Battery-Electric Buses 101

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Battery Electric Buses 101

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Minneapolis, MN

Erik Bigelow
Senior Project Manager
Center for Transportation and the Environment
About CTE

• Mission: To advance clean, sustainable, innovative transportation and energy technologies
• 501(3)(c) non-profit
• Portfolio - $400+ million
  – Research, demonstration, deployment
  – Alt. fuel and advanced vehicle technologies
• National presence
  Atlanta, Berkeley, Los Angeles, St. Paul
CTE Activity Roadmap

Over $217 million active project portfolio
CTE Zero Emission Bus Projects

More than 140 ZEB’s with over 30 Transit Agencies
Overview & Agenda

- Why switch to electric buses?
- Battery electric bus history
- Understanding batteries
- Charging overview
- Driving range
- Electric rates and fuel cost
- Planning for your fleet
Warming Up the Batteries

• Where are you from?

• What is your experience with zero emission buses so far?
Electric Bus Fleet Trivia

• Where is the current largest US Zero Emission Fleet?
• Where is the longest (in years) running battery electric bus operation?
What do you want to hear about?

• Key concerns?
• Open questions?
• Getting started?
Key Terms

• ZEB – Zero Emission Bus
• BEB – Battery Electric Bus
Why Electrify Buses Now?
Why Electrify Buses Now?

• Currently a global movement to electrify transportation underway

  Volvo
  “Every Volvo from 2019 on will have an electric motor”

  Toyota
  “All cars will be only battery electric or fuel cell by 2050”

  France & UK
  Planning to ban sales of combustion engines by 2040
Why Electrify Buses Now?

• Transportation GHG is now above power generation for the first time
Local Pollution Control

• Most bus emissions are concentrated where people are most concentrated
• Shifting energy production to centers outside of cities, or to zero emission, reduces impacts on population

LA, Nov 2015 - from LA Times
Overall Energy Efficiency – “Well to Wheels”

- Combustion vehicles convert 17-21% of gasoline energy to power at the wheels (U.S. EPA)
- FCEVs convert 36-44% of hydrogen energy to power at the wheels (ANL GREET model)
- BEVs convert 59-62% of grid energy to power at the wheels (U.S. EPA)

https://cafcp.org/sites/default/files/W2W-2016.pdf

GREET V1_2013

Fuel Production
Fuel Consumption

[Image of bar charts showing energy efficiency values for different fuels]
Regulatory Environment

• Increasing complexity of Emissions Controls
• Zero Emission Bus Mandates

Modern diesel emissions control Technology
• DOC
• DPF
• DEF
• SCR
• AOC
• EGR
Zero emission buses are quiet

• Quieter interiors are more comfortable
• Quieting city centers makes transit more desirable
Key Current Challenges

1. Initial Capital Cost
2. New Operational Requirements
3. Procurement Hurdles
4. Charging Interfaces/Standards
5. Long Term Energy Needs

Adapted from UITP eBus Training Program, June 2017
Hydrogen Fuel Cell vs. Battery Electric

- Both are all-electric drivetrains
- Both are zero point source emission

Battery Electric Vehicle
Hydrogen Fuel Cell vs. Battery Electric

• Both are all-electric drivetrains
• Both are zero point source emission
Hydrogen Refueling

- Vehicle fueling is similar to CNG
- Station fuels buses in \(~15\) minutes, which are then ready for the next pull out
- Sufficient range for most transit service
Hydrogen Fuel Cell Buses

- Pro: Simpler logistics and fueling
- Con: Higher capital and operating cost
- Costs are coming down rapidly

<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$3.2 mm</td>
</tr>
<tr>
<td>2010</td>
<td>$2.2 mm</td>
</tr>
<tr>
<td>2016</td>
<td>$1.1 mm</td>
</tr>
<tr>
<td>2019</td>
<td>Under $1 mm</td>
</tr>
</tbody>
</table>

40’ Fuel Cell Transit Bus Price History
Battery Electric Bus History

• Similar history to light duty vehicles
  – Technology has been generally available for decades, but the right combination of affordability and capability are here

• Earliest electric buses were before gasoline vehicles were reliable

1915  1974  1992
Understanding Batteries

High capacity batteries are the key enabler of modern electric buses

Key Topics to Discuss

• Battery Chemistries
• System Architecture
• Safety
• Units of Measure
Battery Chemistries

• All batteries in new buses today are variations of Lithium Ion batteries
• Different battery chemistries offer different strengths and benefits

• Typical Chemistries:
  – NMC - Nickel Manganese Cobalt
  – LiFe – Lithium Iron Phosphate
  – LiTo – Lithium Titanate
Energy Storage Architecture

Cell $\rightarrow$ Module $\rightarrow$ String $\rightarrow$ Pack

$3V_{\text{DC}}$ $\rightarrow$ $30V_{\text{DC}}$ $\rightarrow$ $400-600V_{\text{DC}}$

