Rail Technologies: A California Cross-fuel Comparison, and Discussion of Hydrogen's Potential Advantages

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WHY EVEN STUDY RAIL ENERGY (ESPECIALLY HERE IN THE US)?

- **Rail** accounts for **2.3%** of all domestic transportation energy (ORNL) and **8%** of domestic transportation diesel fuel use (ORNL)
- 2.3% translates into **600 Trillion BTU/year! → 500 Trillion for freight, alone (ORNL)**
- U.S. passenger and freight rail sub-sectors both experiencing considerable growth
  - Caltrain (San Jose – SF) ridership has more than **doubled** (to **58,000 passengers/day**) since the late 1990s
  - Amtrak nationwide ridership ↑ **29%** since 2005 (WSJ), NEC Ridership highest ever in FY 2014 (Amtrak)
  - Commuter rail ↑ **2.9%** in 2014(APTA))
  - 2014 domestic freight traffic up **6.4%** from 2013, **10%** from 2010, **27.2%** from 2000 (AAR & BTS)
- Alternative technologies developed in recent decades for on-road applications are transferable to rail, though potentials and costs are not well understood
- As car technologies become cleaner, rail's relative contribution to transportation GHGs will only increase.
- Potential opportunities for cost savings in addition to environmental benefits

→ **Billions** of gallons of diesel consumed per year, domestically, > **3.5 Bill.** for freight alone (AAR)

ELECTRICITY & DIESEL-ELECTRIC: DOMINANT TECHNOLOGIES OF THE 20TH CENTURY

- Diesel-electric → **87%** of all U.S. domestic rail service (NREL, *Transportation Energy Futures*)
- Electricity and its associated infrastructure and locomotive technologies → Remaining **13%**. (Freight is all diesel, with some very limited exceptions.)
  - **2-3% of track** over which **passenger** rail operates in the U.S. is electrified (Amtrak); however, due to the uneven distribution of passenger rail traffic (e.g. NE Corridor has unusually frequent train service), operational energy is split about equally between two sources: **47% of BTU → diesel**, **53% → electric** (ORNL)
- Diesel-electric has the significant cost advantage of the two ($ for catenary million/mile) while electric is cleaner (and quieter) and has smoother acceleration/deceleration
  - Even annual maintenance of electric infrastructure can be up to 1/3 cost of total annual power costs (based on recent Amtrak operating data)
- Tunnels pose a challenge for building catenary (Hybrid Diesel-Electrics?)
- Europe has undergone extensive electrification over the last couple of decades (not even including where high speed rail is now operating)

Courtesy Amtrak

ONE COMMUTER RAIL SYSTEM IN CALIFORNIA IS SERIOUSLY EXPLORING ELECTRIFYING, TOO…

Courtesy Caltrain.com

…citing ↓ GHGs, reduced noise, and emissions, along with ↑ Frequency and faster trips…

…though not without significant cost, at $1.5 Billion (130-140 single-track mile corridor) (Caltrain/Samtrans).

UP-AND-COMING GENERATION OF (DIESEL-ELECTRIC) PASSENGER LOCOMOTIVES

- Top speed of 125 mph
- Power: ~ 3.3-3.5 MW (EMD/Siemens)

F125

Courtesy EMD

'Charger'

Courtesy Siemens

NATURAL GAS (LNG)

Courtesy GE Transportation

- LNG must be heated and vaporized
  - Engine coolant can be used for this task
- Current Technologies:
  - Westport-EMD HPDI engine - Utilizes standard locomotive and Westport tender
  - (Tender is necessary in freight due to lower energy density **(1/2 Diesel)**
  - Runs on up to 95% LNG
  - Add'l cost (of tender) of $800,000 to $1.2M, depending on tender size (B. Dracup, Westport)
  - GE Low Pressure Injection (~80% LNG) retrofit → Additional cost - $400,000 to $500,000 per locomotive

Pros:

- Infrequent refueling requirements (using LNG tender for freight)
- Cost savings (based on recent fuel costs)
- Near-term climate benefit

Cons:

- Leakage – Rate highly uncertain (Dominguez-Faus, 2015), but could be significant
- Low storage temperature (-162 deg. C) requirement means potential for boiloff

BIODIESEL

- Fatty-acid methyl esters (FAME), usually formed from vegetable oils, but animal fats have also been used: Feedstocks likely to expand in the coming years

Courtesy of Amtrak

Pros:

- Drop-in fuel requires no change to locomotive
- Proven technology in blend form (i.e. B-20) -->Amtrak 'Heartland Flyer': Tier 0 Locomotive, 2010 to 2011 (FRA)
- Usage of this fuel, a relatively early-generation biofuel, required no additional maintenance despite a service run well over 100,000 route miles (FRA)

