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Impact of Hydrogen for Rail Applications

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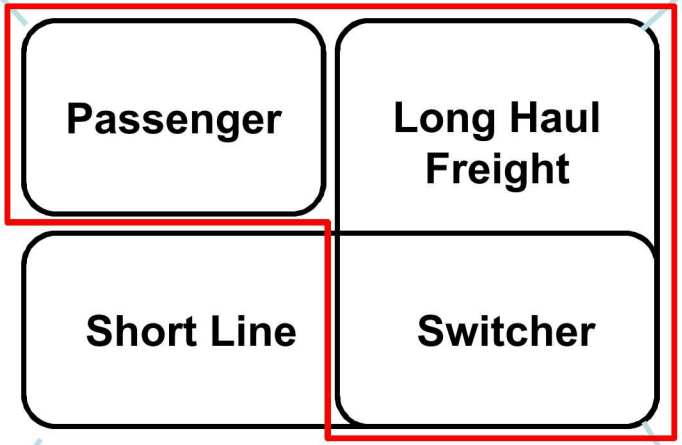
Railway Focus Areas

- 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

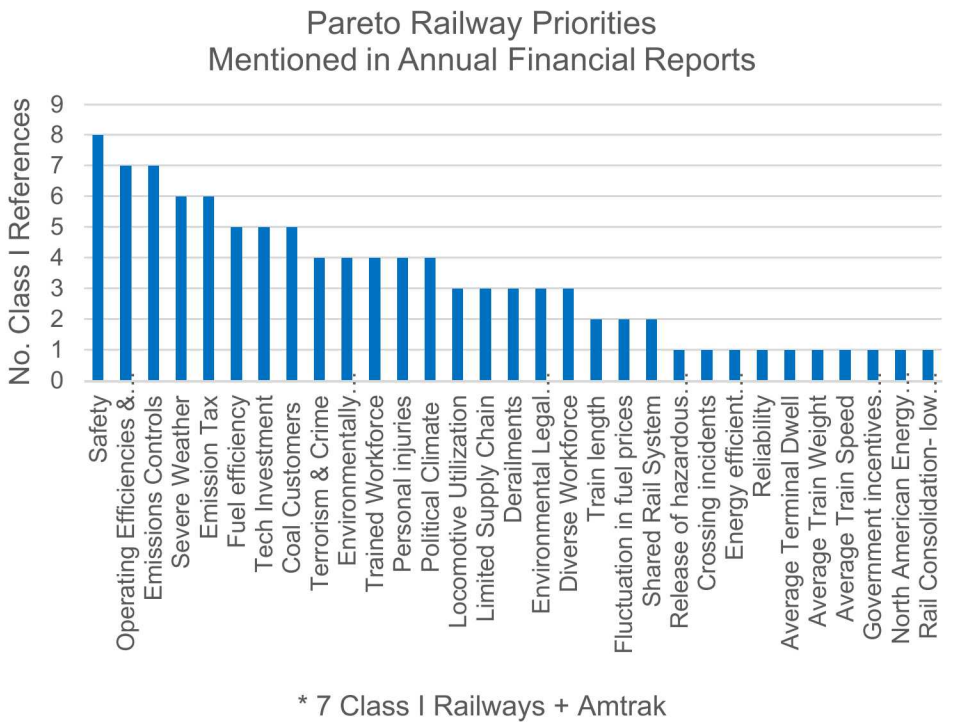
- Class I, 7 Railroads
- 1.4k Locomotives
- 40 yrs Average Age
- 48k miles of track
- Switching Yard Freight

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

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

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!*

Methodology

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

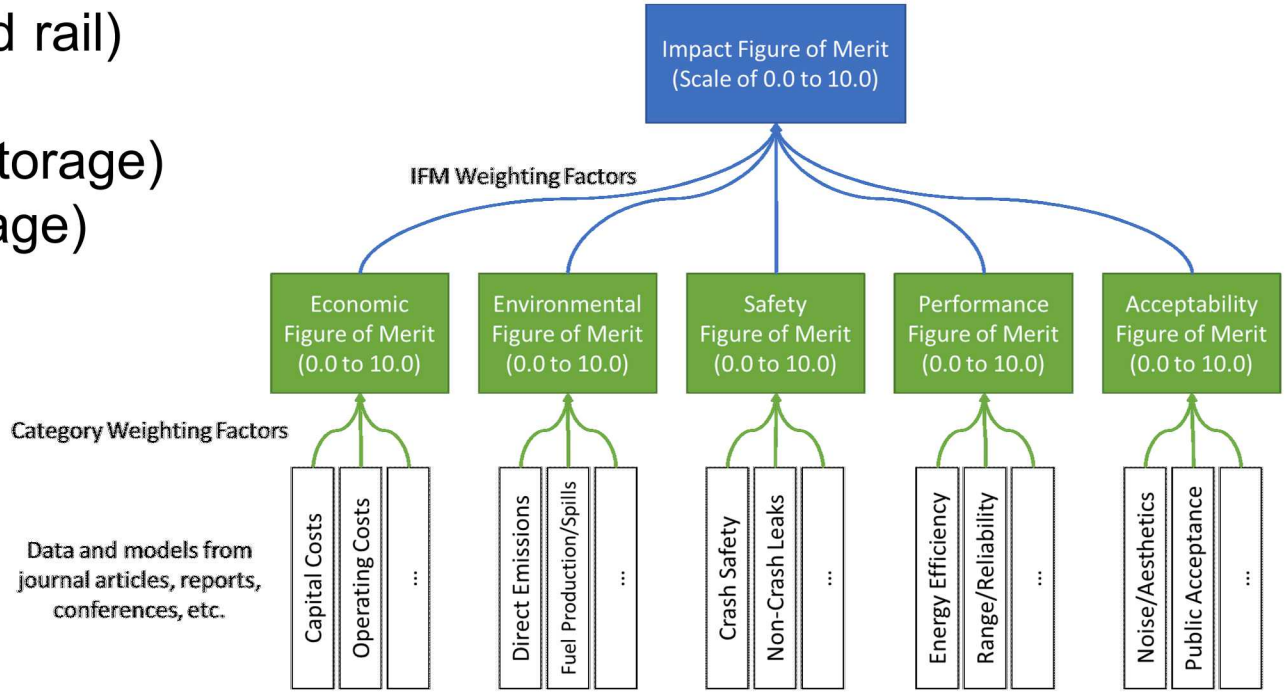
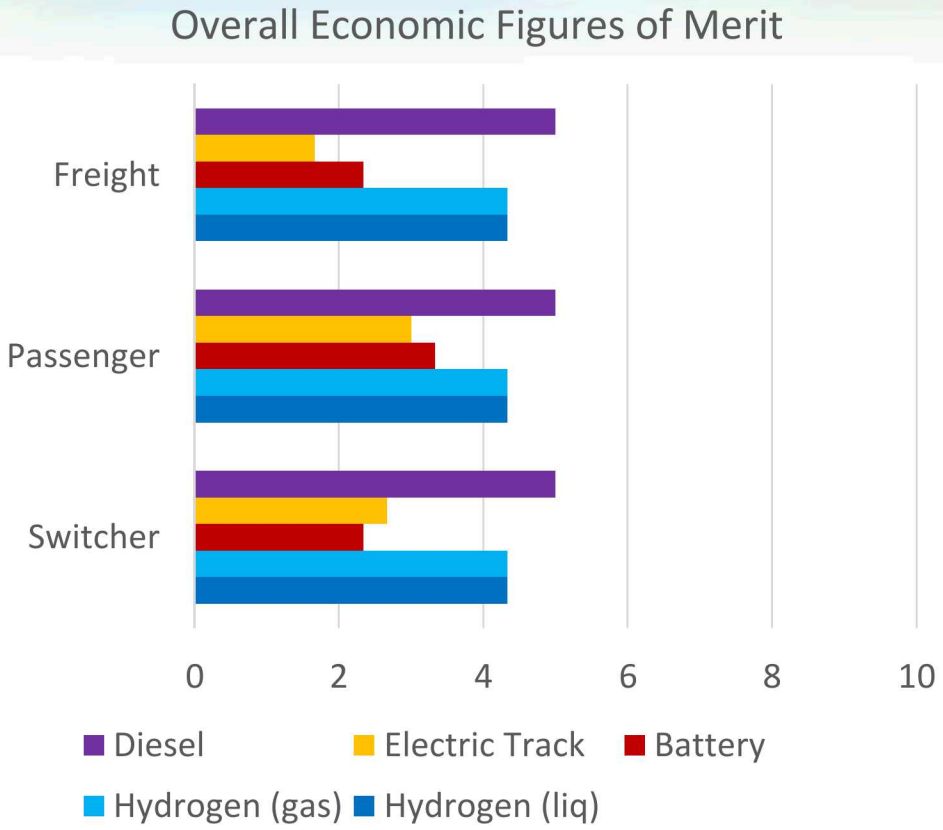


