NREL
Transforming ENERGY

ALTRIOS - Advanced Locomotive Technology and Rail Infrastructure Optimization System

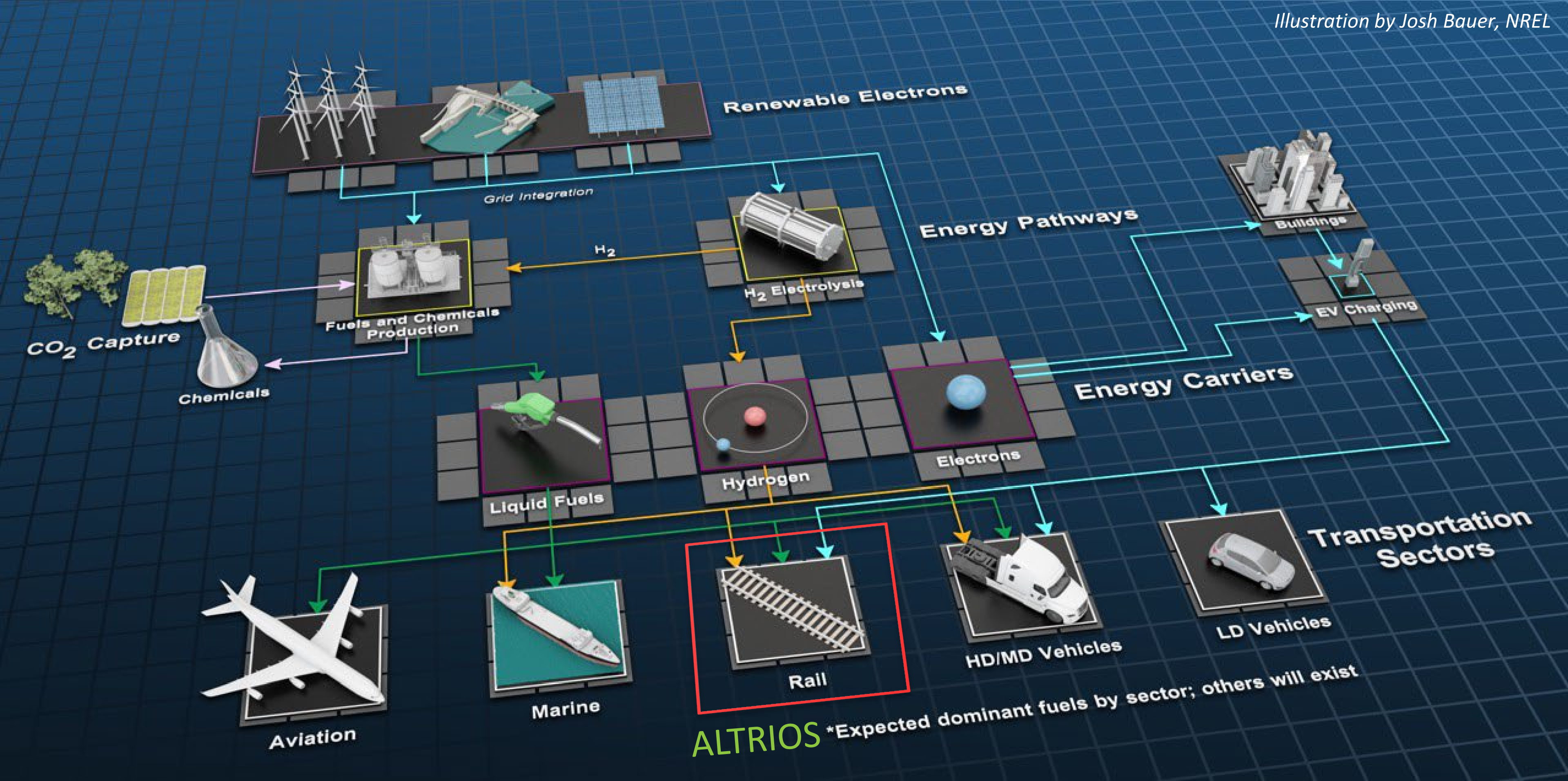
https://www.nrel.gov/transportation/altrios.html

FRA 2023 Workshop on Decarbonization of Rail Transportation

An ARPA-e LOCOMOTIVES Project
May 17th, 2023

- National Renewable Energy Laboratory (NREL): Jason Lustbader (PI), Chad Baker, Grant Payne, Nicholas Reinicke, Kandler Smith, Matt Bruchon, and Alicia Birky
- University of Illinois Urbana-Champaign (UIUC) RailTEC: Tyler Dick (Co-PI), Geordie Roscoe, and Steven Shi
- Southwest Research Institute (SwRI): Steven Fritz, Garrett Anderson, and Chris Hennessy
- BNSF Railway: Corey Pasta, Mike Swaney, Allen Doyel, Nathan Williams, Matthew Duncan, and Joshua Soles

