



# 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

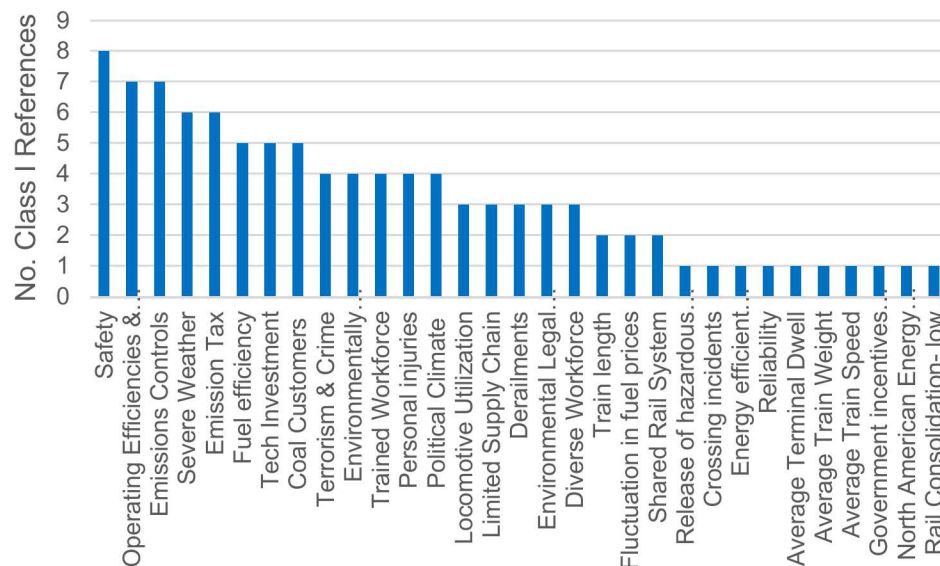
## 2. Operational Efficiencies & Network Congestion

- 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

Pareto Railway Priorities  
Mentioned in Annual Financial Reports



\* 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:

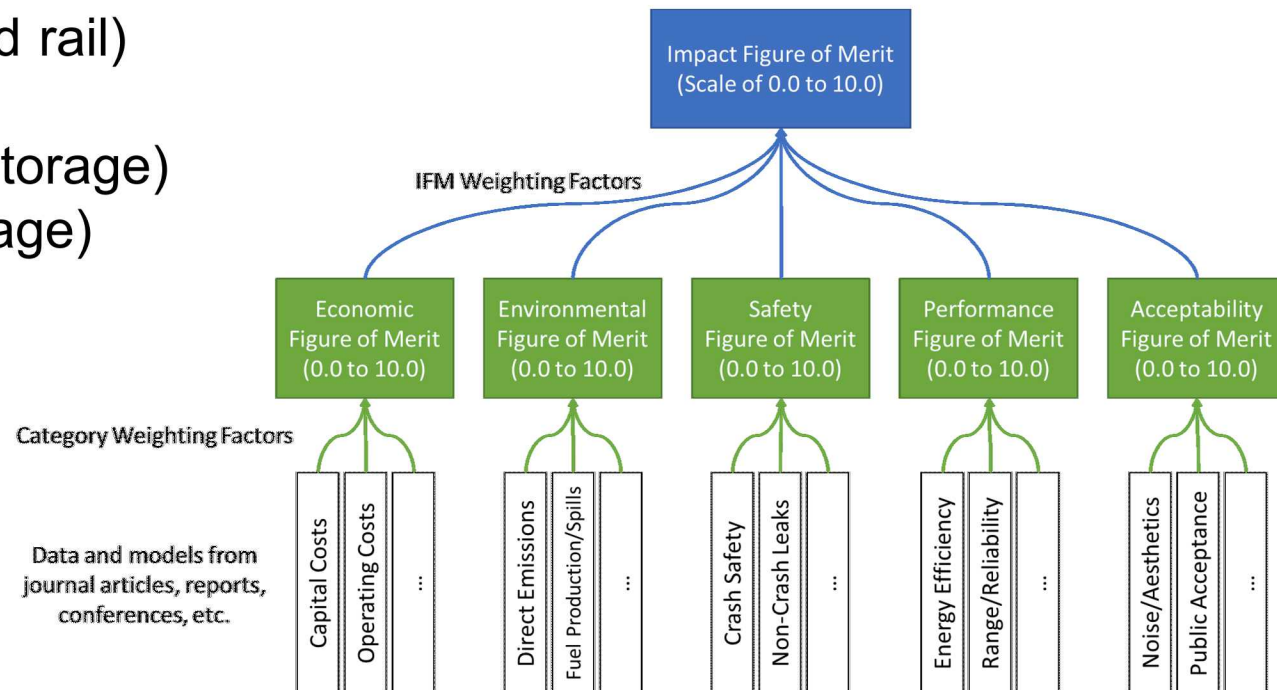
- Diesel
- Electric (catenary/third rail)
- Battery Electric
- Hydrogen (gaseous storage)
- Hydrogen (liquid storage)

