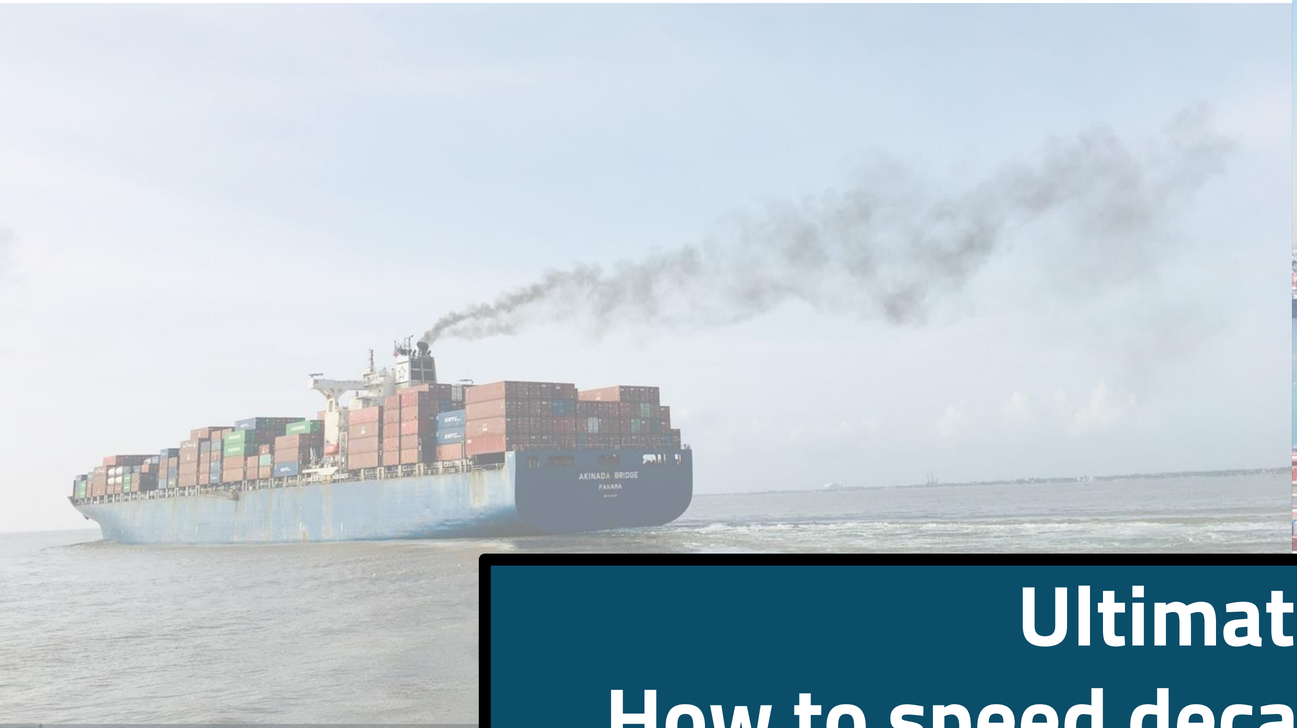
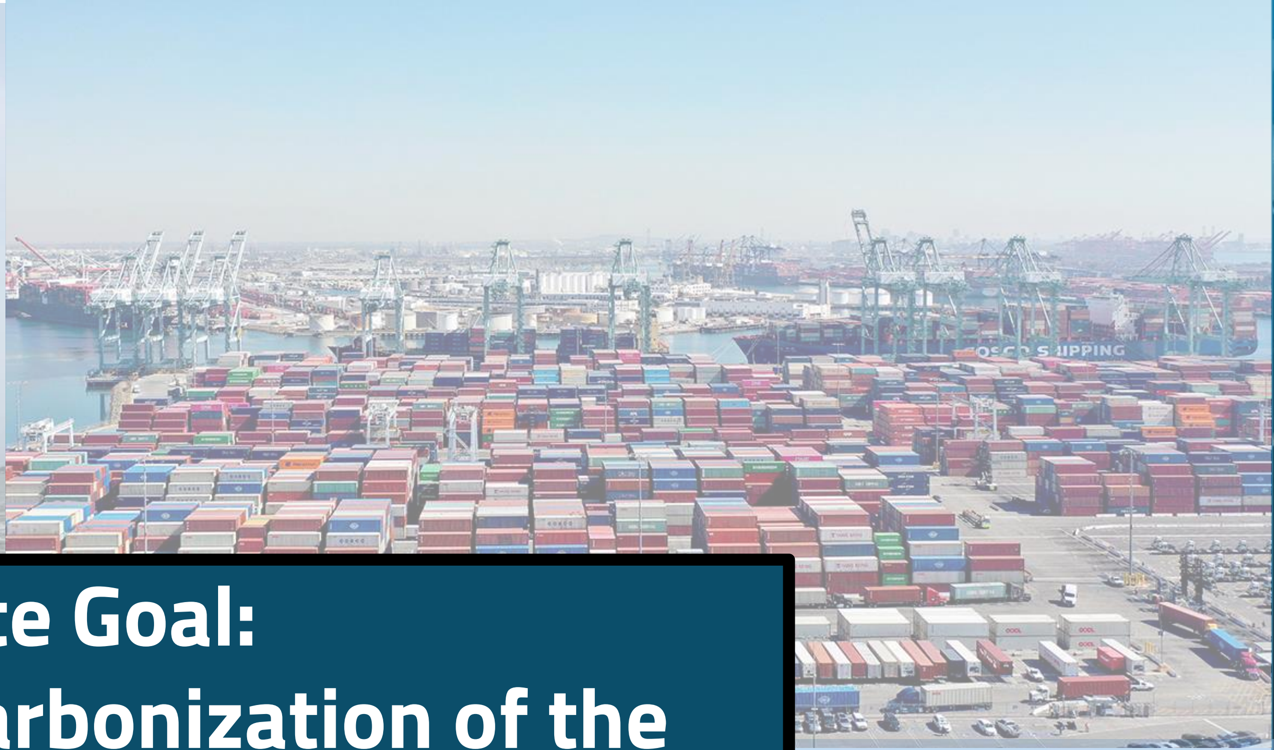
Energy Storage in Railroad Applications

Battery 1K Workshop

Bob Ledoux, ARPA-E Program Director

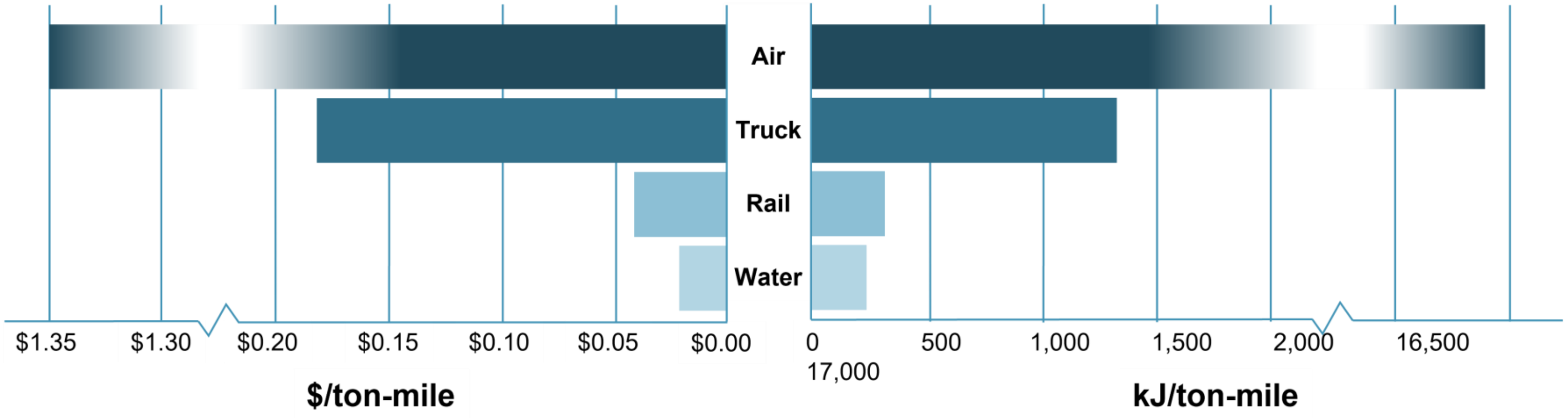
July 13, 2023

Ultimate Goal:
How to speed decarbonization of the freight sector while increasing energy and supply chain resiliency?


