed to protect equipment from voltages that are simultaneously present on both the positive and negative terminals with respect to ground. Two off-the-shelf 2.4mH, 17A rated chokes (common mode windings) were purchased. An assembly was constructed to add fuses, a terminal block, and the two chokes (wired in series). The incoming battery voltage connects into the fuses, and the filter output voltage is available at the terminal block. This type of filter is known as a Type 1 since the attenuation factor is approximately proportional to the inverse frequency of operation. The advantage of this filter over the second approach is that is simpler and smaller. A second order filter was constructed as backup. This type of filter uses inductive, capacitive, and resistive components. Its advantage is that attenuation is proportional to the inverse of frequency squared. Therefore, it can be much more effective when compared to Type I. The inductive and capacitive components were selected for a corner point frequency of 3KHZ (which is half the IMC operating frequency). The resistive component was selected to provide damping and thereby avoid resonance. The filter was implemented with two legs so each of the power connections (positive and negative) could be attenuated separately.

A second training was held at SARTA in May 2018. The main objectives of the training were to install an air conditioning unit power filter to allow the air conditioner to operate while the traction inverter was operating and install a maintenance computer in the bus.

Battery Box

The traction batteries are located in a removable box assembly in the rear of the bus. The assembly is "removable" for maintenance purposes using a fork lift. The battery box was removed to provide SARTA technicians with training in the removal and installation process. The battery should be inspected once a year for safety reasons. The battery box was removed and re-installed without incident. While it was out, construction of the battery was discussed. The locations of the cells, LMU modules, and the BMU module were pointed out, and the torque specification was checked for all battery power connections.

All 28 battery voltages were checked with a Fluke meter and averaged 25.85V, with a maximum deviation of approximately +/- 50 mV. Individual cells were not checked, but the data indicated that the cells were well balanced.

Some minor issues were found:

- Light oxidation on some of the bolts for the battery connections
- Evidence of water entry into the box in a couple of areas

High-voltage dielectric grease was added to all bolts in the battery power circuit. New rubber O rings were installed around all screws securing the cover.

Additional Items

Spare Parts List

EPC reviewed the spare parts list with the group.

Critical Component Repair

CSCC identified the major issues with the bus that required repair before it could be placed into service—repairing the air conditioner, installing the remote diagnostic computer, and obtaining spare parts for critical items such as the fuel cell and stack coolant pump.

The team did not drive the bus on the road but did drive it several hundred yards around the facility. At the end of the drive, a SARTA technician noticed that the Altairnano BMS system was reporting "battery unbalanced." This did not occur during operation in Birmingham. The issue meant that not all the cells in the battery (qty 280) had equal voltages. Likely, the cause was due to self-leakage while the bus was sitting around for a year or so. The Altairnano BMS uses very light balancing resistors, so the bus perhaps needed to operate for a while before the cells balanced. The bus was left connected to the charger where the best balancing occurs.

Safety Procedures

CSCC, with input on device locations, reviewed the safety procedures needed to pass along to first responders. EPC provided a document developed for UAB that was used as the basis for the discussion and gave a PDF to SARTA and CSCC. Valves for the emergency shutdown of the hydrogen were pointed out, as were the proper places for disconnecting the traction battery voltage.

Maintenance PC

The maintenance PC, cellular modem, RS232 isolators, antennas, and other miscellaneous components were shipped to SARTA in March 2018 and were available to start work on May 16. EPC supplied a preliminary bracket for mounting the PC in the bus. CSCC and SARTA technicians provided valuable help in making the mechanical modifications necessary to permanently install the computer physically. The PC was installed over the IMC module.

The antennas were installed on the roof of the bus, and the coax cables were routed to the cellular modem. Collectively, the two existing power wire points were located. The power relay was mounted, and wiring was completed to the computer such that it would be powered from the 12V on-board power whenever a driver was present but powered by the shore charger while charging (to avoid loading the on-board 12V battery). A feature of the computer (internal battery) allows five minutes of operation after the power is removed from its terminals. During this time, logging files are transferred to the internet.

Each traction system module (VSC, IMC, and FCDC) was connected and checked for communication with the computer over the RS232 cables between them. The Peak CAN adaptor was connected to the BMS CAN network so the Altairnano battery information could be remotely monitored.

The PC computer was tested for remote operation using an Android Galaxy SX6 cell phone. The PC performed properly and was accessible. The cell phone was used to set the variables being logged for diagnostics.

