Impact of Hydrogen for Rail Applications

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Class I Railroad Priorities

1. **Safety**
   - Severe weather e.g. Hurricane Harvey
   - Terrorism and Crime
   - Personal Injuries
   - Derailments

2. **Operational Efficiencies & Network Congestion**
   - Fuel efficiency
   - Technology, real time status
   - North America Shared Rail System

3. **Emissions Controls**
   - Environmentally Responsible
   - Carbon Emission Tax
   - Coal Customers, higher tax or business loss
   - Legal Claims
   - Unpredictable Shipping Resulting from Government Incentives

* 7 Class I Railways + Amtrak

Class I focus on Safety, Operations, and Emissions Controls

Where can hydrogen address these concerns?
Methodology: Impact Figure of Merit

Applications considered:
- Freight
- Passenger
- Switcher

Technologies considered:
- Diesel
- Electric (catenary/third rail)
- Battery Electric
- Hydrogen (gaseous storage)
- Hydrogen (liquid storage)

Figure of merit for each technology/application pair
(bad) 0.0 – 10.0 (good)

Some values estimated qualitatively, some calculated quantitatively

1. Topical figures of merit calculated
2. Weighted average of topical figures of merit leads to overall Impact Figure of Merit

Data and models from journal articles, reports, conferences, etc.
Environmental Topics

- Emissions of major pollutants per hour of operation
  - CO₂, NOₓ, HCs, PM
- Calculations based on notch-weighted fuel consumption
  - Tier 4 diesel emissions standards
  - California grid emissions assumed
- Emissions differ by source of H₂
  - Natural gas reformation
  - Electrolysis from grid energy
  - Renewable resources
  - Currently averaged in analysis
- Possible future considerations:
  - Fuel spills, end-of-life

Overall Environmental Figures of Merit

<table>
<thead>
<tr>
<th>Source of Hydrogen</th>
<th>Freight</th>
<th>Passenger</th>
<th>Switcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Electric Track</td>
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<tr>
<td>Battery</td>
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<tr>
<td>Hydrogen (gas)</td>
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<tr>
<td>Hydrogen (liq)</td>
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<tr>
<td>NG LH2</td>
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<td></td>
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<tr>
<td>Elec. LH2</td>
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<tr>
<td>Renewable LH2</td>
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</tr>
</tbody>
</table>

3 40 CFR 1033.101, Table 2
4 EPA eGRID Summary Tables 2016
Acceptance Topics

- **Noise**
  - Not a large impact, mostly wheel noise

- **Aesthetics**
  - Catenaries undesirable

- **Public acceptance**
  - Public may be initially concerned about hydrogen nearby

- **For future investigations:**
  - Interface with other industries/markets
  - Smog and appearance

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**Overall Acceptability Figures of Merit**

- **Freight**
- **Passenger**
- **Switcher**

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Safety Topics

- **Acute effects on public from fuel release due to leak or crash**
  - Qualitative trend (Low, Med, High)

- **Fire**
  - Effect of fuel fire, hydrogen may have slightly larger effect

- **Health**
  - Acute health effects due to diesel emissions

- **Electric**
  - Exposure to electric track/catenary

- **Pressure**
  - Gaseous hydrogen

![Overall Safety Figures of Merit](chart)

- **Freight**
- **Passenger**
- **Switcher**

- Diesel
- Electric Track
- Battery
- Hydrogen (gas)
- Hydrogen (liq)
Performance Topics

- Maintenance interval \(^1,^2\)
- Energy/fuel efficiency
  - Notch-weighted
  - Hydrogenics HD-30, EMD GP38-2
  - *Estimated increased efficiency at low power notches*
- Weight
  - \(H_2/\text{tank ratios (6\% GH}_2, 20\% LH}_2^3\)
  - Negative impact (decrease in range)
    - Can improve traction for freight
- Volume
  - Density of “fuels”
    - Electric track does not have “fuel”
  - Electrified rail based on Toshiba power conversion unit for rail
- Refueling time and system life considered for future work

