Overview

Timeline
• Project started in FY03
• First-generation FCB completed in FY09
• Second-generation FCBs begin 3rd Qtr 2009

Budget
• FY 2009: $205K
• FY 2008: $300K
• FY 2007: $288K

Barriers
A. Lack of fuel cell vehicle performance and durability data
B. Lack of H₂ fueling infrastructure performance and availability data
D. Need for maintenance and training facilities

Partners
• Fleets: Operational data, fleet experience
• Manufacturers: Vehicle specs, data and review
• Fuel providers: Fueling data and review
Objectives

• Overall: Validate fuel cell and hydrogen technologies in transit applications
  – Measure progress of the technology toward commercialization
  – Provide “lessons learned” on implementing next-generation fuel cell systems in transit operations
  – Harmonize data collection efforts with other fuel cell bus demonstrations worldwide (in coordination with FTA and other U.S. and international partners)

• 2009
  – Complete data reports on CTTRANSIT and SunLine
  – Begin data collection and analysis for next-generation fuel cell buses at Burbank and AC Transit
  – Crosscutting analysis of FCB status at all sites
## Planned FCB Evaluations for DOE and FTA

### NREL Hydrogen Bus Evaluations for DOE and FTA

<table>
<thead>
<tr>
<th>Site/Location</th>
<th>State</th>
<th>Eval. Funding</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Transit/ SF Bay Area</td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SunLine/ Thousand Palms</td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SunLine/ Thousand Palms</td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTTRANSIT/ Hartford</td>
<td>CT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City of Burbank/ Burbank</td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Transit/ Oakland</td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SunLine/ Thousand Palms</td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTTRANSIT/ Hartford</td>
<td>CT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Columbia / Site 2/ CTTRANSIT</td>
<td>SC/CT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logan Airport / Boston</td>
<td>MA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TBD / NY</td>
<td>NY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TBD / NY</td>
<td>NY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFMTA / San Francisco</td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **DOE Technology Validation**
  - CA ZEB Advanced Demo
  - FCB Extended Testing
  - Advanced FCB Project
  - CTTRANSIT FCB Demo
  - Burbank

- **Accelerated Testing**
  - American FCB Demo
  - Nutmeg Hybrid FCB Demo
  - Dual Variable Output Hybrid FCB
  - MA H2 FCB Demo
  - Lightweight FCB Demo
  - NYPA H2 Powered FCB
  - FC APU Hybrid

**Demonstration sites color coded by geographic area:**

- **Northern California**
- **New England**
- **Southeast**
- **Southern California**
- **New York**
- **South**
Milestones

• Begin data collection on buses at cold climate sites – Hartford, CT: FY07
• Complete evaluations of 1st generation FCBs:
  – Santa Clara VTA: completed in FY07
  – AC Transit: completed in FY09
  – SunLine: FY09
  – CTTRANSIT: FY09
• Begin evaluations of 2nd generation FCBs
  – City of Burbank: FY09
  – AC Transit: FY09
### Evaluation Approach

- **Data collection & analysis at separate transit sites**
  - Follows existing, standard protocol
  - Cost-effective process utilizing data already collected by agency
  - Includes data on baseline vehicles in same service
  - Builds database of evaluations

- **Annual crosscutting analysis measuring progress toward commercialization**
  - Includes summary of data across all sites
  - Assessment of progress and needs for continued success

- **Continual assessment of data collection process**
  - Investigate opportunities to expand data collected and analyzed as resources allow
Comparison of Fuel Cell Buses to Conventional Technology Baseline

Metrics for assessing progress toward commercialization

- Performance characteristics
- Bus use
- Fuel economy
- Availability
- Reliability – miles between road call (MBRC)
- Cost – capital, fueling, and maintenance
- Implementation experience
Fleet Data Summary: SunLine

**Fuel Cell Bus (hybrid system)**

- 7 months operation of 1 FCB
- Total miles: 11,461
- New, updated version of fuel cell installed
- Total FC system hours: 885

**CNG Bus**

- 7 months operation of 5 CNG buses
- Total miles: 159,150

---

### Average Monthly Miles

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>CNG Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles</td>
<td>1,694</td>
<td>4,547</td>
</tr>
</tbody>
</table>