Test Drive

After the traction battery was re-installed, the vehicle was taken for a test drive around SARTA and included a few miles at 55 MPH on a nearby four-lane highway. The test drive lasted approximately one hour, including some stops, and was approximately 19 km. The air conditioning unit operated the entire time without incident. The traction system was monitored remotely by the maintenance PC. No problems were reported during the test drive. The SARTA technicians were impressed by the performance of the vehicle, especially the smoothness of the drive train and the acceleration capability. Some drive line resonance was present at speeds above 45 MPH. The same issue was reported with other fuel cell buses.

Bus Repairs

The team needed to repair a number of items on the bus prior to operation, including the air conditioner, heater, complete computer diagnostics, and tire replacement. These repairs were completed by the end of June 2018. Repairs made before the end of September 2018 are listed in Table 2-1.

Table 2-1

Bus Repairs by Date

Date	Repair
07/09/18	Cleaned and flushed preheater and tested
08/08/18	Started on defects, tested chiller
08/13/18	Fixed defects
08/14/18	R&R all tires
08/22/18	Found and ordered fuse
08/22/18	Made safety bar for back seat
08/27/18	R&R chiller fuse, road tested
08/28/18	R&R another ruse, fixed wire, unplugged green light
09/10/18	Filled heater tank, ran for 2 hours
09/10/18	Fixed light, R&R fuse, blown fuse, ordered fuses
09/12/18	R&R fuse, test drove for 0.5 hrs, blew fuse
09/20/18	Ran for fuse
09/20/18	Installed fuse on bus, tested
09/21/18	Tested, R&R chiller solenoid, tested

SARTA also needed to replace a leaky hydrogen valve on the roof, which was conducted in October 2018. Also replaced and recharged was a low-voltage battery, and SARTA installed a farebox, cleaned the heating system, and recertified the fuel tanks.

CSCC drafted a manual for the bus based on what it learned during the two trainings. The 500-page manual contains information and schematics related to the vehicle, including a description and operation of the bus and sections on maintenance and service, batteries, battery balance, shore battery charger, chassis wiring diagrams, HV/CAN network/block diagram, air conditioning, heater, electric motors and controllers, cooling systems, fuel cell system, and storage tank layouts. Appendices to the manual include information on safety warnings, a spare parts list, a seat layout, drawings, and weight slip.

SECTION
3

Outreach Events

CSCC used the bus for outreach events at middle schools in Ohio. New materials were developed for these events, including a bus wrap (Figures 3-1 and 3-2) and educational interior placards (Figure 3-3).

Figure 3-1
Front view of bus with new wrap

Figure 3-2
Side view of bus with new wrap

Figure 3-3

Interior placard on EVAmerica bus

MHCoE and CSCC conducted outreach events at middle schools in the Cleveland and Canton areas. Prior to the events with students, CSCC and MHCoE conducted a continuing education program for middle school teachers. In December 2018, they presented to nearly 1,000 students from four middle schools in Canton, Massillon, Cleveland, and Alliance and visited Cleveland State University to present on alternative energy sources and hydrogen fuel cells and take the students on bus rides. The events were publicized in multiple media outlets, including *Gas World* and *The Alliance Review.*

SECTION

4

SARTA Bus Fleet Operation Comparison

CTE was aware of many anecdotal reports about the performance of electric-drive buses compared to conventionally-fueled buses. These have included comments such as "the electric bus pulls into traffic more easily" or "the electric bus can't drive as fast on the highway as a diesel." CTE proposed to look into these anecdotes to determine any quantitative support for these claims.

CTE contracted with CAR to collect speed profile data on multiple SARTA buses. CAR investigated which loggers would be appropriate, eventually selecting one that could collect 10 Hz speed data.

CAR ordered 10 loggers for the data collection effort. In March, CAR-ES installed a data logger on a SARTA bus to test the logger and collect preliminary data before installing the remainder of the loggers. The logger was successfully tested, and in the second quarter of 2018, CAR-ES ordered nine additional loggers. Due to the data transfer rate when downloading information from the loggers, CAR-ES decided to conduct all data downloads and processing at its facility rather than on-site at SARTA.

Nine loggers were shipped to SARTA and installed on vehicles (three hydrogen fuel cell electric, three CNG, one diesel hybrid, and two diesels) in July 2018. Two loggers were shipped back to CAR-ES at the end of July to verify that the data collection was working; those data worked as expected. The remaining loggers were removed on August 31 and shipped to CAR for data download.

Following the initial analysis, CTE determined that more data were required. The loggers were re-installed in November and removed in January. CAR-ES downloaded the data and shared them with CTE.

