Overview

Timeline and Budget

- Project start date: 09/01/03
- FY19 DOE funding: $150K
- FY20 planned DOE funding: $150K
- Total DOE funds received to date: $4.4M (over 18 years)

Barriers

- Lack of current fuel cell vehicle (bus) performance and durability data
- Lack of current hydrogen fueling infrastructure performance and availability data

Partners

- Transit fleets: Operational data, fleet experience
- Manufacturers: Vehicle specs, data, and review
- Fuel providers: Fueling data and review
Relevance

- Validate fuel cell electric bus (FCEB) performance and cost compared to DOE/DOT targets and conventional technologies
- Document progress and “lessons learned” on implementing fuel cell systems in transit operations to address barriers to market acceptance

<table>
<thead>
<tr>
<th>Current Targets&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Units</th>
<th>2016 Target</th>
<th>Ultimate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus lifetime</td>
<td>years/miles</td>
<td>12/500,000</td>
<td>12/500,000</td>
</tr>
<tr>
<td>Powerplant lifetime</td>
<td>hours</td>
<td>18,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Bus availability</td>
<td>%</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>Roadcall frequency</td>
<td>miles between roadcall</td>
<td>3,500/15,000</td>
<td>4,000/20,000</td>
</tr>
<tr>
<td>Operation time</td>
<td>hours per day/ days per week</td>
<td>20/7</td>
<td>20/7</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>$/mile</td>
<td>0.75</td>
<td>0.40</td>
</tr>
<tr>
<td>Fuel economy</td>
<td>miles per diesel gallon equivalent</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Bus Cost</td>
<td>$</td>
<td>1,000,000</td>
<td>600,000</td>
</tr>
</tbody>
</table>

Approach

Data Collection/Analysis
• Standard protocol
• Third-party analysis
• Comparisons to conventional-technology buses in similar service (diesel, CNG, diesel hybrid)

Individual Site Reports
• Documents performance by site
• Builds database of results
• Reports posted on NREL website

Annual FCEB Status Report (milestone)
• Analysis comparing results from all sites
• Assesses progress and needs for continued success
• Provides input on annual status for DOE/DOT targets

CNG = compressed natural gas
### Selected specifications for FCEBs included in data summary

<table>
<thead>
<tr>
<th>Bus Manufacturer</th>
<th>Van Hool</th>
<th>ENC</th>
<th>New Flyer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>A330</td>
<td>AFCB/Axcess</td>
<td>Xcelsior/XHE40</td>
</tr>
<tr>
<td><strong>Bus length/height</strong></td>
<td>40 ft/136 in.</td>
<td>40 ft/140 in.</td>
<td>40 ft/130 in.</td>
</tr>
<tr>
<td><strong>Fuel cell OEM</strong></td>
<td>UTC Power</td>
<td>Ballard</td>
<td>Ballard</td>
</tr>
<tr>
<td><strong>Model</strong></td>
<td>PureMotion 120</td>
<td>FCvelocity–HD6</td>
<td>FCvelocity-HD85</td>
</tr>
<tr>
<td><strong>Power (kW)</strong></td>
<td>120</td>
<td>150</td>
<td>85</td>
</tr>
<tr>
<td><strong>Hybrid system</strong></td>
<td>Siemens ELFA, Van Hool integration</td>
<td>BAE Systems HybriDrive</td>
<td>Siemens ELFA, New Flyer integration</td>
</tr>
<tr>
<td><strong>Design strategy</strong></td>
<td>Fuel cell dominant</td>
<td>Fuel cell dominant</td>
<td>Battery dominant</td>
</tr>
<tr>
<td><strong>Energy storage – OEM</strong></td>
<td>EnerDel</td>
<td>A123</td>
<td>A123</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Li-ion</td>
<td>Li-ion</td>
<td>Li-ion</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>17.4 kWh</td>
<td>11 kWh</td>
<td>100 kWh</td>
</tr>
<tr>
<td><strong>Altoona tested</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

ENC = ElDorado National California  
AFCB = American Fuel Cell Bus  
OEM = original equipment manufacturer
Approach: Data Summary for 2020