Cons:

- Uncertainty regarding economics and actual emissions impacts of growing biofuels in large amounts: CO_2 and other GHG emissions released during feedstock and fuel production can be significant, as can other potential effects (land use changes, soil carbon changes, co-product impacts, etc.), many of which are not easily quantifiable.
- Slight decrease in energy density as compared to conventional diesel

HYDROGEN/FUEL CELL

- In experimentation in the UK, observed efficiency of 40-43 %. (Hoffrichter, 2013)
- Can be PEM-based or solid oxide-based (Former more common in transport applications)
  - UC Irvine researchers claim advantages for a solid oxide fuel cell (SOFC)-gas turbine (GT) hybrid system → Captured heat leads to ↑ efficiency; Also envision transition (in stages) from diesel to NG to H_2

(Dissertation, Martinez, Andrew, Ph.D., UC Irvine)

Pros:

- Significantly lower cost than electrification and essentially "maintenance-free" (Hoffrichter)
- Proven technology in buses in CA (AC Transit) → 2X fuel efficiency (in DGE)

Cons:

- 40K hours' lifetime needed to compete with diesel (Presently near 15K Hours max. [Wancura])
- Specifications will be unique for rail applications due to high power requirements
  - Current stacks are not designed to be operated in multiples, in series; would create sparks and shorts (Wancura, H.)
  - Operating current stacks in parallel would lead to excessive Ohmic Losses (Power Loss = $I^2 * R$) (Wancura, H.)
  - Extensive piping needed to deal with system cooling (Wancura, H.)

…therefore stack costs will be high, particularly in the near-term (Wancura, H.)

BATTERIES/ULTRACAPACITORS/HYBRIDS

- Batteries (high energy) & ultracapacitors (high power, long lifetime) are beginning to play a role
- SEPTA (Pennsylvania) has had (stationary) pilot system for its subway; Germany also recently attempted pilot retrofit (Siemens Desiro Classic) to to hybridize diesel-electric streetcar with lithium-ion battery pack

Courtesy of TransPower

- (Large) Battery Concepts: TransPower's "Rail-Saver"™
- Battery tender enables zero-emission operation of a 100-car freight train for 50 miles
  - Large pack of lithium batteries; 3,000 cycles; Works with standard diesel locomotive; Savings up to ~$5m over 10 years (after subtracting out capital costs, including battery replacement every five years)
- Supplemental, and perhaps especially useful on short-range (e.g. port-related) routes

UC DAVIS STUDY BASELINE: MODIFIED CAPITOL CORRIDOR

Courtesy Capitol Corridor

- Capitol Corridor JPA provided us with current operating data.
  - Capitol Corridor Is **3rd busiest** inter-city rail route in the nation (CCJPA)
  - Current locomotive is the **F59PHI,** related to the F59PH, which operates here in North Carolina (Piedmont Service)
- Current Capital Corridor Service:
  - 15 round trips per day; Starts from either Oakland or San Jose on the southwestern end, and goes to Sacramento on the northeastern end (with one round trip per day going to Auburn, an outer suburb of Sacramento)
- CCJPA is looking to expand service to 10 round trips to/from Roseville; For our analysis, we further expanded service to the following scenario:

  15 round trips to/from Roseville (300 miles per round trip)
- Acquired and developed cost data through a variety of methods
  - (Amtrak, manufacturers, public contract information, CA-GREET, consultants, etc.)

HYDROGEN RAIL TECHNOLOGY SPECIFICATIONS FOR UC DAVIS ANALYSIS

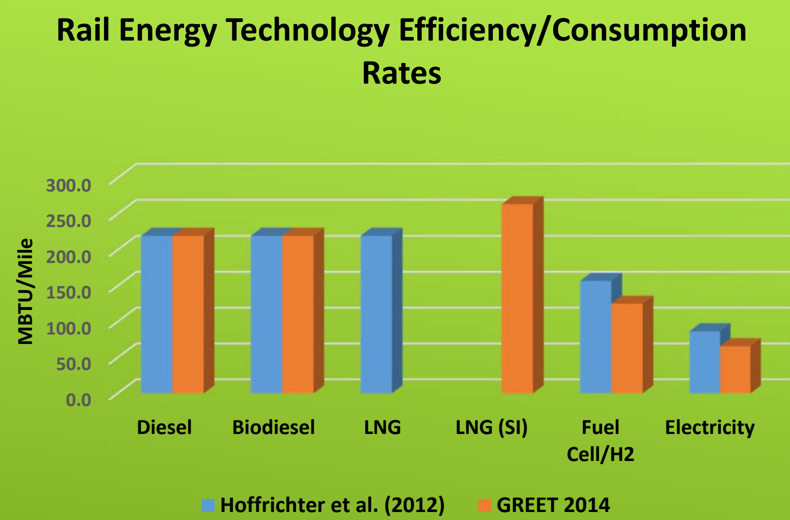
* Removal of the diesel engine, which gives an estimated cost reduction of $1 Million

* Addition of a specialized H2 fuel tank, about $1 million (Wancura, H.)