Rail Freight Facts

- 28% of domestic freight moves on rail
- Mostly linear system – routes are fixed and privately owned
- 7 privately owned class 1 railroads – support their own infrastructure
- Short haul freight rail not well integrated into long haul
- Two major manufactures of diesel-electric class 1 locomotives - > 25-year service life



https://www.trade.gov/maritime-services-trade-data
https://www.up.com/customers/track-record/tr120120-freight-rail-how-much-ships-by-rail.htm

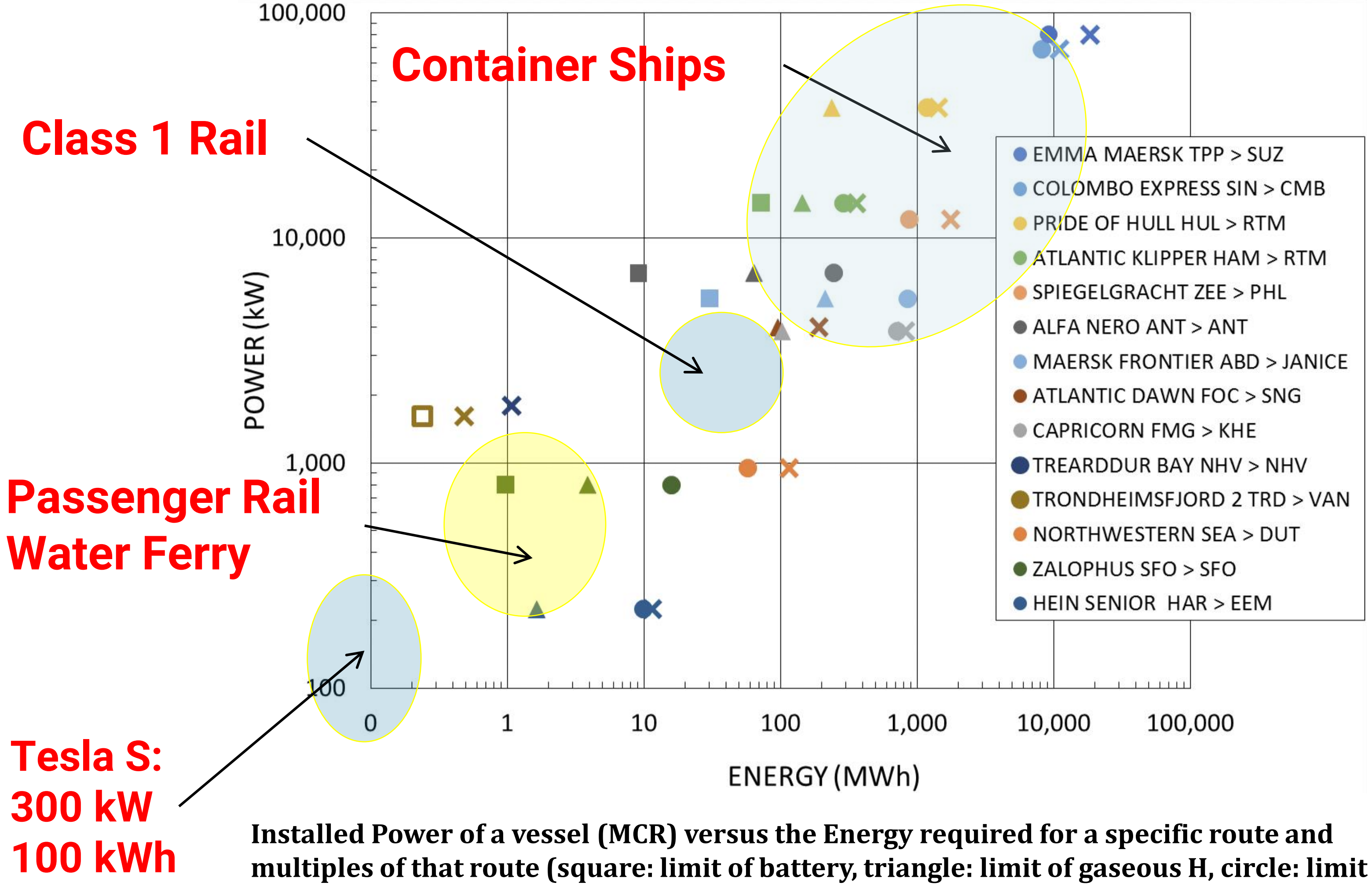
Rail Transportation Industry Operational Overview

- Fuel cost are a significant (10%) operational cost.
- Power storage is <u>not</u> always dominant issue – Refuel time is !
- Emission reduction requirements have been partially mandated
- Already universally diesel-electric
- Safety is crucial
- Ports, rail yards have mature infrastructure – ISO rail cars, etc.
- Operating costs reduction drives investment in new technologies
- Technology adoption requires interoperability between lines
- Serious risk aversion! 25-50 year lifetime of locomotives (3-5% turnover/year)
- All capital investments need to be “future proof”
- Is Battery Electric the Best Way Forward? If so, What is Needed and When!

Challenges to Rail Decarbonization

- High power drive systems (≈ few MW "continuous")
- Very high energy storage requirements (≈ 10-50 MWh)
- Stringent Environmental and Safety Factors
- Need for widely distributed infrastructure
- Industry has been moving to larger trains – hybrid consists may mitigate
- High capital costs → long lifecycle for new technology
- Mostly privately owned

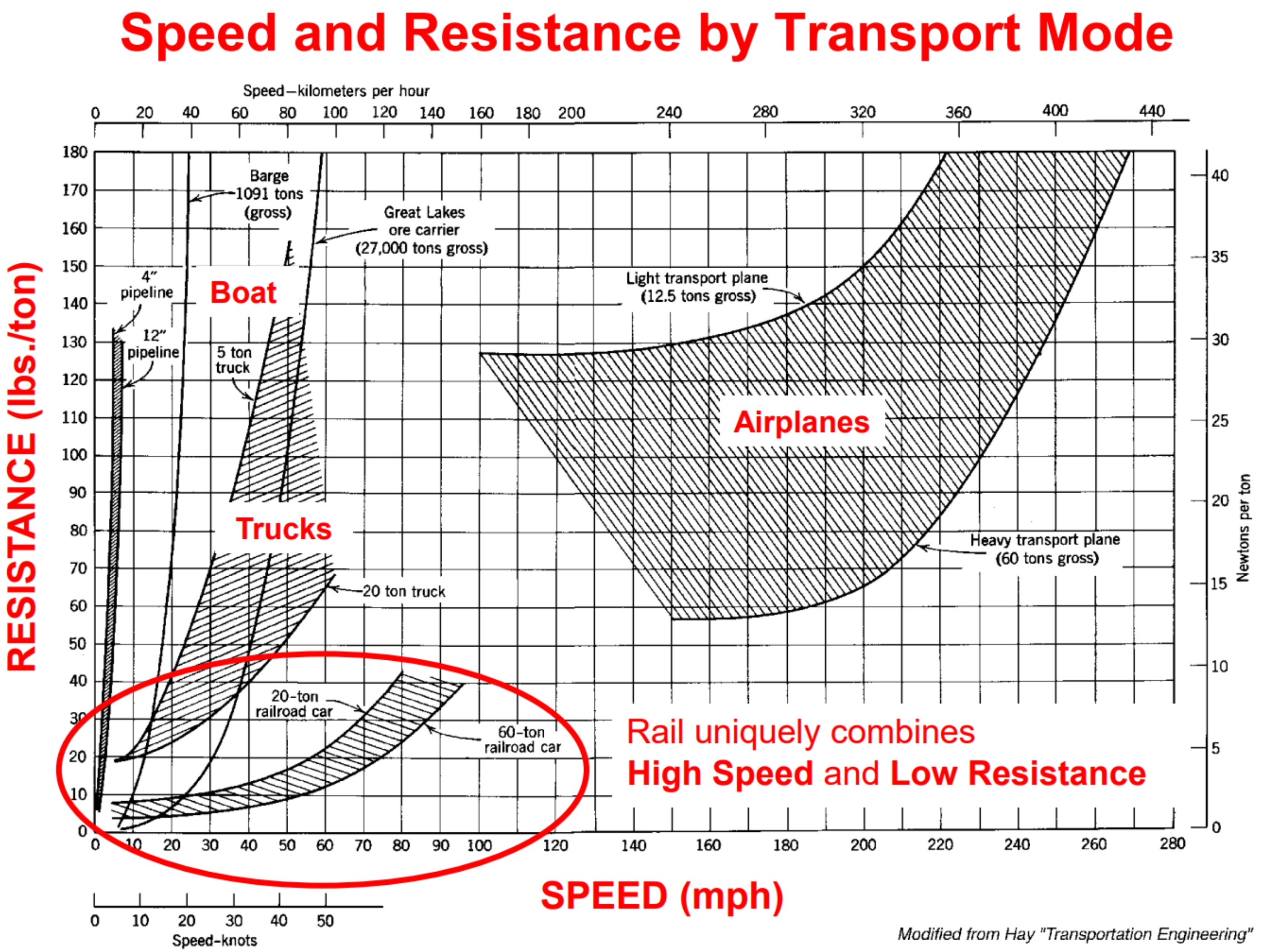
Rail and Maritime Energy System Requirements



Installed Power of a vessel (MCR) versus the Energy required for a specific route and multiples of that route (square: limit of battery, triangle: limit of gaseous H, circle: limit of liquid H, open symbol, no solution, adapted from IEEE 2017)

arpa·e CHANGING WHAT'S POSSIBLE

Trains Are Efficient!



Modified from Hay "Transportation Engineering"

REES Module #3 - Train Energy, Power and Traffic Control 7

The Way We Are…Were?