Note: manufacturers may use different terms

• A battery energy storage system is comprised of components:
  – Battery cells
  – Packaging – mechanical, thermal management
  – Safety – fusing, ground fault detection
  – Battery Management System
Battery Capacity Terminology

• **State of Charge (SOC)**
  – Percent of total energy currently in batteries

• **State of Health (SOH)**
  – Measure of degradation from BOL

• **Beginning of Life (BOL) Capacity**
  – Energy storage capacity when new

• **End of Life (EOL) Capacity**
  – Energy storage capacity when useful limit, or warranty condition, is reached
Batteries Units of Measure

• kW and kWh measure very different things

<table>
<thead>
<tr>
<th>Unit</th>
<th>Describes what?</th>
<th>Conventional Equivalent</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW</td>
<td>Power</td>
<td>Horsepower (hp)</td>
<td>This battery pack can provide 230 kW (308 hp)</td>
</tr>
<tr>
<td>kWh</td>
<td>Energy</td>
<td>Gallons of diesel</td>
<td>This bus stores 300 kWh (7.9 gallons diesel)</td>
</tr>
</tbody>
</table>
Battery Capacity Terminology

Beginning-of-Life Batteries

OEM Minimum Allowable SOC

Unusable Energy

Reserved Energy

Usable Energy

OEM Maximum Allowable SOC

Unusable Energy

Total Battery Energy
Battery Capacity Terminology

End-of-Life Batteries

Note: Batteries all lose capacity through use and aging
• Different batteries have different safety related characteristics, **effective cell management is the most critical**

*Any* energy storage that can move a bus (diesel, CNG, or battery) can lead to a hazard in the wrong conditions
New vs. Similar Bus Systems

• Many onboard systems will be identical to diesel counterparts

• New Systems
  – Electric Heating and Air Conditioning
  – Electric Accessories: Power Steering, Air Compressor
  – Electric drivetrain: Batteries, Motor, Controls

• Vehicle Charging Interface
Charging Infrastructure Installation

• Installation can be a significant infrastructure project
• We typically budget around 1 year for the entire process for on-route infrastructure
• Identify how this fits in to longer range plans if possible
Charging Option Overview

**Depot Charge**
- Conductive

**On Route Charge**
- Conductive
  - Static
  - Dynamic – trolley style
- Inductive
  - Static
  - Dynamic – early research
Zero Emission Buses & Infrastructure

Depot Charge – Conductive

- Large battery pack
- 70 – 300 mile range
- 50 – 120 kW charger
- Recharge in 3-7 hours
- Fast chargers may be an option in the future
Zero Emission Buses & Infrastructure

Pros

– On site infrastructure (chargers at depot)
– Takes advantage of lower off-peak electricity rate
– Flexibility for route selection and route changes

Cons

– Must be taken out of service to recharge
– Larger, heavier battery packs
– Scalability at the depot can be a challenge
Zero Emission Buses & Infrastructure

On-Route Charge – Conductive Stationary

– Smaller battery pack
– 20 – 50 miles range
– 300 – 500 kW charger
– Full charge in 5 - 15 mins.
Zero Emission Buses & Infrastructure

On-Route Charge – Stationary Conductive

• Pros
  – Charging while on-route, 24/7 operation possible
  – Smaller Battery Pack
  – Distributed demand may minimize grid impacts

• Cons
  – Higher cost of charging infrastructure
  – Overhead systems may require dedicated/restricted pull-off
  – May require change to service schedule to charge
  – Costly to modify routes in the future
Zero Emission Buses & Infrastructure

On-Route Charge – Inductive Stationary

- Profile:
  - 50 kW charger
    - 200-250 kW in development
  - Can be primary charger with 250 kW version
Zero Emission Buses & Infrastructure

On-Route Charge – Inductive Stationary

• Pros
  – Can remain in service while charging on-route
  – Extends range of depot-charged BEB
  – Smaller on-route infrastructure footprint

• Cons
  – At current power level, cannot be used as sole source
  – Infrastructure and cost for on-route charging system
  – Costly to modify routes in the future
• It depends!
• Different bus models will have different installed energy capacity
  – All else being equal, usable range depends directly on capacity
• Larger battery packs are heavier
  – Causes slight efficiency penalty
• Headlights are not a big draw
Range – HVAC Impacts

- Heating and cooling will cause the single largest impact on usable range
- In most of the US, heating on the coldest days will have a larger impact than AC on the hottest days
- Vehicle planning needs to include varied HVAC impact
- Diesel fired heaters are typically available for cold climates
Range Impacts – How is the Bus Used

• The next largest impact to efficiency is sitting in the driver’s seat
• Regenerative breaking recovers significant energy
• Hard braking will increase overall energy use
## Range Impacts – How is the Bus Used