### Fuel Economy (diesel equiv. gal)

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>CNG Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>86%</td>
<td>3.2</td>
</tr>
</tbody>
</table>

### Percent Availability

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>CNG Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>76%</td>
<td>86%</td>
</tr>
</tbody>
</table>

### MBRC: Propulsion only

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>CNG Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles</td>
<td>14,468</td>
<td>2,292</td>
</tr>
</tbody>
</table>

National Renewable Energy Laboratory
Innovation for Our Energy Future
Fleet Data Summary: SunLine

Summary of Costs*

<table>
<thead>
<tr>
<th>CNG</th>
<th>FCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.61</td>
<td>$0.11</td>
</tr>
<tr>
<td>$1.10</td>
<td>$0.45</td>
</tr>
<tr>
<td>$0.42</td>
<td>$0.21</td>
</tr>
<tr>
<td>$1.04</td>
<td>$1.04</td>
</tr>
<tr>
<td>$1.74</td>
<td>$1.60</td>
</tr>
</tbody>
</table>

- **Average fuel cost (per kg or gge)**: $1.74
- **Total Cost per mile**: $8.00
- **Fuel cost per mile**: $1.10
- **Total Maintenance Cost per mile**: $8.00
- **Propulsion system maintenance cost per mile**: $1.04

* Warranty data are not included in calculations. Manufacturer’s staff are conducting most of the system repairs. Costs are expected to increase as fleet takes over these tasks.

Report published 1/09
Available online at www.nrel.gov/hydrogen/pdfs/44646-1.pdf

Evaluation Status

- **Completed data collection on current-gen. design**: report, June 08
- **Began data collection on bus with new design FC**: report, Jan. 09
Fleet Data Summary: CTTRANSIT

**Fuel Cell Bus (hybrid system)**
- 14 months operation of 1 FCB
- Total miles: 24,127
- Updated version of fuel cell installed
- Total FC system hours: 3,544

**Diesel Bus (baseline)**
- 14 months operation of 3 diesel buses
- Total miles: 137,127
Summary of Costs*

- Fuel cost per mile:
  - Diesel: $0.74
  - FCB: $0.42

- Total Maintenance Cost per mile:
  - Diesel: $1.12
  - FCB: $1.04

- Propulsion system maintenance cost per mile:
  - Diesel: $0.12
  - FCB: $0.76

- Average fuel cost (per kg or gge):
  - $2.70

- Total Cost per mile:
  - $2.16

- Total Maintenance Cost per mile:
  - $2.70

- Average fuel cost:
  - $5.29

* Warranty data are not included in calculations. Manufacturer’s staff are conducting most of the system repairs with assistance from agency staff. Costs are expected to increase as fleet takes over these tasks.

Evaluation Status

- In progress
- First fleet operating in cold climate
- 1st report, Oct. 08
- 2nd report, May 09

Report published 10/08
Available online at www.nrel.gov/hydrogen/pdfs/43847.pdf
Fleet Data Summary: AC Transit

Fuel Cell Bus (hybrid system)

- ~9 months operation of 3 FCBs (Clean point with new FC systems)
- Total miles: 49,600
- Total FC system hours: 4,957

Diesel Bus (baseline)

- 12 months operation of 6 diesel buses
- Total miles: 266,514

---

**Average Monthly Miles**

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>Diesel Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>3,702</td>
<td>1,837</td>
</tr>
</tbody>
</table>

**Fuel Economy (diesel equiv. gal)**

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>Diesel Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>61%</td>
<td>7.3</td>
<td>4.2</td>
</tr>
</tbody>
</table>

**Percent Availability**

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>Diesel Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>61%</td>
<td>85%*</td>
<td>61%</td>
</tr>
</tbody>
</table>

* Goal for ACT buses

**MBRC: Propulsion only**

<table>
<thead>
<tr>
<th></th>
<th>Fuel Cell Bus</th>
<th>Diesel Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,661</td>
<td>1,189</td>
<td>10,661</td>
</tr>
</tbody>
</table>
### Evaluation Status