Figure of merit allows for comparative ranking and illustrates trade-offs

Economic Topics

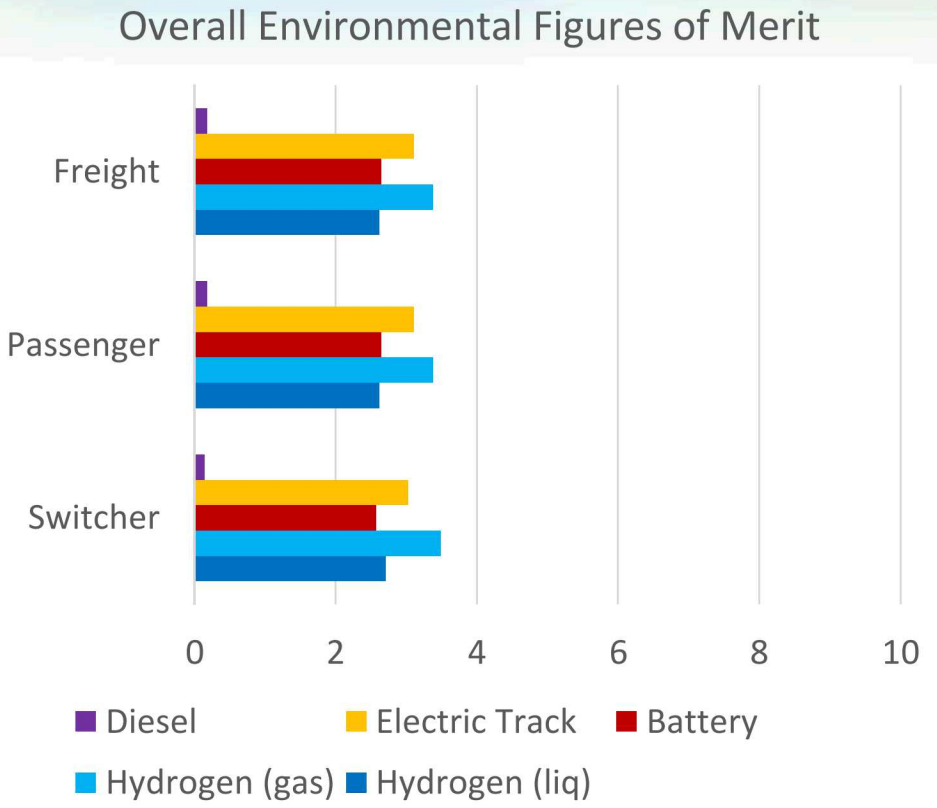
- **Capital Costs**
  - New fueling stations
  - New track (for electric rail)
  - New Power Plants (Freight on Grid)
- **Operating Costs**
  - Cost of fuel, labor hours to fuel
  - Maintenance costs
- **Transition Costs**
  - Fragmented track compatibility
  - Partial fueling station availability
  - New locomotive vs. Modification
  - Invest in new track in locations at risk for flooding? (Scope creep)
- **How to estimate large volume cost for hydrogen fuel?**
  - Will depend on supply/demand with other industries



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

Environmental Topics

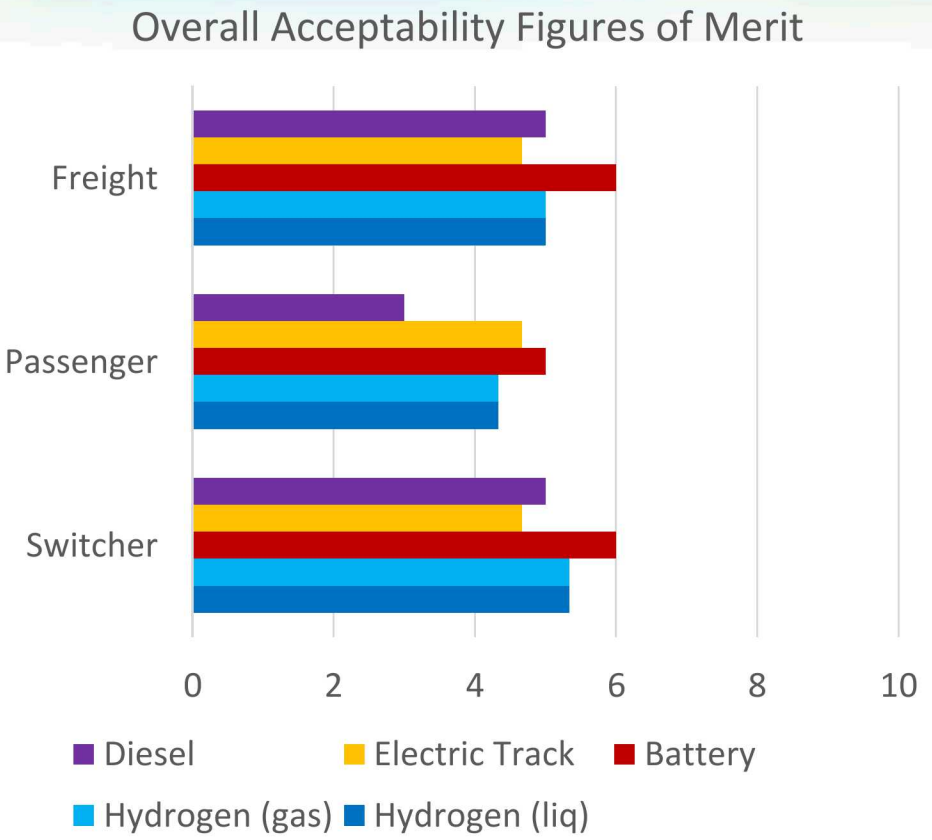
- Emissions of major pollutants per hour of operation
  - CO_2, NOx, HCs, PM
- Calculations based on notch-weighted fuel consumption [1,2]
  - Tier 4 diesel emissions standards[3]
  - California grid emissions assumed[4]
- Emissions differ by source of H_2 [5,6]
  - Natural gas reformation
  - Electrolysis from grid energy
  - Renewable resources
  - Currently averaged in analysis
- Possible future considerations:
  - Fuel spills