BNSF IN THE DESERT
by PETER CROOK
MEMBER SINCE AUGUST 2016
fineartamerica.com/profiles/peter-crook
FINE ART AMERICA

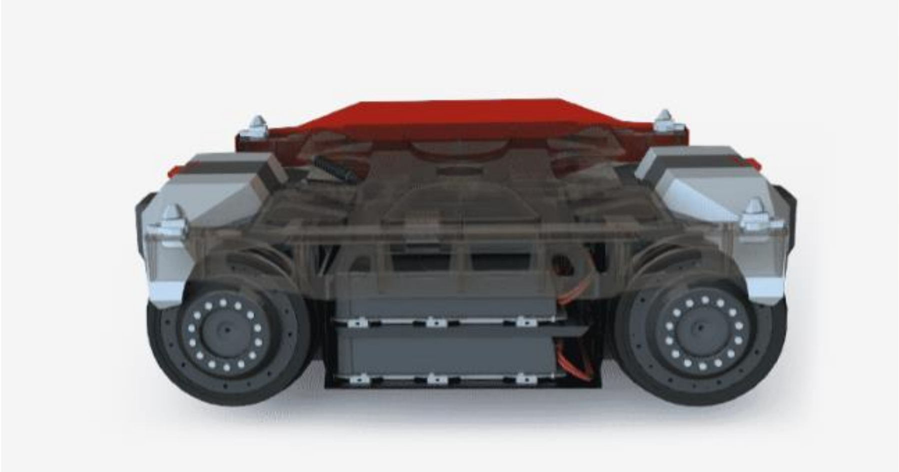
Battery Electric Locomotives

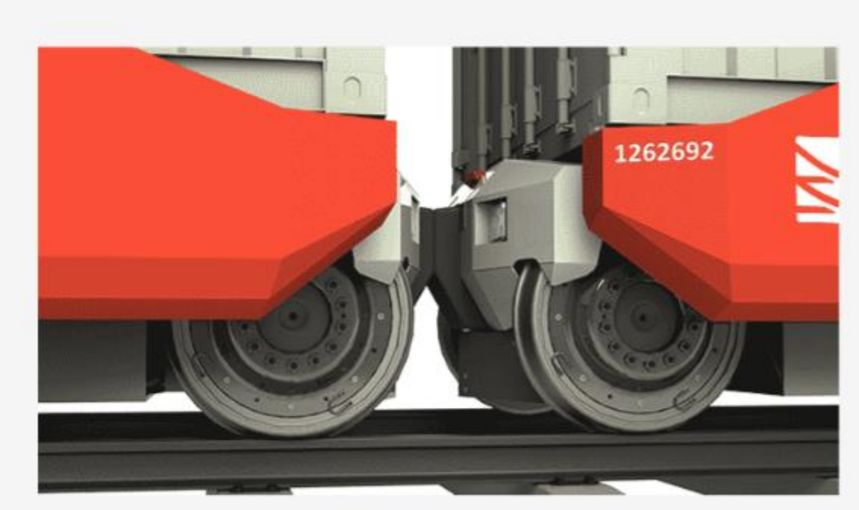
Progress Rail

Wabtec

Rail Decarbonization and Disaggregation?

Parallel Systems





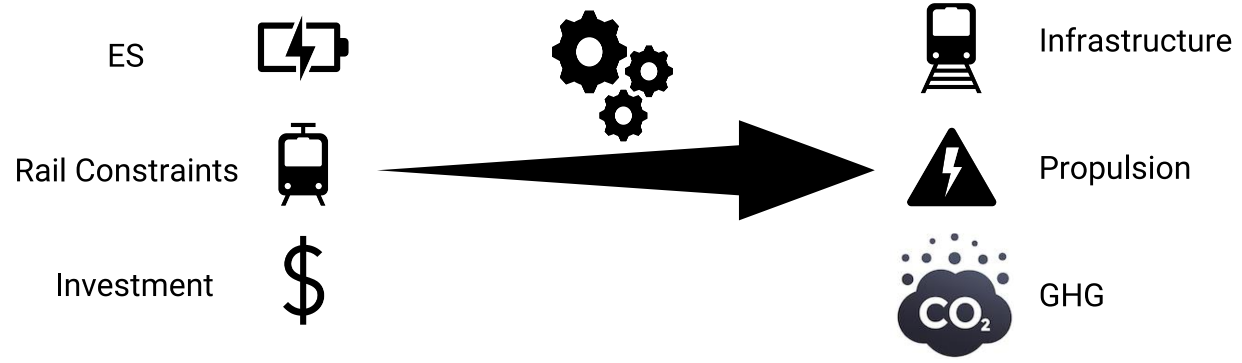
[Product – Parallel (moveparallel.com)](https://moveparallel.com)

Potential New Energy Systems

- Batteries with regenerative braking
- Partial direct electrification – battery hybrid
- Fuel Cells, e.g., hydrogen
- Biofuels
- Hybrid

LOCOMOTIVES: LOwering CO2: Models to Optimize Train Infrastructure, Vehicles, and Energy Storage

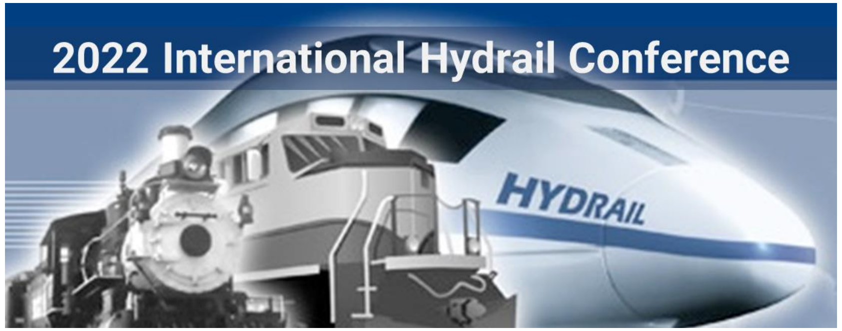
ES - Propulsion	Infrastructure	Potential Impact
Power delivered to wheels, P(t): - acc., + regen	Distance required between refuel for each ES	ES option chosen by route
Acceleration (t): + acc, - deacc	Time between refueling for each ES	% ES option chosen • On a per-route basis • On a per unit energy basis
Energy expended by ES(t), - delivered for propulsion, + regenerative	Fueling time	Lifecycle GHG +/- for each route vs baseline (today), based on chosen ES
Fuel(t) expended (same signage as ES(t)) for each propulsion source	Fuel quantity at each refueling	Cost (LCTKM) +/- for each route vs baseline, based on chosen ES
GHG(t) for each source	Energy content for each refueling	Aggregate impact: lifecycle GHG and cost
	Cost for each refueling	Uncertainty quantification



New ES mix
GHG impact
LCKMT impact

LOCOMOTIVES Summary – Modeling of Class 1 RR

- First completely **Open-Source ARPA-E** program
- Detailed GHG emissions for any train configuration
  - Supports any type of locomotives hybrid configurations
  - Any composition and size of cargos/cars
- Global route map of complete class 1 railroad system at high resolution
  - High spatial resolution with elevation and curvature
- Mapped out required infrastructure as a function of new ES requirements
- Global optimization of RR scheduling based on user determined constraints
- Initial LCA for locomotives life cycle - GREET
- **Expanded the dialogue for decarbonization!**



LOCOMOTIVES - Outreach and Current Performers

National Labs/Academia

- Argonne National Laboratory
- NREL Transforming ENERGY
- PennState
- Northwestern Transportation Center
- Hofstra University
- arpa·e Changing What's Possible
- Virginia Tech
- NC State University
- Oregon State University
- Carnegie Mellon University, Pittsburgh Pennsylvania 1900

Industry

- LA The Port of Los Angeles
- Port of Seattle
- CALSTART
- Wabtec Corporation
- BNSF Railway
- searoutes
- DB
- amazon
- Nautilus Labs
- SwRI Southwest Research Institute
- flexport.
- AAPA American Association of Port Authorities
- CROWLEY

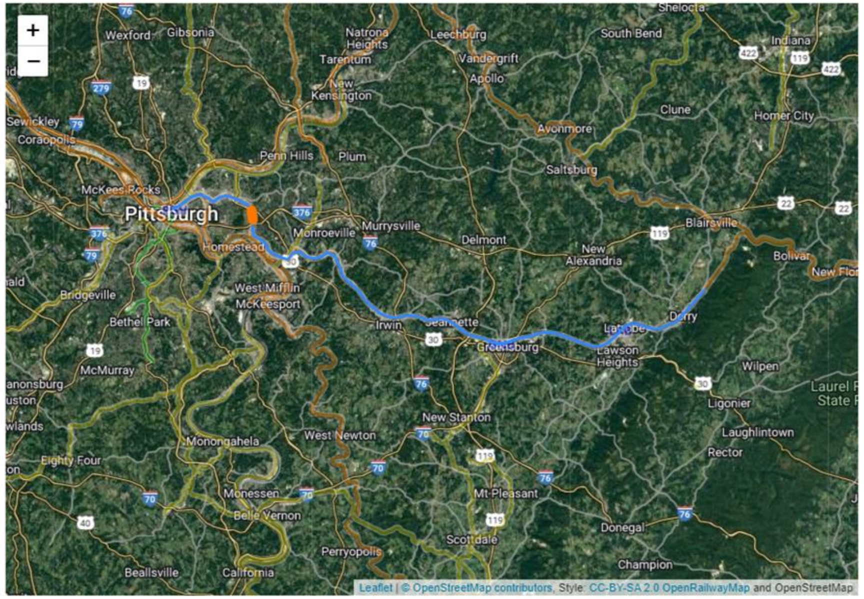
Government

- Maritime Administration, United States of America, 1950
- Department of Transportation, United States of America
- U.S. Department of Energy, Energy Efficiency & Renewable Energy, Vehicle Technologies Office
- FRA
- Surface Transportation Board, 1996
- U.S. Department of Energy, Energy Efficiency & Renewable Energy, Bioenergy Technologies Office

SCORE Fuel and GHG Analysis : Hybrid Locomotive

Route : Pittsburgh_Latrobe

Detailed information of the route, including elevation data (USGS Elevation Service), gradient, curvature, and maximum speed along the route.