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

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

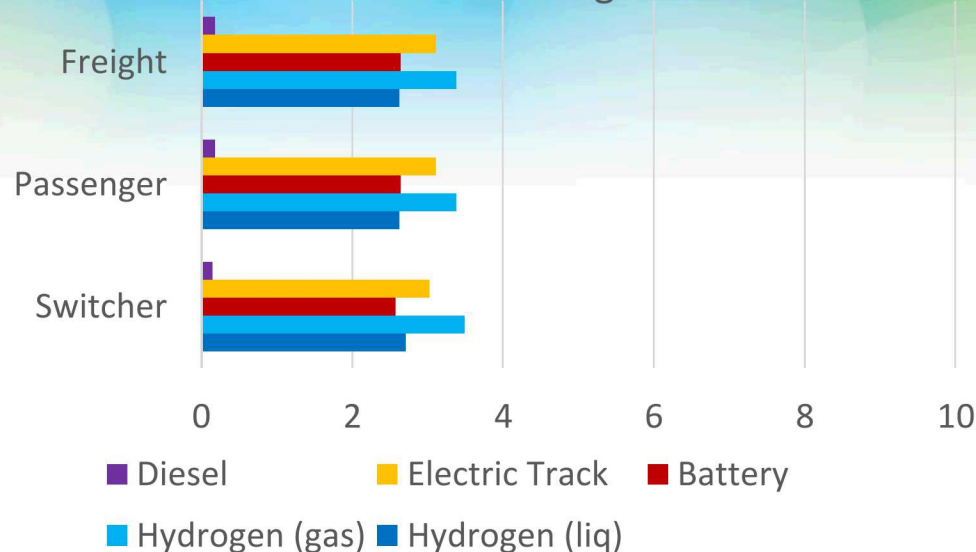




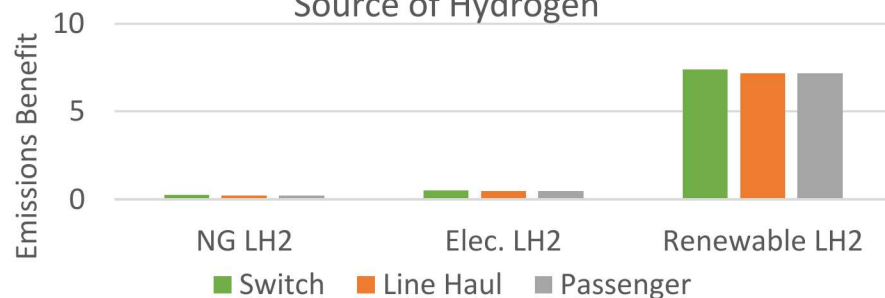
# Environmental Topics

- Emissions of major pollutants per hour of operation
  - CO<sub>2</sub>, NO<sub>x</sub>, HCs, PM
- Calculations based on notch-weighted fuel consumption<sup>1,2</sup>
  - Tier 4 diesel emissions standards<sup>3</sup>
  - California grid emissions assumed<sup>4</sup>
- Emissions differ by source of H<sub>2</sub><sup>5,6</sup>
  - 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



Source of Hydrogen



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.

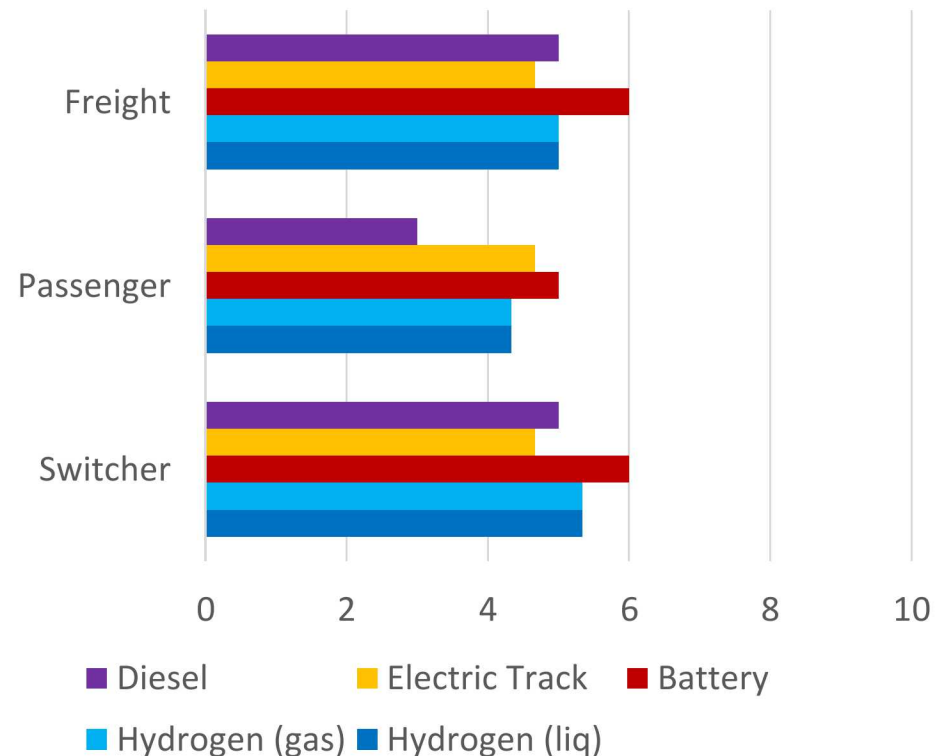




# Acceptance Topics

- Noise <sup>1</sup>
  - Not a large impact, mostly wheel noise
- Aesthetics <sup>2</sup>
  - Catenaries undesirable
- Public acceptance <sup>3</sup>
  - 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

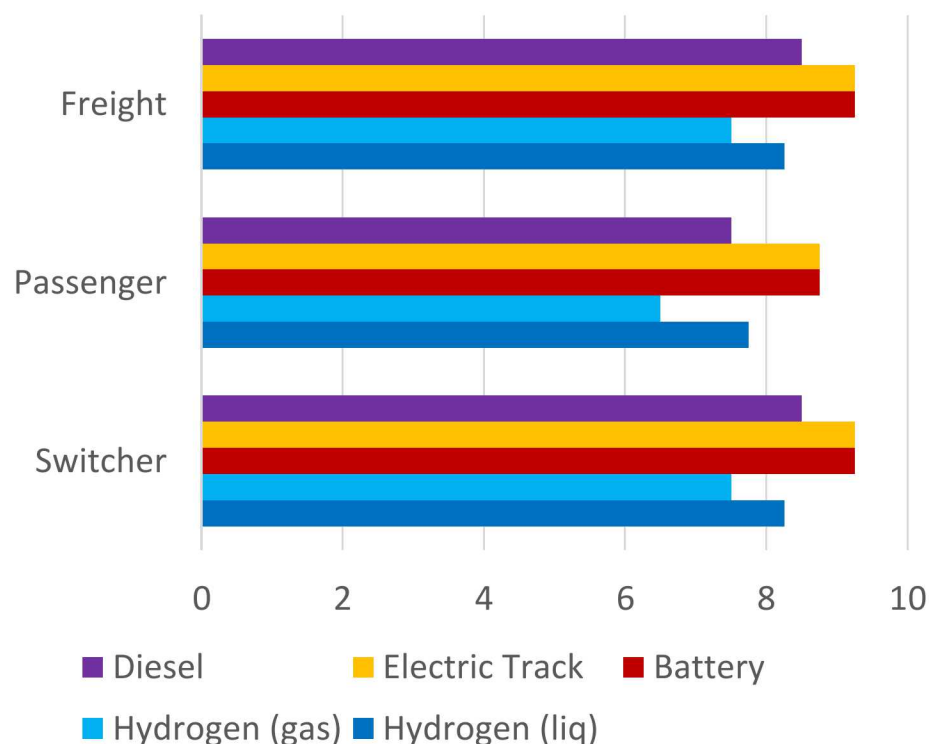
[3] R. L. Schmoyer, Tykey Truett, and Christy Cooper, Results of the 2004 Knowledge and Opinions Surveys for the Baseline Knowledge Assessment of the U.S. Department of Energy Hydrogen Program, ORNL/TM-2006/417 (April 2006).