- **Complete for current-generation buses – report, 7/08**
- **Data collection continues under FTA funding (accelerated testing of current generation)**
- **Next-generation buses arrive 2009 (planned DOE evaluation)**

---

### Summary of Costs*

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost per Mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average fuel cost (per kg or gal)</td>
<td>$2.29</td>
</tr>
<tr>
<td>Fuel cost per mile</td>
<td>$1.23</td>
</tr>
<tr>
<td>Total Maintenance Cost per mile</td>
<td>$1.23</td>
</tr>
<tr>
<td>Propulsion system maintenance cost per mile</td>
<td>$0.14</td>
</tr>
<tr>
<td>Total Cost per mile</td>
<td>$1.89</td>
</tr>
<tr>
<td><strong>Total Maintenance Cost per mile</strong></td>
<td><strong>$8.00</strong></td>
</tr>
</tbody>
</table>

* Warranty data are not included in calculations. Manufacturer’s staff are conducting most of the system repairs. Costs are expected to increase as fleet takes over these tasks.

Update report published 7/08
Infrastructure Data Summary

**VTA**
- Air Products
- Liquid $\text{H}_2$ storage
- Dispenses compressed $\text{H}_2$
- 32 months of data

**SunLine**
- HyRadix
- Natural gas reformer
- 24 months of data

**AC Transit**
- Chevron
- Natural gas reformer
- 34 months of data

**CTTRANSIT**
- UTC Power station
- Praxair
- Liquid $\text{H}_2$ storage
- Dispenses compressed $\text{H}_2$
- 20 months of data
Infrastructure Data Summary

Fueling Rate Histogram

- Number of fueling events: 2,469
- Average kg/fill: 23.6 kg
- Total kg dispensed: 58,179
- Average fueling rate: 1.4 kg/min
- Average fill time: 16.5 min
Future Work

• Remainder of FY 2009
  – Complete data analysis reports on CTTRANSIT and SunLine
  – Initiate data collection on next-generation fuel cell buses at AC Transit and City of Burbank
  – Initiate detailed data collection on first FCBs developed under the FTA program
  – Complete annual crosscutting analysis across sites

• FY 2010
  – Complete data analysis and reports on CTTRANSIT, City of Burbank, and AC Transit
  – Initiate detailed data collection on additional FCBs developed under the FTA program
  – Continue coordinating data collection activities with FTA
Summary

Progress

- Continued data collection & analysis of five FCBs in real-world service at three transit agencies
- Agencies working to maximize service of buses: Operating up to 19 hours/day, 7 days/week
- Fuel economy improvement over conventional technology as high as 2 times (depending on duty cycle)
- Manufacturer has modified FC based on early results. New version installed in all 5 buses beginning in late 2007
- Biggest improvement seen in availability with new fuel cell system
- Results show improvements in reliability

<table>
<thead>
<tr>
<th>Agency</th>
<th>Total Miles</th>
<th>Total FC hours</th>
<th>Clean Point Miles</th>
<th>Clean Point FC hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Transit</td>
<td>142,176</td>
<td>13,819</td>
<td>77,332</td>
<td>7,821</td>
</tr>
<tr>
<td>SunLine</td>
<td>68,436</td>
<td>5,255</td>
<td>16,102</td>
<td>1,228</td>
</tr>
<tr>
<td>CTTRANSIT</td>
<td>29,284</td>
<td>4,451</td>
<td>24,127</td>
<td>3,544</td>
</tr>
</tbody>
</table>

![Fuel Economy Comparison Across Fleets](chart1.jpg)

![Average Availability](chart2.jpg)
OEMs working through early issues

- **Fuel cell durability**
  - Early versions were showing more degradation than expected
  - Modifications were made to address issues

- **Energy storage issues**
  - Issues encountered with ZEBRA batteries
  - Manufacturers have been investigating problems, solutions include software modifications

- **Issues to be addressed in next generation**
  - Investigating new energy storage solution
  - Modifications to reduce height and weight of bus will eliminate need for current speed limitations
  - Increase training levels to transfer more maintenance work to transit staff