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

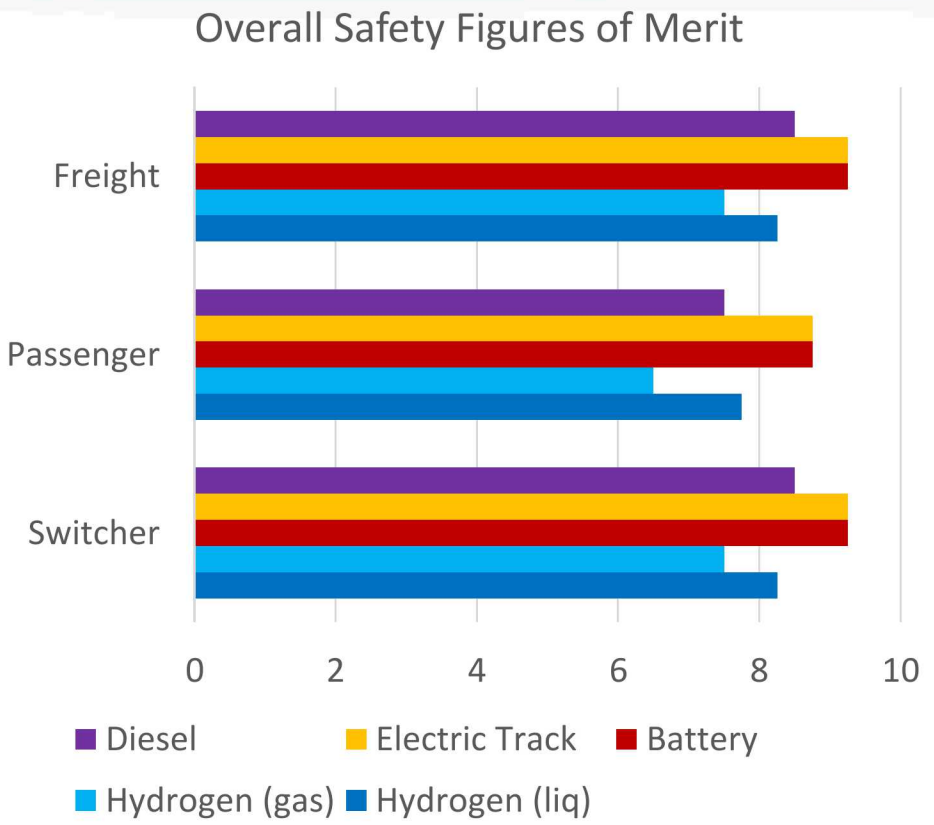
- Noise [1]
  - Not a large impact, mostly wheel noise
- Aesthetics [2]
  - Catenaries undesirable for Electric: Passenger
- Public acceptance [3]
  - Public may be initially concerned about hydrogen nearby
- For future investigations:
  - Interface with other industries/markets



[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).