FCEB fleets included in data summary

<table>
<thead>
<tr>
<th>Transit Agency</th>
<th>Abbreviation</th>
<th>Location</th>
<th>Bus OEM</th>
<th># Buses</th>
<th>Data Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Transit</td>
<td>ACT</td>
<td>Oakland, CA</td>
<td>Van Hool</td>
<td>13</td>
<td>Fuel cell hours only</td>
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<tr>
<td>SunLine Transit Agency</td>
<td>SL</td>
<td>Thousand Palms, CA</td>
<td>ENC</td>
<td>8</td>
<td>All, prototype bus removed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>New Flyer</td>
<td>5</td>
<td>Preliminary fuel economy data</td>
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<tr>
<td>Orange County Transportation Authority</td>
<td>OCTA</td>
<td>Santa Ana, CA</td>
<td>ENC</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Stark Area Regional Transit Authority</td>
<td>SARTA</td>
<td>Canton, OH</td>
<td>ENC</td>
<td>5</td>
<td>All</td>
</tr>
</tbody>
</table>

AC Transit

SARTA

SunLine, New Flyer

OCTA

SunLine, ENC
Accomplishments and Progress
Top Fuel Cell Powerplant Exceeds 32,000 Hours

- Top fuel cell powerplant (FCPP) >32,000 hours
- 12 FCPPs have surpassed DOE/DOT ultimate target

AC Transit FCEBs

Total hours accumulated on each FCPP as of 3/1/2020
Accomplishments and Progress

FCEB Capital Costs Dropping

Newest FCEB order 2.8x lower cost compared to early demonstrations

OEM estimate for a 40-bus order

DOE Ultimate Target
Accomplishments and Progress
Reliability: Miles Between Roadcall (MBRC)

- Data from newer ENC buses
- Meeting ultimate target at the end of the data period
- Fuel cell system roadcalls are caused by balance of plant components, not stack issues
Accomplishments and Progress
Maintenance Cost by System

- Cost for propulsion system repairs highest for FCEBs
- Propulsion issues include:
  - Cooling system labor
  - Low-voltage batteries
  - Fuel cell BOP

- Cumulative cost from in-service date
- Labor @ $50/h

BEB = battery electric bus
BOP = balance of plant
PMI = preventive maintenance inspection
HVAC = heating, ventilation, and air conditioning
Accomplishments and Progress
Propulsion Maintenance Cost by Sub-System

<table>
<thead>
<tr>
<th>Cost by System ($/mi)</th>
<th>Exhaust</th>
<th>Hydraulic</th>
<th>Electric drive/Transmission</th>
<th>Fuel System</th>
<th>Cooling</th>
<th>Air Intake</th>
<th>Cranking/Charging</th>
<th>Electrical</th>
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<tbody>
<tr>
<td>FCEB</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>CNG</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Diesel</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>BEB</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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</tbody>
</table>

- FC costs for FCEB primarily labor
- ESS cost for FCEBs included in electric drive category
- Cooling costs primarily labor for checking/topping off fluids

Cumulative cost from in-service date
Labor @ $50/h

BEB = battery electric bus
BOP = balance of plant
ESS = energy storage system
Accomplishments and Progress
Maintenance Cost Trends

Cumulative maintenance cost from start of service

**Total Maintenance Cost**

- FCEB cost stabilizes over time

**Propulsion System Maintenance Cost**

- Propulsion system costs for FCEB currently higher than other technologies

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<table>
<thead>
<tr>
<th>Months from start of service</th>
<th>FCEB</th>
<th>Diesel</th>
<th>CNG (2008)</th>
<th>CNG (2016)</th>
<th>BEB</th>
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<tbody>
<tr>
<td>1</td>
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<td>10</td>
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</tbody>
</table>
Accomplishments and Progress
Maintenance Cost Trends

Cumulative maintenance cost from start of service

FCEB costs driven by labor costs

Parts cost for FCEBs currently low because most of the buses are still under warranty
Accomplishments and Progress
Fuel Economy

- Preliminary data on new design FCEBs
- Average fuel economy: 7.52 mi/kg, 8.52 mpdgeo
- Meets DOE/DOT ultimate target
Accomplishments and Progress: Responses to Previous Year Reviewers’ Comments

- Project should combine key data to generate insight into the total cost of ownership.
  - Response: NREL is evaluating how to incorporate this type of analysis in the future.