NREL's Vision for Decarbonizing the Transportation Sector



ALTRIOS - Advanced Locomotive Technology and Rail Infrastructure Optimization System

Accelerate rail decarbonization through development and distribution of a validated comprehensive modeling framework

- Open-source software tool to evaluate strategies for deploying advanced locomotive technologies and associated infrastructure for cost-effective decarbonization
- Simulate train dynamics, energy conversion and storage technologies, meet-pass planning, and freight-demand driven train scheduling
- Provide guidance on the risk/reward tradeoffs of different technology rollout strategies.
- Identify Pareto optimal, geospatial-temporal deployment strategies for advanced locomotive technologies and associated infrastructure

ALTRIOS Team: Multi-Disciplinary team combining strengths of a national lab, university research center, research laboratory, and railway operator

NREL – NATIONAL RENEWABLE ENERGY LABORATORY ❯ Deep experience in energy efficient transportation technologies, energy storage/conversion, and developing and deploying open source software

RAILTEC – UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN ❯ Expertise in railroad operations, train dynamics, and train energy modeling

SwRI – SOUTHWEST RESEARCH INSTITUTE ❯ Locomotive powertrain expertise and performance data.

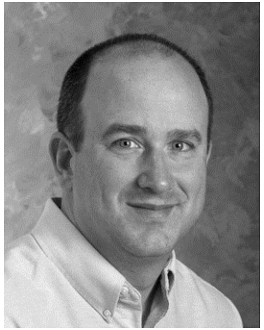
BNSF RAILWAY ❯ Applied engineering expertise in train dynamics and operating efficiency. Experience implementing and evaluating transformative train solutions.