# 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

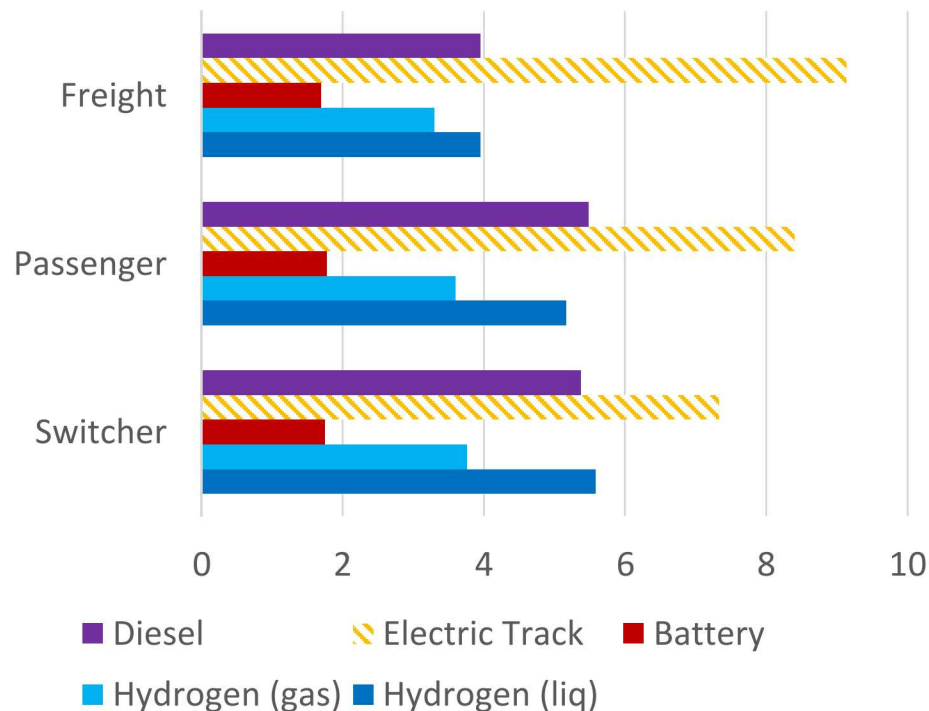
Overall Safety Figures of Merit



# Performance Topics

- Maintenance interval <sup>1, 2</sup>
- Energy/fuel efficiency
  - Notch-weighted
  - Hydrogenics HD-30, EMD GP38-2
  - *Estimated increased efficiency at low power notches*
- Weight
  - H<sub>2</sub>/tank ratios (6% GH<sub>2</sub>, 20% LH<sub>2</sub><sup>3</sup>)
  - 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



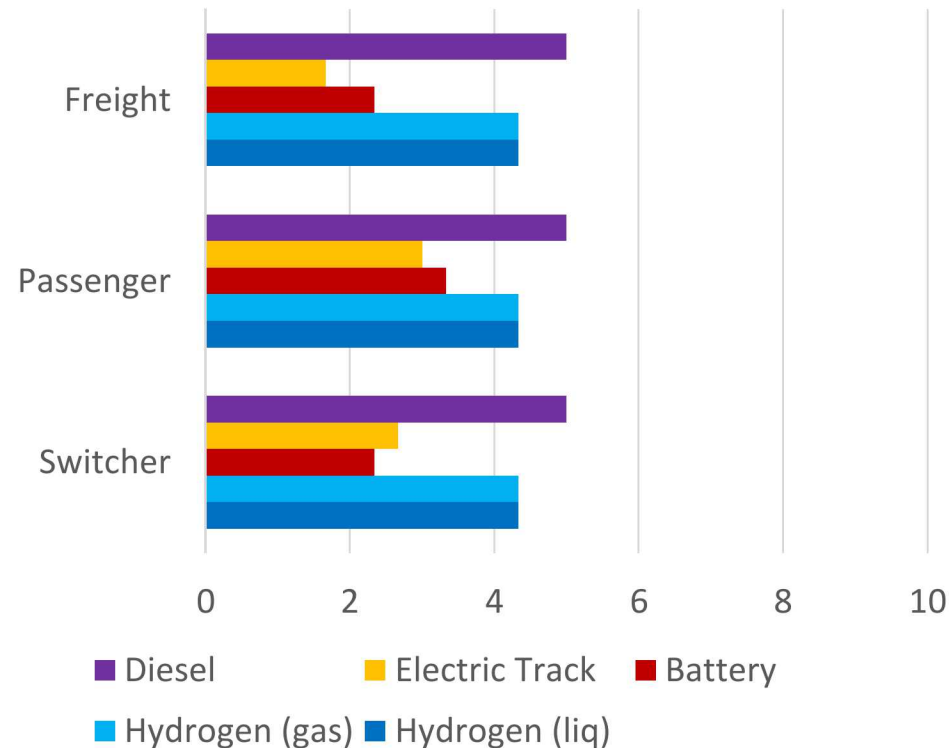
- [1] G. Marin, G. Naterer, and K. Gabriel, "Rail transportation by hydrogen vs. electrification—Case study for Ontario Canada, I: Propulsion and storage," *International Journal of Hydrogen Energy*, vol. 35, no. 12, pp. 6084-6096, 2010.
- [2] R. Nunno. (2018). *Electrification of U.S. Railways: Pie 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





