



Impact of Hydrogen for Rail Applications

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Class I Railroad Priorities

1. Safety

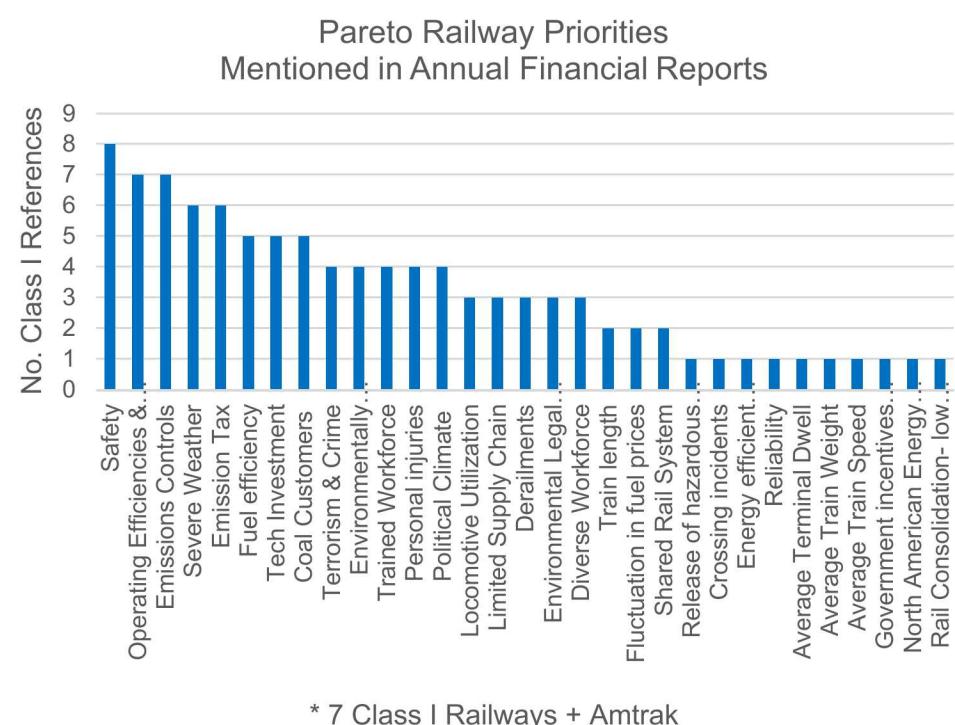
- Severe weather e.g. Hurricane Harvey
- Terrorism and Crime
- Personal Injuries
- Derailments

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:

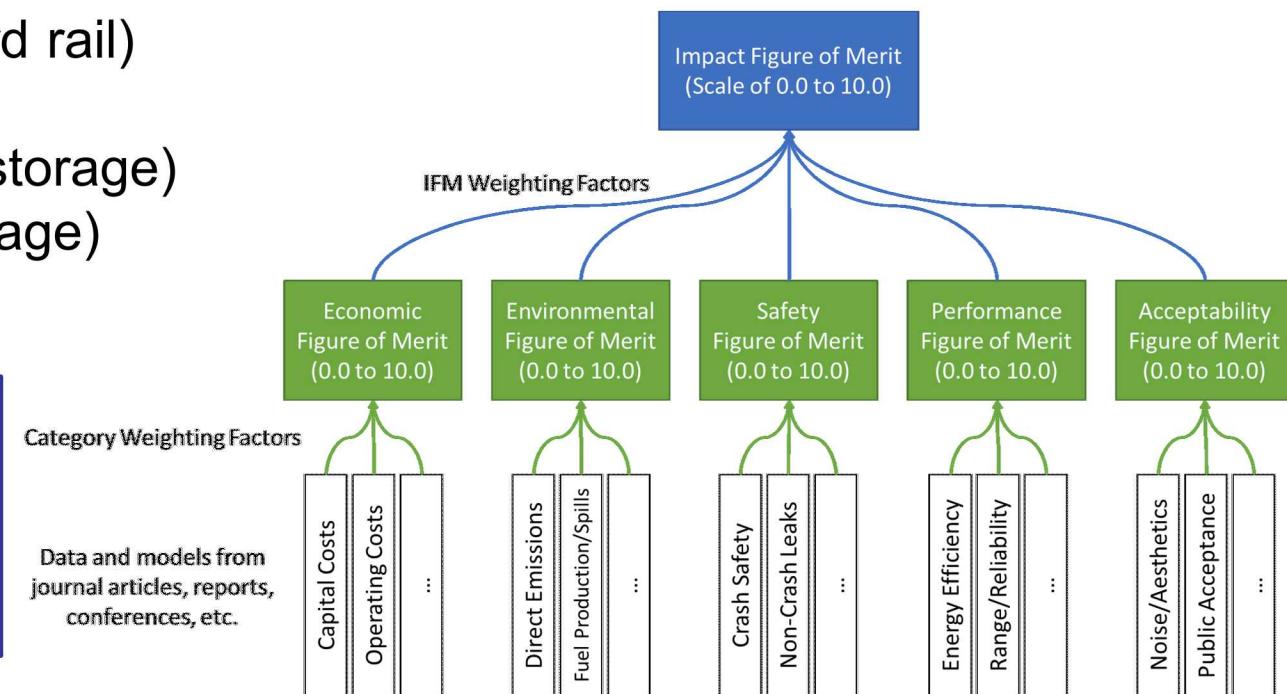
- Diesel
- Electric (catenary/third rail)
- Battery Electric
- Hydrogen (gaseous storage)
- Hydrogen (liquid storage)

Figure of merit allows for comparative ranking and illustrates drivers and trade-offs

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

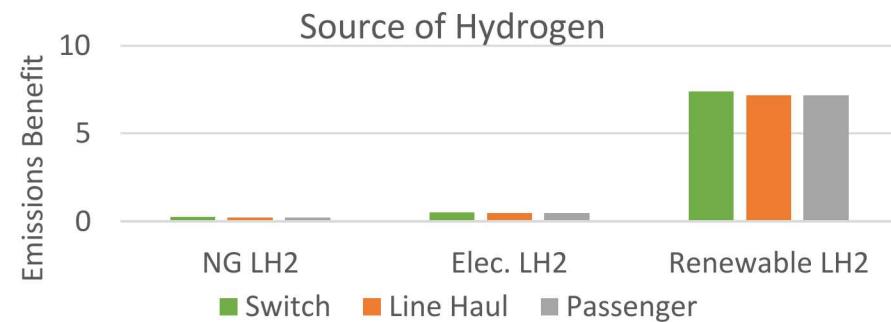
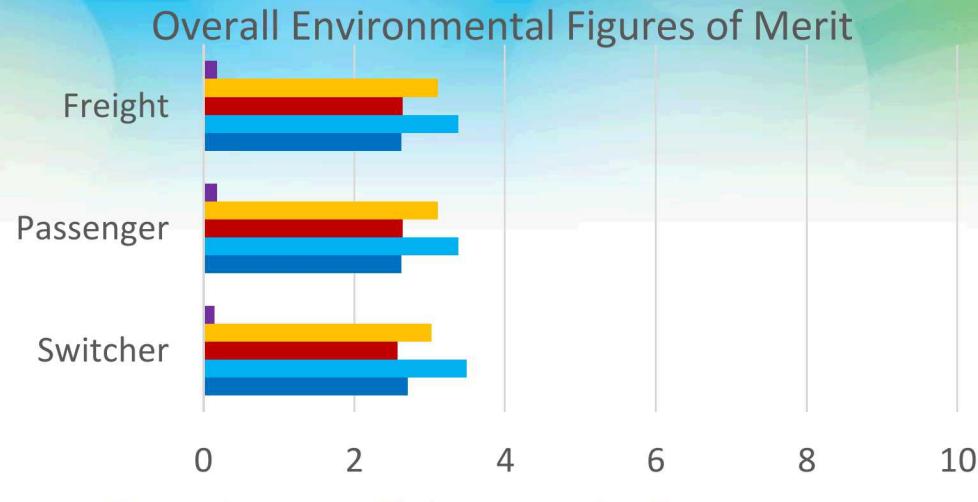
Some values estimated qualitatively, some calculated quantitatively