Organizational Leads

NREL (PI):
Jason Lustbader

NREL (Model Lead):
Chad Baker

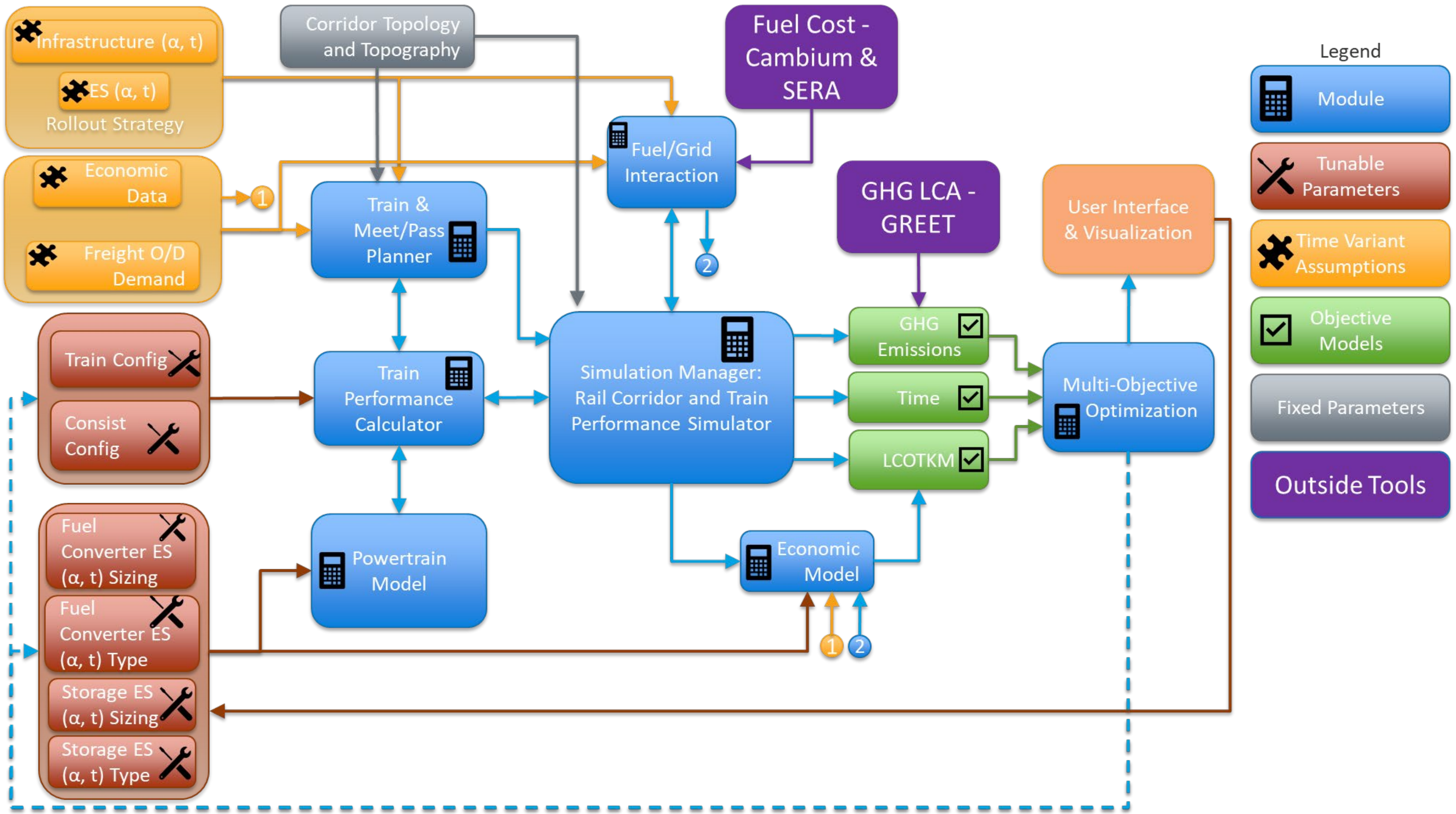
UIUC RailTEC (co-PI)
C. Tyler Dick



SwRI:
Steven Fritz

BNSF (Industry):
Mike Swaney

Framework: Overview
ALTRIOS Modeling Framework



ALTRIOS: Train Corridor Simulator

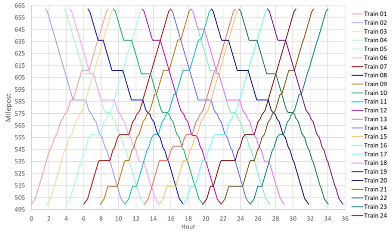
Train Consist Planner

Pool B	Engine_Number	Type	Capacity_Cars	Capacity_Tonnage	Refill_Time
0	2009.0	BEL	100.0	25000.0	0.0
1	2011.0	BEL	100.0	25000.0	0.0
2	2012.0	Type1	60.0	30000.0	0.0
3	2013.0	Hydrogen_Cell	80.0	20000.0	0.0
4	2014.0	Type1	60.0	30000.0	0.0
5	2015.0	Hydrogen_Cell	80.0	20000.0	0.0
6	2016.0	Type2	100.0	25000.0	0.0
7	2017.0	Hydrogen_Cell	80.0	20000.0	0.0
8	2018.0	Diesel_Medium	120.0	30000.0	0.0
9	2019.0	Diesel_Small	90.0	20000.0	0.0
10	4000.0	Diesel_Medium	120.0	30000.0	0.0
11	4001.0	Type2	100.0	25000.0	0.0
12	1000.0	BEL	100.0	25000.0	0.0
13	3002.0	Diesel_Small	90.0	20000.0	0.0
14	4004.0	Diesel_Small	90.0	20000.0	0.0
15	4005.0	Type2	100.0	25000.0	0.0

Builds train plan schedule and train consist including locomotive ID, type of train, O/D information, and carload information

Python

Meet/Pass Planner

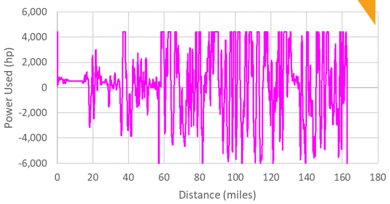


Generates target speed profiles for multiple trains using train performance calculator for individual train simulation and simplified train interactions

Rust

Train Performance Calculator

Avail. Power

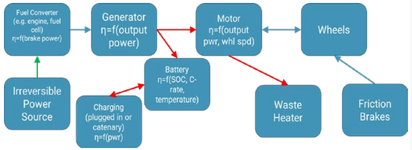


Physics-based model calculates detailed train resistance, speed and tractive power required to achieve target speeds

Rust

Req. Tractive Power

Powertrain Model



Solves for optimal energy flows between components and overall fuel/electricity usage at power output required by train