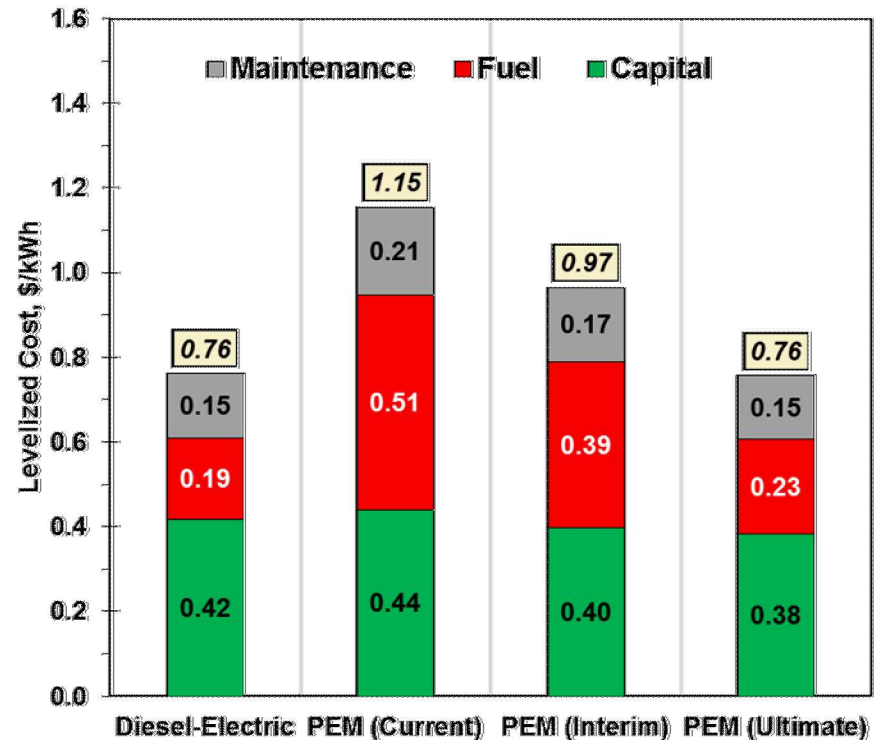
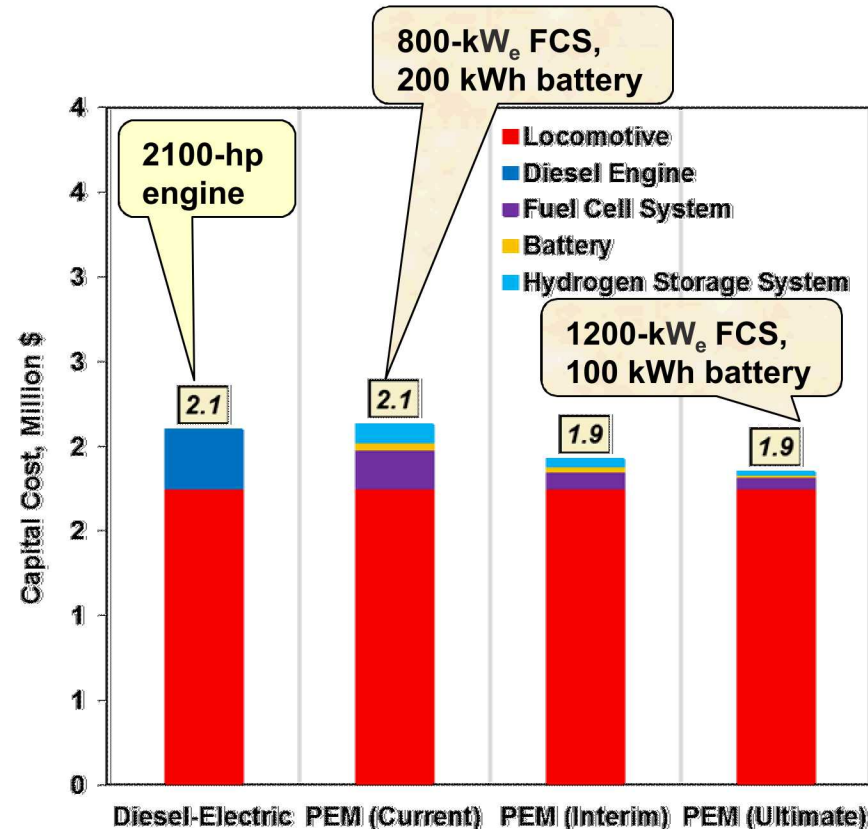
## Findings So Far

- 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

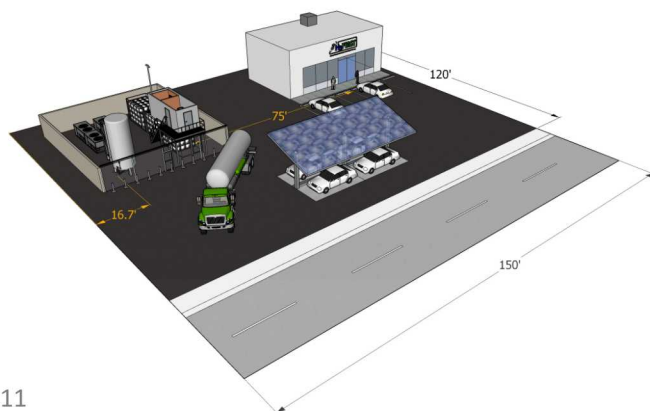
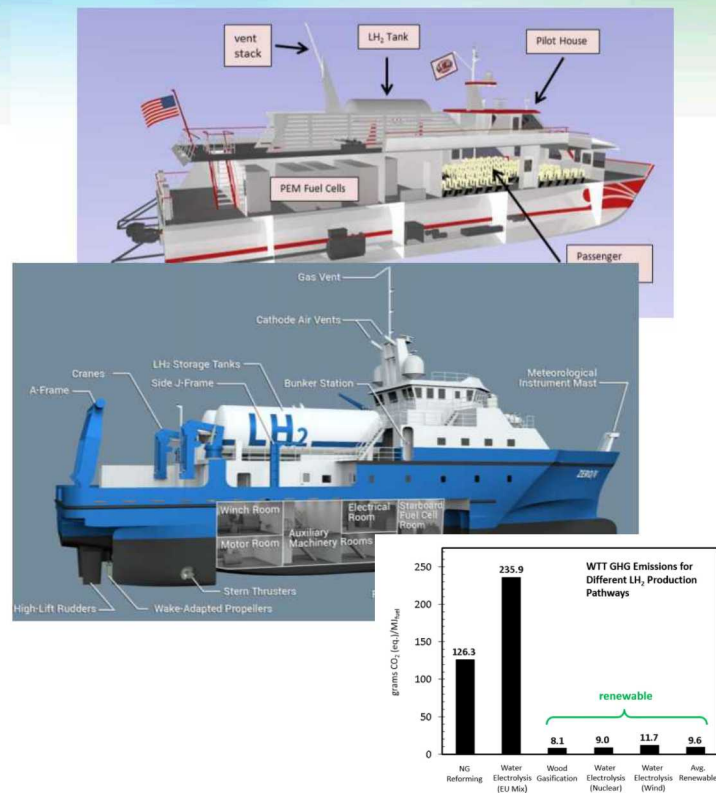
- On EPA duty cycles for switchers, 76% higher FCS drive cycle efficiency relative to diesel engine
- On TCO basis, fuel cells can be cost competitive if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at \$4/kg
- **Break-even delivered hydrogen cost 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 LH<sub>2</sub>
- 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