- Provide data in more severe climates (hot and humid, extreme cold)
  - Response: As FCEBs are deployed in different locations, NREL will explore the potential to add those vehicles to the data collection and analysis.

- Expand the scope to other emerging applications
  - NREL will be evaluating medium and heavy-duty fuel cell trucks as they are deployed.
Collaboration and Coordination

• Transit agencies (1) provide data on buses, fleet experience, and training and (2) review reports
  – California: AC Transit, SunLine, OCTA

• Manufacturers provide some data on buses and review reports
  – Bus OEMs: New Flyer, ElDorado National
  – Fuel cell OEMs: Ballard, Hydrogenics, US Hybrid
  – Hybrid system OEMs: BAE Systems, New Flyer

• FTA provided funding to cover evaluations of both FCEBs and BEBs – funding ended in 2019

• Other organizations share information and analysis results
  – California Air Resources Board, Center for Transportation and the Environment, CALSTART
Remaining Challenges and Barriers

• For technology acceleration and data collection project:
  – Continue data collection to track progress of newer-generation designs
  – Establish good relationships with additional transit agencies to add to the data set

• For industry to commercialize FCEBs:
  – Deploy larger fleets:
  • Lower per-bus price: OEMs estimate ~$1M/bus for higher volumes
  • Incorporate training into current course work
  • Accelerate learning curve for staff
  • Add trained technicians to staff at local OEM support centers
  – Install hydrogen stations
  • High capital cost to install, but easier to scale up compared to battery fleet
  • Standardization: each installation is different, making it challenging to plan budget
Proposed Future Work

• Remainder of FY 2020
  – Data collection focused on new designs at three fleets:
    • SunLine, 5 New Flyer FCEBs, 1 battery dominant FCEB
    • OCTA, 10 New Flyer FCEBs
    • AC Transit, 10 New Flyer FCEBs
  – Complete the following data analyses/reports:
    • SunLine AFCB Report, May 2020 (final report for this design)
    • 2020 Annual Status Report, September 2020
  – Analyze fuel cell truck projects

• FY 2021
  – Analyze and report on data from New Flyer FCEBs
  – Complete annual crosscutting analysis across sites

Any proposed future work is subject to change based on funding levels.
Technology Transfer Activities

• Project provides non-biased evaluation of technology developed by industry

• Project documents performance results and lessons learned to aid market in understanding needs for full commercialization
  – Manufacturers
  – Transit agencies
  – Policymaking organizations
  – Funding organizations

• No technology (hardware/software) is developed through this project
Summary: Progress Toward Targets

- Bus lifetime target: 12 years/ 500,000 miles
  - Multiple buses have reached 8 years in service
- Powerplant lifetime: 25K hours ultimate target
  - Ultimate target met
- Capital cost: $600K
  - New orders 2.8 times lower cost compared to early demo buses
- Fuel economy/range: 8 mpg/300 miles
  - Preliminary data on new bus model meets target
- Both FCEB U.S. models have completed Altoona testing
- Increasing interest in the U.S. primarily driven by advantages over BEB technology: increased range, fast fueling, easier scale-up of infrastructure
- Availability: 85% interim, 90% ultimate
  - Current data show FCEBs do not yet meet interim target (72%)
- Operation cost: $0.75/mi interim, $0.40/mi ultimate
  - Current cost is slightly more than ultimate target, some buses still under warranty. Need to track cost for newest design after warranty ends.
Backup Slides
Accomplishments and Progress
Maintenance Cost: Parts and Labor

- Majority of FCEB cost is from labor—troubleshooting and training increase labor hours
- Parts costs are low while the buses are under warranty
- BEBs out of warranty, some replacement parts are expensive (DC-DC converter >$14K)

- Cumulative cost from in-service date
- Labor @ $50/h
Accomplishments and Progress
Maintenance Cost: Scheduled and Unscheduled

- Similar costs for scheduled maintenance, with BEB the lowest
- Diesel buses experiencing issues with emissions equipment as they age
- BEBs had increased cost for parts once out of warranty – low-voltage batteries as well as advanced technology components

- Cumulative cost from in-service date
- Labor @ $50/h