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Overall Performance Figures of Merit

![Overall Performance Figures of Merit](chart.png)

Economic Topics

• **Capital Costs**
  – New fueling stations
  – New track (for electric rail)
  – New Power Plants (Freight on Grid)

• **Operating Costs**
  – Cost of fuel, labor hours to fuel
  – Maintenance costs

• **Transition Costs**
  – Fragmented track compatibility
  – Partial fueling station availability
  – New locomotive vs. Modification

• **How to estimate large volume cost for hydrogen fuel?**
  – Will depend on supply/demand with other industries

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**Overall Economic Figures of Merit**

- **Freight**
- **Passenger**
- **Switcher**

Current spend on diesel used as baseline
More detailed implementation plans for H2 will support refinement of cost estimate
Combining Figures of Merit

- Figures of merit summarize comparison about underlying trends
  - Scale can be simple, inverse, exponential, qualitative, etc.
- Currently, all weighting is equal for combining figures of merit
  - Combining individual topics into categories
  - Combining topics into overall figure of merit
- Different locations, regions, jurisdictions will have different preferences
  - Sensitivity analysis can show how different weights can contribute to different rankings
Findings So Far

- Methodology is being created to examine the potential beneficial impact of hydrogen fuel cells for rail applications
  - Areas of analysis are economic, environmental, performance, acceptability, and safety
- Preliminary results show trade-offs between all technologies
  - *More refinement and exploration needed, which will change rankings*
- Emissions reduction benefit from hydrogen depends on the source of hydrogen
- Reliability of hydrogen locomotives needs to be investigated
  - Impacts performance and economics
- Fueling infrastructure needs to be investigated further
- Safety needs to be investigated further
Future Work

• Improve impact figures of merit
  – Many current preliminary results are qualitative
  – Identify what data exists, and what further study is needed
  – We want your feedback!

• Regional figure of merit
  – Identify 3 regions in the USA that match well to high impact figure of merit for hydrogen for rail
  – Examine impact/value of:
    • Electricity grid mixes
    • Amounts of different types of rail usage
    • Emissions displacement

• Liquid hydrogen refueling technology assessment
  – Assess technology, safety, codes and regulations, and feasibility for LH2 fueling of a locomotive
Hydrogen for Maritime Applications

- Feasibility studies funded by DOT/MARAD
- SF-BREEZE high-speed hydrogen fuel cell ferry
  - 1,000+ kg/day hydrogen demand
- Zero-V hydrogen fuel cell coastal research vessel
  - 2,400 nautical mile range
  - Refueled with ~11,000 kg of LH2
- High capacity fueling also needed for rail
- Leveraging emissions displacement calculations

Hydrogen Vehicle Refueling Station Reference Designs

- Gas and liquid hydrogen systems
- Identification of improvements for dispensers
Extending Safety Analysis to Rail Applications

What can go wrong, how likely it is, and what could happen

- **Hazard and frequency/probability analyses**
  - Vehicles in tunnels
  - Safety codes and standards for vehicles and infrastructure

- **Consequence analyses**
  - Vehicles in tunnels
  - Maritime vent stack
  - Liquid H2 release model development
Thank you!

QUESTIONS?
BACK-UP SLIDES
Impact Figure of Merit Framework

• **Goal:** Develop impact figure of merit (IFM) to evaluate the benefits of hydrogen fuel cell technology in rail use
  – Formulation that assesses impact in many areas (economic, environmental, safety, performance, acceptability)
  – Framework for identifying applications with the largest IFM for hydrogen relative to traditional and competing locomotion
  – Enable identification of IFM drivers to determine where more information is needed and/or largest impact is possible

• **Disclaimer:** Any individual project, application, or design can differ greatly from high-level trends
  – This analysis focuses on comparative trends for overall technologies and applications

• *All results are preliminary and meant to solicit discussion and feedback; we want to hear from you!*
Critical Needs