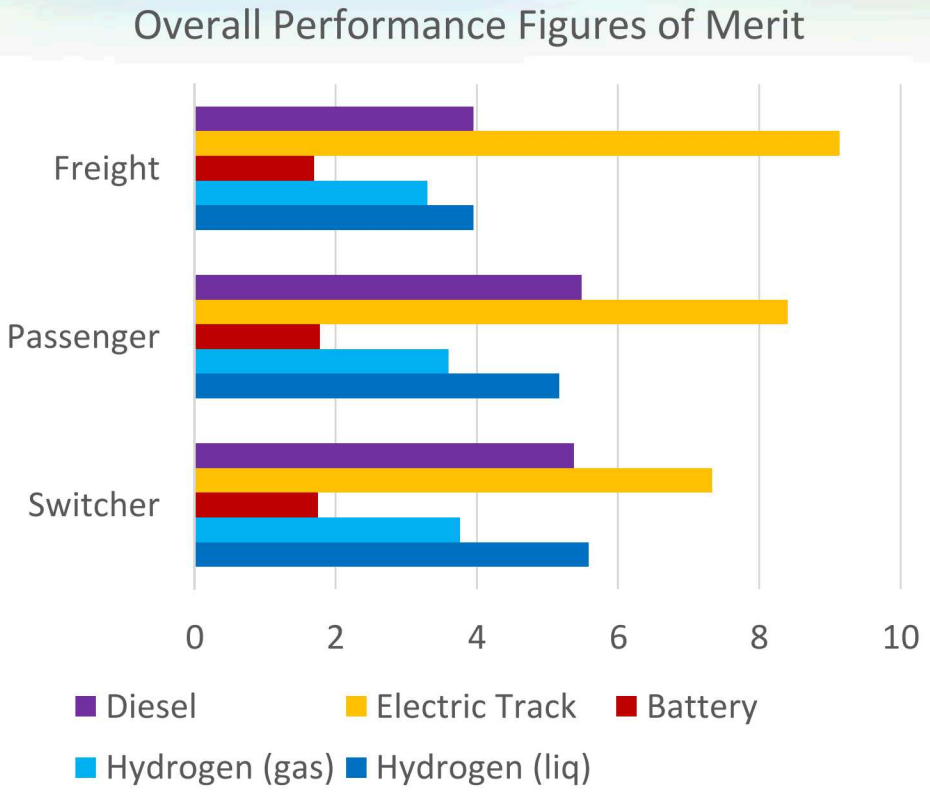
Safety Topics

- *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

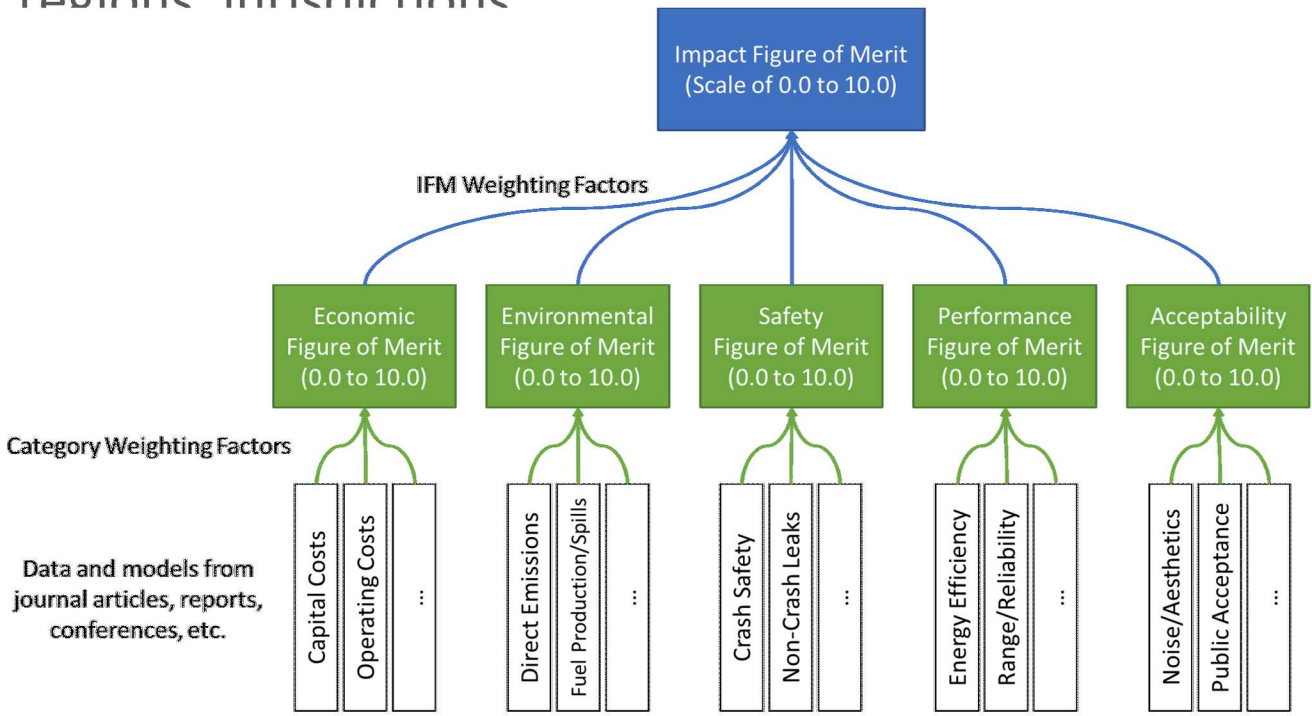
- Maintenance interval [1, 2]
- Energy/fuel efficiency
  - Notch-weighted
  - Hydrogenics HD-30, EMD GP38-2
  - Assumed 33% generation efficiency for electric power (varies)
  - Assumed 85% battery efficiency
- Weight
  - H_2/tank ratios (6% GH_2, 20% LH_2[3])
  - Negative impact (decrease in range)
    - Can improve traction for freight
- Volume
  - Density of "fuels"
  - Electrified rail based on Toshiba power conversion unit for rail
- Refueling time and system life considered for future work



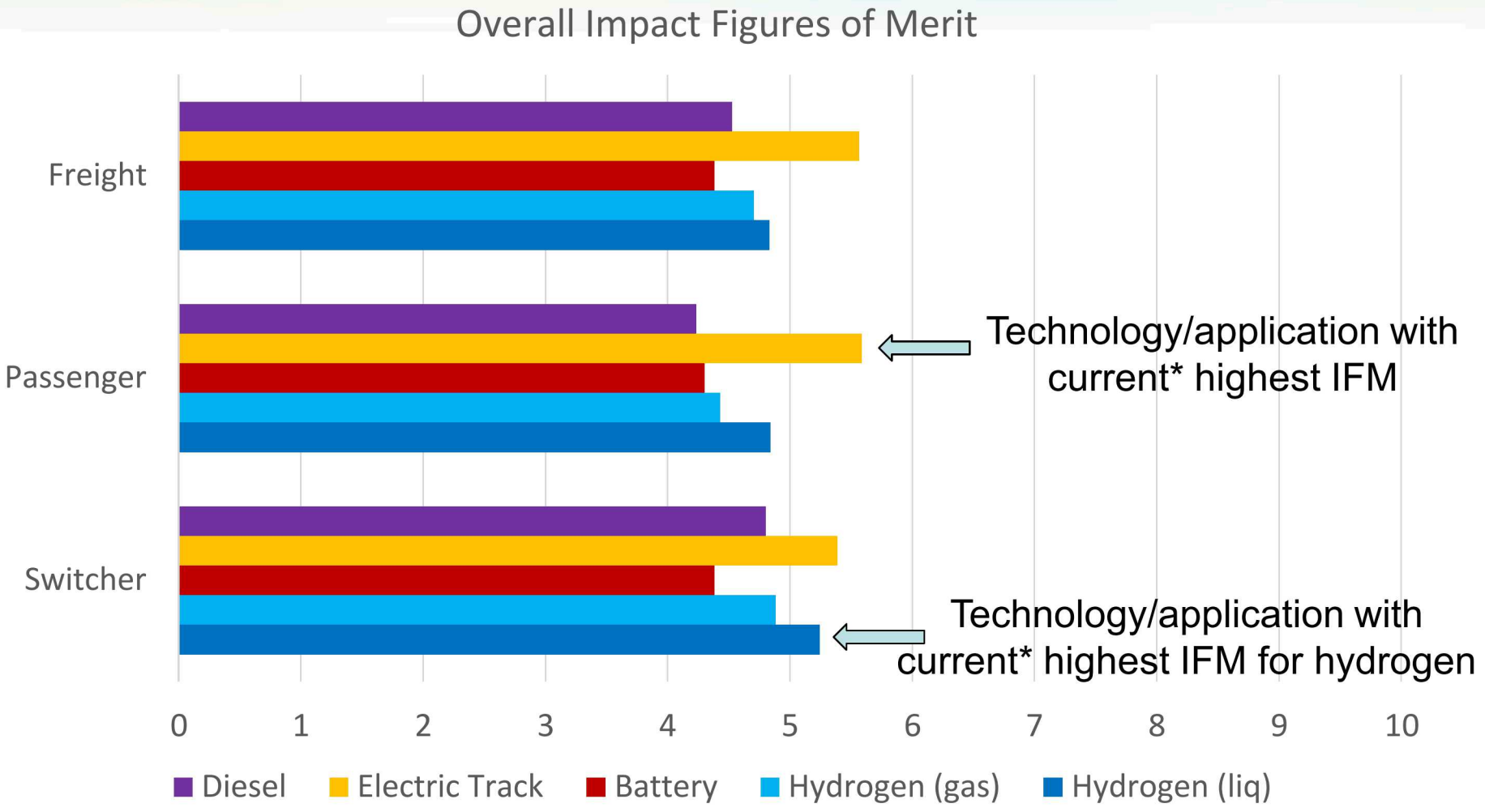
[1] G. Marin, G. Naterer, and K. Gabriel, "Rail transportation by hydrogen vs. electrification–Case study for Ontario Canada, I: Propulsion and storage," *International Journal of Hydrogen Energy,* vol. 35, no. 12, pp. 6084-6096, 2010.
[2] R. Nunno. (2018). *Electrification of U.S. Railways: Pie in the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

