Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives – Preliminary Results

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Total Cost of Ownership (TCO)

Freight and Regional Passenger Locomotives ($/mile)
- Lifetime cost of locomotive, maintenance/refurbishment and fuel levelized over total miles travelled

Yard Switcher Locomotives ($/h)
- Lifetime cost of locomotive, maintenance/refurbishment and fuel levelized over total service hours

TCO for 30-y locomotive service life, 15-y engine lifetime, and $3/gal diesel fuel

<table>
<thead>
<tr>
<th></th>
<th>Freight</th>
<th>Regional</th>
<th>Switcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive Lifetime</td>
<td>3,600,000 miles</td>
<td>4,800,000 miles</td>
<td>138,000 h</td>
</tr>
<tr>
<td>Engine (HP)</td>
<td>4,400</td>
<td>3,600</td>
<td>1,500</td>
</tr>
<tr>
<td>Fuel Tank Capacity (gal)</td>
<td>5,000</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Fuel Consumption</td>
<td>0.40 mpg</td>
<td>0.49 mpg</td>
<td>9.5 gal/h</td>
</tr>
<tr>
<td>Total Locomotive Cost ($)</td>
<td>3,000,000</td>
<td>2,500,000</td>
<td>1,350,000</td>
</tr>
<tr>
<td>Maintenance Cost ($/year)</td>
<td>125,000</td>
<td>125,000</td>
<td>75,000</td>
</tr>
<tr>
<td>Overhaul Lifetime Cost ($)</td>
<td>300,000</td>
<td>250,000</td>
<td>175,000</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>7.50 $/mile</td>
<td>6.12 $/mile</td>
<td>28.05 $/mile</td>
</tr>
<tr>
<td>Levelized Cost</td>
<td>9.46 $/mile</td>
<td>7.48 $/mile</td>
<td>55.41 $/h</td>
</tr>
</tbody>
</table>

- Freight and regional locomotives: Fuel accounts for ~80% of TCO. Besides engine reliability and availability, fuel economy and cost are extremely important.
- Switcher locomotives: Fuel accounts for 55% of TCO. Capital, maintenance & refurbishment, and fuel costs are important.
System costs projected using 90-kW$_e$ automotive style stacks, 2 stacks/module, 2 modules for 360-kW$_e$ heavy-duty vehicles (HDV)*

Current PEM systems ($285$/kW$_e$)
- Pt or Pt alloy cathode electrodes with 0.35 mg/cm$^2$ Pt loading, 400-kW$_e$ gross power, assembled at low production volumes (100 HDV systems/year)

Interim PEM systems ($130$/kW$_e$)
- Same configuration as current systems, cost savings due to higher production volumes (5,000 HDV systems/year)

Ultimate PEM systems ($60$/kW$_e$)
- Cost savings from higher production volumes (>100,000 HDV systems/year) and technology advancements (higher activity catalysts with lower Pt loading, improved air management system)

*Strategic Analysis, Fuel Cell System Analysis, Fuel Cell Tech Team Meeting, 20 February 2019
Fuel Economy (FE) on EPA Duty Cycles

FE Multiplier (FEM): Ratio of FCS to diesel fuel economy

- Freight duty cycle: Significant fuel consumption at high notch levels where diesel is most efficient, FEM = 1.1
- Regional duty cycle: Frequent start-stops, actual cycle depends on service route, FEM = 1.2*
- Yard-switcher duty cycle: Significant fuel consumption at idle and low notch levels where FCS has distinct advantages, FEM = 1.7

*Alstom Lint (Coradia Specs, Ludwig-Bölkow-Systemtechnik GmbH, 12th International Hydrail Conference, Graz, 27-28 June, 2017)
Cryo-Compressed Hydrogen (CcH₂) Storage System for Freight and Regional Locomotives

**Freight Locomotives**: One tender car needed, 4850 kg-H₂ stored at 500 bar, 70 K
- 93 m³ and ~48.5 tonne required storage volume and weight for ~10 wt% gravimetric and 50 g/L volumetric capacities

**Regional Locomotives**: Tender car not needed, if 2 refuelings/day, 500-kg stored H₂

*Liquid H₂ tender* in lieu of CcH₂ tender also needs to be investigated

350-bar Compressed Hydrogen (cH₂) Storage System for Switcher Locomotives

**Tender car not needed** for 100 kg-H₂ stored at 350 bar, room temperature
- 5 m³ required storage volume for 6-7 wt% gravimetric and ~19 g/L volumetric capacities