Rust/Python

O/D Pairs

Train Plan

Train Plan

Train Paths

Train Path

Train Energy

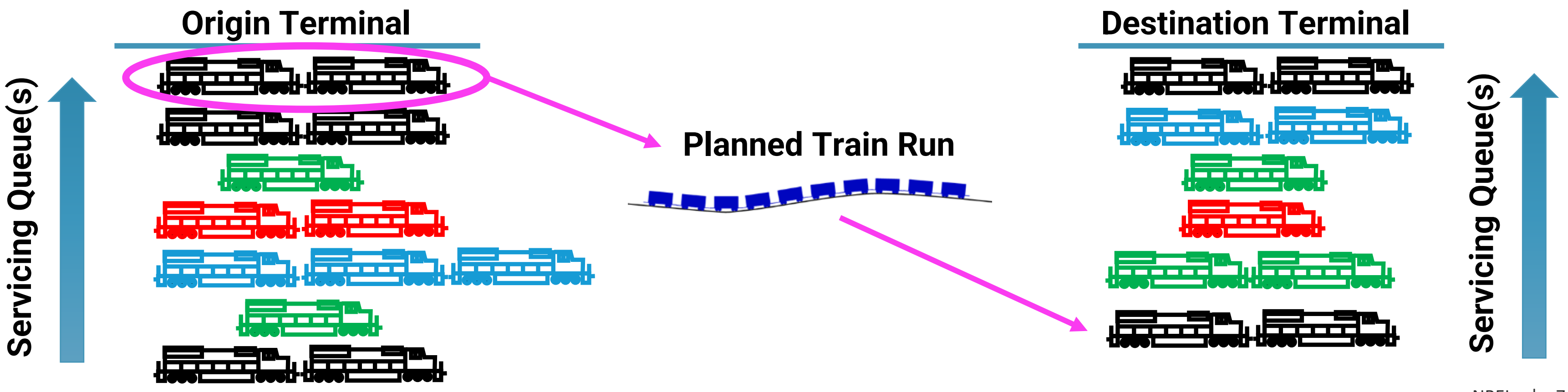
Performance Metrics

Simulation Manager **- Python**

Train Consist Planner, Overview

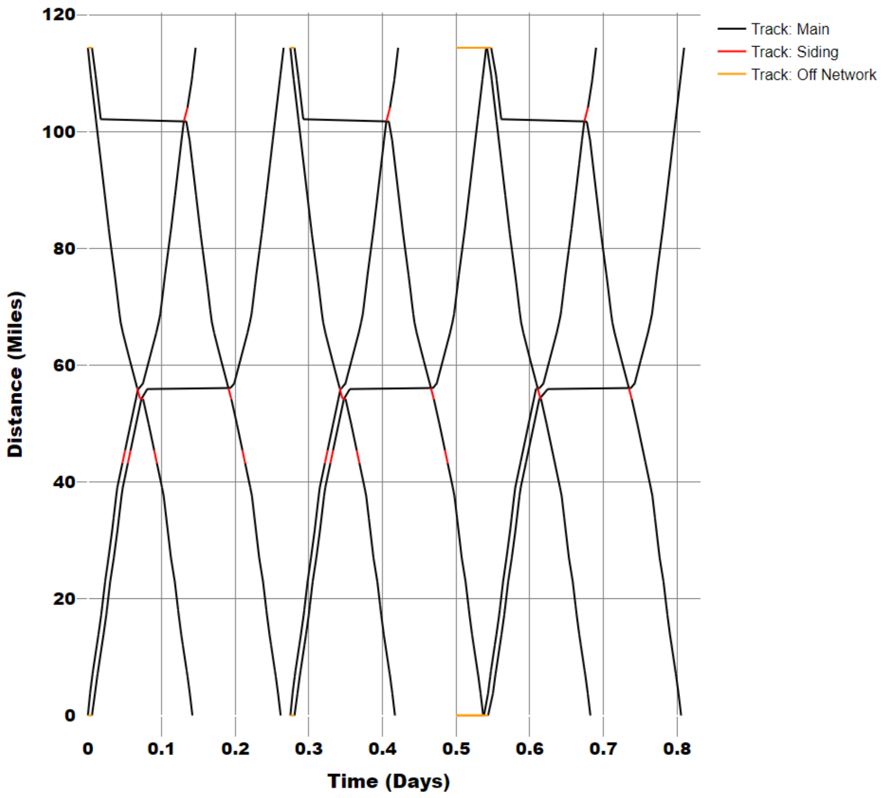
- Train consist planner builds a train plan including Locomotive ID, type of train, origin and destination on simulated network, and number of empty and loaded railcars

- **Input**
  - Annual O/D pair traffic demand
  - Locomotive characteristics
  - Initial locomotive and railcar distributions
- **Output**
  - List of consist information for each train
  - Corresponding planned departure time



Meet/Pass Planner

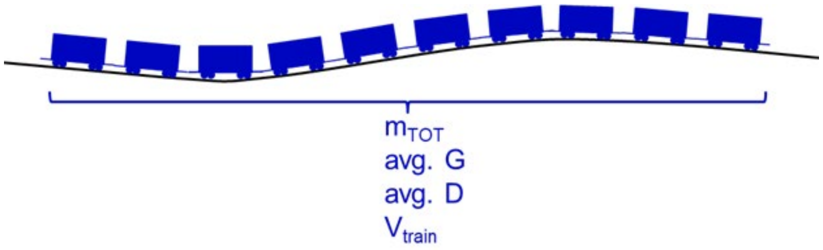
- Develops a complete plan for the path each train will take through the track network along with estimated times for traversing each segment
  - Estimated times derived from simulating each train using the train performance calculator
- Uses a high-performance free-path-based deadlock avoidance algorithm
- “Stringline” diagram train meet/pass plan output shows the algorithm chooses to meet trains at passing sidings that generally minimize total overall delay