<table>
<thead>
<tr>
<th>Route</th>
<th>OEM Brochure</th>
<th>CTE Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Route A</strong> (summer, no passengers)</td>
<td>1.7 – 2.0</td>
<td>1.72</td>
</tr>
<tr>
<td><strong>Route A</strong> (summer, avg. passengers)</td>
<td>1.7 – 2.0</td>
<td>2.11</td>
</tr>
<tr>
<td><strong>Route A</strong> (summer, max passengers)</td>
<td>1.7 – 2.0</td>
<td>2.46</td>
</tr>
<tr>
<td><strong>Route A</strong> (winter, no passengers)</td>
<td>1.7 – 2.0</td>
<td>1.91</td>
</tr>
<tr>
<td><strong>Route A</strong> (winter, avg. passengers)</td>
<td>1.7 – 2.0</td>
<td>2.64</td>
</tr>
<tr>
<td><strong>Route A</strong> (winter, max passengers)</td>
<td>1.7 – 2.0</td>
<td>3.10</td>
</tr>
<tr>
<td><strong>Route B</strong> (fall, no passengers)</td>
<td>1.7 – 2.0</td>
<td>1.68</td>
</tr>
<tr>
<td><strong>Route B</strong> (fall, avg. passengers)</td>
<td>1.7 – 2.0</td>
<td>2.06</td>
</tr>
<tr>
<td><strong>Route B</strong> (fall, max passengers)</td>
<td>1.7 – 2.0</td>
<td>2.20</td>
</tr>
</tbody>
</table>

**Worst Route, Worst Case**: 6.17 kWh/mile consumption
Understanding Electric Fuel Cost

Electric rates are typically a combination of:

1. Consumption charges
   - Varies with amount of energy used

2. Demand charges
   - Based on the highest power draw that month

3. Fees
   - Fixed and variable
Understanding Electric Fuel Cost

Actual electric fuel cost can be higher or lower than existing fuel costs based on:

• **Baseline** - Existing conventional fuel price
• **New Fuel Cost** - Electric rate structure
• **Usage** - Bus use and recharging pattern
Time of Use Rates (TOU)

• Time of Use Rates have a varied cost structure depending on the time of day to match grid supply and demand
• Consumption and demand charges can vary significantly over the day
• Highest costs during highest demand
Charging Standards

• Charging system standards will allow common hardware between different manufacturers
• Standards are currently in development
How Do You Add Electric Buses?

• Electric buses are operationally different than conventional buses – how do you get started?

Go for it!
Go for it, conservatively!

Strategy, Planning, Implementation
Key Elements for ZEB Deployment

- Determine which technology is right for your routes
  - Bus Modeling & Route Simulation
- Estimate Operating Costs
  - Rate Modeling & Fuel Cost Analysis
- Establish the Business Case
  - Life Cycle Cost Analysis
  - Risk Assessment
Bus Modeling and Route Simulation

Service Requirement

- Route Logistics
  - Length
  - Duration
  - Schedule
  - Frequency
- Duty Cycle
  - Speed
  - Accel/Decel
  - Grades
  - Passenger Load
  - Auxiliary Load
  - Deadhead
- Operating Environment
  - Traffic Congestion
  - Climate
ZEB Modeling Methodology

- Autonomie™ Simulation Software (developed by Argonne National Lab.)

- GUI utilizing MATLAB & Simulink software package

- Quick assembly of complex ZEB specifications:
  - Vehicle weight
  - Battery chemistry and energy capacity
  - Motor power output and energy requirements
  - Rolling resistance
Typical Route Model Results

- route data
- bus specifications
- operation plan
- expected energy use
- average bus efficiency
- charging requirements

Bus Speed
Layover
Battery SOC
Charge Rate
Rate Modeling & Fuel Cost Analysis

• Battery Electric Charging
  – Energy Consumption estimate from Route Modeling
  – Charger Specifications
  – Charging Profile
    • Charge Rate, Duration, Time of Day
  – Utility Rate Schedules
Key Performance Indicators

Track & Analyze Performance - Take Corrective Action - Realize Benefits - Repeat
Fleet Introduction Planning

• Training
  – Maintenance
    • New technologies and diagnostics
    • Safe handling
  – Operators
    • OEMs aim for seamless experience, some familiarization is needed
    • Charge docking, if on-route charging
Fleet Introduction Planning

• Schedule Adjustment, if needed
• Safety Planning
  – BEB: Similar training requirements as diesel electric hybrids for high voltage
  – Hydrogen Fuel Cell: Combination of requirements similar to CNG and hybrid safety
What’s next for your fleet?

Zero Emission Buses work!

- Define your agency goals
- Create deployment strategy
- Start operating Zero Emission Buses
Questions?

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