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
  - Sensitivity analy how different w can contribute to different rank



Preliminary Impact Figures of Merit



* Will change as figures of merit and weighting methodology changes

Interpretation of Impact Figures of Merit

- Ranking can identify good matches and generate discussion
  - Current* results give some examples:
    - Electrified track/catenary for passenger rail
    - LH2 for switcher use
- Quantitative comparison may not always applicable
- Category impact factors can identify drivers of overall impact factor
  - High IFM* for electric passenger case driven by safety and performance, not excluded by economics
    - Performance metrics different for electric
  - High IFM* for LH2 case driven by safety, performance; would be increased with renewable hydrogen
- This can identify where more refinement is needed

**** These numbers are just preliminary; rankings will change based on updated values and weights***

Conclusions

- 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 no clear application/technology where H_2 is the obvious choice, nor where H_2 is categorically excluded
  - All technologies have trade-offs
  - ***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
- Larger systems may use liquid hydrogen due to increased density

Future Work

- Improve impact figures of merit
  - Many current preliminary results are qualitative
  - Identify where data exists, and what further study is needed
- Sensitivity study on figure of merit weighting
  - Scaling between factors not consistent
  - Different regions/stakeholders will have different preferences
- Regional figure of merit
  - Identify 3 regions in the USA that match well to high impact figure of merit for hydrogen for rail
- Liquid hydrogen refueling technology assessment
  - Assess technology, safety codes and regulations, and feasibility for LH2 fueling of a freight locomotive

Thank you!

QUESTIONS?

BACK-UP SLIDES

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

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}

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 (CO_2 (eq.), NO_x, 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, H_2 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.

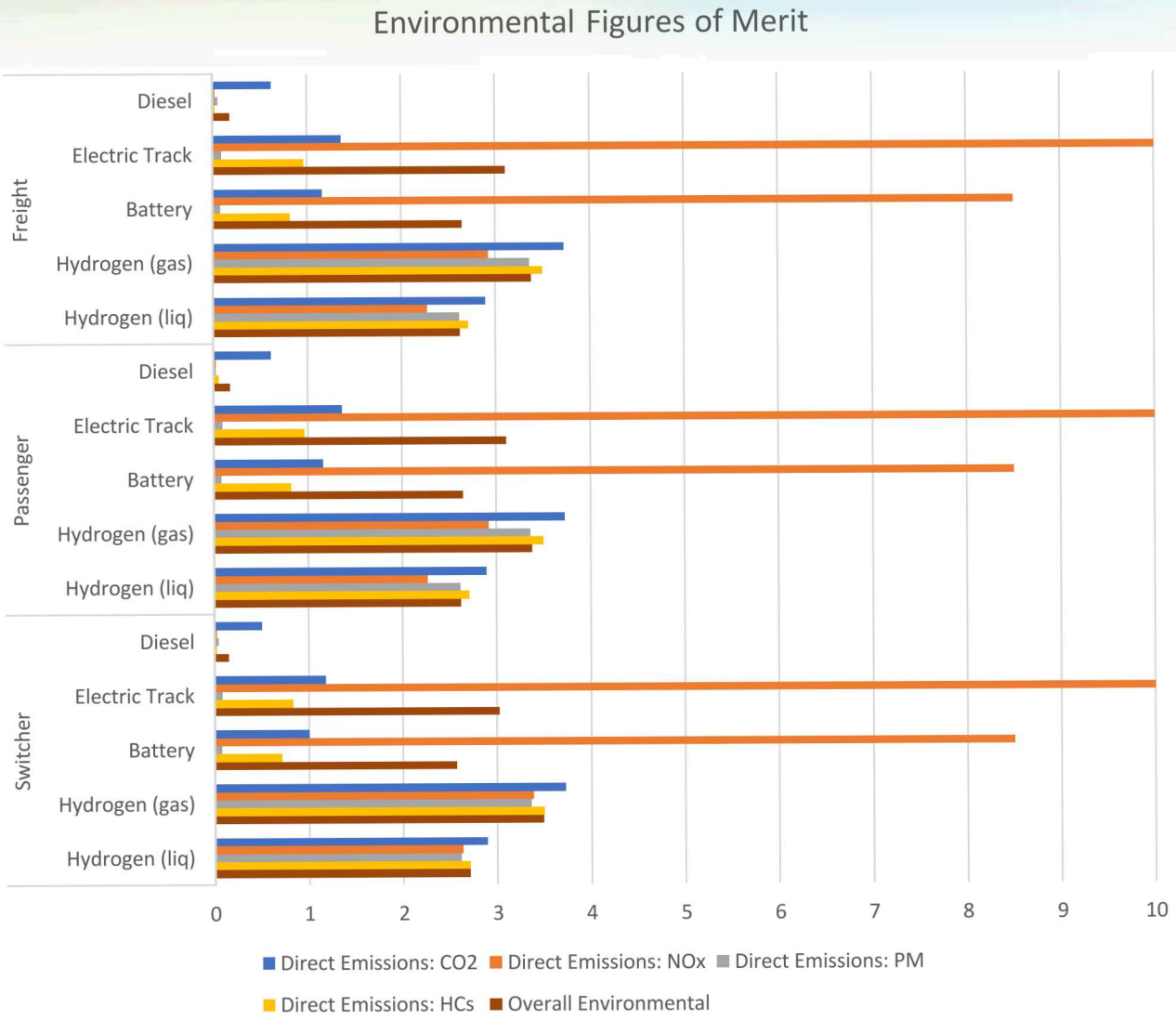
Step 2: Take each Step 1 number, divide by the largest Step 1 number (most benefit) amongst the technologies, then multiply by 10.0. This give you the impact factor (IF) for that technology, for that pollutant, on the desired 0 – 10 scale where 10 is the most benefit.