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



Environmental Topics

- Emissions of major pollutants per hour of operation
 - CO₂, NOx, HC_s, PM
- Calculations based on notch-weighted fuel consumption^{1,2}
 - Tier 4 diesel emissions standards³
 - California grid emissions assumed⁴
- Emissions differ by source of H₂^{5,6}
 - Natural gas reformation
 - Electrolysis from grid energy
 - Renewable resources
 - Currently averaged in analysis
- Possible future considerations:
 - Fuel spills, end-of-life



1 Fritz, S.G., "Evaluation of Biodiesel Fuel in an EMD GP38-2 Locomotive" May 2004, NREL/SR-510-33436

2 Klebanoff, et al. "Comparison of the greenhouse gas and criteria pollutant emissions from the SF-BREEZE high-speed fuel-cell ferry with a diesel ferry" Transportation Research Part D 54 (2017) 250-268 3 40 CFR 1033.101, Table 2

4 EPA eGRID Summary Tables 2016

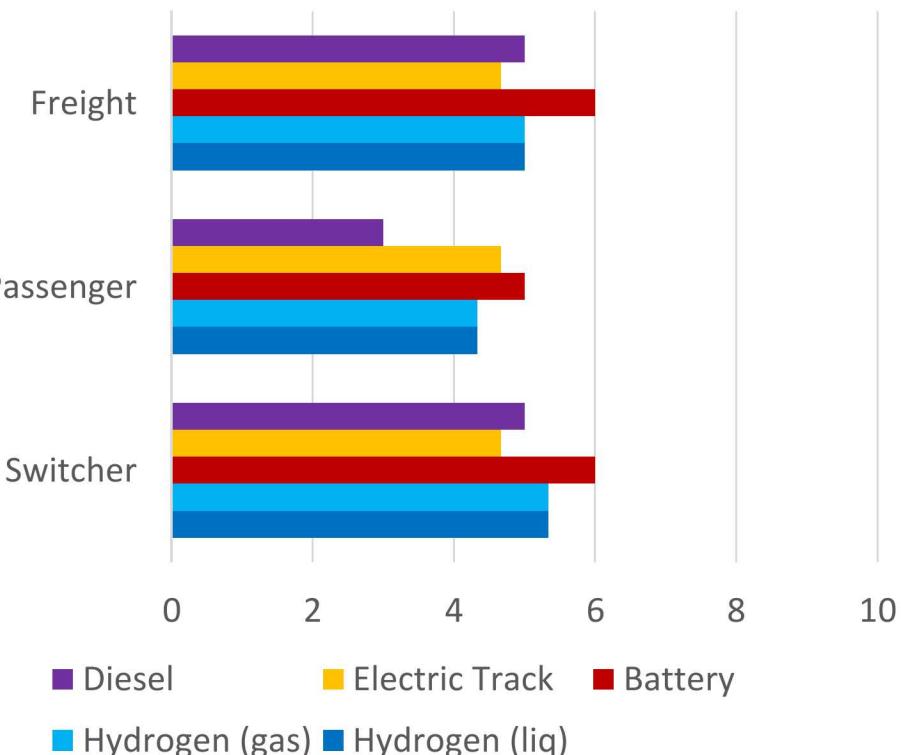
5 Edwards, et al., "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context: Well-to-Tank Report," Version 4, Technical Report by the Joint Research Center of the European Commission, July 2013.

6 Stoner, et al., "Full Fuel Cycle Assessment Well to Tank Energy Inputs, Emissions and Water Impacts," California Energy Commission Report CEC-600-2007-002-D, 2007.

Acceptance Topics

- Noise¹
 - Not a large impact, mostly wheel noise
- Aesthetics²
 - Catenaries undesirable
- Public acceptance³
 - Public may be initially concerned about hydrogen nearby
- For future investigations:
 - Interface with other industries/markets
 - Smog and appearance

Overall Acceptability Figures of Merit



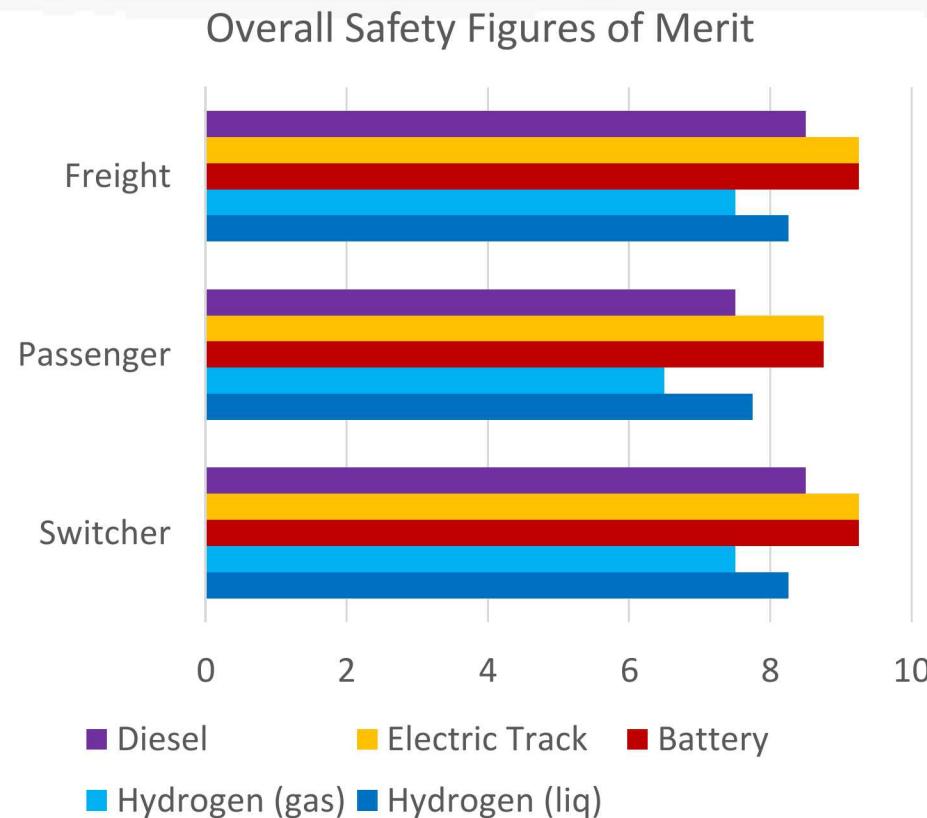
[1] D. H. Cato, Prediction of Environmental Noise from Fast Electric Trains, *Journal of Sound and Vibration* 46(4) 1976, pp. 483-500

[2] F. Calvo and A. Nash, Wireless Electric Propulsion Light Rail Transit Systems in Spain

[3] R. L. Schmoyer, Tykey Truett, and Christy Cooper, Results of the 2004 Knowledge and Opinions Surveys for the Baseline Knowledge Assessment of the U.S. Department of Energy Hydrogen Program, ORNL/TM-2006/417 (April 2006).