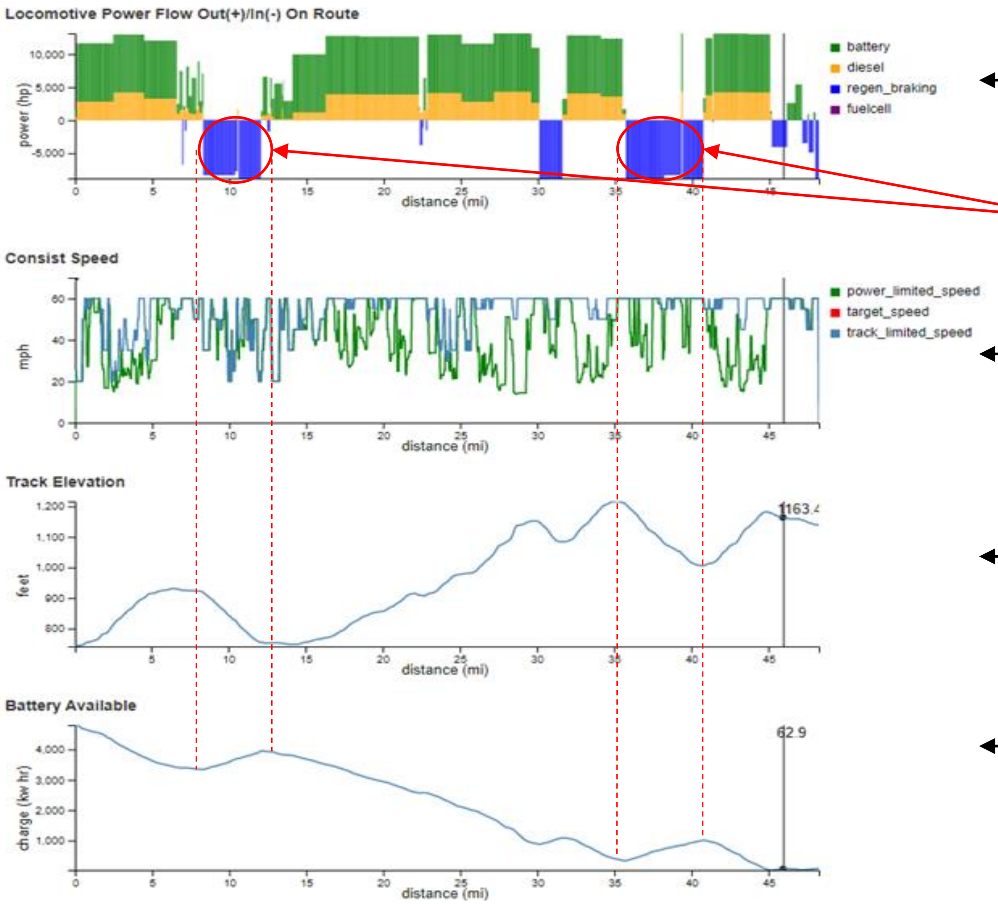
2 Battery/Electric,1 Diesel Locomotive(s)

- Battery Max Power = 2*4398 hp = 8796 hp
- Diesel Max Power = 4336 hp

50 Tank Cars (143.0 tons each)

Duration = 1.34 hours

Web-Based Analysis Results View



Diesel, Battery, and Regenerative Braking power used or gained over the route

Charging Battery from Gradient

Blue line : maximum track speed

Green line : speed of consist based on available power

Track elevation

Battery charge available over the route

Total Diesel Energy = 2662 kw hr

Battery Energy Used = 4708 kw hr

Total Energy Regenerated = 1635 kw hr

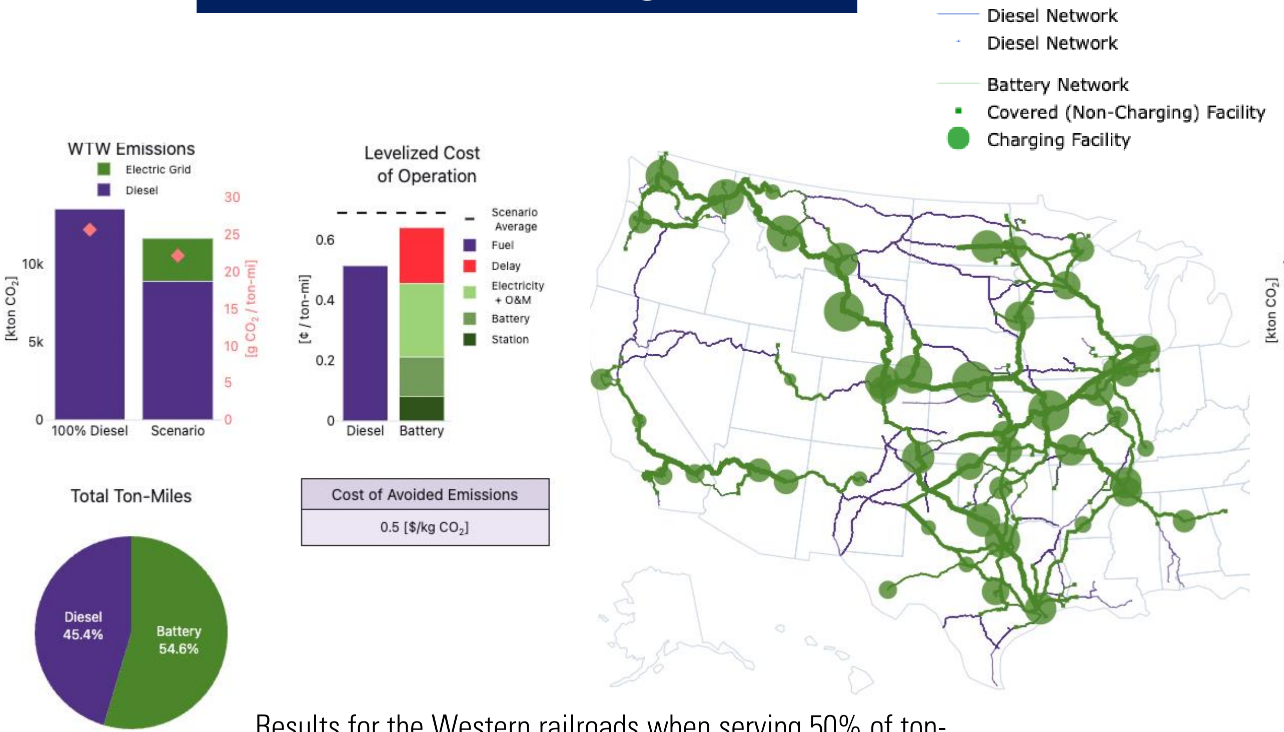
Total Emissions (HC, CO, NO, PM) = 42 kg

Total Diesel Fuel = 198 gal ($693 @ $3.50/gal)

What happens if battery range increases from 400 to 800 miles?

