Project Goal

- Validate fuel cell electric bus (FCEB) performance and cost
  - Determine status toward meeting DOE/U.S. Department of Transportation (DOT) technical targets
  - Compare to conventional technologies in similar service
- Document progress on implementing FCEBs in transit operations
  - Share early adopter lessons learned
  - Address barriers to market acceptance
  - Publish results for widespread industry and stakeholder use
- Assess future research needs to increase durability and reliability.
Overview

Timeline and Budget

- Project start date: 09/01/03
- FY20 DOE funding: $150,000
- FY21 planned DOE funding: $150,000
- Total DOE funds received to date*: $4,575,000
  * Since the project started

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
With industry input, DOE and DOT established technical targets that FCEBs need to meet to reach commercial viability.

Data collected are used to assess the progress toward meeting those targets and to provide feedback to DOE on what research is needed.

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### Selected Targets from DOE/DOT Program Record

<table>
<thead>
<tr>
<th>Metric</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>$/mile</td>
<td>0.75</td>
<td>0.40</td>
</tr>
<tr>
<td>Fuel economy</td>
<td>miles per diesel gallon equivalent (mpdge)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Bus cost</td>
<td>$</td>
<td>1,000,000</td>
<td>600,000</td>
</tr>
</tbody>
</table>

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Approach

Data Collection/Analysis
- Standard protocol, uses existing data from transit agencies
- Third-party analysis with comparisons to conventional technology.

Individual Reports
- Document performance by transit site
- Builds database of results
- Reports posted on NREL website for industry access.

Annual Status Report
- Analysis comparing results for all sites
- Assess progress toward meeting technical and cost targets
- Provide input to DOE for future R&D needs.
## Approach: Data Summary for 2021

### FCEB Fleets Included in Data Summary

<table>
<thead>
<tr>
<th>Transit Agency</th>
<th>Location</th>
<th>Bus OEM</th>
<th># Buses</th>
<th>Data Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Transit</td>
<td>Oakland, CA</td>
<td>Van Hool</td>
<td>13</td>
<td>Fuel cell hours only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>New Flyer</td>
<td>10</td>
<td>All</td>
</tr>
<tr>
<td>SunLine Transit Agency</td>
<td>Thousand Palms, CA</td>
<td>New Flyer</td>
<td>5</td>
<td>All</td>
</tr>
<tr>
<td>Orange County Transportation Authority (OCTA)</td>
<td>Santa Ana, CA</td>
<td>New Flyer</td>
<td>10</td>
<td>All</td>
</tr>
</tbody>
</table>

**OEM:** original equipment manufacturer
Accomplishments and Progress: Top Fuel Cell Powerplant Exceeds 32,000 Hours

Total hours accumulated on each FCPP as of 7/31/2020

AC Transit Van Hool FCEB Fleet

- Top fuel cell powerplant (FCPP) >32,000 hours
- 12 FCPPs have surpassed 25,000 hours

Durability
DOE’s benchmark is 20% F Fuel cell voltage degradation, but FCPP voltage/current data were not available. Therefore, using fuel economy as alternative, AC Transit’s FCEBs reached 20% degradation at 17,000 hours, nearing interim target.
Accomplishments and Progress: Fuel Economy Surpasses Target

~35% fuel economy increase over previous-generation FCEB

New Flyer FCEB Fleets

<table>
<thead>
<tr>
<th>Bus type</th>
<th>mphpge</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCEB</td>
<td>8.89</td>
</tr>
<tr>
<td>Compressed natural gas (CNG)</td>
<td>4.19</td>
</tr>
<tr>
<td>Diesel</td>
<td>4.13</td>
</tr>
<tr>
<td>Hybrid</td>
<td>5.35</td>
</tr>
</tbody>
</table>

FCEB fuel economy 2 times greater than that of CNG and diesel buses; 1.6 times greater than that of hybrid buses.
Accomplishments and Progress: FCEB Availability

Availability by Month

First FCEB of this design from OEM, agencies helping work through early deployment issues typical of any new design.

FCEB Reasons for Unavailability

Most unavailable days are due to general bus issues.

PM = preventive maintenance
Accomplishments and Progress: Maintenance Cost by System

- Cost for FCEBs similar to that of diesel and BEBs
- Propulsion costs include:
  - Labor for troubleshooting
  - Consumables
- PMI is labor for inspections

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

- Cumulative cost trends over time to compare FCEBs to other technologies
- Indication of primary cost drivers
- Data aligned to the start date for each fleet.

<table>
<thead>
<tr>
<th>Technology</th>
<th># of Buses</th>
<th>Data Period</th>
<th># of Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCEB 1</td>
<td>14</td>
<td>June 2014–July 2019</td>
<td>61</td>
</tr>
<tr>
<td>CNG (2016)</td>
<td>15</td>
<td>June 2016–July 2019</td>
<td>38</td>
</tr>
<tr>
<td>Diesel</td>
<td>10</td>
<td>July 2013–July 2017</td>
<td>49</td>
</tr>
<tr>
<td>BEB 1</td>
<td>12</td>
<td>Jan. 2015–Dec. 2019</td>
<td>60</td>
</tr>
</tbody>
</table>

Fleets included in trend charts

Cumulative maintenance cost from start of service
Accomplishments and Progress: Maintenance Cost Trends

Cumulative maintenance cost from start of service

Total Maintenance Cost

FCEB cost stabilizes over time. CNG and diesel cost show a steady climb as the buses age.