Train Resistance and Motion Calculations

- Grade resistance
  - Train modeled as uniform mass strap

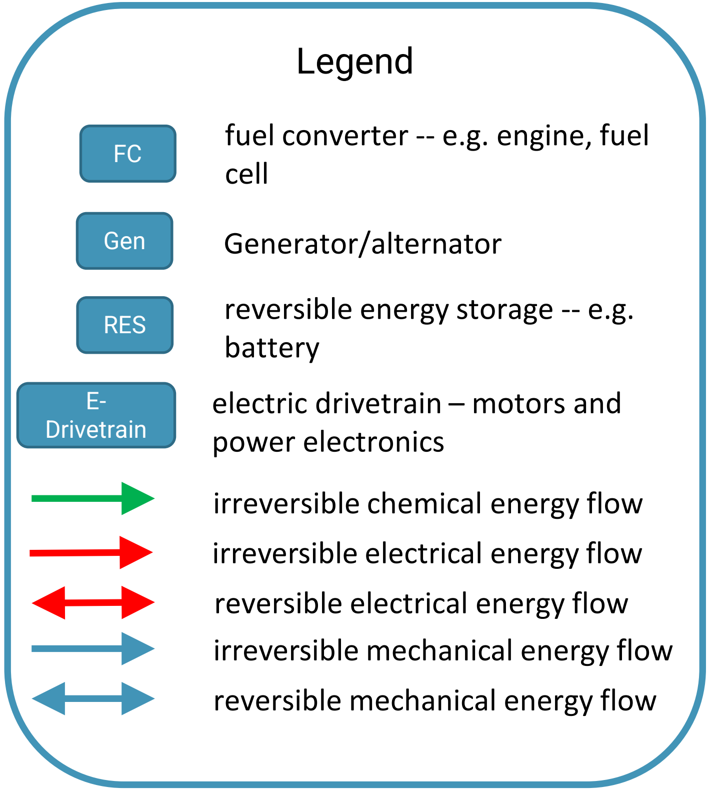
    $(R_{grade} = mg \frac{\Delta elevation}{train\ length})$

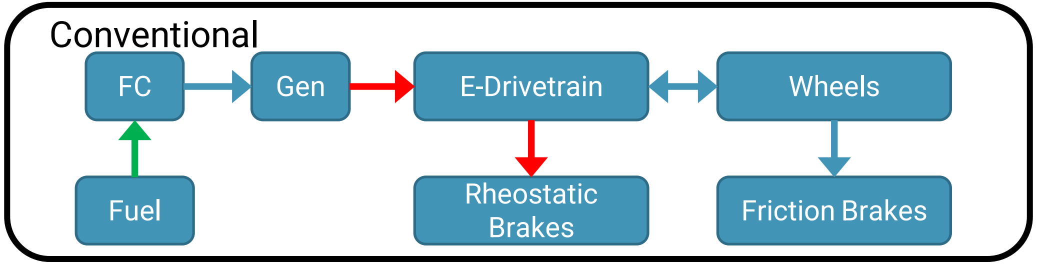


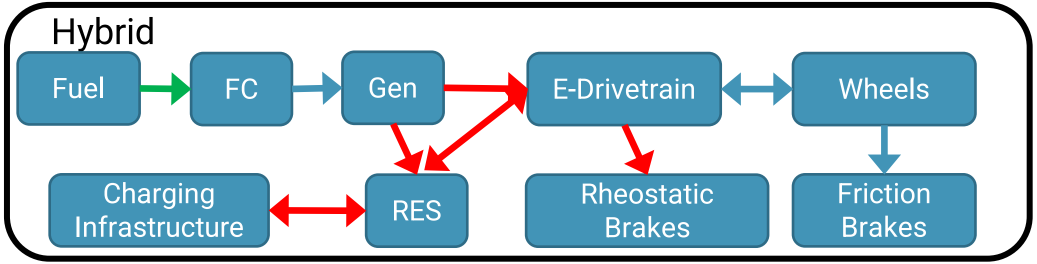
- Rolling resistance
  - Constant value, recalculated only if train mass changes
- Aerodynamic resistance
  - Function of square of speed and air density
  - Air density will be estimated from front of train elevation
- Curve resistance
  - Calculated using truck-type specific curve resistance coefficients derived from quadratic regression on AAR Train Energy Model tables