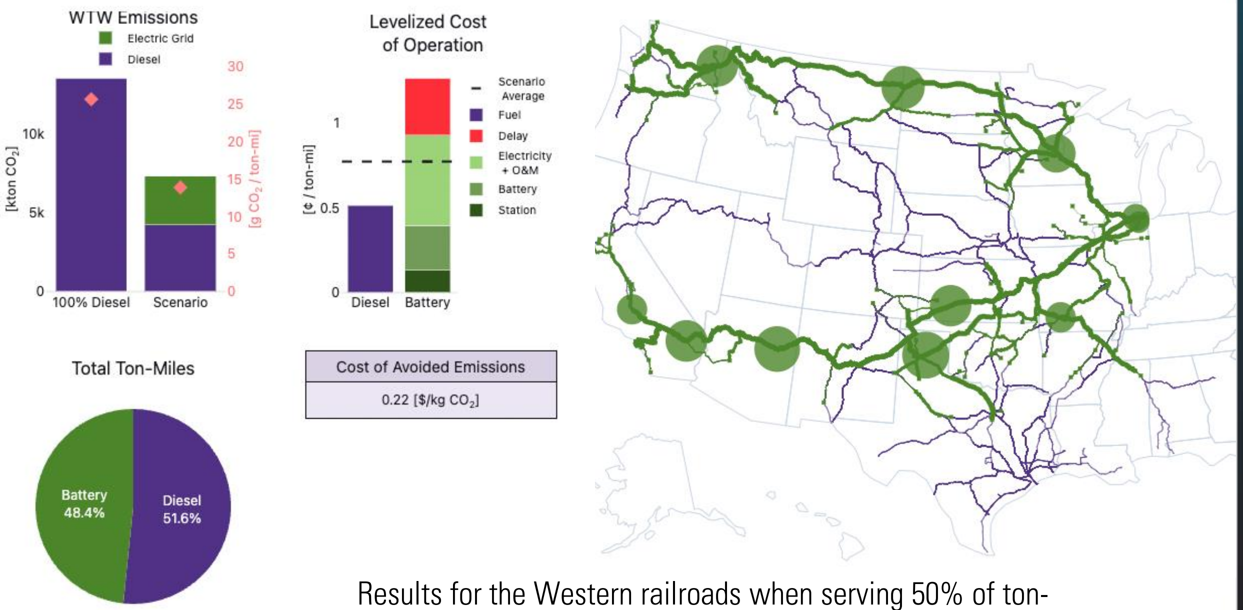
Consolidation on key rail corridors contributes to a **50% decrease in the cost of avoided emissions**, from \$0.5/kgCO_2 to \$0.22/kgCO_2

400-mile range



Results for the Western railroads when serving 50% of ton-miles by battery-electric locomotives with a range of 400 mi.

800-mile range



Results for the Western railroads when serving 50% of ton-miles by battery-electric locomotives with a range of 800 mi.

NU/ANL Preliminary Results

What Are Some Key Take-aways from Analysis of Railroads

- Time is Money! - time to refuel is critical
- Infrastructure placement strongly dependent on range
- Must operate in extreme conditions – high-g/vibrations, large temperature swings, “cold” start
- Interoperability among RR is crucial
- Operational consistency with existing procedures is very important for rapid deployment
- Disaggregation for short haul and resiliency is a new concept – are its energy requirements the same as “standard” locomotives?

Preview of Rail Panel

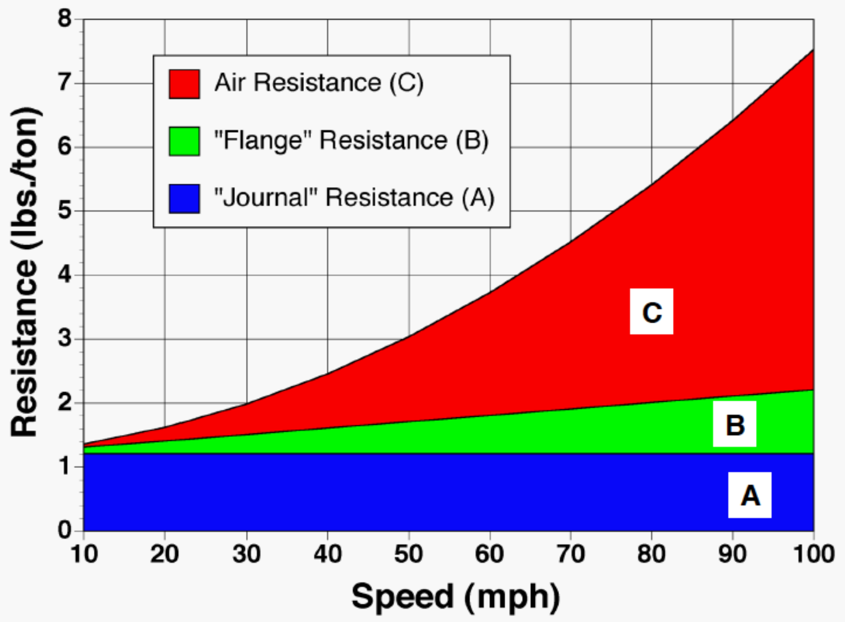
- Wendy Schugar-Martin (Director, Regulatory & Grants, Progress Rail)
- Michael Swaney (Director of Advanced Energy Innovation, BNSF Railway)
- John Howard (Vice President of Engineering, Parallel Systems)
- Venu Gupta (Director of Product Management, Wabtec)

Let's Continue the Conversation!

Thank You!

Rail Resistance as a Function of Speed

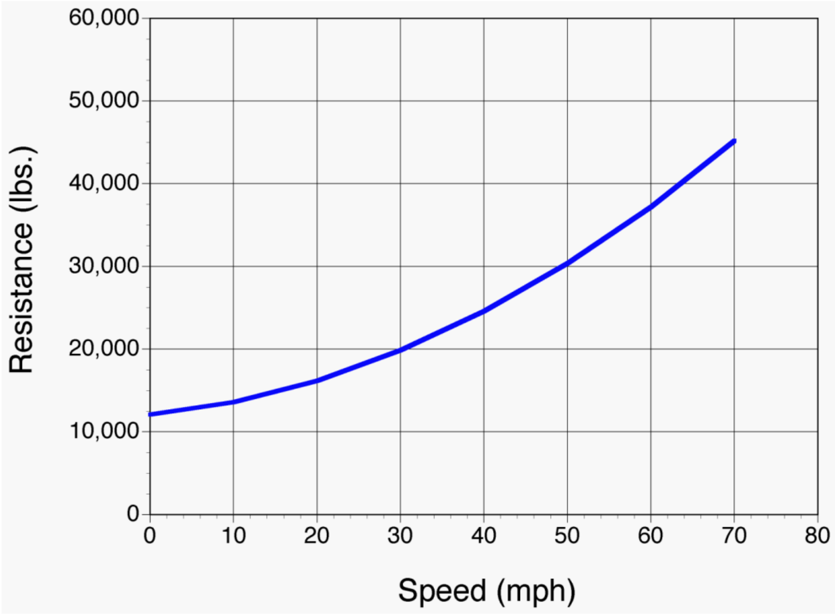
Speed and resistance for conventional freight trair



At low speeds, journal resistance dominates, but as speed increases air resistance is increasingly the most important term

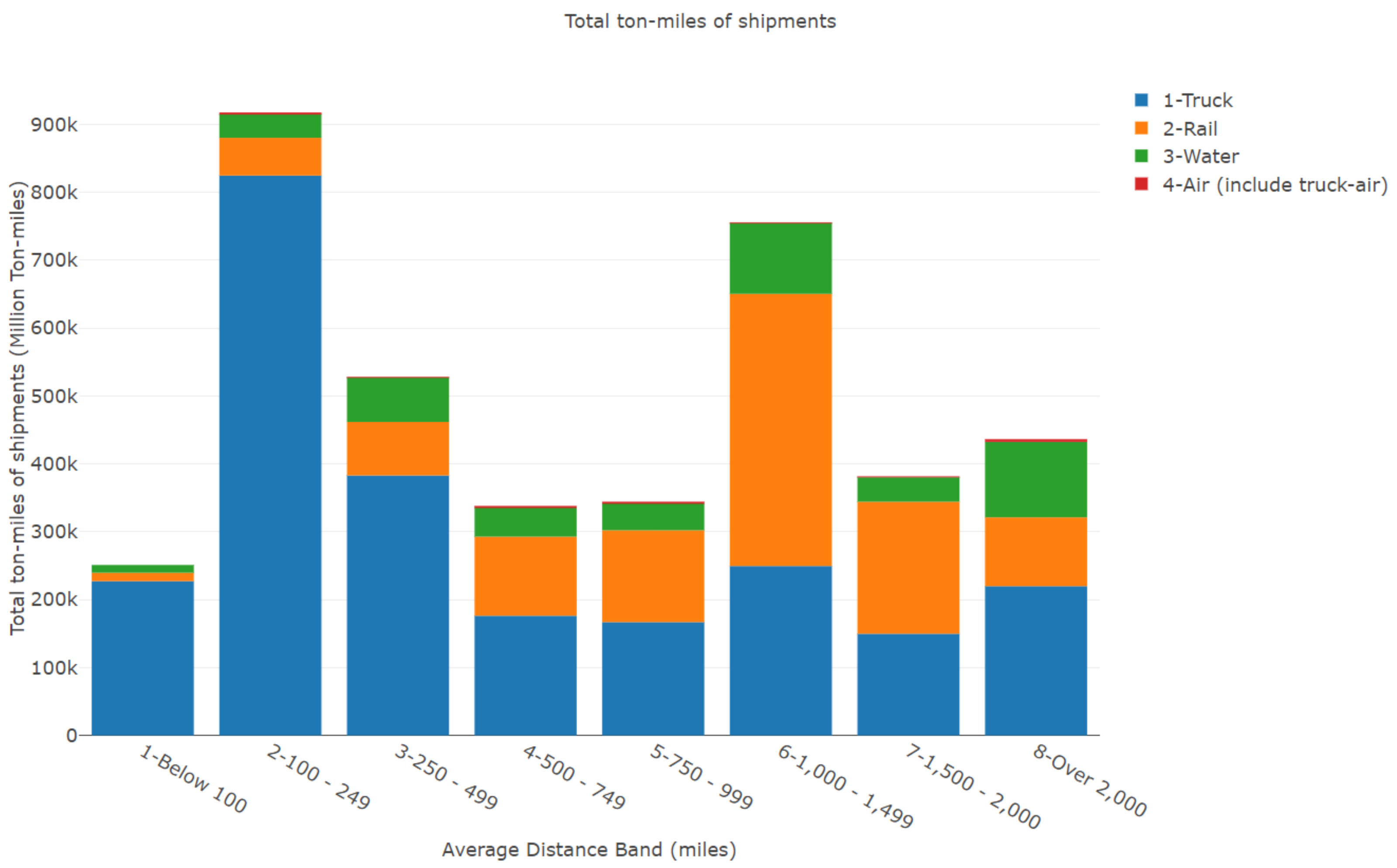
REES Module #3 - Train Energy, Power and Traffic Control