Propulsion System Maintenance Cost

Propulsion system costs for FCEB currently higher than other technologies.
Accomplishments and Progress: Maintenance Cost Trends

Cumulative maintenance cost from start of service

Labor hours per 1,000 miles

FCEB costs driven by labor costs
Learning curve for new technology/designs

Parts
Parts cost for FCEBs currently low because most of the buses are still under warranty, or supported by OEMs under extended agreements

Accomplishments and Progress: Maintenance Cost Trends

Cost per Mile ($)

Cumulative maintenance cost from start of service

FCEB costs driven by labor costs
Learning curve for new technology/designs

Parts
Parts cost for FCEBs currently low because most of the buses are still under warranty, or supported by OEMs under extended agreements

Accomplishments and Progress: Maintenance Cost Trends

Cost per Mile ($)

Cumulative maintenance cost from start of service

FCEB costs driven by labor costs
Learning curve for new technology/designs

Parts
Parts cost for FCEBs currently low because most of the buses are still under warranty, or supported by OEMs under extended agreements
Accomplishments and Progress: Response 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.

Any proposed future work is subject to change based on funding levels.
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. Current FCEB OEMs:
  - Bus OEM: New Flyer
  - Fuel cell OEM: Ballard
  - Hybrid system OEM: New Flyer
- 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
  – Explore gathering data to assess fuel cell powerplant degradation
  – 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 coursework
    • 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 2021
  - Continue data collection on new designs at three fleets:
    - SunLine, 5 New Flyer FCEBs
    - OCTA, 10 New Flyer FCEBs
    - AC Transit, 10 New Flyer FCEBs
  - Complete the following data analyses/reports:
    - AC Transit New Flyer FCEB Progress Report, May 2021
    - 2021 Annual Status Report, September 2021
  - Work with OEMs to determine what detailed data can be collected.
- FY 2022
  - 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.
Summary

• Project uses existing data primarily from transit agencies to assess the progress of FCEB technology toward commercialization
• Collected and analyzed data on newest FCEB design at three agencies
• Collected data on three baseline technologies for comparison: CNG, diesel, and diesel hybrid
• Documented progress toward meeting DOE/DOT targets:
  – Powerplant lifetime: 25,000 hours ultimate target @ <20% FC voltage degradation
    • Using fuel economy degradation as a substitute, AC Transit FCEBs reached 20% fuel economy degradation at 17,000 hours, nearing interim target of 18,000 hours
  – Fuel economy/range: 8 mpdge/300 miles
    • New bus model meets fuel economy target at 8.89 mpdge, range based on 95% useful fuel capacity (37.5-kg tank) is 280 miles
• Published reports to aid other transit agencies considering FCEBs.
Thank You
Technical Backup and Additional Information
Technology Transfer Activities

• Project provides unbiased 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
  o Multiple buses have reached 9 years in service
• Powerplant lifetime: 25,000 hours ultimate target @ <20% voltage degradation
  o Using fuel economy degradation as a substitute, AC Transit FCEBs reached 20% fuel economy degradation at 17,000 hours, nearing interim target of 18,000 hours
• Capital cost: $600,000
  o New orders 2.8 times lower cost compared to early demonstration buses
• Fuel economy/range: 8 mpd/ge/300 miles
  o New bus model meets fuel economy target at 8.89 mpd/ge, range based on 95% useful fuel capacity (37.5-kg tank) is 280 miles
• Both FCEB U.S. models have completed Altoona testing
• Increasing interest in the United States primarily driven by advantages over BEB technology: increased range, fast fueling, easier scale-up of infrastructure
• Availability: 85% interim, 90% ultimate
  o Current data show FCEBs do not yet meet interim target (72%)
• Operation cost: $0.75/mi interim, $0.40/mi ultimate
  o Current cost is less than ultimate target; however, buses are still under warranty. Need to track cost for newest design after warranty ends.
Accomplishments and Progress: Maintenance Cost: Scheduled and Unscheduled

- All fleets under warranty except hybrids
- Similar costs for scheduled maintenance, with BEB the lowest
- Similar unscheduled costs for FCEB, diesel, and BEB fleets.

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

New Flyer FCEB Fleets

- FCEB costs are primarily labor for troubleshooting issues
- Parts not covered under warranty include consumables such as filters and compressor oil.

- Cumulative cost from in-service date
- Labor @ $50/h
Accomplishments and Progress: Propulsion Maintenance Cost by Subsystem

- FC costs for FCEB primarily labor and scheduled maintenance parts (filters, coolant)
- ESS cost for FCEBs included in electric drive category

ESS = energy storage system

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

New Flyer FCEB Fleets
Planned and Potential Purchases in California

- Based on 18 zero emission bus (ZEB) Rollout plans for California agencies
- TBD category could be either FCEB or BEB
Publications and Presentations