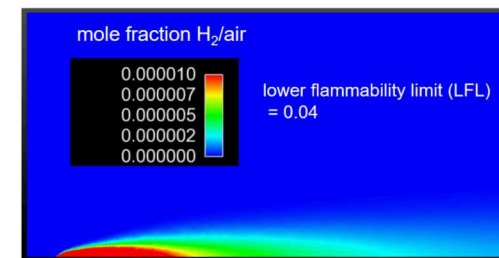
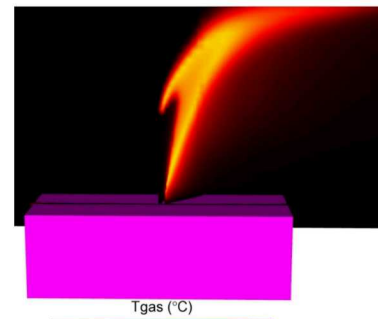
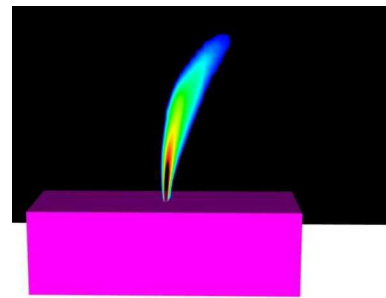
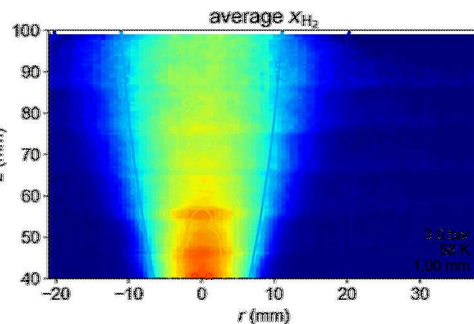
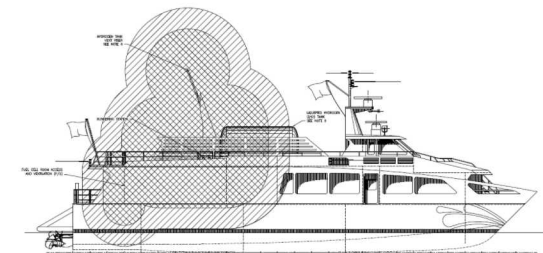
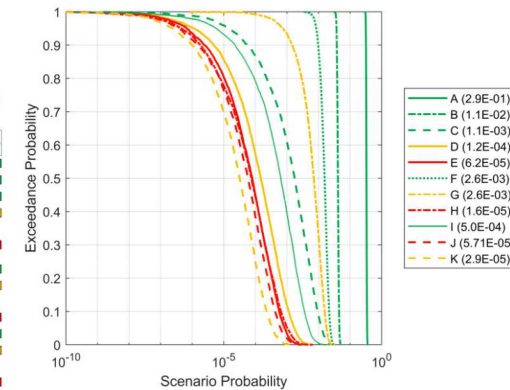
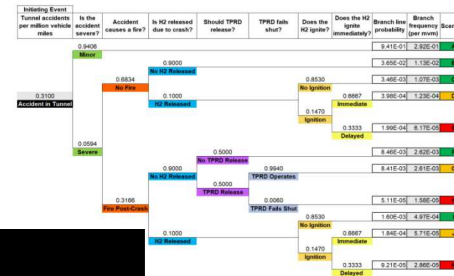
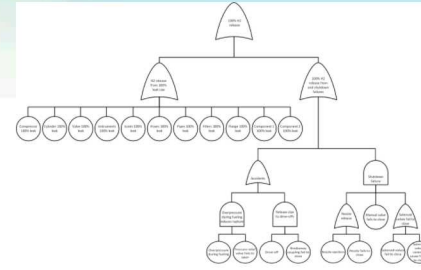
*What can go wrong, how likely it is, and what could happen*

- **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 H<sub>2</sub> 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	$10^{-4}$



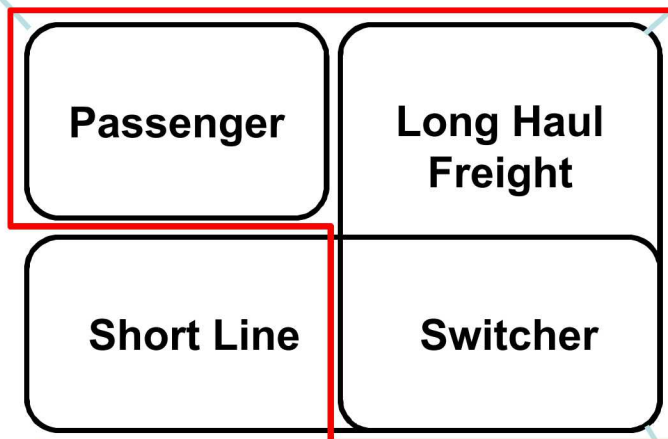


# Railway Focus Areas

- 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

Focus of this work



- 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

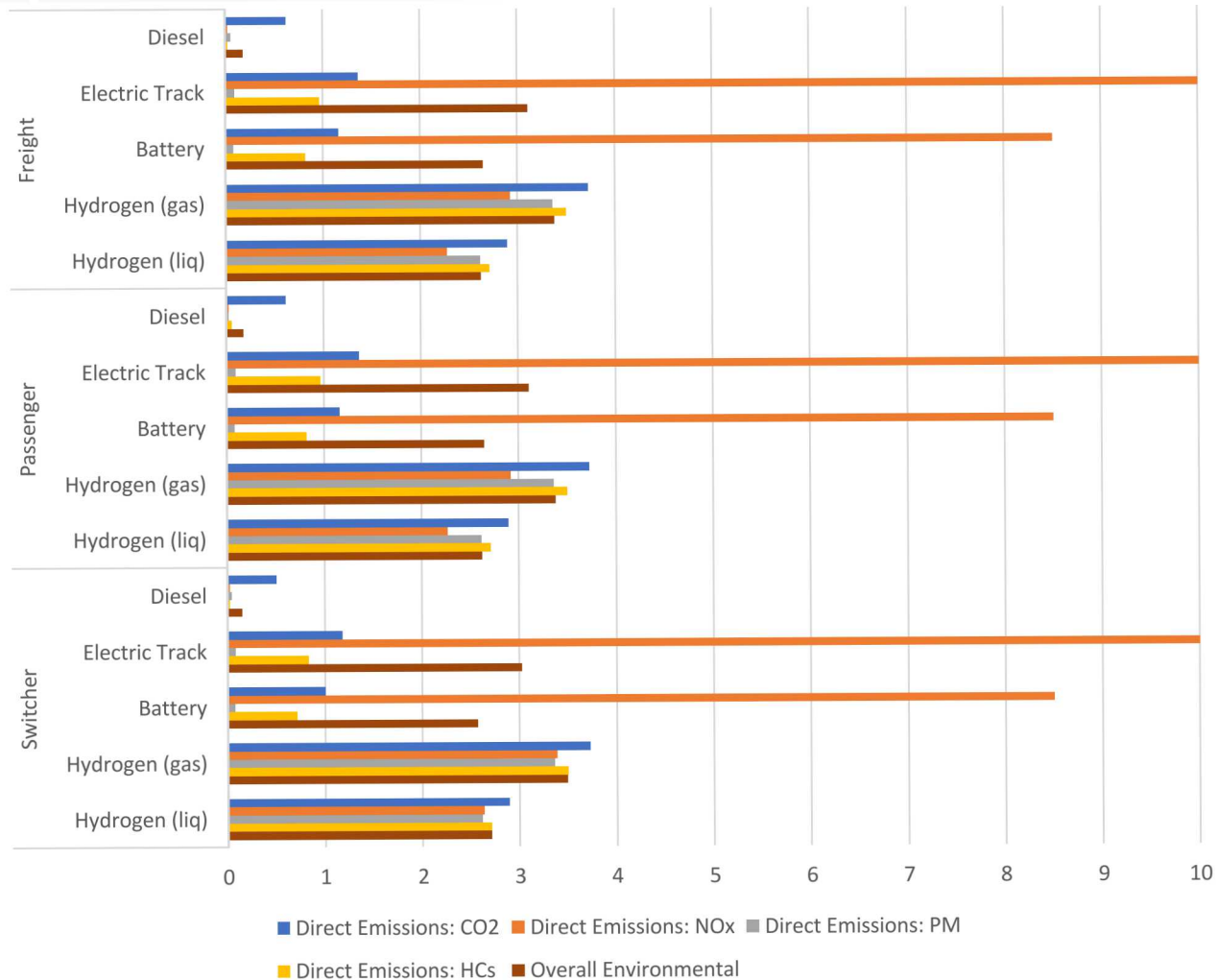
Class III: Annual revenues less than \$20M