Resistance versus speed for a 10,000 ton train



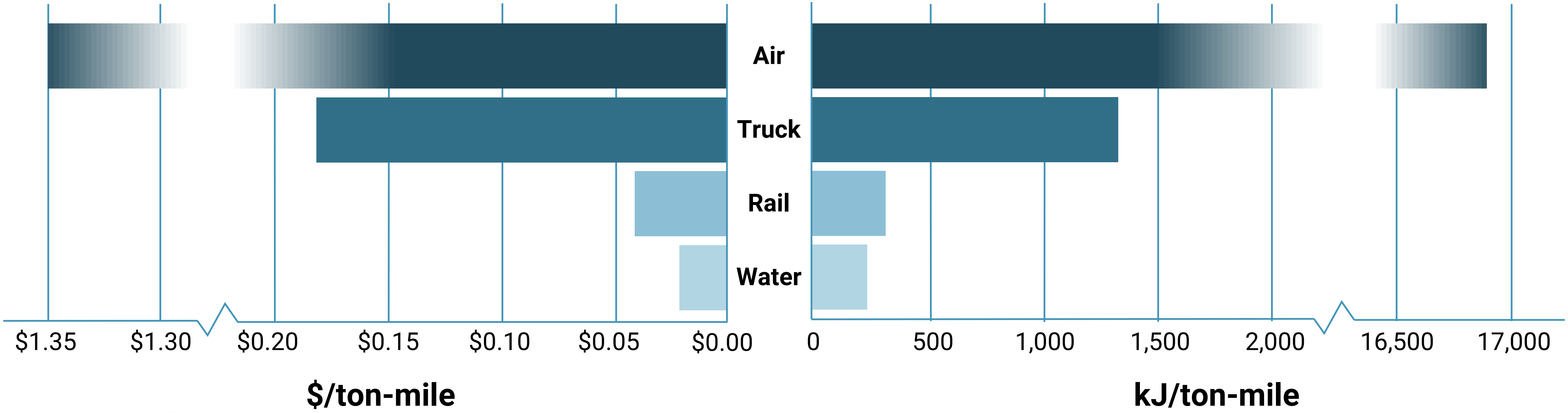
- Train resistance is calculated by multiplying the resistance per ton at each speed, by the total tonnage of the train.

REES Module #3 - Train Energy, Power and Traffic Control


Total ton-miles of shipments
Total ton-miles of shipments (Million Ton-miles)
900k
800k
700k
600k
500k
400k
300k
200k
100k
0
1-Below 100
2-100 - 249
3-250 - 499
4-500 - 749
5-750 - 999
6-1,000 - 1,499
7-1,500 - 2,000
8-Over 2,000
Average Distance Band (miles)
1-Truck
2-Rail
3-Water
4-Air (include truck-air)

All modes are not created equal

- 60% freight (ton-miles) moved by truck -> 25% total transport emissions
- 40% moved by rail/water -> 4% total transport emissions
- Modal shift: if just a quarter of truck journeys over 100 miles were switched off-road, **120 million tons CO_2eq** saved



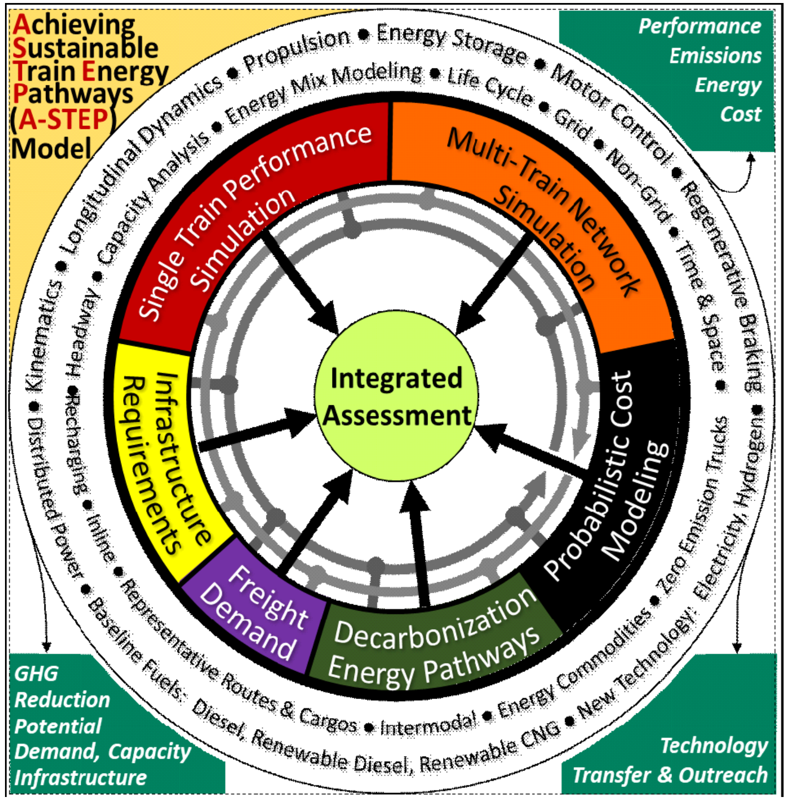
SMART Mobility – Multi-Modal Freight Capstone Report 2020. Department of Transportation.

LOCOMOTIVES Plus-ups – Extend Models

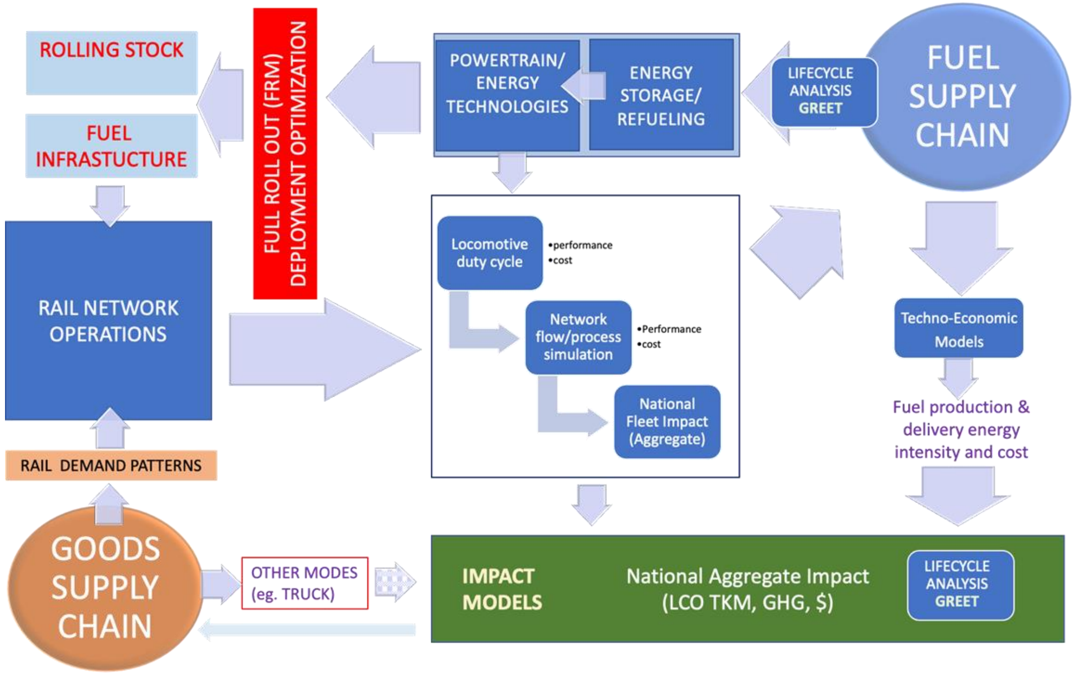
- Disaggregation and the intermodal system
  - Single powered rail cars, container transfer
  - Route planning tool prototype
  - Synergy with OPEN awardee Parallel Systems
- Electrification and Charging infrastructure details
- Green corridors and hydrogen as energy source
  - Link with maritime routes
  - Integrate hydrogen storage and transport
- Short line railroads, short haul (regional), passenger rail
- Full LCA for Class I rail

