CALIFORNIA RAIL FUELS UPDATE: A CLOSER LOOK AT FUEL COST RANGES, AND AN INTRODUCTION TO ONGOING POWERTRAIN SIMULATIONS

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* WITH THE HELP OF SEVERAL COLLABORATORS
STUDY BACKGROUND/MOTIVATION

- **Rail:** 2.3% of all domestic and 3.6% of all global transportation emissions
  
  **600 Trillion BTU! → 500 Trillion BTU** for freight, alone

- **8%** of domestic transportation diesel fuel use

  ~ **4 Billion gallons of diesel** use by Class I railroads (USA) in 2014, alone!

- Rail is experiencing considerable growth in the US:
  - Amtrak ridership ↑ **29%** since 2005 *(WSJ)*, NEC ridership highest ever in FY 2014, and remained steady in FY 2015 *(Amtrak)*
  - Commuter Rail ↑ **2.9%** in 2014 *(APTA)*
  - Class I revenue ton-miles ↑ **6.4%** in 2014 *(AAR)*
GROWTH AT THE GLOBAL LEVEL, TOO…

Fig. 7: Railway passenger transport activity by geographic area, 1975-2012 (trillion pkm)

Fig. 8: Railway freight transport activity by geographic area, 1975-2012 (trillion tkm)

Source: Elaboration by IEA based on UIC (2014a)

Courtesy UIC, 2015
As cars shift over to cleaner fuels, how can trains do their part to help achieve sustainability/climate (i.e. CO₂) goals?

GHG emissions impact as compared to automobiles; HOWEVER, several centralized operators rather than millions of individual operators

Trains have key role to play → 1 in 4 auto trips (US) is now affected by severe and extreme congestion levels (Schrank, Eisele, Lomax, & Bak, 2015)
STUDY APPROACH

- What is the economic viability of a fuel change within all or parts of the rail sector? How effective is a given technology in reducing emissions? Any major logistical challenges that need to be addressed?

- **Candidate fuels**: Diesel, Electricity (Catenary), Natural Gas, Biodiesel, & Hydrogen

- **Methodology**: Set up realistic example scenarios, given a set travel distance that allow us to compare energy & infrastructure requirements across fuels and analyze the costs and benefits of each on as equal a footing as possible.
In the US, 87% of trains run via diesel-electric; the remainder run on electricity via catenary (overhead wire); The actual amount of electric track is much lower, only 3% for passenger rail.

In other countries, electricity via catenary is much more common; e.g. 6 European countries have 50% or more of their track electrified (BBC, 2009); Switzerland stands at 100% (ibid.)!

Diesel → Not so clean at the point of use; however infrastructure for electricity is VERY expensive! (Like on the order of 1$-8$ million per mile**!) Acceleration is slower with diesel trains, too; so in areas of high traffic, catenary-supplied electricity is advantageous (and potentially cost-effective, too)

** Based on author’s research
ELECTRIFICATION IS SIMILAR TO H\textsubscript{2}, BUT HAS CHALLENGES

- Tunnels pose a challenge for building catenary (overhead wires)
- Some find infrastructure aesthetically unpleasant
- Infrastructure buildout costs perhaps the most significant challenge (again ranges from approx. $1.25 million (RTD) to $8 million (SamTrans)), based on current/upcoming US projects
  - Fixed infrastructure maintenance costs too!
“HEAVY DUTY” EXPLORATION HAS BEGUN IN THE US…

Note: These are hybridized vehicles, with batteries that take advantage of regenerative braking

Coachella Valley (Riverside)

AC Transit, Bay Area

Courtesy NREL

Figure 5. AFCB at SunLine’s fueling station

Figure 8. Bus fueling at the Emeryville hydrogen station: fueling area (left) and close-up of the bus dispenser (right)
AND WE HAVE ALREADY HEARD ABOUT THIS, TOO…

Courtesy Railly News
HYDROGEN’S BENEFITS, AS WE ALL KNOW…

- Fuel cells: No pollutant or GHG emissions at the “tailpipe”
- ↑ efficiency than diesel engine; Some literature suggests 50% fuel cell stack efficiency for rail application (Hoffrichter et al, 2015 cite Miller et al., 2011 & Yamamoto et al, 2010)
- Lower infrastructure costs
HYDROGEN CHALLENGES

- 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)

- Where available, not currently an inexpensive fuel: \( \sim \$5 - \$9/\text{diesel gallon equivalent (DGE)} \)

- Even in liquid form, \( \text{H}_2 \) per gallon energy density (i.e. energy content for a given volume) much lower than diesel.
AND, OF COURSE, HOW TO PRODUCE IT SO THAT IT RETAINS (AND EVEN MAXIMIZES) EMISSIONS BENEFITS

Courtesy, Dr. Paul Erickson, UC Davis
AND ONE LAST ONE: FC STACK LIFETIME

Not shown above: AC Transit (Fecteau): One bus system close to 23,000 hours in 2015!! (Though now begin to show some signs of wearing down.)
EXAMINING ENERGY LOSSES:
HOW TO STORE H2 ON THE TRAIN?