* Cost of the fuel cell power plant, sized to provide 3.5 MW peak power. Assumed as $300/kW (figure developed with help of Herbert Wancura), totaling $1.05 million. (In addition to earlier points, Wancura notes that the limited production levels for such a unique stack would also result in upward pressure on prices.)

* No additional tender car would be necessary for passenger train service, as previous work has shown that removal of a diesel engine in a rail locomotive could free up about 59 cubic meters of space within the locomotive (Wancura 2014), which would allow for both the fuel cell power plant and the additional tank space required for hydrogen to fit into a standard sized locomotive (Wancura 2014).

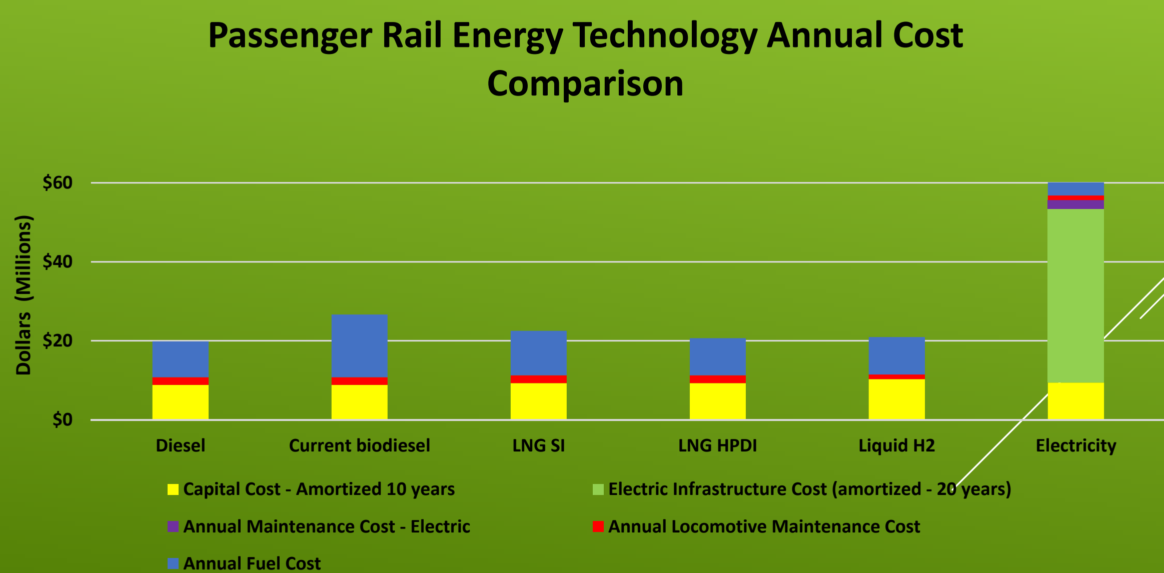
Most efficient options…



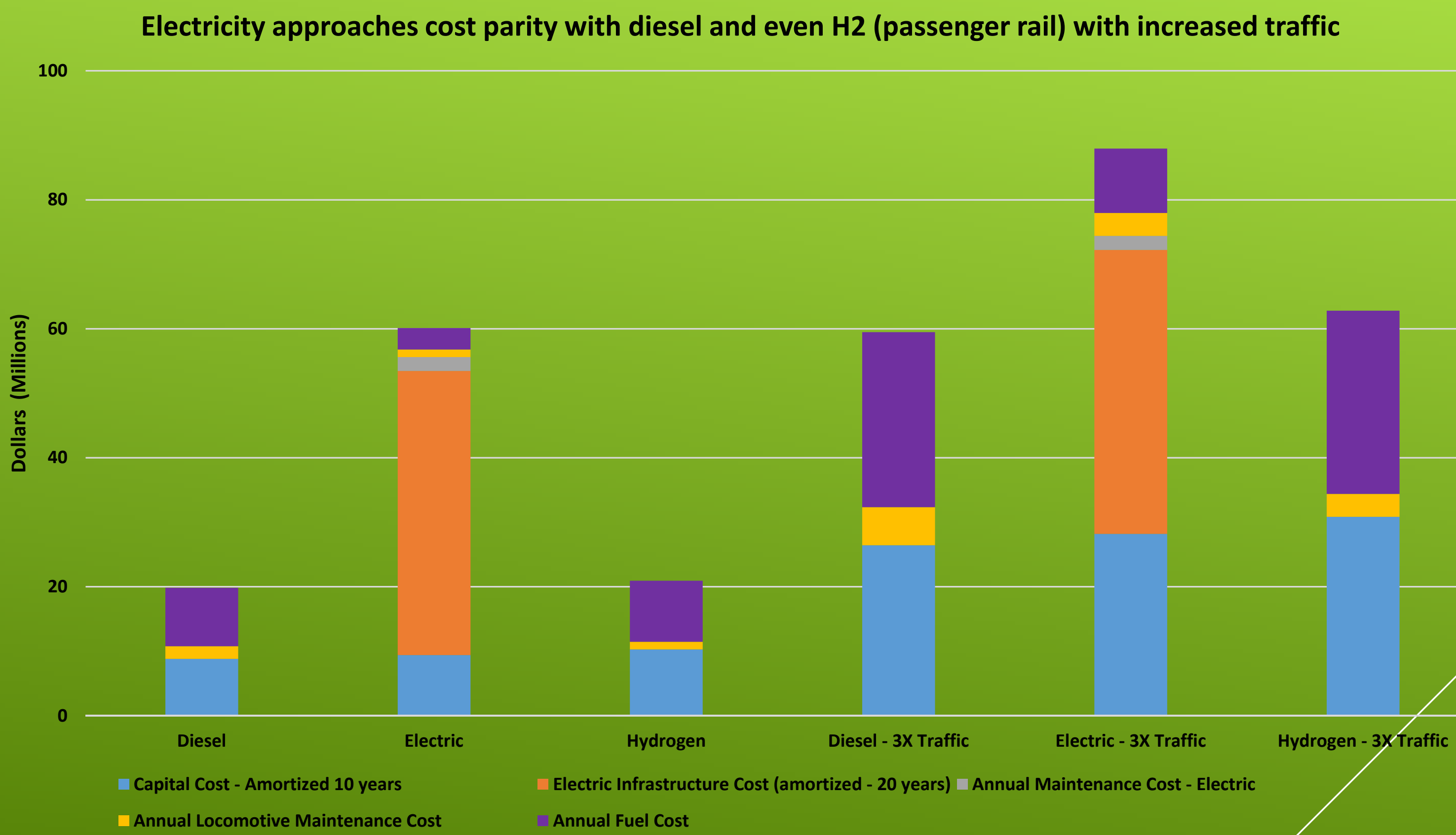
…are not necessarily the most cost-effective

→ Electric Infrastructure Costs (due to catenary) – Especially where rail traffic is low to moderate

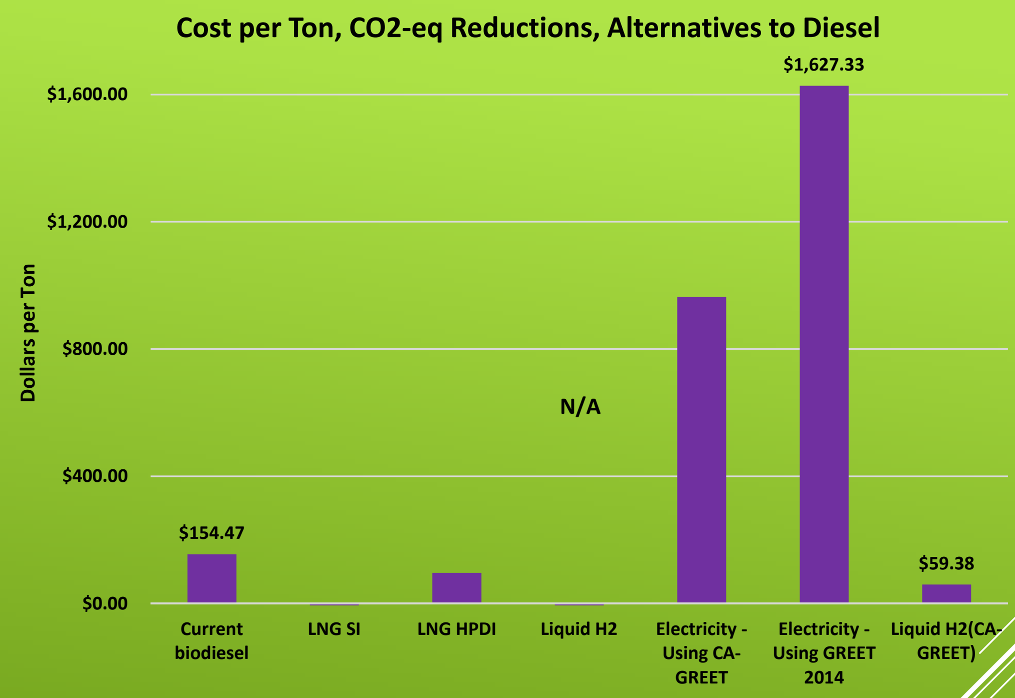
→ Hydrogen is energy dense, but not from a per-gallon perspective