Values collected from investor disclosure statements



# Environmental Figures of Merit Details

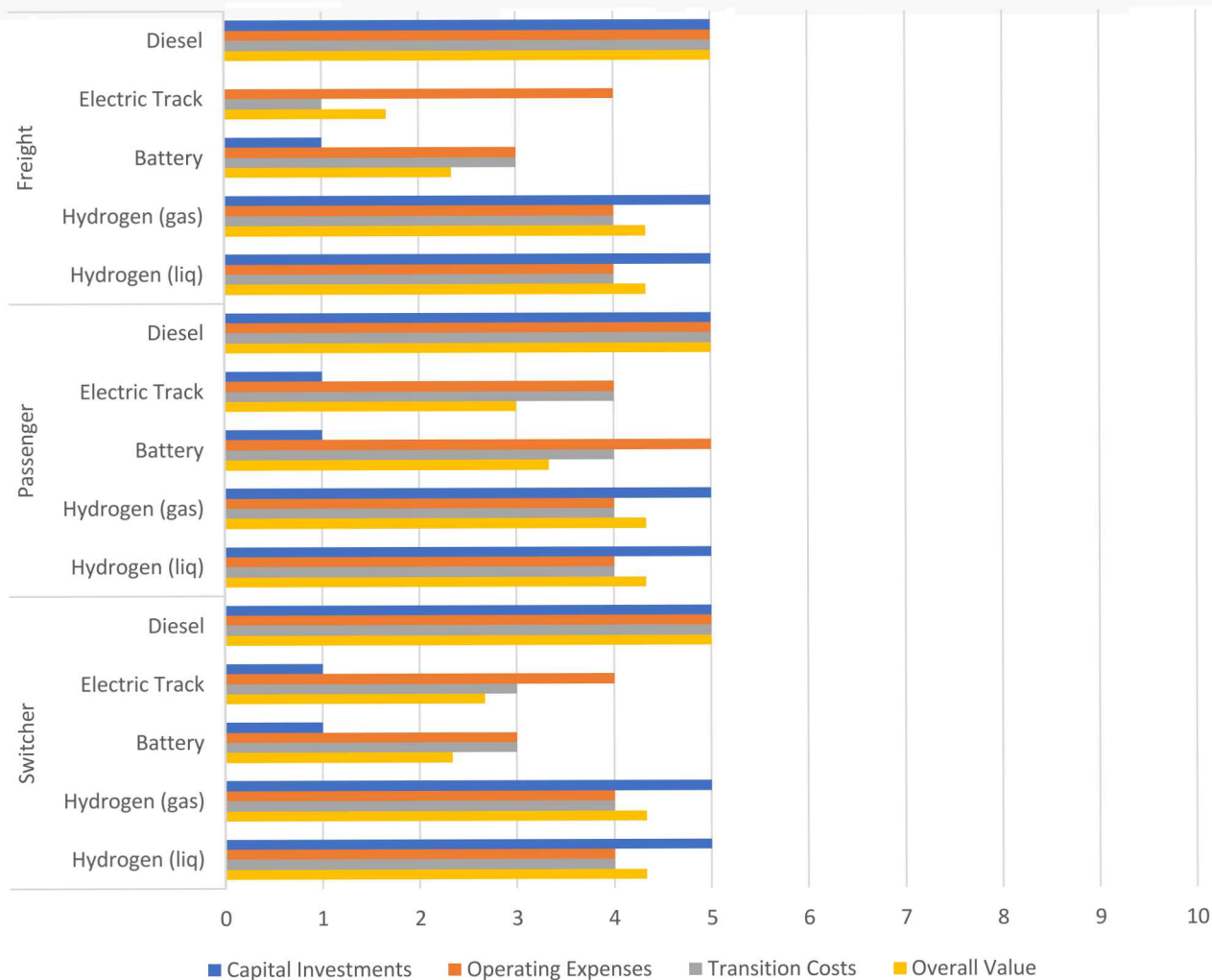
Environmental Figures of Merit





# Economic Figures of Merit

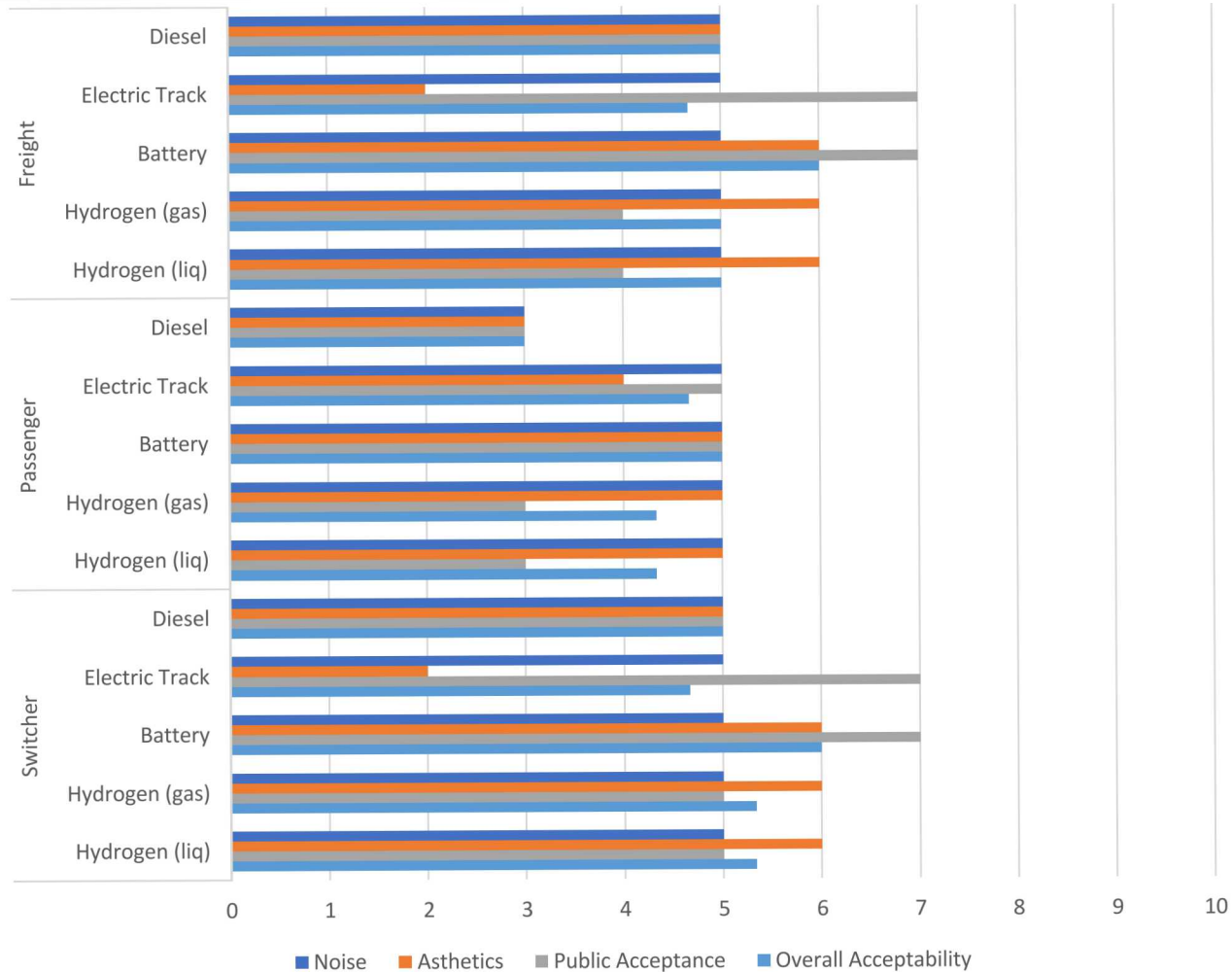
Economic Figures of Merit





# Acceptance Figures of Merit Details

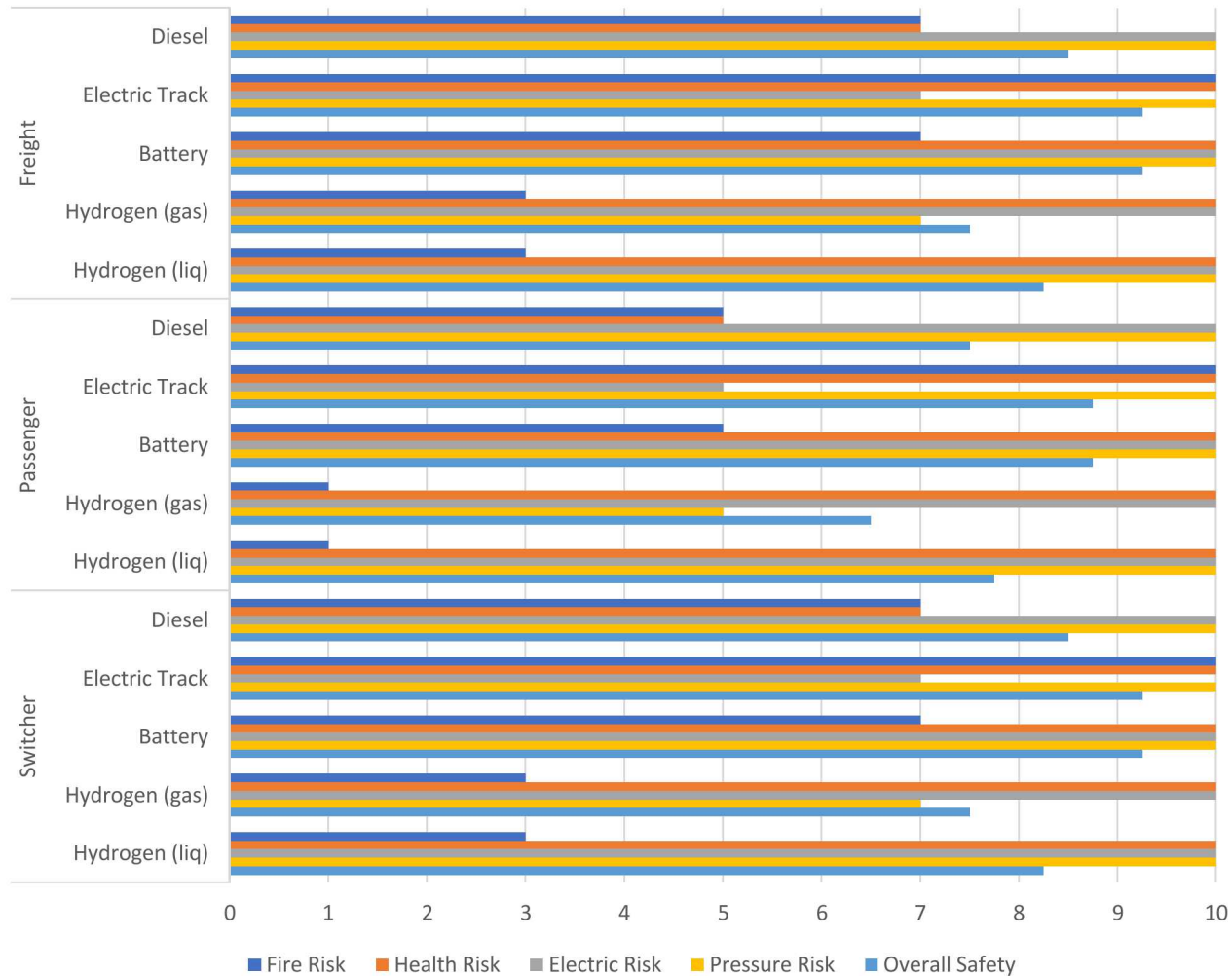
Acceptability Figures of Merit





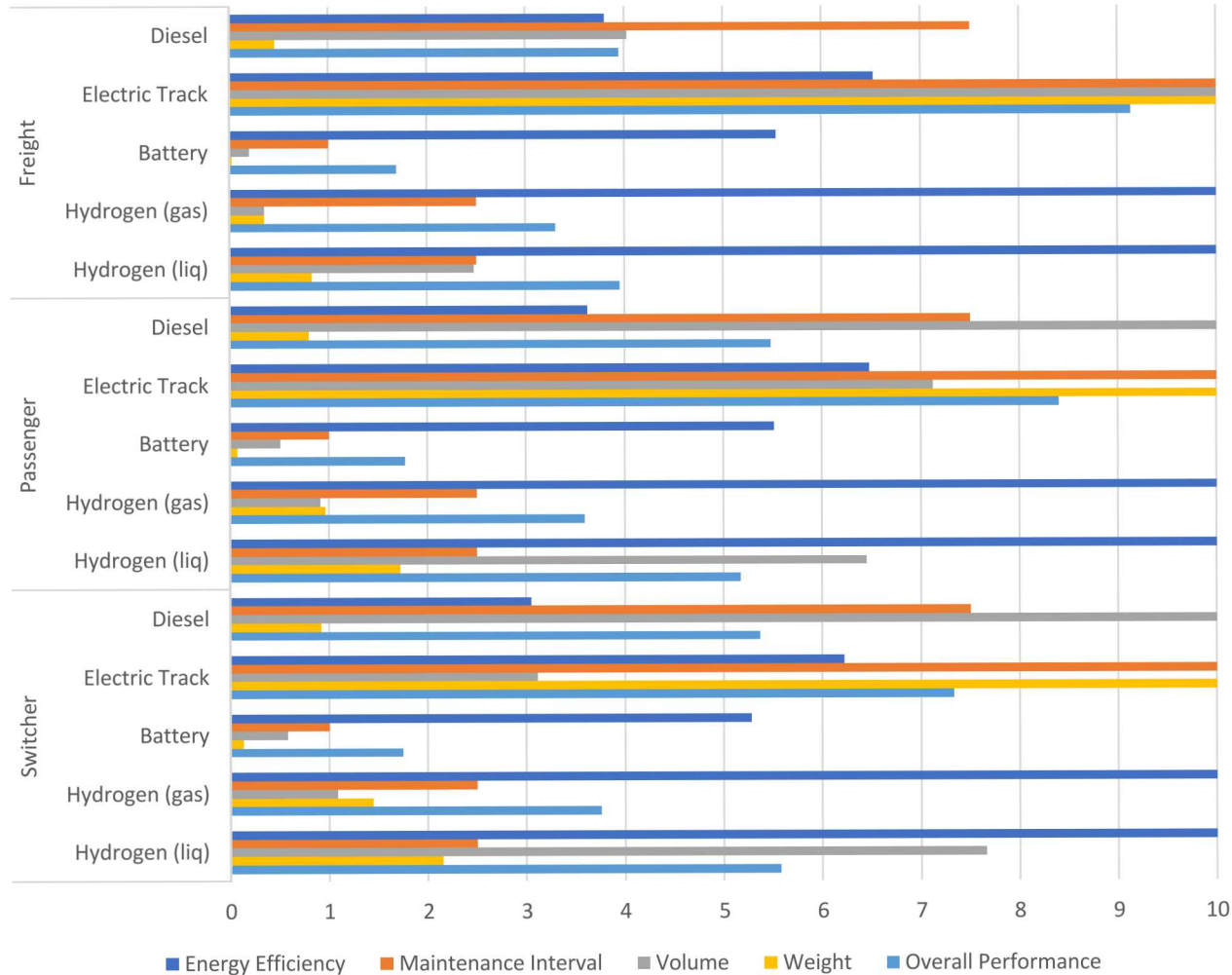
# Safety Figures of Merit Details

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)<sup>1</sup>