CTE worked with an outside party to initiate development of a Matlab program to process the data received from CAR before finishing that work internally. CTE collected more than 5,000 hours of 10 Hz data that needed to be parsed into individual blocks to compare the performance of SARTA's buses with different propulsion types.

Definition of Terms

The 5,000 hours of raw logger data were compiled and analyzed using a Matlab script that calculated different metrics based on a single day of service for each bus. The metrics are defined and were calculated as follows:

- Average Speed – average of all speed values in data files, converted to mph
- Daily Max Speed – fastest a bus went in a single day
- Positive Acceleration – average positive acceleration that a bus experienced in a day; calculated by dividing the difference in speed by difference in time of two data entries
- Upper Quartile Acceleration – median of upper half of positive acceleration data points in a day
- Stop Time – total time in a day when bus was in service and speed was equal to zero
- Moving Time – total time in a day when bus was in service and speed was positive
- Total Time – total time a bus was in service
- Total Distance – total distance traveled by bus; data provided by SARTA, not calculated using logger data

Due to some issues with the loggers, some data were not usable. Additionally, days on which buses drove fewer than 40 miles were not included, as there was interest only in bus performance in revenue service or service-like conditions.

Summary of Results

Table 4-1 shows the average of all the daily metrics produced from the logger data from the four different bus types—diesel, diesel electric, CNG, and hydrogen. CTE combined diesel and diesel electric vehicles for this analysis because the two data sets individually were too small to provide additional value and the values were similar enough that they warranted combination. Through the rest of this report, diesel and diesel electric are used interchangeably.

Table 4-1

Average Value for Each Calculated Metric Across Four Propulsion Types

Propulsion Type	Avg. Speed (mph)	Daily Max Speed (mph)	Avg. Positive Acc. (m/s^2)	Upper Quartile Acc. (m/s^2)	Avg. Acc. in 30 sec (m/s^2)	Stop Time (hrs)	Moving Time (hrs)	Total Time (hrs)	Total Distance (mi)
Diesel Electric (n = 118)	15.59	57.03	0.51	0.79	0.27	4.13	8.93	13.07	215.85
CNG (n = 120)	17.60	56.51	0.46	0.69	0.26	4.37	8.44	12.81	268.63
Hydrogen (n = 74)	12.45	52.41	0.53	0.94	0.26	4.93	8.14	13.07	170.0

There were clear differences between the average daily values for many of the metrics among the propulsion types. Comparing the hydrogen fuel cell bus to the other two propulsion types, the speed, acceleration, and mileage stood out as significantly different. Part of this discrepancy can be explained by the normal route assignments for the vehicles. The hydrogen buses were nominally put on three specific routes (102, 105, Football Hall of Fame). The diesel electric and CNG buses, however, traveled on additional routes on which SARTA does not deploy its fuel cell buses. To make a more direct comparison between the bus types, the main analysis focused on data from routes 102 and 105 (Table 4-2). The Hall of Fame route was not included, as it is a non-standard transit route.

Table 4-2

Metrics for Buses Operated on SARTA Routes 102 and 105

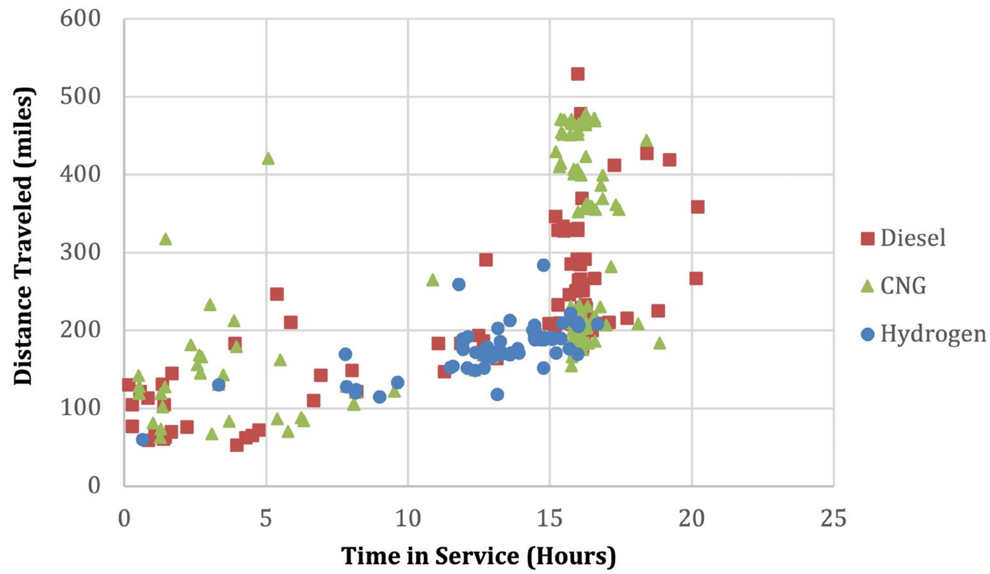
Propulsion Type	Avg. Speed (mph)	Daily Max Speed (mph)	Avg. Positive Acc. (m/s^2)	Upper Quartile Acc. (m/s^2)	Avg. Acc. in 30 sec (m/s^2)	Stop Time (hrs)	Moving Time (hrs)	Total Time (hrs)	Total Distance (mi)
Diesel Electric (n = 22)	12.97	56.30	0.50	0.75	0.26	4.49	9.58	14.07	186.5
CNG (n = 38)	13.65	55.51	0.52	0.79	0.26	4.57	7.04	11.61	171.84
Hydrogen (n = 74)	12.61	52.99	0.54	0.95	0.26	4.99	8.25	13.24	170