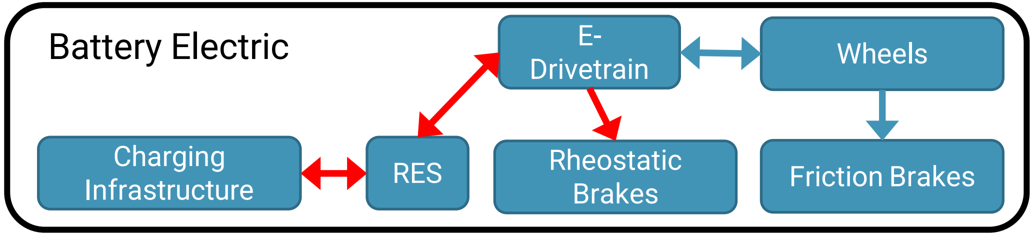
Locomotive Powertrain Architectures

Conventional, hybrid, and battery locomotives





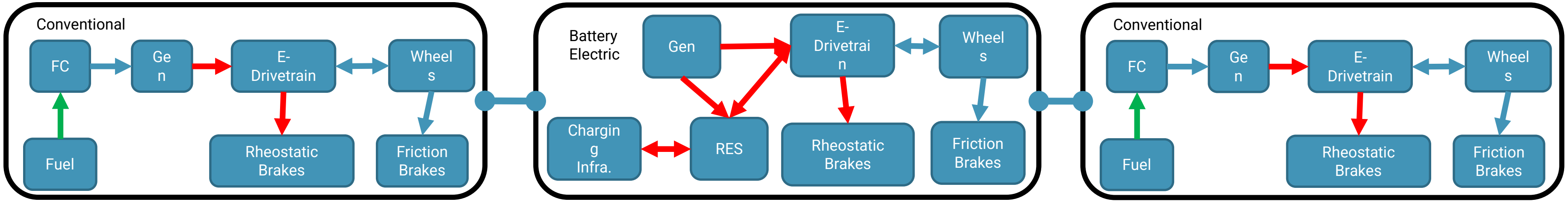




Consist Powertrain

- Consist is modeled as a vector of locomotives, allowing flexibility in configuration.
- Tractive power is distributed based on positive tractive power capacity and regenerative braking capacity
- If any BELs are present in the consist, power is taken from or provided to BELs preferentially while respecting battery state of charge limits.

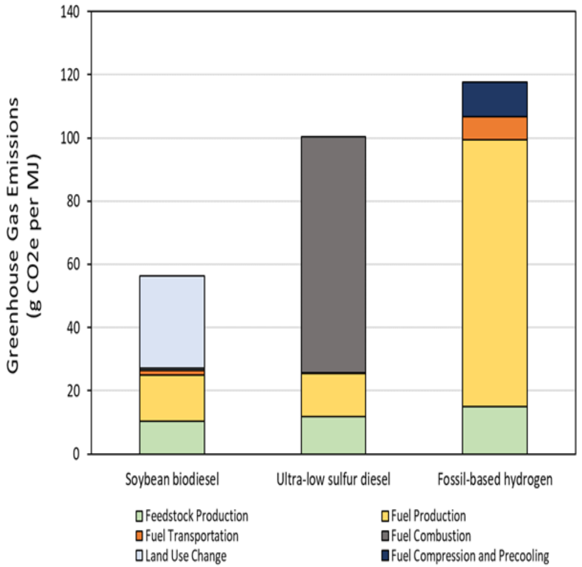
Example hybrid consist, including a BEL in 2nd position

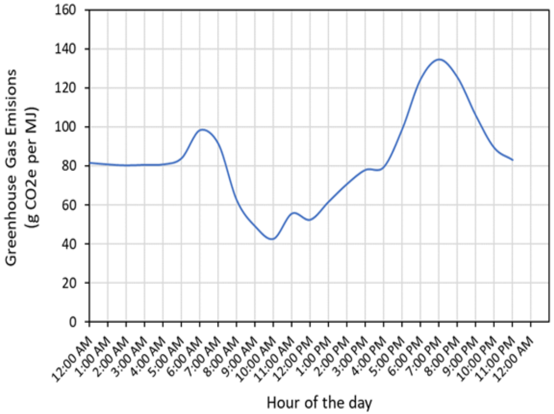


Metric Calculators: Greenhouse Gas LCA

- Flexible input format to define Greenhouse gas emission LCA values by fuel type, region, and time of day.
- Life cycle carbon intensities of selected fuels are being determined, including:
  - Ultra-low sulfur diesel
  - Soybean Biodiesel
  - Hydrogen
  - Electricity
- All emissions are reported in units of carbon dioxide equivalent (CO_{2e}) per energy unit (e.g., MJ of fuel), calculated using the global warming potentials of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) of 1, 25, and 298 g CO_{2e} per g of greenhouse gas, respectively, for a 100-year time horizon, per California GREET (CA-GREET 3.0) model*.