Safety Topics

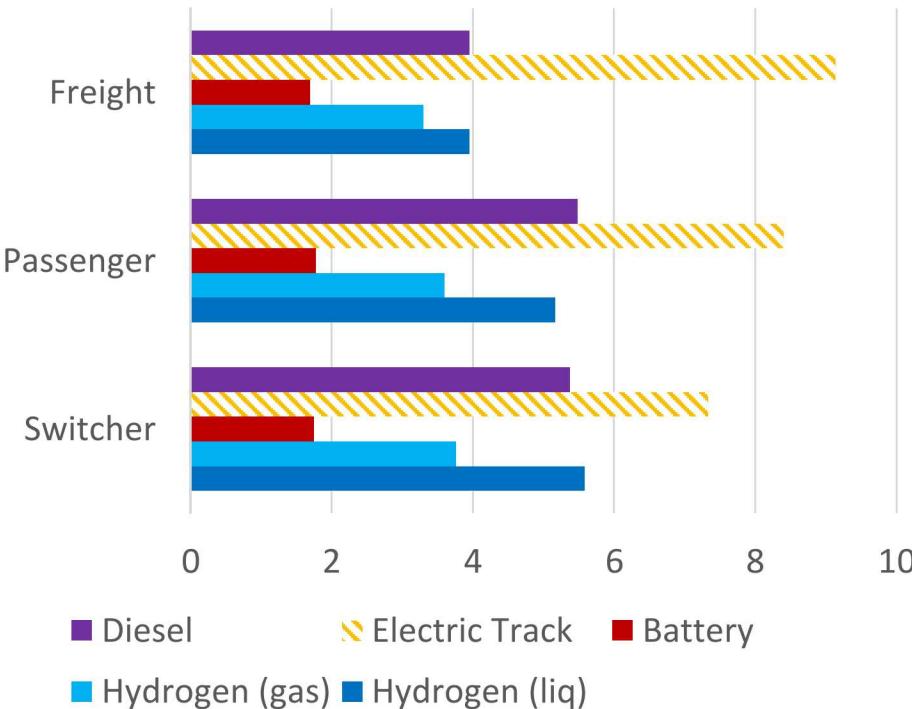
- *Acute effects on public from fuel release due to leak or crash*
 - Qualitative trend (Low, Med, High)
- Fire
 - Effect of fuel fire, hydrogen may have slightly larger effect
- Health
 - Acute health effects due to diesel emissions
- Electric
 - Exposure to electric track/catenary
- Pressure
 - Gaseous hydrogen



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
 - H₂/tank ratios (6% GH₂, 20% LH₂³)
 - 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

Overall Performance Figures of Merit



[1] G. Marin, G. Naterer, and K. Gabriel, "Rail transportation by hydrogen vs. electrification—Case study for Ontario Canada, I: Propulsion and storage," *International Journal of Hydrogen Energy*, vol. 35, no. 12, pp. 6084-6096, 2010.

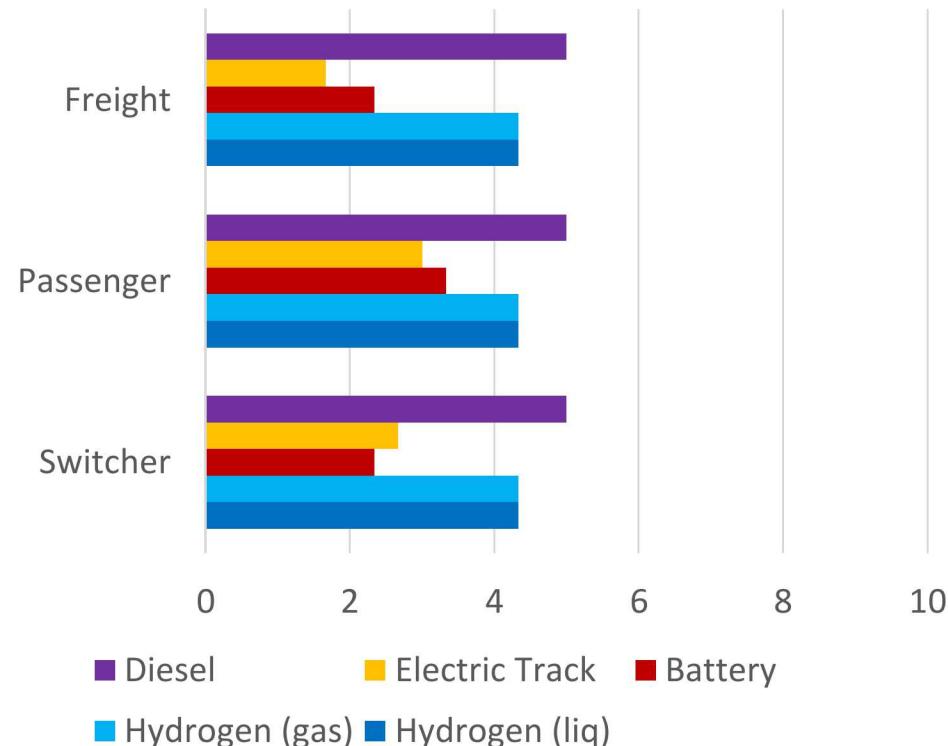
[2] R. Nunno. (2018). *Electrification of U.S. Railways: Pie in the Sky, or Realistic Goal?* <https://www.eesi.org/articles/view/electrification-of-u-s-railways-pie-in-the-sky-or-realistic-goal>

[3] J. Hogerwaard and I. Dincer, "Comparative efficiency and environmental impact assessments of a hydrogen assisted hybrid locomotive," *International Journal of Hydrogen Energy*, vol. 41, no. 16, pp. 6894-6904, 2016.