$500k currently in reserve –
requesting additional $0.5-1M plus-up

LOCOMOTIVES Projects



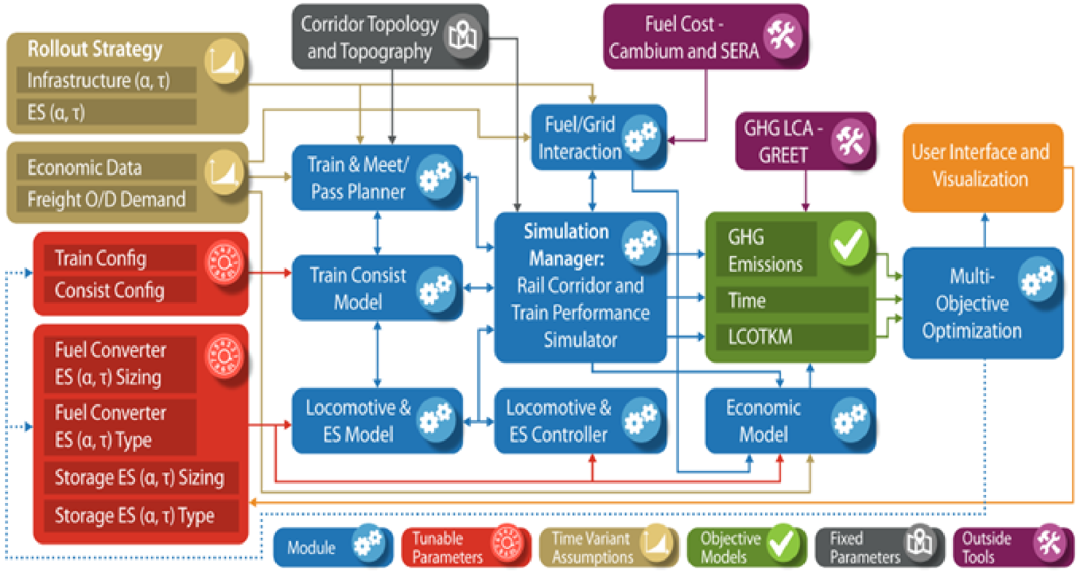
Innovation:
Identify, quantify, and compare decarbonization options for the railroad freight industry over multiple spatial and multi-decadal time scales



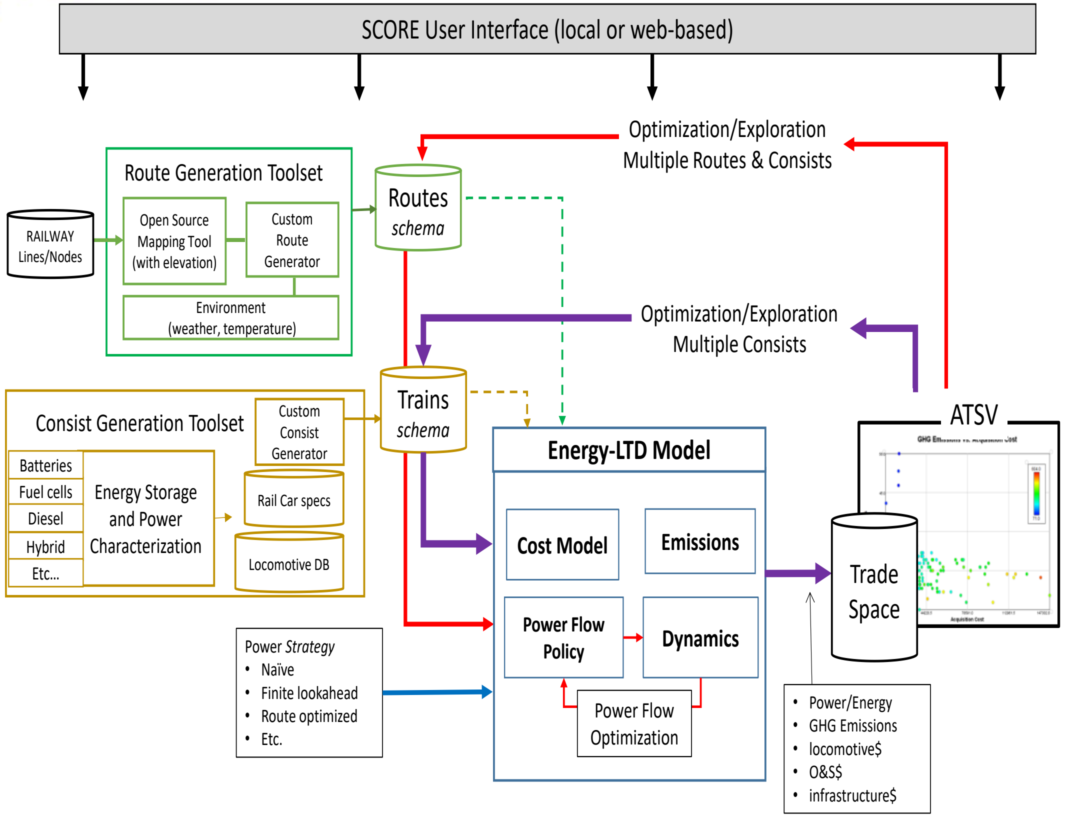
Innovation:
New propulsion and energy storage (ES) systems technologies, as well as the charging/fueling infrastructure to fully decarbonize U.S. rail freight greenhouse gas (GHG) emissions

arpa·e CHANGING WHAT'S POSSIBLE

LOCOMOTIVES Projects

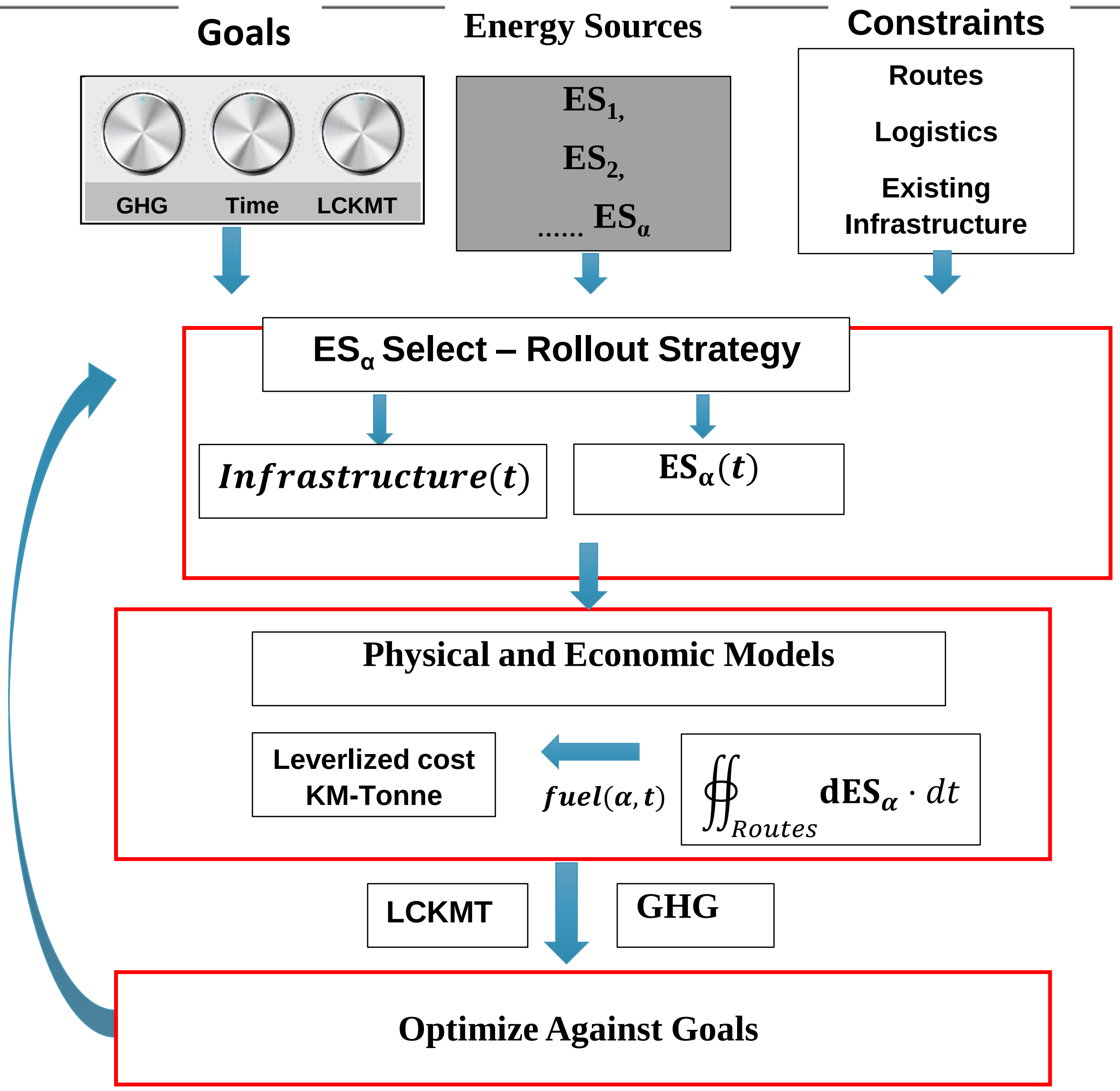


Innovation:
Identify Pareto optimal geospatial-temporal deployment strategies for advanced locomotive technologies and associated infrastructure