For Example: Freight (Line-haul) Application

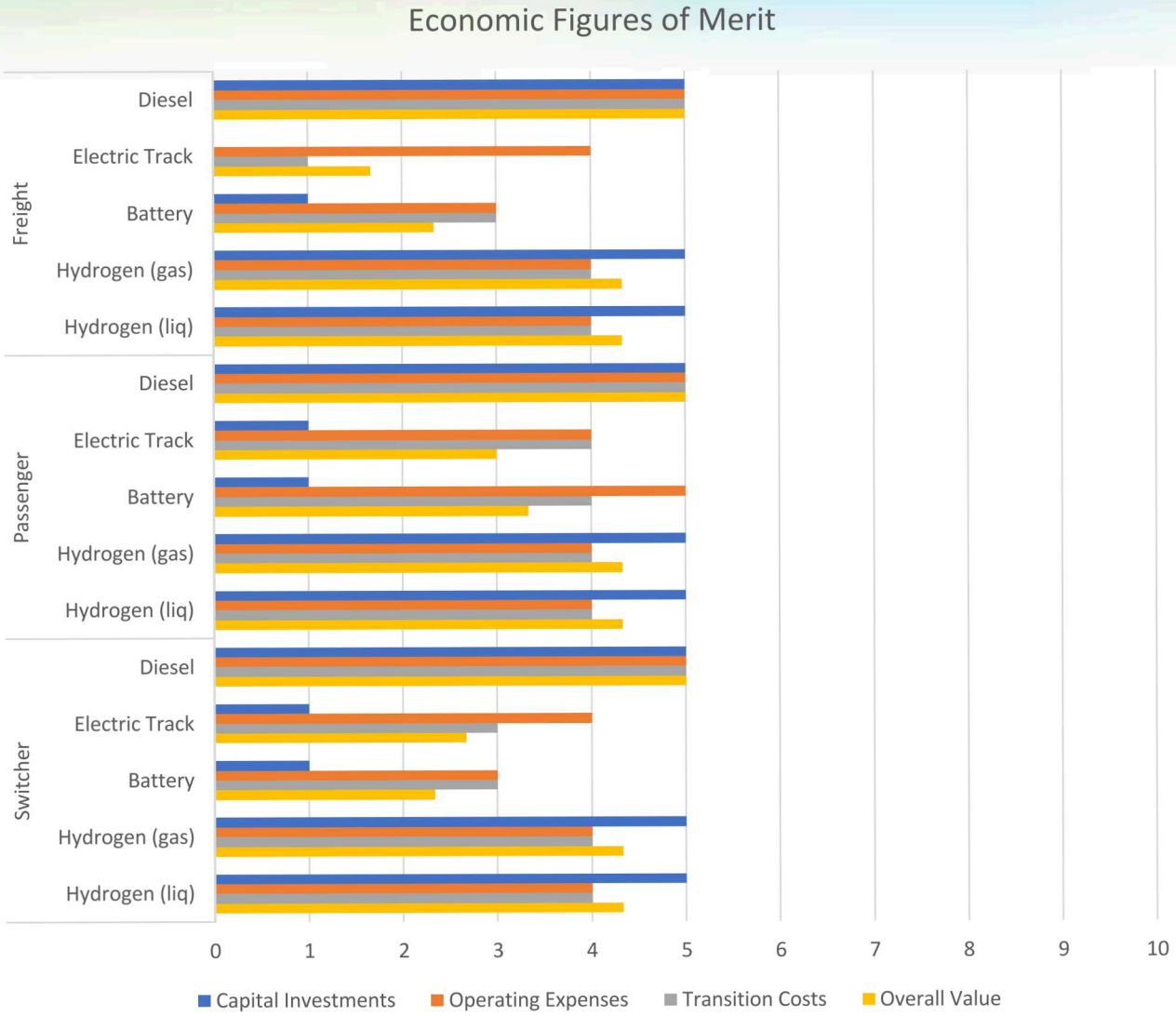
	x	y = 901.312/x	IF_{CO2} = [y/31.60] x 10
Technologies	CO_2(eq.) kg/hr	STEP 1 CO_2(eq.) kg/hr	Step 2 CO_2(eq.) kg/hr
Diesel	463.300	1.945	0.615
FC NG LH_2	482.559	1.867	0.591
FC Electrolysis LH_2	901.312	1	0.316
FC Renewable	36.679	24.572	7.776
Cat. Electric	209.411	4.304	1.361
Battery Only	246.267	3.659	1.158
FC NG H_2 350 bar	375.238	2.401	0.760
FC Elect. H_2 350 bar	700.860	1.286	0.406
FC Ren. H_2 350 bar	28.521	31.600	10

For each technology, determine an overall emissions IF: = (IF_{CO2} + IF_{NOX} + IF_{HC} +IF_{PM}) /4)