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

Overall Economic Figures of Merit



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

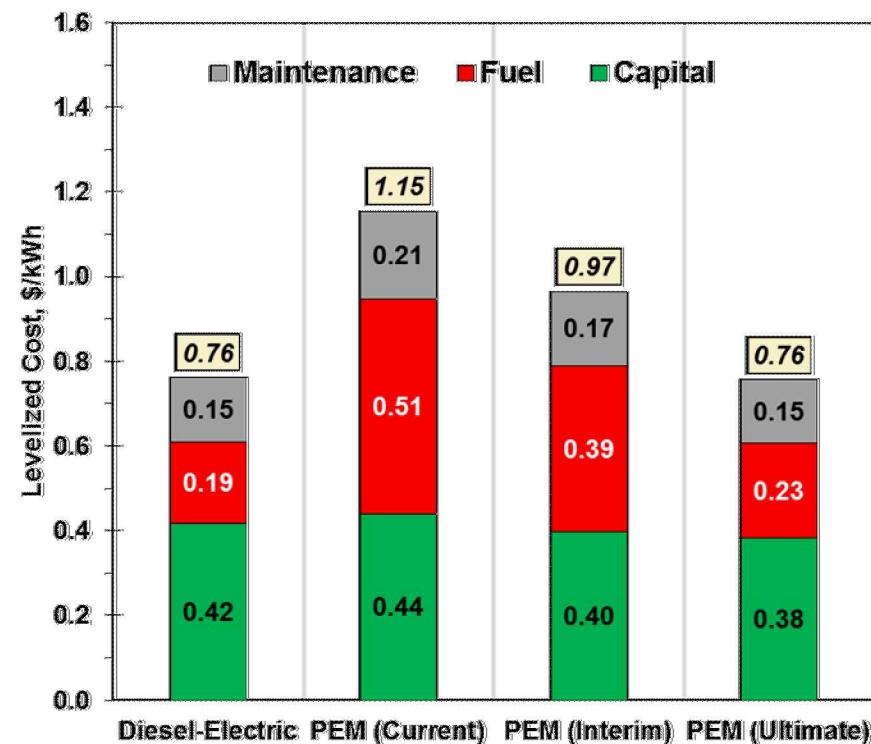
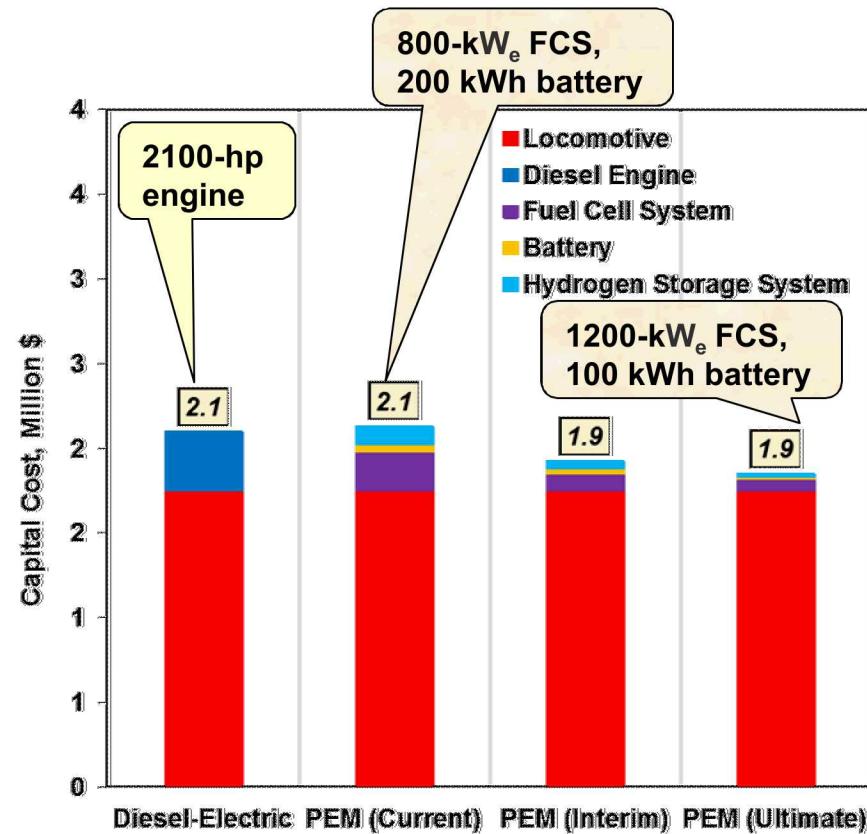
Findings So Far

- 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 and cost of hydrogen locomotives needs to be investigated
 - Impacts performance and economics
- Fueling infrastructure needs to be investigated further
- Safety needs to be investigated further

Preliminary Total Cost of Ownership Fuel Cell Yard-Switcher Locomotives

Preliminary TCO of fuel cells more favorable for yard switchers than freights or regionals

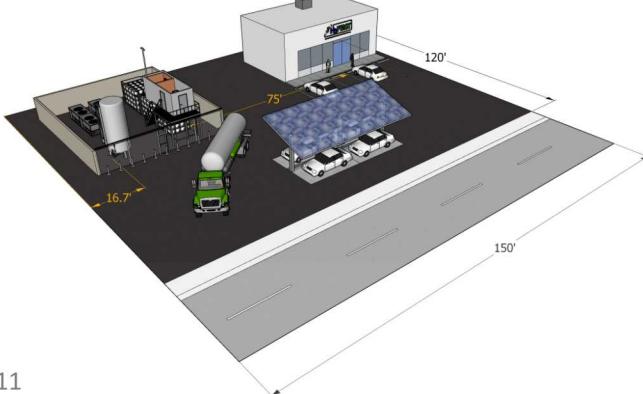
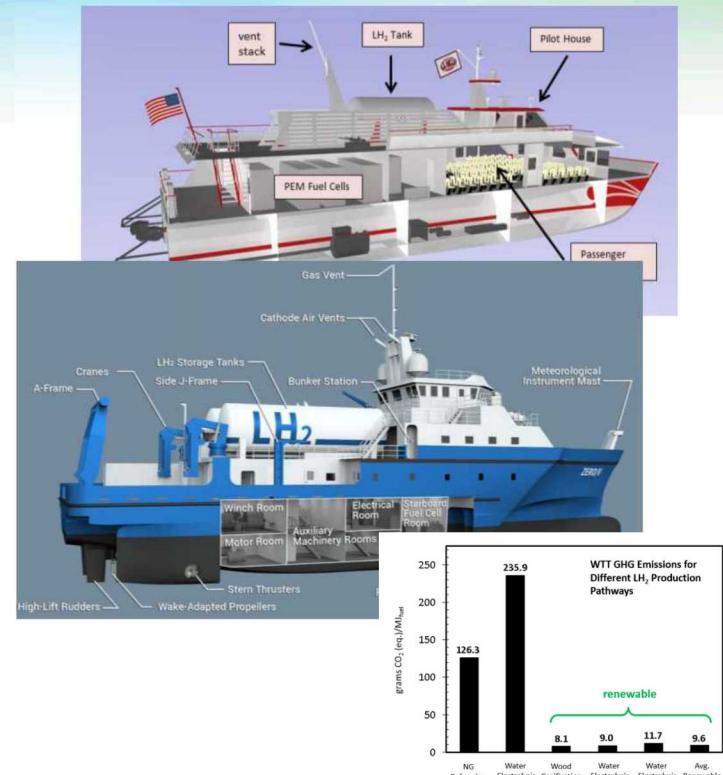
- On EPA duty cycles for switchers, 76% higher FCS drive cycle efficiency relative to diesel engine
- On TCO basis, fuel cells can be cost competitive if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at \$4/kg
- **Break-even delivered hydrogen cost relative to \$2.25/gal diesel: \$4.00/kg**