- Usage data for all three rail applications
  - Freight-miles, passenger-miles, train-miles
  - Different areas of the country
- Duty cycles for all three rail applications
  - Power output, fuel consumed, profile over time
  - Multiple examples to show variability
- Source of power for electric trains? New power plant additions?
- Source/method of obtaining fuel
- Pricing of diesel vs electricity and H2 fuel at scale
- Effect of public perception on rail policy by region
### Different Methods of Scaling

<table>
<thead>
<tr>
<th>Figure of Merit</th>
<th>Qualitative</th>
<th>Linear</th>
<th>Logarithmic</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>High</td>
<td>Better</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>90</td>
</tr>
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<td>6</td>
<td></td>
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<td>60</td>
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<tr>
<td>5</td>
<td>Medium</td>
<td>Same</td>
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<tr>
<td>2</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>Low</td>
<td>Worse</td>
<td>10</td>
</tr>
</tbody>
</table>
Railway Focus Areas

- Amtrak, 1 Railroad
  - 350 locomotives
  - 21k miles of track
  - City: City Passengers

- Class II, 10 Railroads
  - Class III, 557 Railroads
  - 6k locomotives
  - 40 yrs Average Age
  - 45k miles of track
  - City: Rural Freight

- Class I, 7 Railroads
  - 30k Locomotives
  - 20 yrs Average Age
  - 120k miles of track
  - City: City Freight

Focus of this work

- Passenger

- Long Haul Freight

- Short Line

- Switcher

Class I: Annual carrier operating revenues of $452M
Class II: Annual revenues between $20M and $452M
Class III: Annual revenues less than $20M

Values collected from investor disclosure statements
Different Methods of Calculating Figures of Merit

**Environmental**
- Quantitative scaled calculations of pollutants
  - Example: powering freight rail
    - Calculate pollutant release rate
      - Well-to-wheels: includes production/delivery and use
      - For freight duty cycle
    - Determine pollutant impact factors
      - Preserves comparative relationship
      - Assign best value to 10.0
      - Example calculation on next slide
    - Overall Environmental FoM is average of these values for the 4 pollutants considered

**Safety**
- Qualitative estimates of potential effects
  - 1 = High
  - 5 = Medium
  - 10 = Low
  - Example: GH2 for freight
    - Fire: medium-high (3)
      - Jet fire from leak or crash
    - Health: low (10)
    - Electric: low (10)
    - Pressure: medium-low (7)
      - Pressurized hydrogen
    - Overall Safety FoM is average
      - \[(3+10+10+7)/4 = 7.5\]
Different Methods of Calculating Figures of Merit

First Consider the Quantitative Environmental Emissions

- Quantitative calculations of pollutant emissions (CO₂ (eq.), NOₓ, HC, PM)
- Consider each type of application in turn (freight, passenger, switch)
  - Calculate pollutant release rate (kg/hr)
    - Adopt a duty cycle (percentage of time spent on each Notch and in Dynamic Brake and Idle) for the particular application.
    - Comprehensive Well-to Wheels Analysis that includes production, delivery and use of energy
  - Determine pollutant impact factors for each application (freight, passenger, switch), for each technology (diesel, catenary electric, H₂ fuel cell, etc.) for the 4 pollutants based on quantitative calculation of the WTW pollutant release rates.
  - Design impact factors (IFs) such that the best performing technology is given a 10 score, and all other (lower) IFs for that pollutant reflect the correct relative emissions for the different technologies for the particular application.

Step 1: For each pollutant species, identify the largest emission. Then divide this largest emission by the other emission values. This produces large numbers for low emission paths.