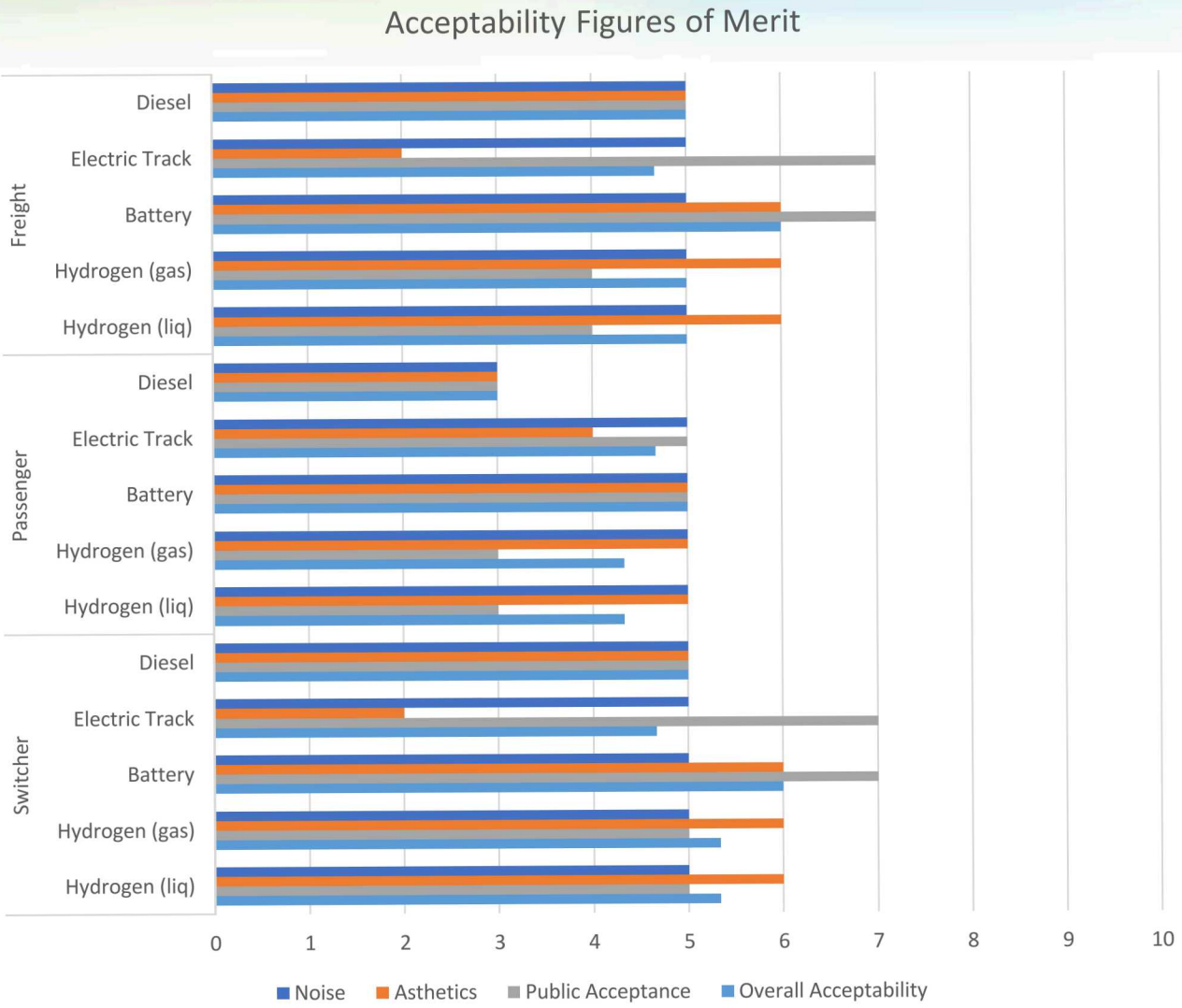
Environmental Figures of Merit Details



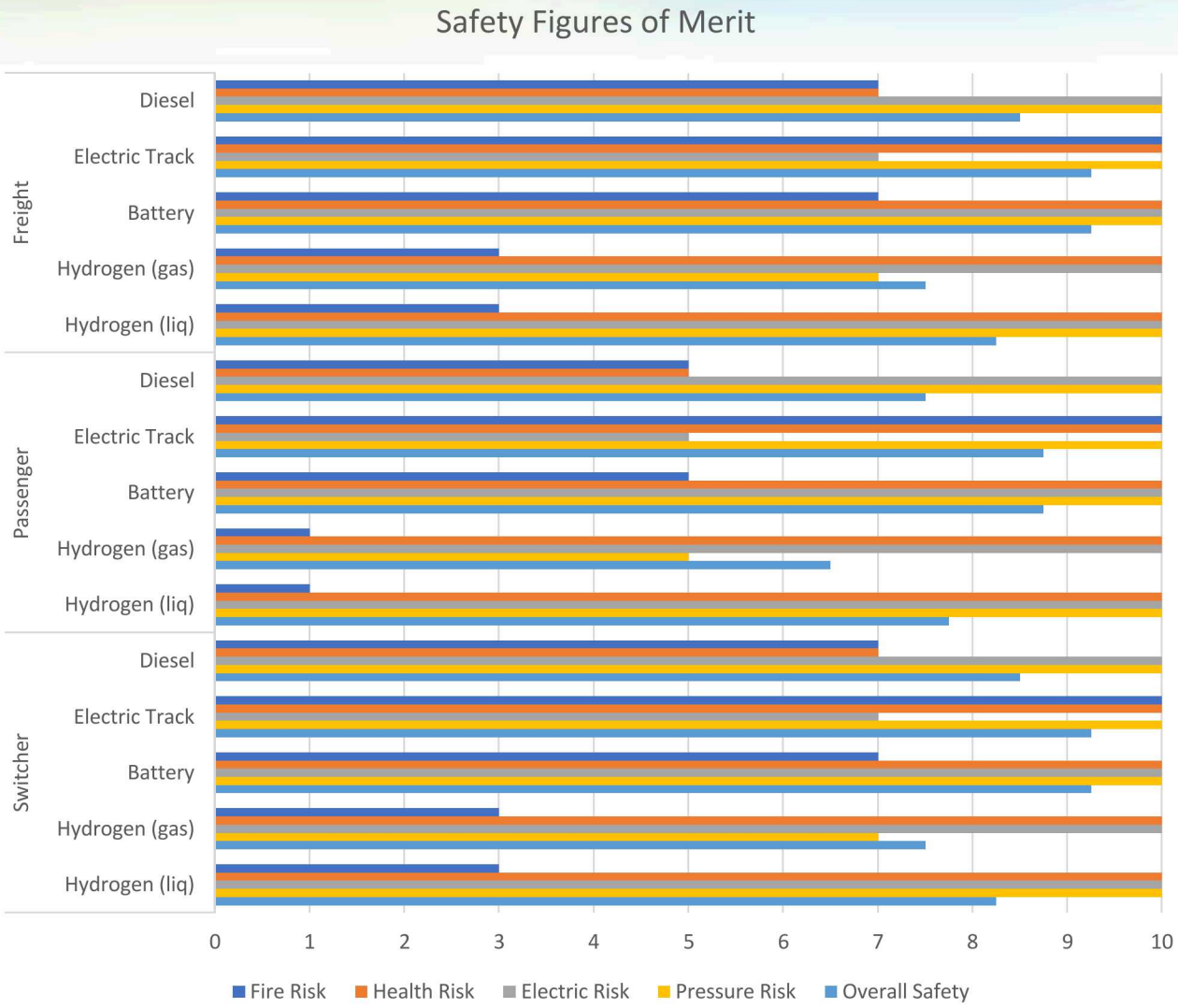
Economic Figures of Merit



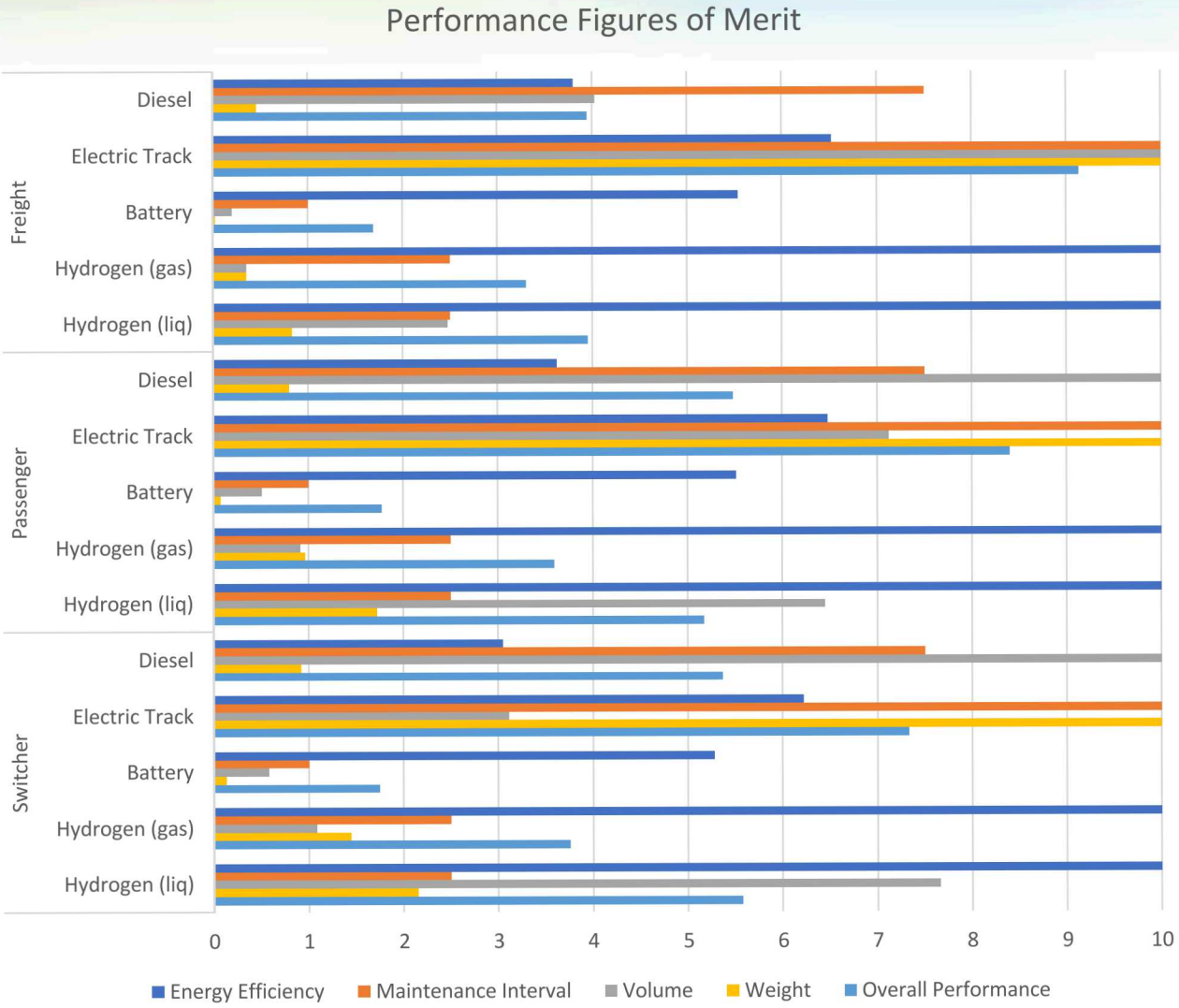
Acceptance Figures of Merit Details



Safety Figures of Merit Details



Performance Figures of Merit Details



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

[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 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