Detailed Data Analysis and Results

CTE compared some of the observed data points with each other to identify patterns in vehicle behavior. Figure 4-1 shows how far each bus went on a specific day. From this, it is clear that the hydrogen buses do not travel on SARTA's highest mileage routes or routes with the highest average speeds. A hydrogen fuel cell bus rarely exceeded 200 miles in a day. These data used information as provided by SARTA. It is likely for the days with mileage over 300 that it is reflecting the combined mileage of two days due to errors in reporting. These were differentiated based on when the buses were fueled, which sometimes resulted in two consecutive days of service being included in the same data point. As CTE was unable to parse which ones combined two days of service and which represented only one day of service, all data points were included in its analysis.

Figure 4-1

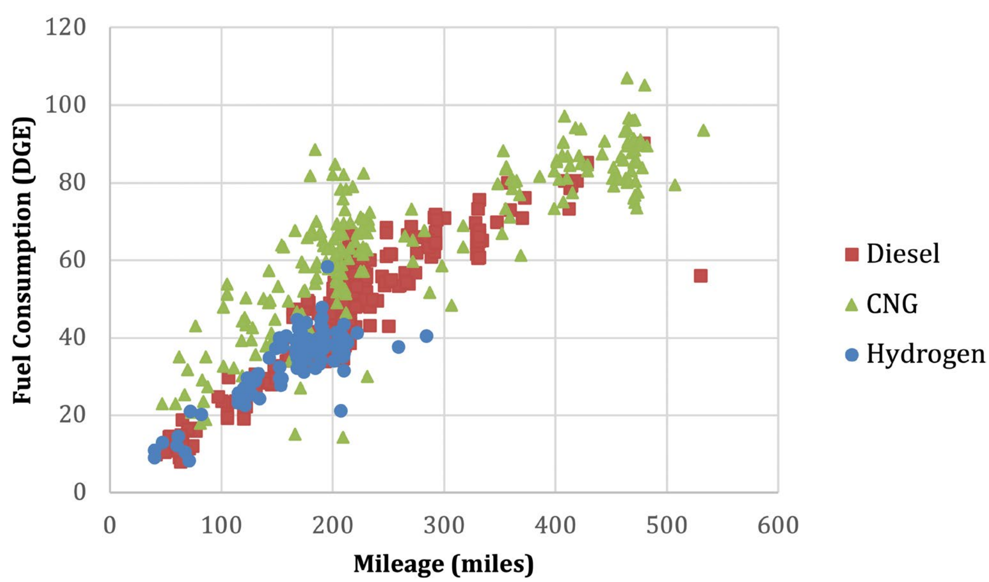
Hours bus in service on single day vs. miles traveled



CTE also was interested in comparing the fuel economies of the different propulsion types (Figure 4-2) and decided to use diesel gallon equivalent (dge) as the metric for comparison. These data rely on fuel economy calculated using data recorded by the loggers. The loggers parsed the data sets based on stopped time rather than fuel records, which is what the SARTA recorded data used. Both methods of identifying a block resulted in some data points appearing to have combined two days of service. As CTE could not parse single days from combined days, all data points were included.