Leveraging Results from Maritime and Vehicles

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



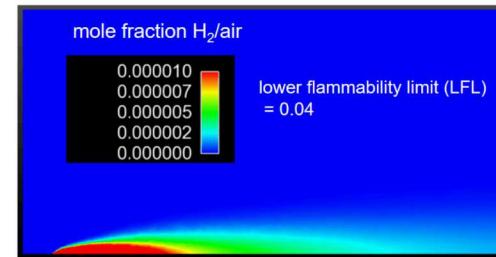
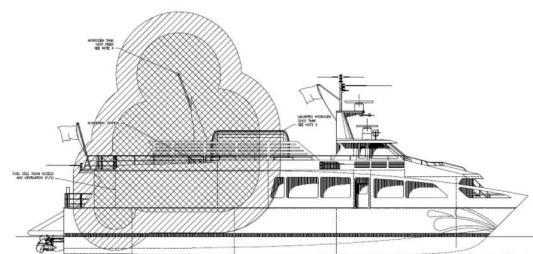
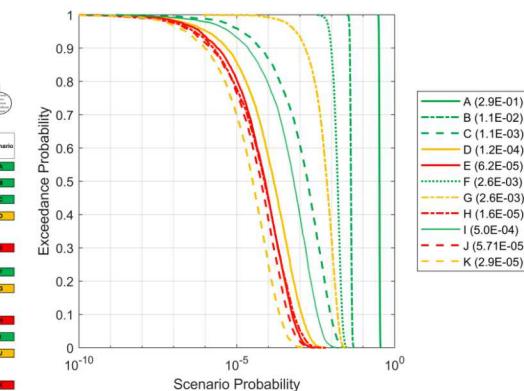
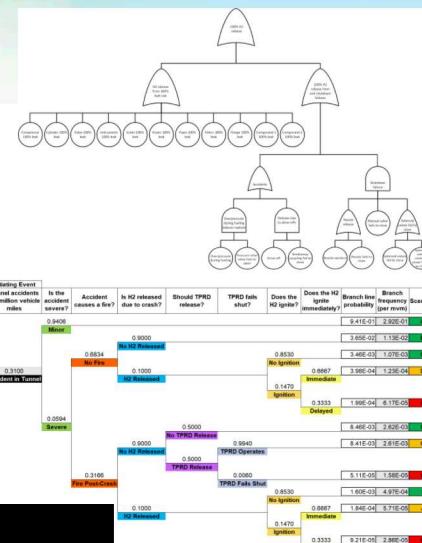
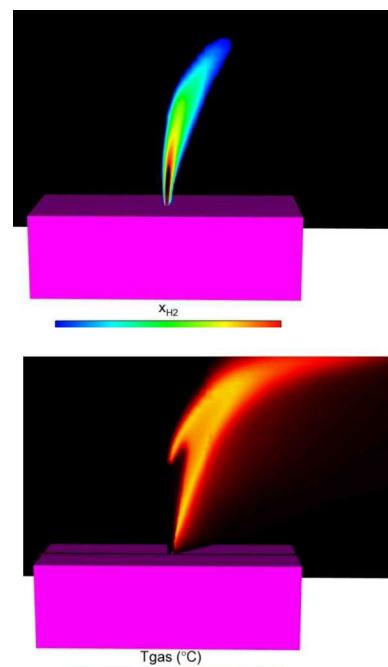
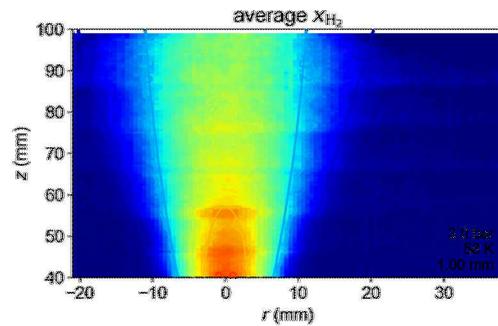
Hydrogen Vehicle Refueling Station Reference Designs

- 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



Current Efforts: Hydrogen Rail Infrastructure Analysis

- Leveraging results from light-duty vehicle infrastructure analysis
 - Capacity and equipment sizing
 - Siting and footprint (lot area)
 - 3 representative locations: rural, urban, port
 - Cost and economic estimation
- Safety, codes, and standards analysis
 - Identification of applicable regulations, codes, and standards
 - Identification of gaps and research needs
 - Identification of lessons-learned in other heavy-duty applications

Thank you!

QUESTIONS?

BACK-UP SLIDES

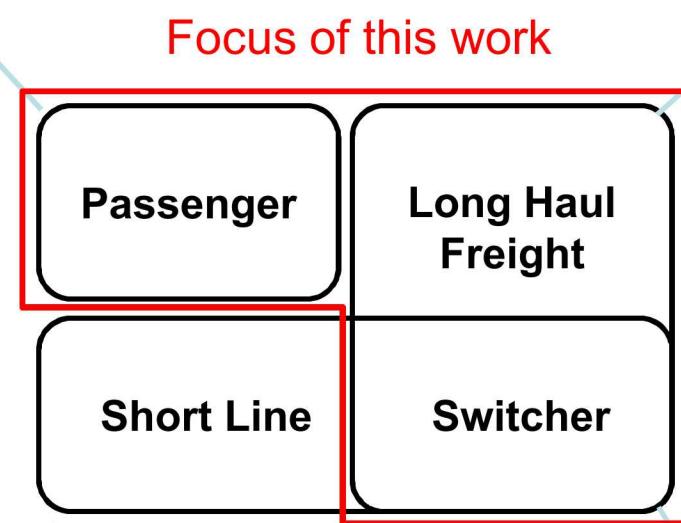
Different Methods of Scaling

Figure of Merit	Qualitative		Linear	Logarithmic
10	High	Better	100	10^5
9			90	10^4
8			80	10^3
7			70	10^2
6			60	10^1
5	Medium	Same	50	10^0
4			40	10^{-1}
3			30	10^{-2}
2			20	10^{-3}
1	Low	Worse	10	10^{-4}

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

- Class I, **7 Railroads**
- **1.4k** Locomotives
- **40 yrs** Average Age
- **48k miles** of track
- Switching Yard Freight