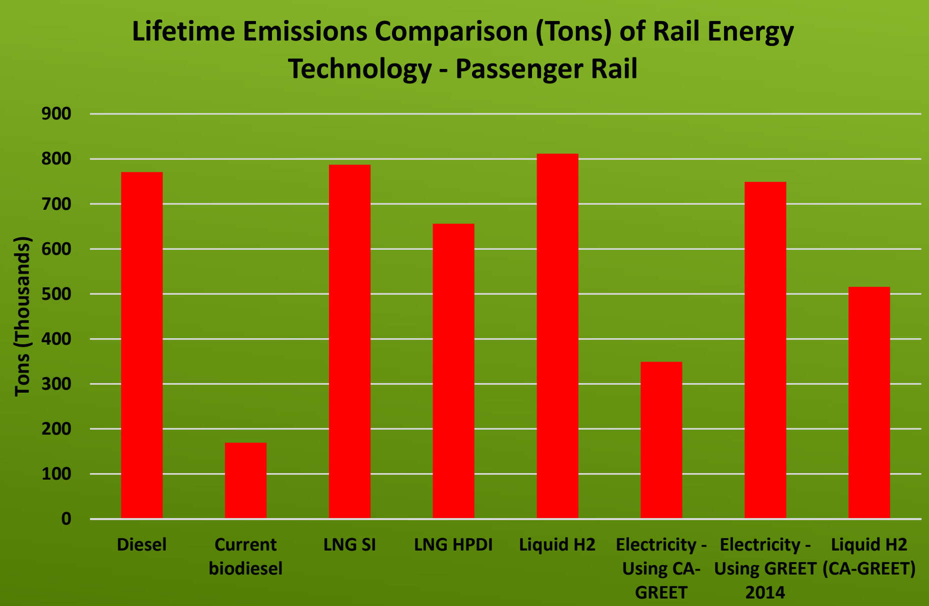


Amount of rail traffic significantly affects cost-effectiveness of options…



Translated into Cost per Ton…





INITIAL THOUGHTS ABOUT FREIGHT RAIL AND HYDROGEN

- ***Good news:*** With freight rail, fuel costs dominate → Cost of additional tender cars to carry the fuel does NOT take Hydrogen "out of the game"
- ***Not-so-good news:*** Freight rail firms tend to be quite conservative in their investments; only clear evidence of cost savings will get them to seriously consider a switch to Hydrogen

WHAT EXACTLY ARE HYDROGEN'S ADVANTAGES? CHALLENGES?

Advantages -

* Cleaner than current technology, potentially significantly so…HOWEVER this depends on the technology used to produce it

→ e.g. GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model assumes SMR of natural gas, popular method currently

→ Solar, Photoelectro-chemical, maybe even biological/biomass would be IDEAL

* Lower maintenance of the locomotive costs (due to minimal moving parts)

Challenges –

* Lifetime far short of typical locomotive lifetimes, especially for freight the equipment for which can last 40+ years
* Stack costs
* Freight tenders are essentially "dead weight," as they limit already optimized train lengths, though if costs can continue to decrease, this may be overcome

RESEARCH NEXT STEPS

- Explore, in depth, the impact of batteries/ultracapacitors for hybridized applications; perhaps perform simulation of hybridized H_2 vehicle to determine CA system power requirements
- Sensitivity analysis of H_2/Fuel cell costs
- Closer examination of pollutant impacts (e.g. shift toward the upstream, given current H2 production methods)

COMPANIES/AGENCIES THAT PROVIDED INFORMATION OF HELP TO OUR RESEARCH

Capitol Corridor Joint Powers Authority

Amtrak (DC/PHL)

General Electric

Westport

Synergesis, Inc.

Dr. Andreas Hoffrichter

Samtrans ('Caltrain')

AC Transit

Vehicle Projects

Union Pacific

Regional Transit District

THANK YOU/QUESTIONS?

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