Step 2: Take each Step 1 number, divide by the largest Step 1 number (most benefit) amongst the technologies, then multiply by 10.0. This give you the impact factor (IF) for that technology, for that pollutant, on the desired 0 – 10 scale where 10 is the most benefit.
For Example: Freight (Line-haul) Application

For each technology, determine an overall emissions IF: $\text{IF} = \frac{\text{IF}_{\text{CO2}} + \text{IF}_{\text{NOx}} + \text{IF}_{\text{HC}} + \text{IF}_{\text{PM}}}{4}$

<table>
<thead>
<tr>
<th>Technologies</th>
<th>CO$_2$(eq.) kg/hr</th>
<th>STEP 1 CO$_2$(eq.) kg/hr</th>
<th>Step 2 CO$_2$(eq.) kg/hr</th>
<th>$\text{IF}_{\text{CO2}} = \left[\frac{y}{31.60}\right] \times 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>463.300</td>
<td>1.945</td>
<td>0.615</td>
<td></td>
</tr>
<tr>
<td>FC NG LH$_2$</td>
<td>482.559</td>
<td>1.867</td>
<td>0.591</td>
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</tr>
<tr>
<td>FC Electrolysis LH$_2$</td>
<td>901.312</td>
<td>1</td>
<td>0.316</td>
<td></td>
</tr>
<tr>
<td>FC Renewable</td>
<td>36.679</td>
<td>24.572</td>
<td>7.776</td>
<td></td>
</tr>
<tr>
<td>Cat. Electric</td>
<td>209.411</td>
<td>4.304</td>
<td>1.361</td>
<td></td>
</tr>
<tr>
<td>Battery Only</td>
<td>246.267</td>
<td>3.659</td>
<td>1.158</td>
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<tr>
<td>FC NG H$_2$ 350 bar</td>
<td>375.238</td>
<td>2.401</td>
<td>0.760</td>
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<tr>
<td>FC Elect. H$_2$ 350 bar</td>
<td>700.860</td>
<td>1.286</td>
<td>0.406</td>
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<tr>
<td>FC Ren. H$_2$ 350 bar</td>
<td>28.521</td>
<td>31.600</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
Environmental Figures of Merit Details

Direct Emissions: CO2
Direct Emissions: NOx
Direct Emissions: PM
Direct Emissions: HCs
Overall Environmental
Acceptance Figures of Merit Details

Acceptability Figures of Merit

Freight

- Diesel
- Electric Track
- Battery
- Hydrogen (gas)
- Hydrogen (liq)

Passenger

- Diesel
- Electric Track
- Battery
- Hydrogen (gas)
- Hydrogen (liq)

Switcher

- Diesel
- Electric Track
- Battery
- Hydrogen (gas)
- Hydrogen (liq)

Legend:
- Noise
- Aesthetics
- Public Acceptance
- Overall Acceptability
Safety Figures of Merit

Freight
- Diesel
- Electric Track
- Battery
- Hydrogen (gas)
- Hydrogen (liq)

Passenger
- Diesel
- Electric Track
- Battery
- Hydrogen (gas)
- Hydrogen (liq)

Switcher
- Diesel
- Electric Track
- Battery
- Hydrogen (gas)
- Hydrogen (liq)
Performance Figures of Merit Details

Performance Figures of Merit

- Temperature
- Oxygen
- Fuel
- Energy Efficiency
- Maintenance Interval
- Volume
- Weight
- Overall Performance

Diesel
Electric Track
Battery
Hydrogen (gas)
Hydrogen (liq)

Diesel
Electric Track
Battery
Hydrogen (gas)
Hydrogen (liq)

Diesel
Electric Track
Battery
Hydrogen (gas)
Hydrogen (liq)
Liquid Hydrogen Fueling

• Two aspects with cryogenic liquid transfer:
  1. Chilling of transfer lines and tanks
  2. Boil-off (to vent) of dormant liquid hydrogen

• LH2 used by NASA for decades
  – Pre-cool for 3 hours, then transfer 340,000 gal LH2 in 90 minutes (maximum 10,000 gpm)\(^1\)

• Recent work by Guillaume Petitpas, et al. (LLNL) on light-duty vehicles and refueling stations\(^2\)
  – LH2 transfer code released open source\(^3\)
  – More frequent fills reduces boil-off
  – Re-capture of boil-off possible, may be economical depending on use

• NFPA 2 Hydrogen Technology fire code may apply to refueling stations

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1 Wybranowski E. (1972) Advances in Cryogenic Engineering. vol 17
3 [https://github.com/LLNL/LH2Transfer](https://github.com/LLNL/LH2Transfer)
Class I: $15B Capital Investments 2018