Class I: Annual carrier operating revenues of \$452M

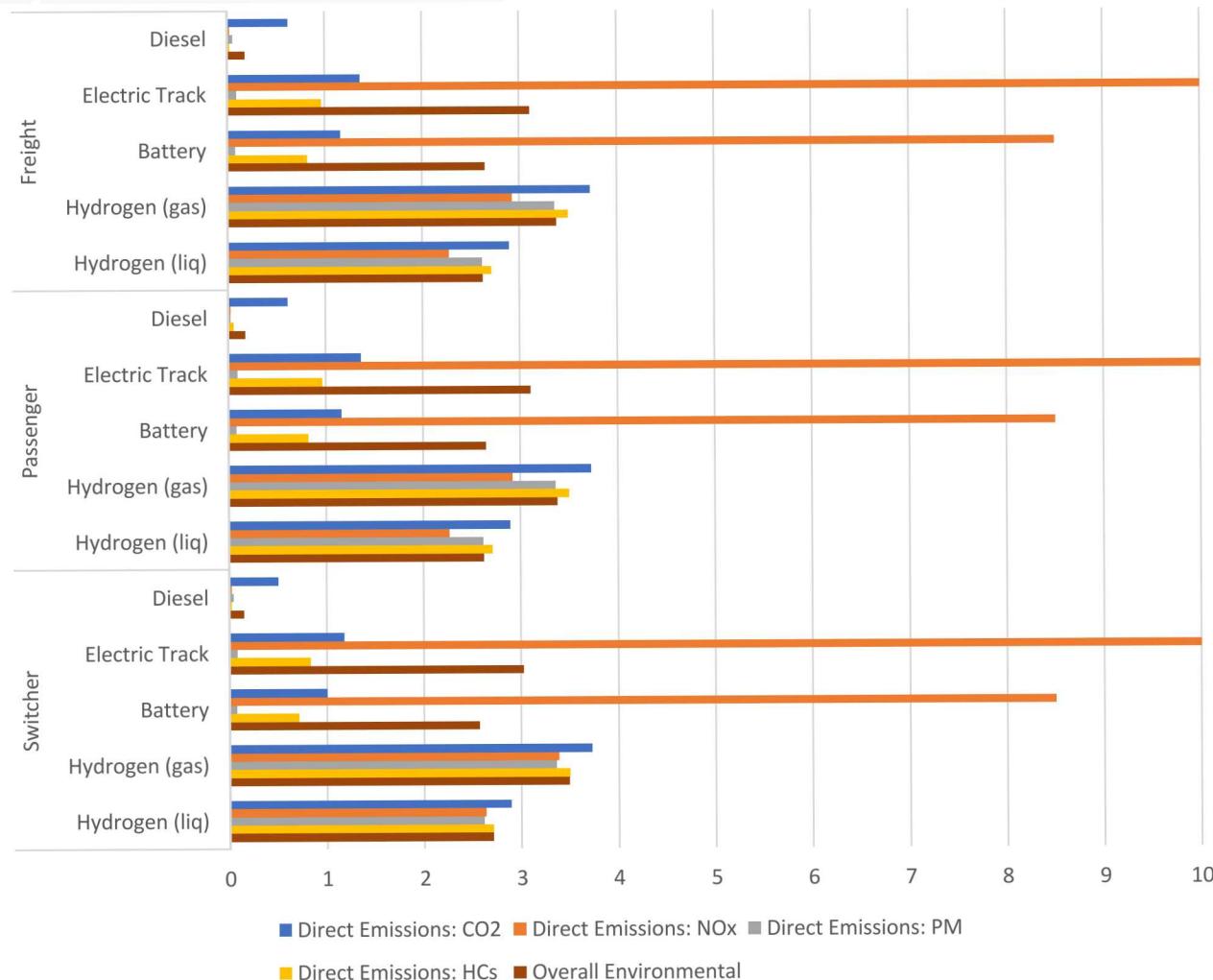
Class II: Annual revenues between \$20M and \$452M

Class III: Annual revenues less than \$20M

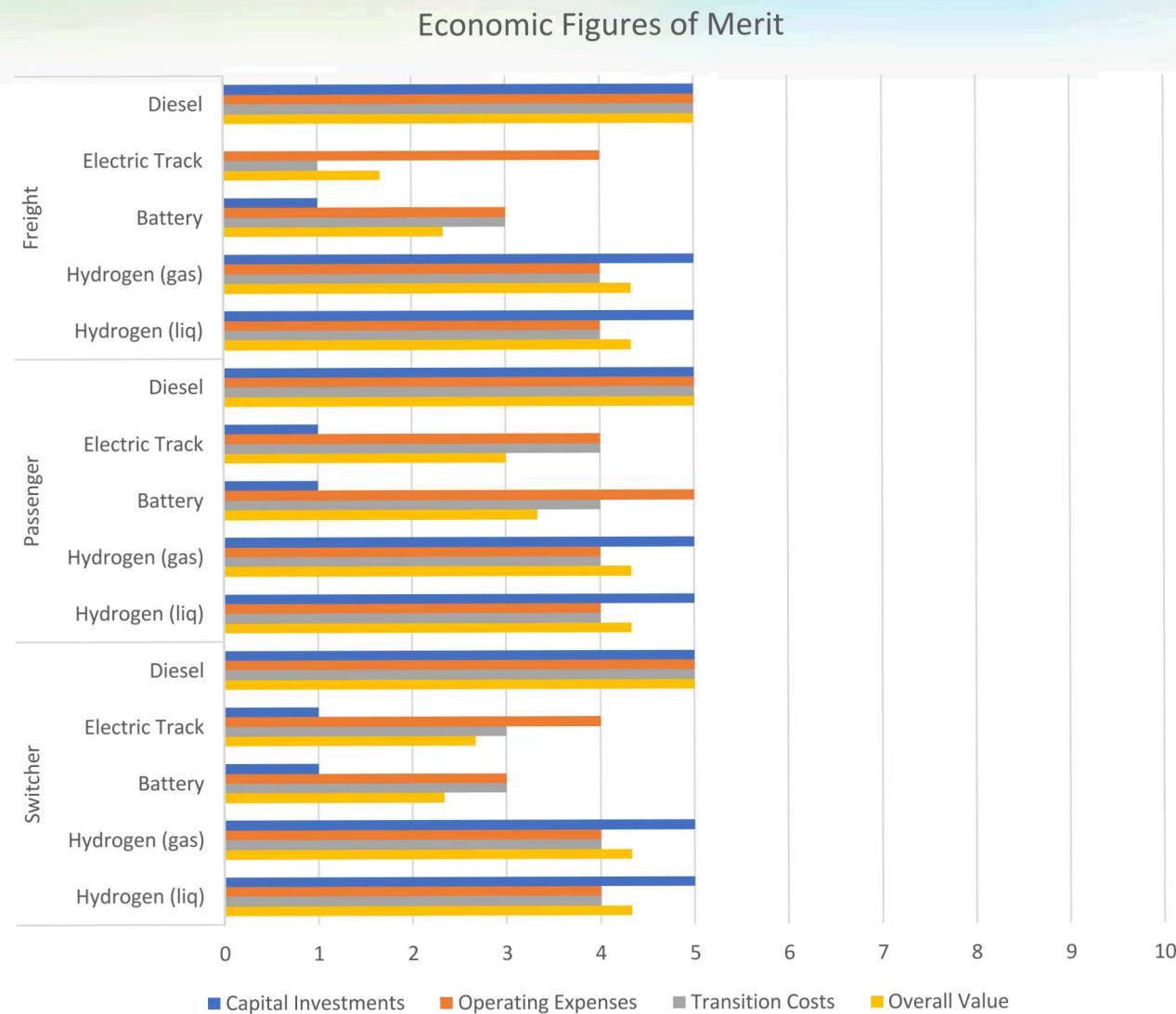
Values collected from investor disclosure statements