- Options **Hoffrichter et al. (2015)** 350 bar (compressed), 700 bar (compressed), and Solid State Hydride (This latter requires less “side energy” and has lower safety risk than Compressed H2 [Gambini et al.], but also can be heavy)

<table>
<thead>
<tr>
<th>Table 5: Characteristics of considered hydrogen storage systems for vehicle design</th>
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<tbody>
<tr>
<td><strong>350 bar</strong></td>
</tr>
<tr>
<td>storage capacity</td>
</tr>
<tr>
<td>tank system mass</td>
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<tr>
<td>tank system volume</td>
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- Other options include liquid form:
  Higher volumetric energy density, though tender required

**Courtesy [www.eoearth.org](http://www.eoearth.org)** (Encyclopedia of Earth)
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.” (Dinca)

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 (25°C) it suffers from weak interactions between the hydrogen and the “framework.” (Dinca)
ANALYSIS ASSUMPTIONS - PASSENGER

- Chart values modeled off of a standard sized Amtrak Capitol Corridor (CA) locomotive, with actual FY 2013 annual mileage adjusted to a potential future schedule.

- 15 round trips from San Jose-Roseville (slight adjustment made to actual current schedule)

  → One-way Distance: 150 miles

Courtesy https://www.flickr.com, Jack Snell
10 intermodal* trains/day assumed to leave origin en route to a 2,000-mile journey, and then back same distance. Round-trip time: 6 days.

3 new locomotives purchased for each of the 60 trips (10 trains x 6 days)

* Intermodal trains carry a variety of goods, typically in containers (which are easily transferred between modes)

** Just a reminder of the key role of freight in the US: In 2000, 38% of US freight (in ton-miles) was carried by rail; only 8% in Europe! (Vassallo & Fagan, 2007)
UPDATED PASSENGER RESULTS

Passenger Annual Energy Technology Cost Comparison
Midpoint capital and maintenance costs, with fuel cost range

- Diesel (Best new model)
- Biodiesel (FAME)
- Renewable Diesel
- LNG
- CNG
- Liquid H2

- Capital Cost - Amortized 10 years
- Electric Infrastructure Cost (amortized - 20 years)
- Annual Maintenance Cost - Electric
- Annual Locomotive Maintenance Cost
- Annual Fuel Cost (Low)
- Additional Annual Fuel Cost (High)
UPDATED EMISSIONS RESULTS (BOTH)
ISSUES TO CONSIDER WITH OUR ANALYSIS:

- Challenge of analyzing moving targets – costs and CO₂ will change
- Level of market development for a given technology, both within rail and beyond, will greatly influence actual costs
Options that would keep costs relatively stable or even offer savings, in the near-term, are not necessarily the ones that will offer significant CO2 benefits. Beyond the near-term, future research and development are likely to lower some of the higher cost options (especially hydrogen).

Beyond cost uncertainty, fuel supply and storage characteristics of alternatives to diesel technology would likely pose the most significant impacts of any transition to these fuels.

Electric catenary installation costs are very high, > $1 million/track-mile. High levels of traffic on a given route can mitigate the high cost of this fixed infrastructure on these routes.
(PASSENGER) RAIL IN THE US VS. THE UK: CLEARLY GOOD REASON TO COLLABORATE WITH THE ENGLISH!

- Great Britain (England, Scotland, & Wales)
  - 59.1 Billion Passenger-km (2013), UK Office of Rail & Road
  - → 36.72 Billion Passenger-miles
- United States
  - 19.019 Billion Passenger-miles (2013), USDOT

Pop: 60.8 Million (2011)
Area: 209,331 km²
80823.15095 mi²

Pop: 309.3 Million (2010)
Area: 3,805,927 sq mi

Courtesy Woodlands Junior School (UK)

Courtesy Edugeography.com
Vassallo & Fagan, 2007, on US vs. Europe:

- US: Much larger distances within the country, less coastline and inland waterways favors freight movement by rail.
- US freight rail advantage reinforced by rail deregulation (’70s and ‘80s)
- Europe: Many borders, and systems across countries traditionally operated independently of one another.
  → Problems with interoperability (e.g. electric/signalling); resulting time loss discourages freight movement by rail.
- Europe has also focused resources on passenger rail.
- CONSEQUENCE: Rail carries **6.25%** of all intercity passenger traffic in Europe compared to **0.3%** in US. In 2000, **38%** of freight (as a measure of total ton-miles) in US carried by rail; only **8%** in Europe!
Working with Andreas Hoffrichter (Michigan State U.) & Athanasios Iraklis (U. Warwick)

Examining 4 options on same route: diesel, diesel hybrid, fuel cell, fuel cell hybrid

**Locomotive characteristics**

- Maximum Speed 125 mph
- Rated Voltage 1080 V @ 50 Hz
- Rated Power maximum 4,400 hp @ 1,800 rpm at
- Operating Range 600 to 1,800 rpm
- Head End Power 600 kW
- Tractive Effort (max.) 65,000 lbs / 290 kN

Data courtesy Siemens
RESULTS FROM THE SIMULATION WILL PRODUCE CHARTS LIKE THIS ONE!

Keeping in mind that...

A varies with weight ("journal" or "bearing" resistance)
B varies directly with velocity ("flange" resistance)
C varies with the square of velocity (air resistance)
The general expression for train resistance is thus:
\[ R = AW + BV + CV^2 \]

Barkan, 2009
AND THESE…
We’ve built relationships with a few different rail component firms, who will each be providing data that will allow us to simulate highly realistic powertrain components, including efficiencies, that vary based on other operating characteristics.

Stay tuned for some interesting results…
QUESTIONS?

Thank you!