Figure 4-2

Miles bus ran in single day vs. fuel consumption for that day in terms of gallons of diesel or gallons of diesel equivalent

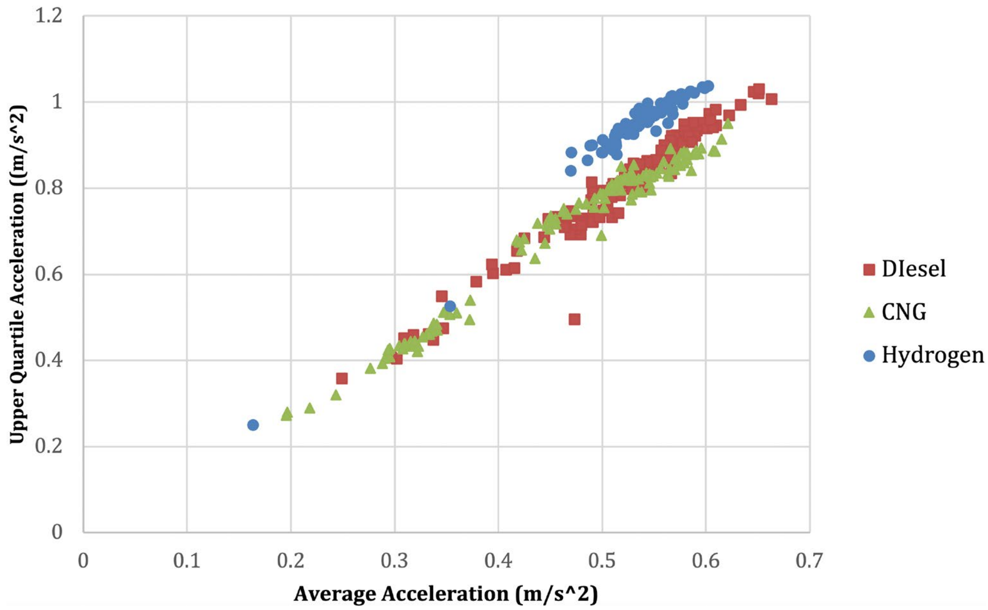


Based on Figure 4-2, the hydrogen buses experienced fuel consumption similar to the diesel buses but less relative fuel consumption than the CNG vehicles.

The remaining comparisons focused on vehicle acceleration metrics, as these seemed to be the most different between the hydrogen fuel cell buses and the other propulsion types. Figure 4-3 shows how average acceleration over the course of an entire block compared to the upper quartile of acceleration points for a day.

Figure 4-3

Average acceleration of bus in single day vs. upper quartile acceleration in a day



It is clear from Figure 4-4 that the hydrogen fuel cell buses experienced much greater positive acceleration values than the diesel and CNG buses, even though the average acceleration was similar. This is true even when controlling for different routes.

Figure 4-4

Average acceleration of bus in single day vs. upper quartile acceleration in a day on SARTA Routes 102 and 105

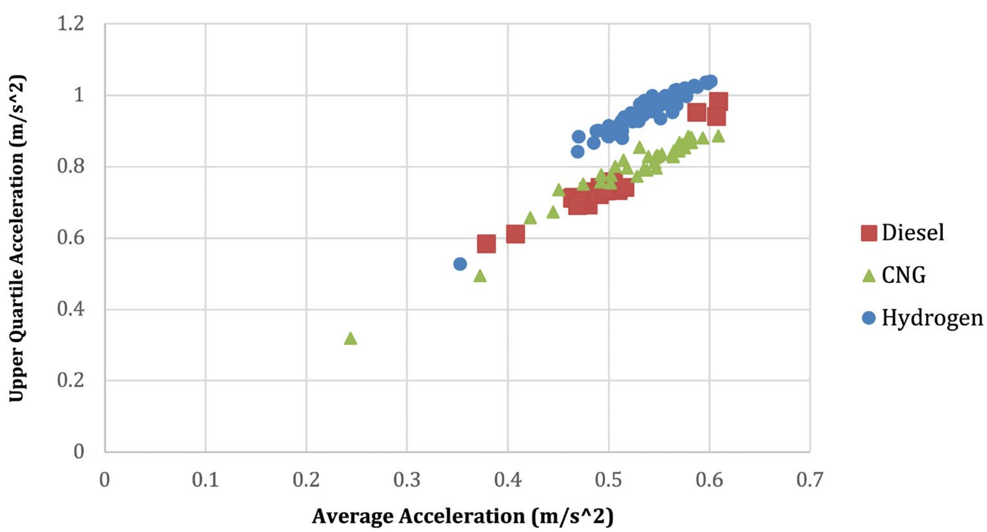


Figure 4-5

Average speed of bus in a single day vs. upper quartile acceleration in a day on SARTA Routes 102 and 105