Environmental Figures of Merit Details

Environmental Figures of Merit

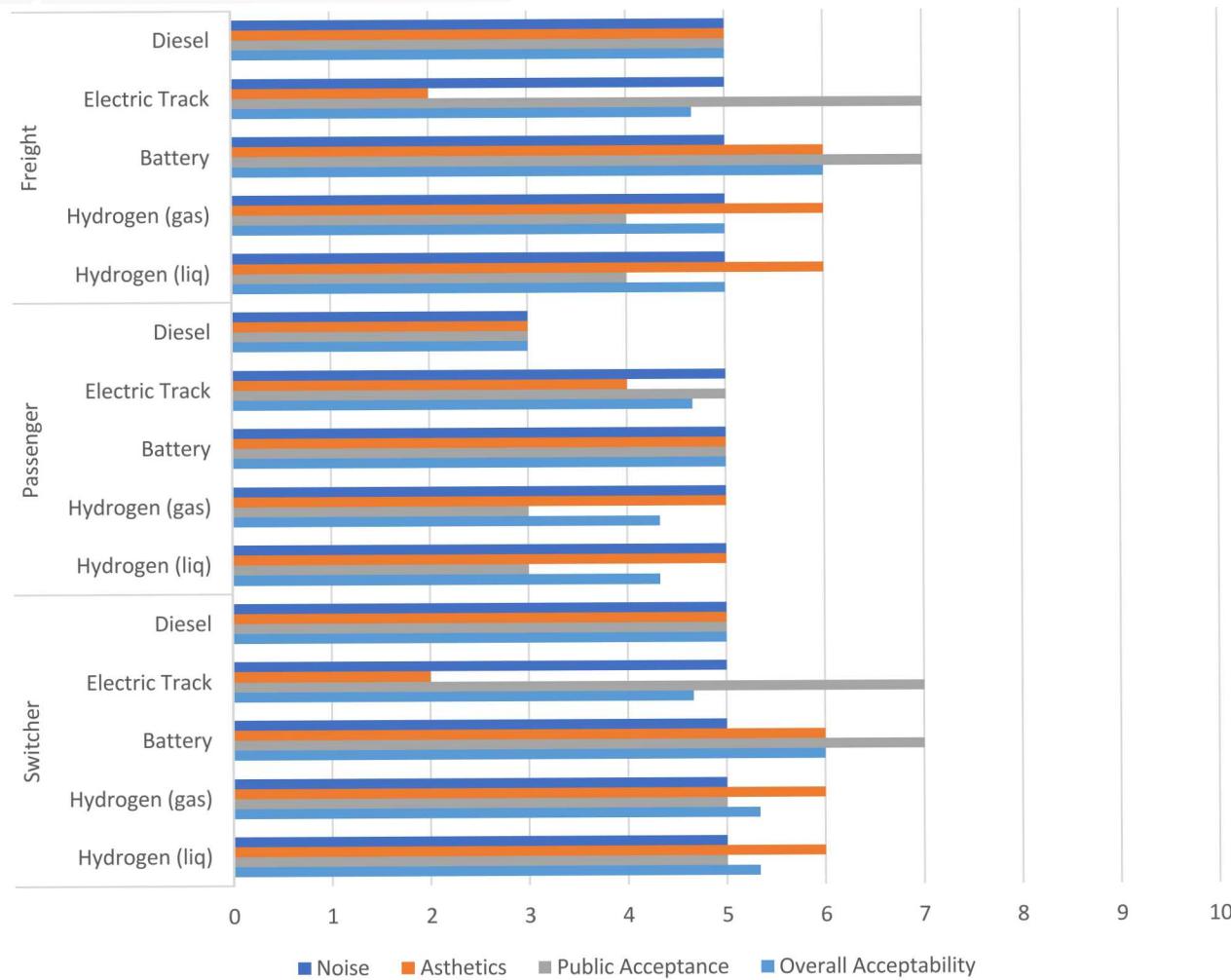


Economic Figures of Merit



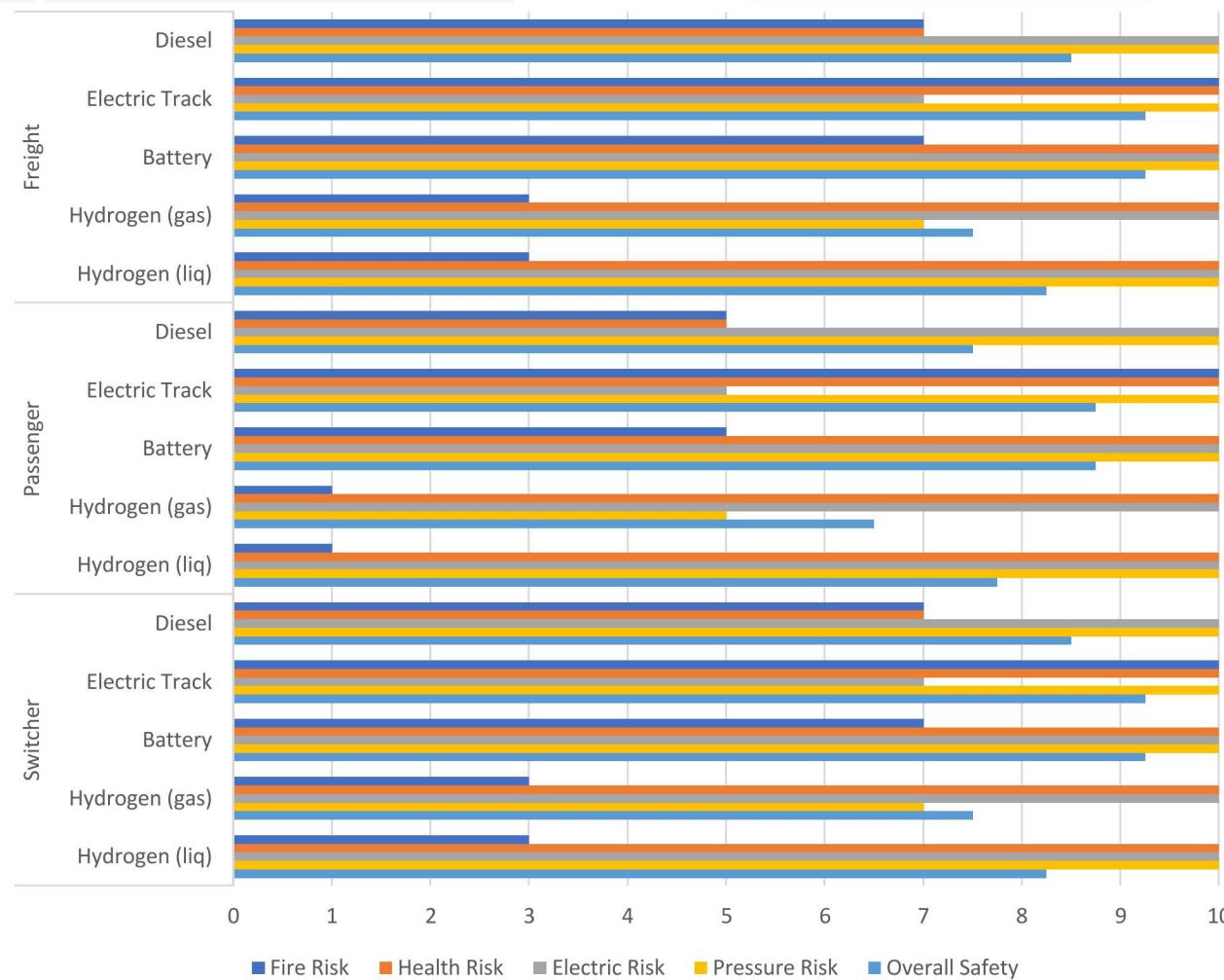
Acceptance Figures of Merit Details

Acceptability Figures of Merit



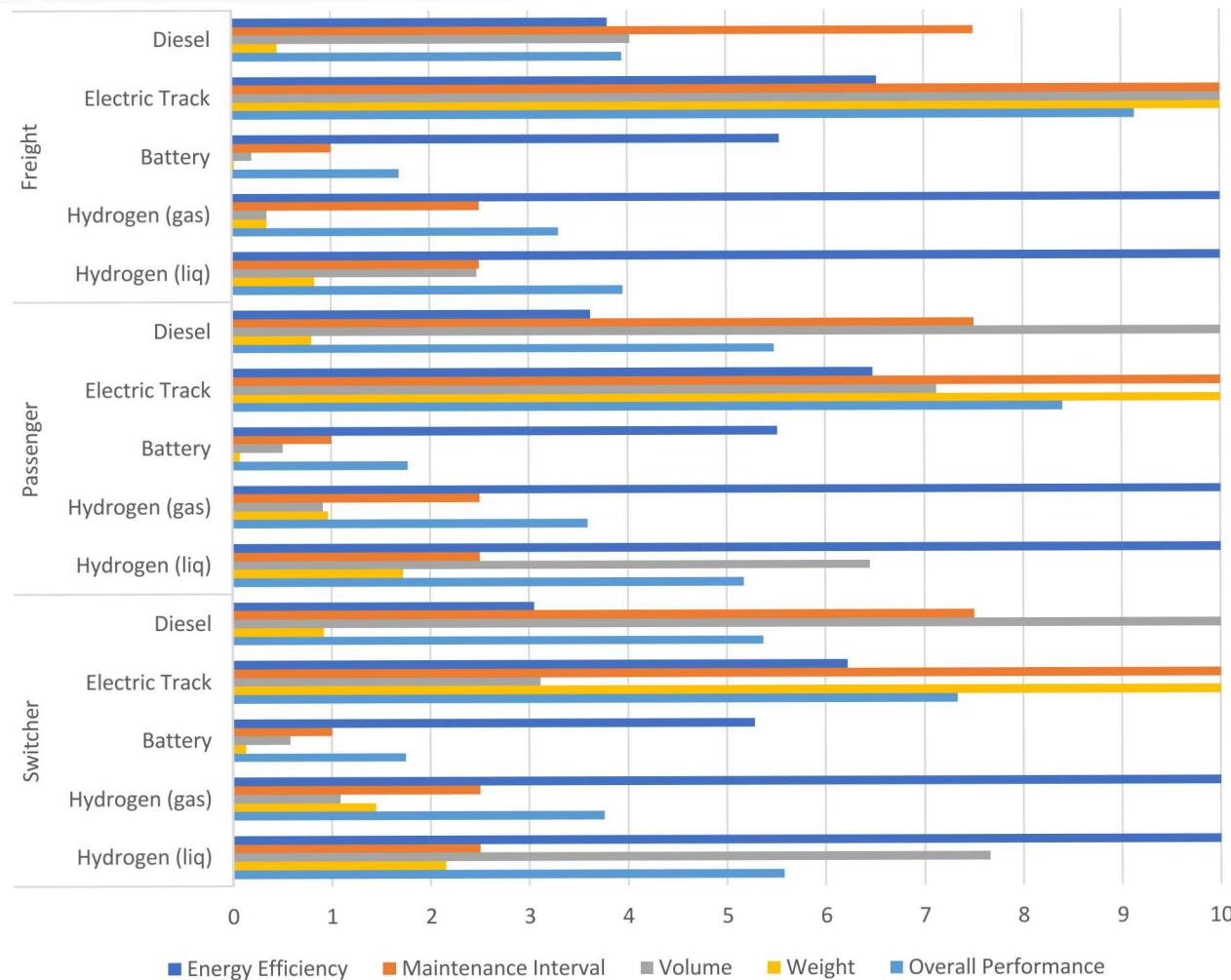
Safety Figures of Merit Details

Safety Figures of Merit



Performance Figures of Merit Details

Performance Figures of Merit



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 stations²
 - LH2 transfer code released open source³
 - 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

¹ Wybranowski E. (1972) Advances in Cryogenic Engineering. vol 17

² G. Petitpas, A.J. Simon, J. Moreno-Blanco, S.M. Aceves (2018) DOE Hydrogen and Fuel Cells Annual Merit Review, Washington D.C.