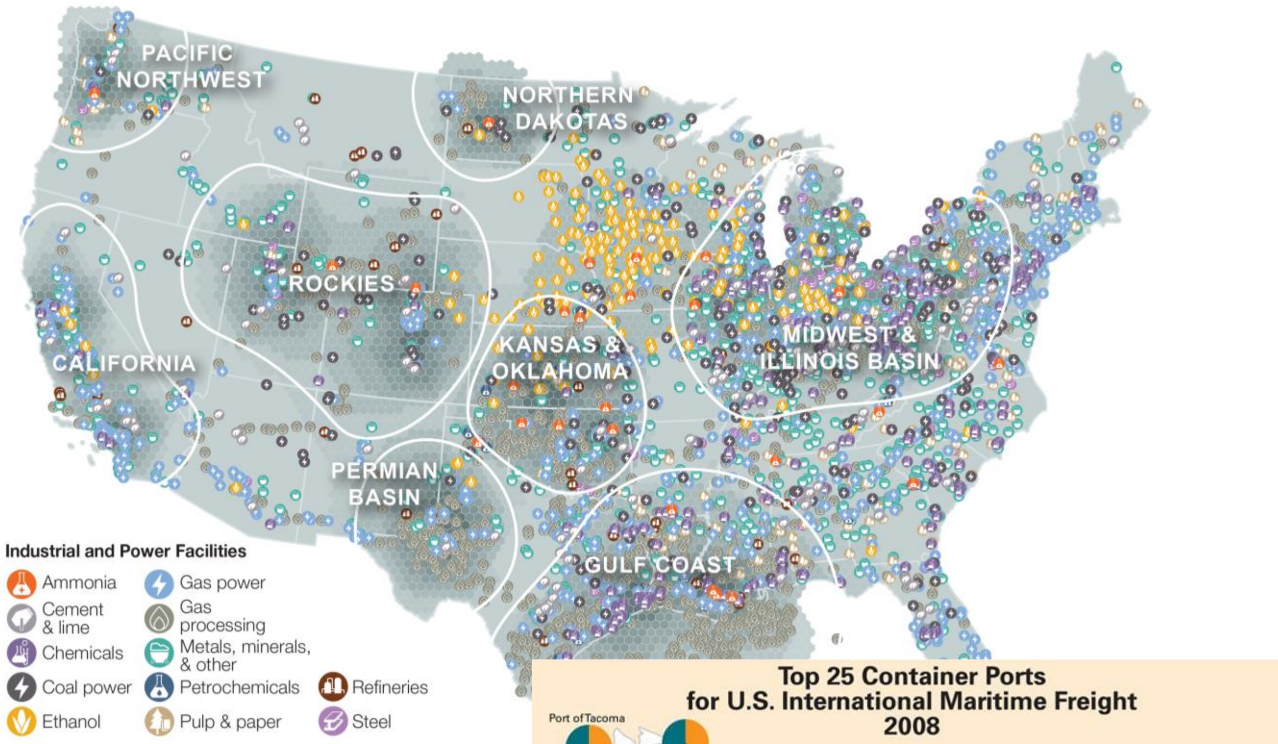


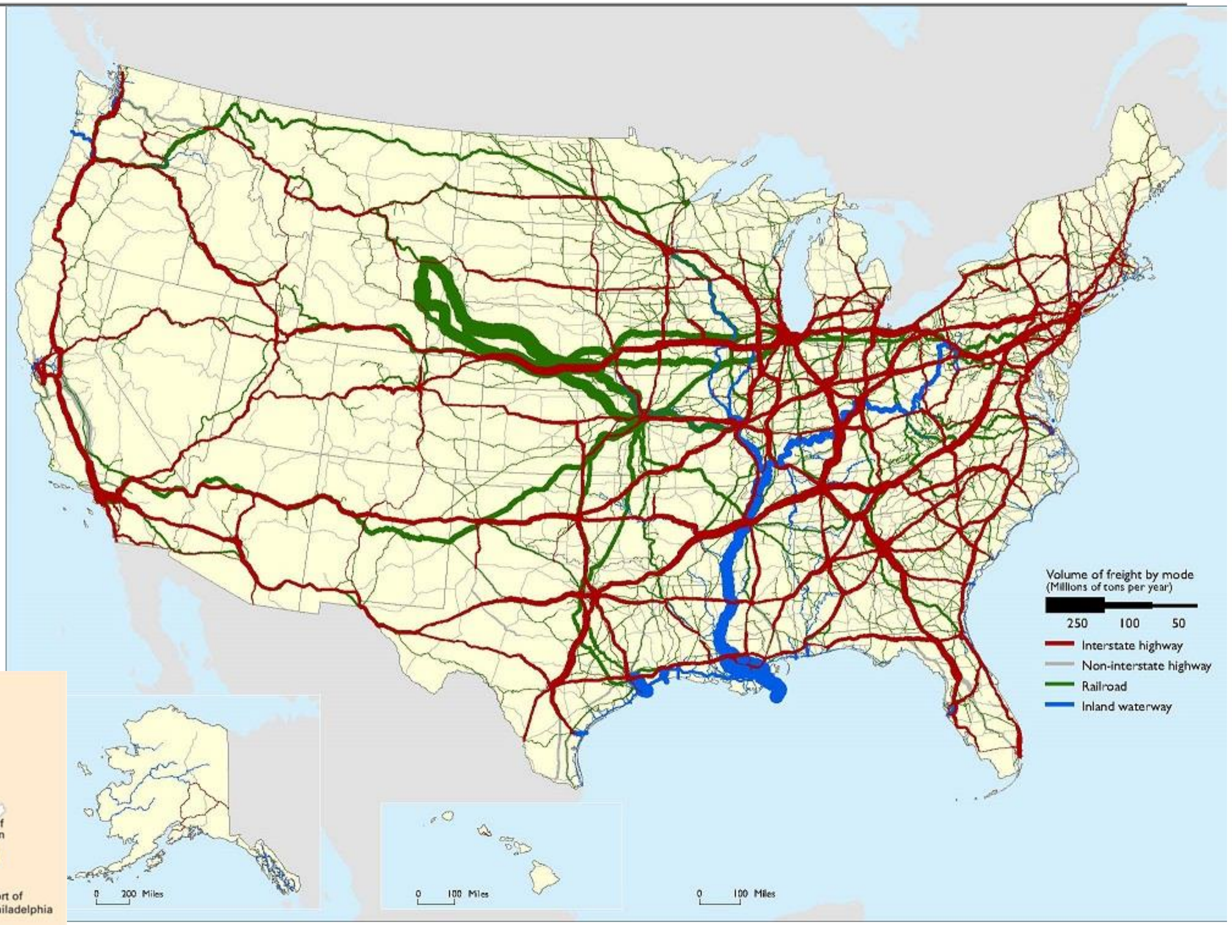
Innovation:
Toolset treats a train as a rolling micro-grid, continuously flowing power between sources (e.g., fossil fuel, hydrogen, battery, flywheel, descending gradients, overhead electric) and sinks (e.g., ascending gradients, resistances, batteries, flywheels)

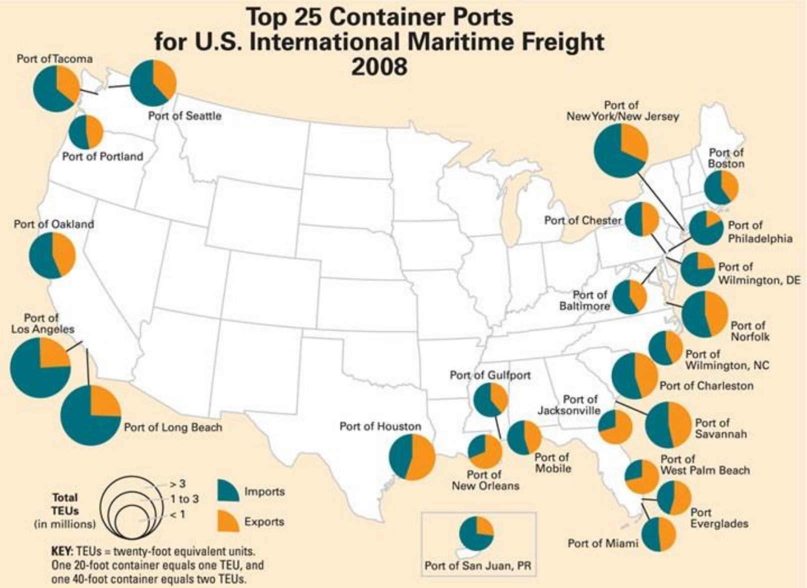
LOCOMOTIVES : Model Structure



External Fuel Infrastructure was not part of LOCOMOTIVES







- Optimization of energy uses and flow could factor in transportation corridors
- Alternative to new transmission?

arpa·e
CHANGING WHAT'S POSSIBLE