**Projected CcH₂ Storage System Costs**
- **Current PEM**: $1130/kg-H₂ (200 HDV systems/year)
- **Interim PEM**: $500/kgkg-H₂ (5000 HDV systems/year)
- **Ultimate PEM**: $266/kg (DOE target)
Dispensed Hydrogen Cost

- AC Transit, CA: 13 buses, 2 stations, liquid H₂ delivery / electrolysis
- Sunline, CA: 10 buses, on-site SMR, new station electrolysis based
- OCTA, CA: 1 bus, H₂ purchased from local retail stations
- SARTA, OH: 7 buses, liquid H₂ delivery
- Fuel cost: $9/kg-H₂ (current), $7/kg-H₂ (interim), $4/kg-H₂ (ultimate)

<table>
<thead>
<tr>
<th>Agency</th>
<th>AC Transit¹</th>
<th>SunLine²</th>
<th>OCTA³</th>
<th>SARTA⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data period</td>
<td>2/13-7/17</td>
<td>3/12-10/18</td>
<td>3/16-12/18</td>
<td>2/18-12/18</td>
</tr>
<tr>
<td>Number of months</td>
<td>54</td>
<td>80</td>
<td>34</td>
<td>11</td>
</tr>
<tr>
<td>Average H₂ cost, $/kg</td>
<td>8.39</td>
<td>10.17</td>
<td>13.95</td>
<td>5.14</td>
</tr>
<tr>
<td>Maximum H₂ cost, $/kg</td>
<td>10.26</td>
<td>26.02</td>
<td>16.99</td>
<td>5.88</td>
</tr>
<tr>
<td>Minimum H₂ cost, $/kg</td>
<td>6.49</td>
<td>2.53</td>
<td>12.99</td>
<td>5.00</td>
</tr>
<tr>
<td>Overall FCEB fuel cost, $/mile</td>
<td>1.41</td>
<td>1.82</td>
<td>1.47</td>
<td>1.03</td>
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<tr>
<td>Baseline technology</td>
<td>Diesel</td>
<td>CNG</td>
<td>CNG</td>
<td>CNG/diesel hybrid</td>
</tr>
<tr>
<td>Average fuel cost, $/gal or gge</td>
<td>2.43</td>
<td>0.96</td>
<td>1.15</td>
<td>1.89 / 2.30</td>
</tr>
<tr>
<td>Overall baseline fuel cost, $/mile</td>
<td>0.57</td>
<td>0.32</td>
<td>0.32</td>
<td>0.45 / 0.51</td>
</tr>
</tbody>
</table>

Fuel cost is based on data provided by agencies, not all are equal comparisons

¹Delivered cost
²Includes station O&M
³Retail cost from local public stations
⁴Delivered cost

Leslie Eudy, Summary of Fuel/Energy Costs for NREL Evaluation Projects, NREL ZEB Technology Showcase and Symposium, February 6, 2019
Fuel Cell System Maintenance Cost

Average long term or life-cycle maintenance costs

- Diesel electric locomotives: 1-1.5 $/mile (Prices and costs in the railway sector, J.P. Baumgartner, 2001, LITep)
- Diesel electric locomotives: $125,000/year (California Air Resources Board)
- Diesel electric locomotives: 30-40% maintenance cost due to engine (Ephraim, M. Maintenance and Capital Costs of Locomotives, Electro-Motive Division, GM)

FCS vs. diesel engine relative maintenance cost from FCEB data: 1.67 (current)

- Majority of issues with FCS are due to balance of plant and not stack: air handling, blowers, cooling pumps, plumbing