*CA-GREET 3.0 model, California Air Resources Board. Effective Jan 4, 2019. Available at https://ww2.arb.ca.gov/resources/documents/lcfs-life-cycle-analysis-models-and-documentation



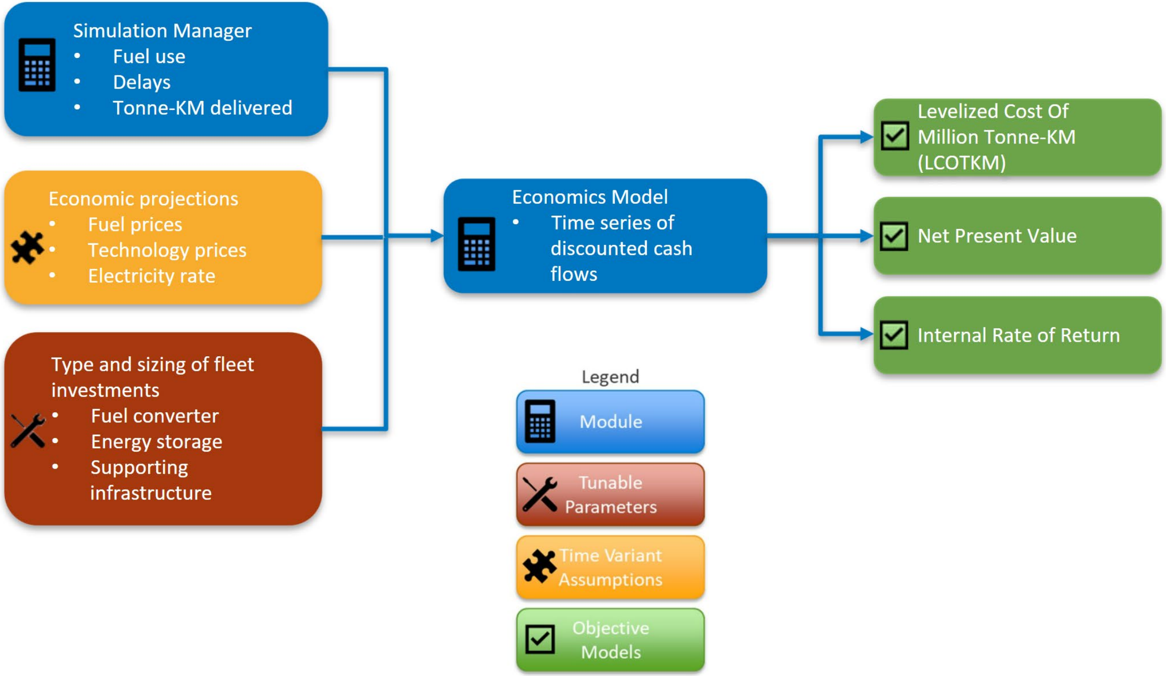


Hourly grid electricity (annual average)

Metric Calculators: Economics

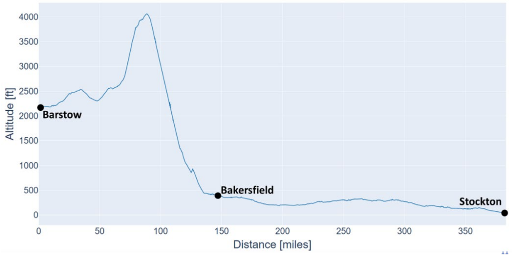
- Flexible input format to define time-varying regional costs and emissions factors
- Base case default values to reflect current technology costs and forecasted changes
- Outputs include:
  - Levelized Cost of Million Tonne-Km
  - Net Present Value
  - Year-by-year costs itemized by category (e.g., locomotives vs. refueling infrastructure vs. energy)

Economics Model Overview



Data Collected for Validation

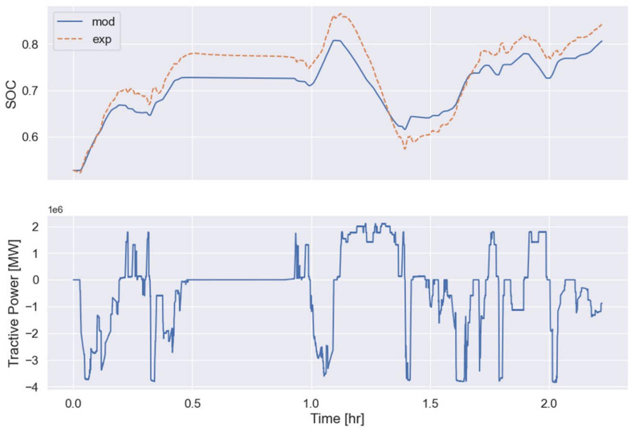
- ~ 375-mile route between Barstow and Stockton, California
- Detail data for 1 BEL & 2 Wabtec Tier 4 ET44C4 diesel locomotives used for complete route
- 17 round trips, with a total of 6,375 miles traveled. The total duration of the data recorded is 900 hours.
- Geography well suited for validation
  – mountains provide opportunities for high power traction or regenerative braking for long durations.
  – Long flat plain between Bakersfield and Stockton provide another extreme in geography.