1. Safety
   - Severe weather e.g. Hurricane Harvey
   - Terrorism and Crime
   - Personal Injuries
   - Derailments

2. Operational Efficiencies & Network Congestion
   - Fuel efficiency
   - Technology, real time status
   - North America Shared Rail System

3. Emissions Controls
   - Environmentally Responsible
   - Carbon Emission Tax
   - Coal Customers, higher tax or business loss
   - Legal Claims
   - Unpredictable Shipping Resulting from Government Incentives

Positive Train Control System (PTC)
- 2008 Rail Safety Improvement Act
- Varying degrees of completion

Main Line Track Upgrade
- 1980 Increased weight limit from 263k-lbs to 286k-lbs
- Class I complete
- Class II & III varying degrees of completion

Exploring Clean Energy Options – Next Steps…
- Diesel
- Electric, Third Rail or Battery
- Hydrogen, Liquid or Gas

Class I Collaborative Capital Investments in Safety and Operations, now Emissions Controls
### Staggers Rail Act of 1980
- Encouraged Class I to sell, not abandon short line service to originate and terminate goods in rural America
- Difficult to restore a line after being shut down

### Federal Financing
- Railroad Rehabilitation and Improvement Financing (RRIF) Program- Loan Program 1998
- Transportation Infrastructure Generating Economic Recovery (TIGER)- Grant Money 2009
- Section 45G Tax Credit 2004

### State Financing
- Loan and Grant Programs: Idaho, Kansas, New Jersey, New York, Ohio, Oregon, Pennsylvania, Virginia, Wisconsin

### Consolidation Under Holding Companies to Improve Bank Financing
- 50% Short Line Railways have been acquired by holding companies
- 297 Short Line Railways remain independent
- 122 Short Line Railways owned by Genesee and Wyoming
- 27 holding companies total, 567 Short Line Railways total

Class II & III are now independent railways and rely on Government Financing
Class II & III Railway and Federal, State, Local Government Priorities

1. Safety
   - Severe weather e.g. Hurricane Harvey
   - Terrorism and Crime
   - Personal Injuries
   - Derailments

2. Operational Efficiencies & Network Congestion
   - Fuel efficiency
   - Technology, real time status
   - North America shared rail system

3. Emissions Controls
   - Environmentally responsible
   - Carbon emission tax
   - Coal Customers, tax or business loss
   - Legal claims
   - Unpredictable shipping resulting from government incentives

Competition with Highway Trucking

4. Maintain Balanced Transportation System
   - Reduce highway maintenance cost
   - Environmentally Sustainable

5. Boost the Economy
   - Increase employment, wages
   - Increase business earnings
   - Increase farm and business opportunities in rural areas
   - Increase local business volume
   - Reduce transportation costs for shippers
   - Reduce highway user cost, traffic

Class II & III share Class I Priorities + Government Priorities
Amtrak

1. Safety
   • Derailments and Personal Injuries

2. Emissions Controls
   • Coastal North East Corridor at high risk for flooding
   • Carbon Emissions
   • Severe Weather, Extreme Temperatures

3. Emergency Management Resource
   • Integral to evacuation plans in case of natural disaster

4. Passenger Amenities
   • Complementary WiFi
   • Checked Bicycle Service
   • Pet Program
   • Spacious seating, Beverages

5. Boost Economic Opportunities
   • Serve communities without intercity bus and airline service

Federally Chartered Corporation
   • Created by Congress 1970, take over of unprofitable intercity passenger rail service
   • Federal Passenger Rail Investment and Improvement Act (PRIIA)
   • Funding from 18 states and 21 agencies

Competition with Airlines, Bus, Private Vehicles
   • 28 new high speed rail locomotives under contract

Amtrak aligns with Government priorities and caters to passengers
Face short term flooding at coastal regions and considered a critical asset to emergency evacuation plans.
Modular fuel cells allow for higher efficiency at lower power ratings.