³ <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 II & III: Transition From Class I to Independent Railways

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
- Tax Benefits: Connecticut, Massachusetts, New Jersey, New York, North Carolina, Pennsylvania, Virginia

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

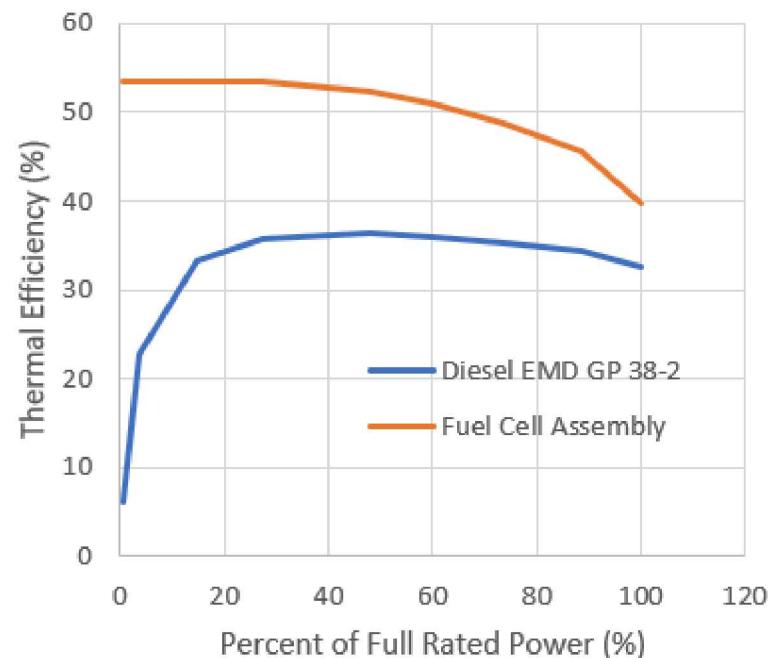
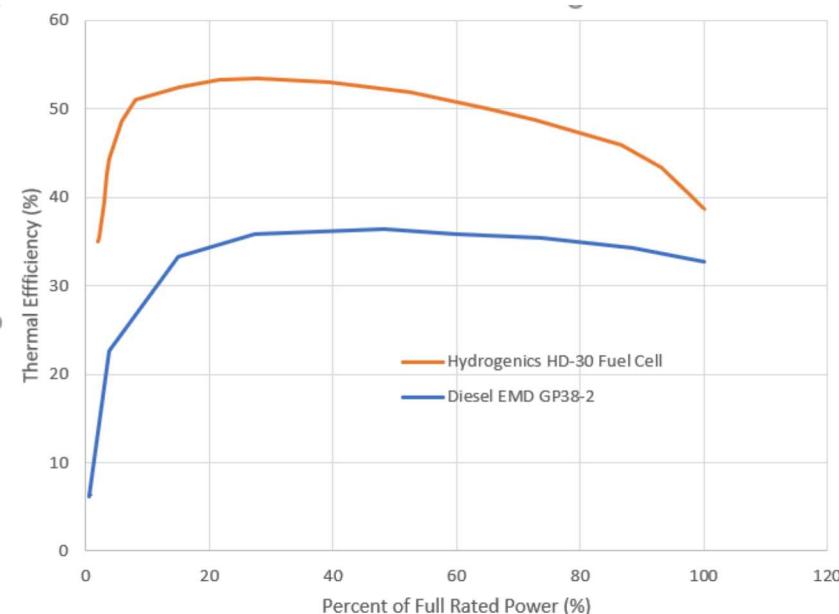
- Created by Congress 1970, take over of unprofitable intercity passenger rail service
- Federal Passenger Rail Investment and Improvement Act (PRIIA)
- Funding from 18 states and 21 agencies

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

Efficiency Curves for Diesel and Hydrogen



Modular fuel cells allow for higher efficiency at lower power ratings