- Recent work by Guillaume Petitpas, et al. (LLNL) on light-duty vehicles and refueling stations<sup>2</sup>
  - LH2 transfer code released open source<sup>3</sup>
  - 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

<sup>1</sup> Wybranowski E. (1972) Advances in Cryogenic Engineering. vol 17

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

<sup>3</sup> <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





## 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

### 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

### 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

### 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

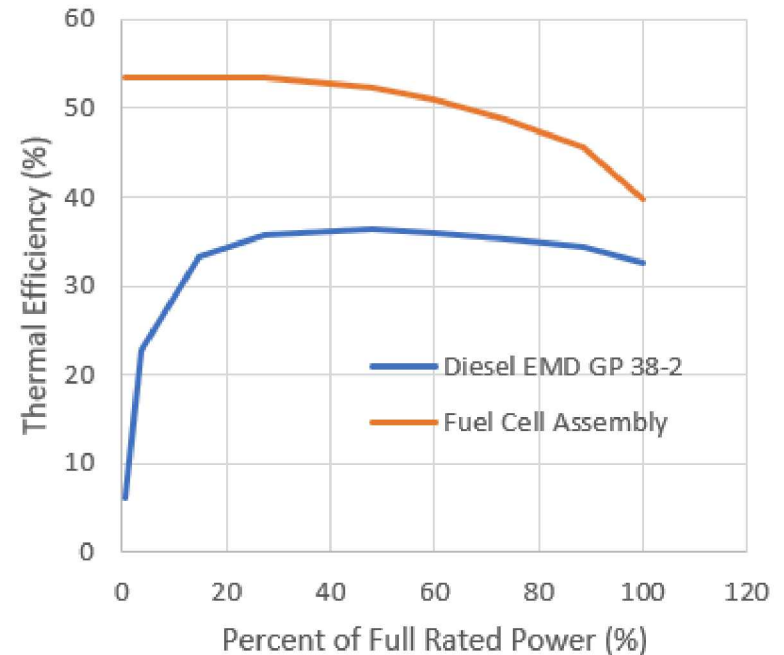
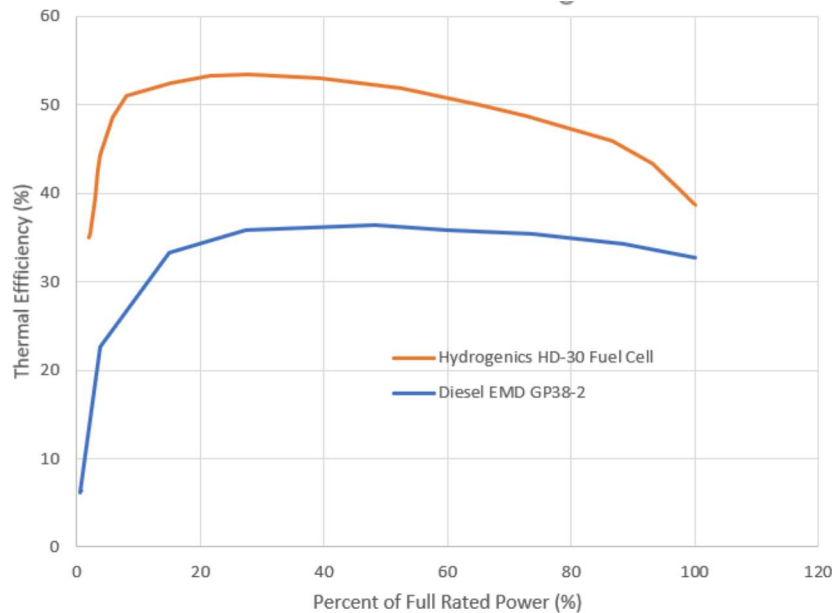
- Created by Congress 1970, take over of unprofitable intercity passenger rail service
- Federal Passenger Rail Investment and Improvement Act (PRIIA)
- Funding from 18 states and 21 agencies

## 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