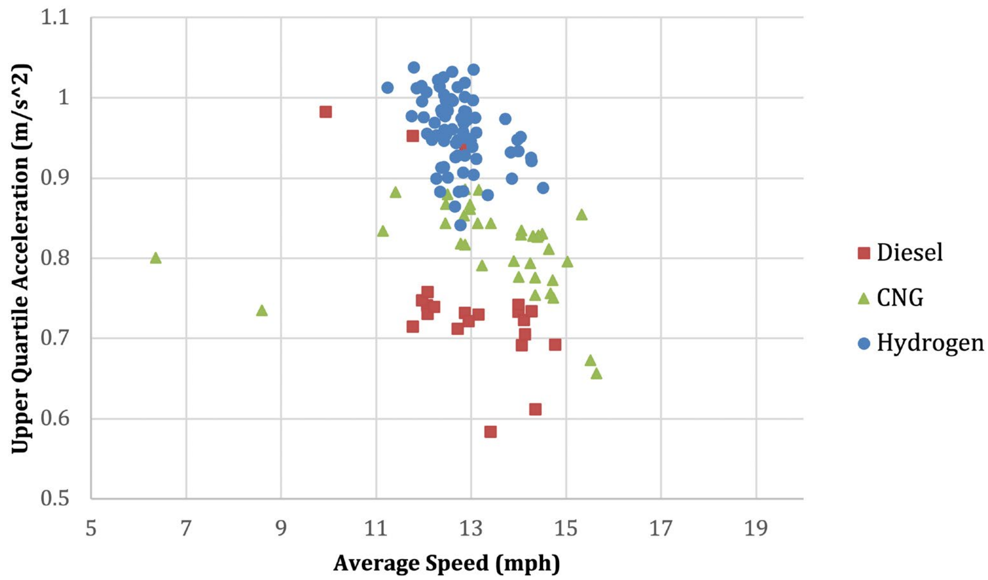


Figure 4-5 indicates that even when buses have similar average speeds, hydrogen fuel cell buses still have higher positive acceleration values than diesel electric or CNG buses. These figures support what CTE heard anecdotally regarding electric bus performance—the vehicles pull out from stops better than diesel buses. The hydrogen fuel cell electric buses have higher positive acceleration values than other propulsion types, which indicates that they can go from a stop to matching the speed of traffic more quickly than other vehicles.

SECTION

5

Conclusions

During this phase of the project, the team was able to successfully repair the EVAmerica bus and use it for outreach. The team also collected more than 5,000 hours of operational data on SARTA's fleet to evaluate if their fuel cell electric buses perform differently than other propulsion types and found that fuel cell buses had higher positive acceleration values than other vehicles, even after controlling for route characteristics.

Two members of the original bus build provided training to SARTA staff on the vehicle, assisted in diagnosing and repairing issues on the bus, and helped with installing a diagnostic maintenance computer on the vehicle and resolving an issue identified at the end of the demonstration in which the traction motor and air conditioning would not run simultaneously. Feedback also was provided to CSCC on its draft of a comprehensive manual for the vehicle for use in maintaining and operating the vehicle.

SARTA conducted minor repairs on the bus, which was fully repaired and ready for use in October 2018. SARTA also developed a new bus wrap and interior placards for the vehicle for use in outreach events.

CSCC and MHCoE conducted a continuing education program for middle school teachers, presented to nearly 1,000 students from four middle schools in Canton, Massillon, Cleveland, and Alliance, and visited Cleveland State University to present on alternative energy sources and hydrogen fuel cells.

CTE contracted with The Ohio State University's CAR to collect speed profile data on multiple SARTA buses. Data loggers were installed on the SARTA buses, and CAR conducted all data downloads and processing at its facility rather than on-site at SARTA. Overall, CAR collected more than 5,000 hours of 10 Hz data that was parsed into individual blocks to compare the performance of SARTA's buses with different propulsion types using a Matlab program. Observed data points were compared to identify patterns in vehicle behavior.

Results indicated that the hydrogen buses experienced fuel consumption similar to the diesel buses but less relative fuel consumption than the CNG vehicles. Other comparisons focused on vehicle acceleration metrics; the hydrogen fuel cell buses experienced much greater positive acceleration values than the diesel and CNG buses, even though the average acceleration was similar and when controlling for different routes. Quantitative evidence is provided that fuel cell buses can pull into traffic more easily than other buses.

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