Hydrogen Fuel Cells in Passenger and Freight Rail: US Context and Simulation Case Studies

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Basic Facts about the (Non-Transit) Rail System

Rail sector:

* **2.4%** of all domestic and **4.2%** of all global transportation emissions in 2015 (UIC 2017)
* ~**8%** of U.S. transportation diesel fuel use (ORNL)
* > **3.7 billion gallons** of diesel used by “Class I” freight railroads (USA) in 2015, alone! (AAR)

Passenger rail experiencing considerable growth in the United States:

- Amtrak ridership at record highs in ~ last 5 years (> **31 million** passengers per year), led by NEC ridership highest ever in FY 2016 (**11.9 million** passengers) (Amtrak)
- Commuter Rail in 2016 ↑ **1.6%** from 2015 (APTA), ↑ **7.2%** from 2011
- Caltrain (San Francisco Bay Area) set ridership records in both FY 2015 and 2016!
Rail Background: Focus on Freight

Trucks dominant mode by value, tons, and ton-miles for shipments moving <750 miles

Rail is dominant mode by tons and ton-miles for shipments moving 750 < X < 2,000 miles (USDOT)

“Class I” railroads accounted for 70% of all freight rail mileage in 2010 (AAR)

Class I’s: 26,000 Locomotives

Fuel costs about 13.7% (2015) - 23.1% (2011) of operating expenses in a given year
Some current fuels context

>98% of U.S. operational rail energy comes from diesel-electric; remainder of energy (largely passenger trains) from electricity (OLE)

OLE infrastructure covers only ~2% of all (non-transit) rail track* in the US, yet 26% of energy for passenger trains via OLE****

Outside of US, OLE much more common; e.g. 6 European countries have 50% or more of their track electrified (BBC, 2009); Switzerland stands at 100% (ibid)!

**Diesel-Electric (no aftertreatment)** → Not so clean at the point of use; Acceleration often slower than fully electric, which means slower trips and lower total track capacity

**Electricity** → Lower loco. maintenance costs and higher “availability”; better hp/weight ratio***; however, VERY expensive (catenary costs, alone, on the order of ~ 1$-8$ million/mile, if not higher**), depending on traffic level and urban development; Tunnels and aesthetics problematic

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* Sources: Amtrak data and Lewis and Verhelle, 2015 
** Based on author’s research 
*** Hay, 1982 
**** US DOE, 2017
Fig. 38: Railway final energy consumption by fuel, 1990-2015 (PJ)

United States

2017 Railway Handbook, UIC/EIA, 2017
### Locomotives: Exhaust Emissions Standards (3/2016)

<table>
<thead>
<tr>
<th>Duty-Cycle</th>
<th>Tier</th>
<th>Year</th>
<th>HC (g/hp-hr)</th>
<th>NOx (g/bhp-hr)</th>
<th>PM (g/bhp-hr)</th>
<th>CO (g/bhp-hr)</th>
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<td>5.5 [ABT]</td>
<td>0.10 [k ABT]</td>
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<td>Tier 3</td>
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<td>0.14</td>
<td>1.3 [ABT]</td>
<td>0.03 [ABT]</td>
<td>1.5</td>
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<td>0.60</td>
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<td>2015+</td>
<td>0.14 [l]</td>
<td>1.3 [l ABT]</td>
<td>0.03 [ABT]</td>
<td>2.4</td>
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</table>

1 hp-hr ~ .75 kWh
California seeks to be ahead of the curve...

<table>
<thead>
<tr>
<th>Tier Level</th>
<th>Proposed Year of Manufacture</th>
<th>NOx</th>
<th>PM</th>
<th>GHG</th>
<th>HC</th>
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<tr>
<td>5</td>
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<td>0.2</td>
<td>&lt;0.01</td>
<td>NA</td>
<td>0.02</td>
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</table>

With capability for zero-emission operation in designated areas.

2. Compared with uncontrolled baseline, reflects percent control over line haul baseline for illustrative purposes; ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.
Rail propulsion equipment

**Passenger Locomotives:**
- Locomotive provides significant power for auxiliaries, e.g., energy for heating, lighting, and air conditioning (HVAC) of passenger cars (~10% to 20% of power/energy requirement)
- Tank typically holds ~ 2,000 gallons of fuel
- Costs higher (partly due to market differences)
- Typically operate with a single locomotive (commuter); intercity 2 to 3

**Freight Locomotives:**
- Minimal power allotted to auxiliaries (primarily for train air braking equipment)
- Maximized for tractive effort (pulling force) rather than speed
- Typically ~5,000 gallons fuel
- Frequently run in groups of 3 or 4 to pull longer, heavier trains
Equipment (cont.)

**Locomotive Advantages:**
- Propulsion equipment concentrated in one unit allows for specialized maintenance
- High power (~3.3MW / 4.4k HP), high tractive effort
- Train consist is flexible (addition / removal of cars)
- Allows for simple, relatively cheap cars
- Can be used for both passenger and freight service

**Multiple Units Advantages:**
- Propulsion equipment distributed throughout the train
- No additional vehicle required for propulsion equipment (typically installed on the roof and underneath the floor of cars)
- Often faster acceleration as more powered axles, higher power to weight ratio
- Lower power requirement per vehicle, allows for easier conversion to alternatives
- Good for dense passenger service, e.g. subways, light rail /streetcar, commuter, or regional trains
Hydrogen in heavy duty in the US

* 26 fuel cell buses in regular operation across the country (18 in California) (NREL, 2017)
* Several more planned

Most of these buses are hybridized with batteries that take advantage of regenerative braking and allow for ‘downsized’ fuel cells

Courtesy NREL

Coachella Valley (Riverside, CA)

AC Transit, Bay Area
Railyards: Favorable characteristics for experimentation with propulsion alternatives

• Local pollutant emissions can be very high, with often 30 to 40 year old locomotives (U.S.)—often ‘cascaded’ line-haul locomotives—which have higher emissions rates—in use
• Low-speed “switcher” locomotives operate at low speed; often idle time a significant portion of duty cycle
• Average power is often significantly lower than peak power (for acceleration)
• Many switchers on hand, in case one develops a problem
Railyards (cont.)