Summary of FCEB Data through February 2018

<table>
<thead>
<tr>
<th></th>
<th>2017 Fleet Average</th>
<th>2018 Fleet Max</th>
<th>2018 Fleet Average</th>
<th>2016 Target</th>
<th>Ultimate Target</th>
<th>Target Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus lifetime (years)</td>
<td>4.7</td>
<td>7.5</td>
<td>5.5</td>
<td>12</td>
<td>12</td>
<td></td>
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<tr>
<td>Bus lifetime (miles)</td>
<td>118,989</td>
<td>189,168</td>
<td>128,656</td>
<td>500,000</td>
<td>500,000</td>
<td></td>
</tr>
<tr>
<td>Powerplant lifetime (hours)</td>
<td>13,801</td>
<td>27,330</td>
<td>13,041</td>
<td>18,000</td>
<td>25,000</td>
<td>2016</td>
</tr>
<tr>
<td>Bus availability (%)</td>
<td>76</td>
<td>90</td>
<td>71</td>
<td>85</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Roadcall frequency (bus)</td>
<td>4,710</td>
<td>4,715</td>
<td>4,516</td>
<td>3,500</td>
<td>4,000</td>
<td>Ultimate</td>
</tr>
<tr>
<td>Roadcall frequency (fuel cell system)</td>
<td>20,705</td>
<td>23,741</td>
<td>18,026</td>
<td>15,000</td>
<td>20,000</td>
<td>Ultimate</td>
</tr>
<tr>
<td>Maintenance cost ($/mi)</td>
<td>1.03</td>
<td>0.56</td>
<td>0.53</td>
<td>0.75</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Fuel economy (mpdje)</td>
<td>6.51</td>
<td>7.82</td>
<td>7.01</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Range (miles)</td>
<td>247</td>
<td>357</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

A challenging application for fuel cells because ~75% of fuel is consumed in freights at notches 6, 7 and 8 where diesel engines are most efficient

- Projected gain in fuel economy is ~10% for fuel cells
- **Break-even delivered hydrogen cost relative to $3/gal diesel: $3.30/kg**

Other factors that may favor fuel cells

- Stricter emission standards for diesel locomotives
- More expensive diesel fuel: EIA projects increase of 21% by 2030 and 27% by 2035
- Carbon credits and if hydrogen is produced from renewables
Preliminary Total Cost of Ownership
Fuel Cell Regional-Passenger Locomotives

Preliminary TCO of fuel cells slightly more suitable for regionals than freights

- Higher gain in fuel economy (1.2x vs 1.1x) because the metropolitan duty cycle includes frequent stops and low speeds
- With 2 refueling/day, only 500-kg H\textsubscript{2} storage is required and can be accommodated without a tender car if H\textsubscript{2} stored as cryo-compressed gas. May also be feasible to eliminate the tender car with 350-bar cH\textsubscript{2} storage system.
- **Break-even delivered hydrogen cost relative to $3/gal diesel: $3.60/kg**
Preliminary Total Cost of Ownership
Fuel Cell Yard-Switcher Locomotives

Preliminary TCO of fuel cells more favorable for yard switchers than freights or regionals
- 70% higher fuel economy than diesels on EPA duty cycles for switchers
- On TCO basis, fuel cells can be >15% cheaper if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at $4/kg
- **Break-even delivered hydrogen cost relative to $3/gal diesel: $5.60/kg**
- No loss of functionality as in a hybrid with an undersized 300-hp diesel engine
Summary and Outlook

Preliminary TCO of fuel cells more favorable for yard switchers than freights and regionals
- Future targets favor a 1000-kWₑ fuel-cell dominant hybrid with 160 kWh battery
- 70% lower fuel consumption than diesels on EPA duty cycles
- On TCO basis, fuel cells can be >15% cheaper if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at $4/kg

Break-even delivered hydrogen cost relative to $3/gal diesel
- Freight locomotives: $3.30/kg
- Regional passenger locomotives: $3.60/kg
- Yard switcher locomotives: $5.60/kg

Hydrogen storage for locomotives
- Fuel tender car with liquid hydrogen refueled CcH₂ storage system for freight locomotives: 4,800 kg stored H₂, 80 kg/min refueling rate for 1-h refueling time
- CcH₂ or 350-bar cH₂ storage for regional locomotives, 500 kg stored H₂
- 350-bar cH₂ storage for yard switcher locomotives, 100 kg stored H₂

Areas for further development
- MEA durability exceeding 1.8-2.4 million miles for freights and regionals, 70,000 h for yard switchers
- Availability and reliability of FCS BOP components including air management
- May be desirable to develop single stacks >250 kWₑ
- Methods for meeting and exceeding the critical target of $4/kg-H₂ at pump