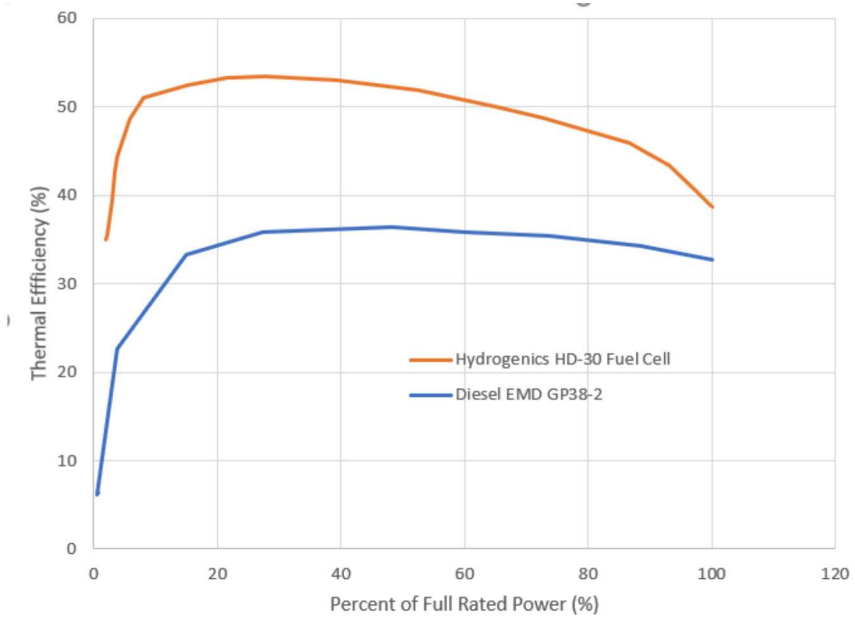
- Created by Congress 1970, take over of unprofitable intercity passenger rail service
- Federal Passenger Rail Investment and Improvement Act (PRIIA)
- Funding from 18 states and 21 agencies

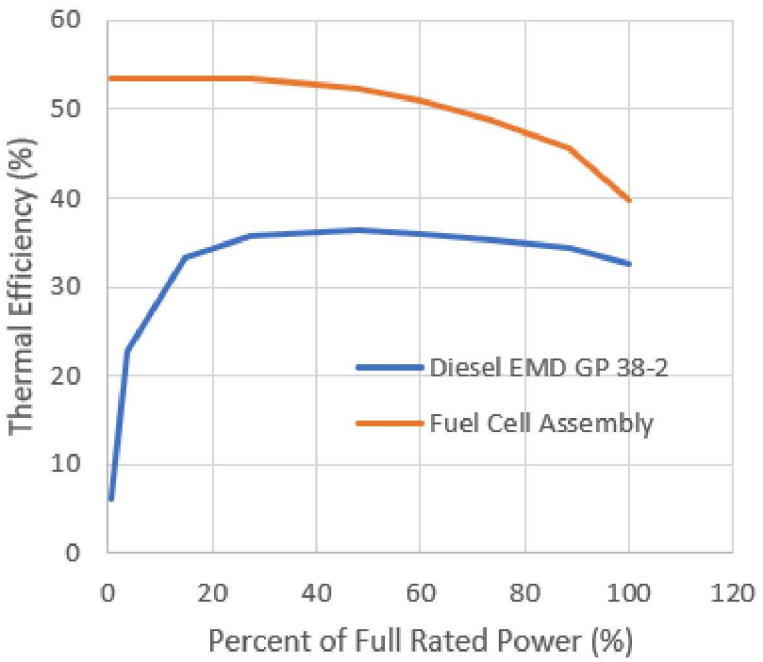
Competition with Airlines, Bus, Private Vehicles

- 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