- 2009: Public-private consortium developed a proof-of-concept switch locomotive
- PEM-based heavy duty fuel cell system (similar to buses)
- Fuel cell system maximum power: 250 kW (2X 125-kW Ballard FC systems)
- Battery to meet peak loads, locomotive maximum power of 1.2 MW

Photo from Dr. Andreas Hoffrichter
Hydrogen/Fuel Cells: Remaining challenges for intercity and freight rail applications

* Compression and/or liquefaction losses: up to $\frac{1}{10}$ of Lower Heating Value for compression and $\frac{1}{3}$ “LHV” for liquefaction (Gardiner 2009)

* Even in liquid form, H$_2$ per gallon energy density much lower than diesel. -> How to store in areas of limited size?
Energy density: Solid State/Metal Hydride?

Goal: “To design low-cost, light-weight materials that can reversibly and rapidly store hydrogen near ambient conditions at a density equal to or greater than liquid hydrogen.” (Murray et al, 2009)

However we’re not there yet...

What is known: H2 can bind to surfaces through weak “dispersive” interactions, a processed called physisorption, or through stronger chemical “associations,” called chemisorption.

For physiosorption, greater gas uptake (a good thing) occurs with higher surface areas. (Strong dipole moments may also increase uptake.) Thus a not-so-dense material with lots of surface area would be ideal.

Among the challenges: **Temperature!** Zn4O(BDC)3, one well-researched option, exhibits excellent hydrogen storage characteristics at 77 K; however, at 298 K (25C) it suffers from weak interactions between the hydrogen and the “framework.” (Murray et al, 2009)
Cryocompressed storage?

“Cryogenic capable pressure vessels can essentially eliminate evaporative losses for practical automotive operation scenarios.” Aceves et al., 2010

Figure to the right: “Generation 2 cryogenic capable pressure vessel design. Inner vessel is an aluminum-lined, carbon fiber wrapped pressure vessel typically used for storage. It is surrounded by a vacuum space filled with numerous sheets of highly reflective metalized plastic (minimizing heat transfer into vessel), and an outer jacket of stainless steel. The outer tank measures 129 cm long with an outer diameter of 58 cm.”

Aceves et al., 2010
But back to benefits: Synergies with H2 development in fleets?

Many fleets have considered moving towards hydrogen; however, justifying the cost and complexity of both the fuel cells and the refueling equipment is not always easy.

Rail vehicle power plants run 3-4 MW for mainline locomotives

Trucks and buses closer to 250-450 kW (about 1/10!).

Cars ~ 80 kW (about 1/50!)

Conclusion: Economies of scale spurred by rail fuel cell development could spur decreased stack cost; Re-fueling facilities could be shared across modes.
Recent Simulation Work

* Utilized the Single Train Simulator, developed by Uni Birmingham and Uni Warwick*

* Special thanks to Athanasios Iraklis, formerly of WMG, who developed the simulation software into its current format.
Caltrain: Diesel Benchmark

a) Power at Wheels and Traction Package Input Power

b) Inputs and Outputs at the DC Bus

c) Fuel Consumption, Power Plant Output, and Powerplant Efficiency
Percentage Reduction in Fuel Consumption from Current Diesel-Electric Benchmark: Caltrain (SAMTRANS)

**Diesel**
- Diesel-Electric, Fully Dynamic Braking (1)
- Diesel-Electric Hybrid (Fully Dynamic) (2)
- D-E Hybrid (Fully Dynamic), Downsized (3)

**Hydrogen**
- Hydrogen, Fully Dynamic Braking (4)
- Hydrogen Hybrid (Fully Dynamic) (5)
- Hydrogen Hybrid (Fully Dynamic), Downsized (6)
Freight cost analysis*

Kansas City – Los Angeles

~ 12,000 movements a year

“Nordland Line,” Norway

~3,000 movements a year

• Different simulation software. Work conducted in partnership with several partners at MSU & SINTEF: Federico Zenith, Andreas Hoffrichter (MSU), Steffen Møller-Holst, Magnus Thomassen
Hydrogen Assumptions

Data:

<table>
<thead>
<tr>
<th>Year</th>
<th>Fuel cells</th>
<th>Tanks</th>
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<th>Compressors</th>
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<tr>
<td></td>
<td>$/kW</td>
<td>lifetime / h</td>
<td>$/kWh</td>
<td>lifetime / y</td>
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<tr>
<td>2020</td>
<td>262</td>
<td>20 000</td>
<td>21</td>
<td>1150</td>
</tr>
<tr>
<td>2030</td>
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<td>40 000</td>
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</tr>
<tr>
<td>2050</td>
<td>40</td>
<td>50 000</td>
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Lifetime estimates from Fuel Cells and Hydrogen Joint Undertaking (2014)
Thank you!!/Grazie

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