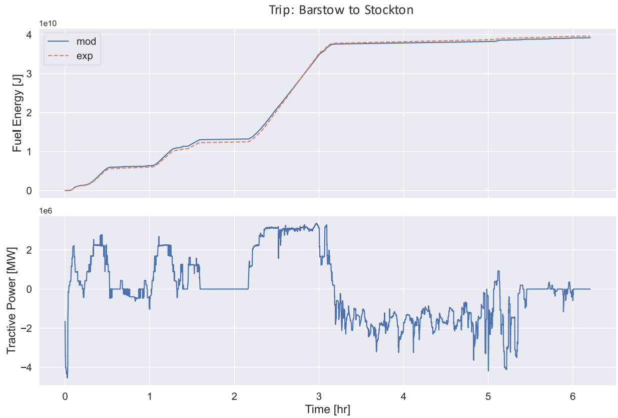
Calibration and Validation: Locomotive

- Conventional Diesel Electric Locomotive
  - Calibrated by adjusting idle fuel rate and drivetrain efficiency
  - Engine efficiency map based on test data from AAR end-of-useful-life testing
  - Fuel energy time-averaged error of 3.94%.
- Battery Electric Locomotive
  - BEL data used for validation of trend-wise behavior
    - Air-cooled battery and unoptimized controls
    - Avoid reverse engineering BEL design

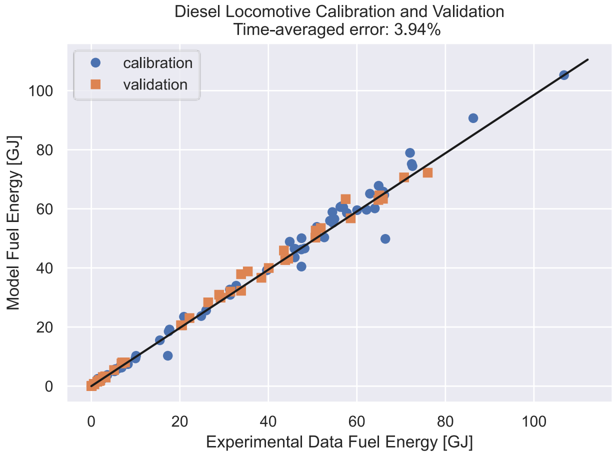
BEL validation



Conventional locomotive validation

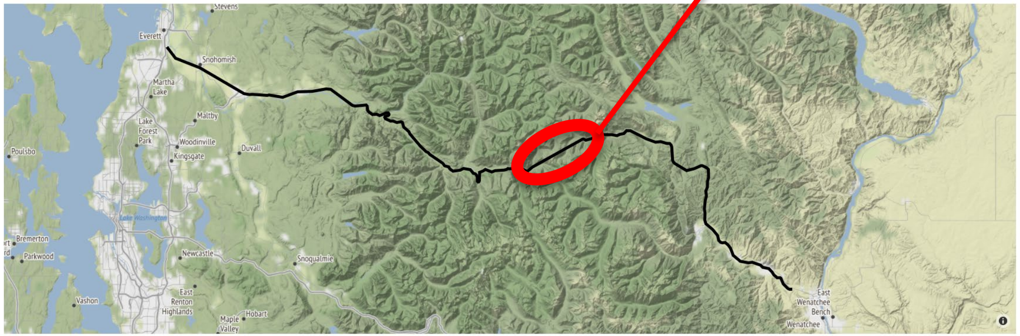


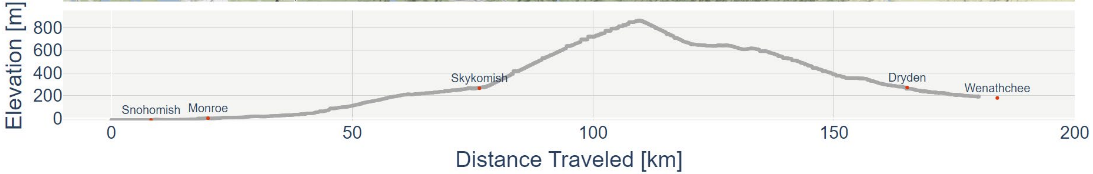
Conventional locomotive validation



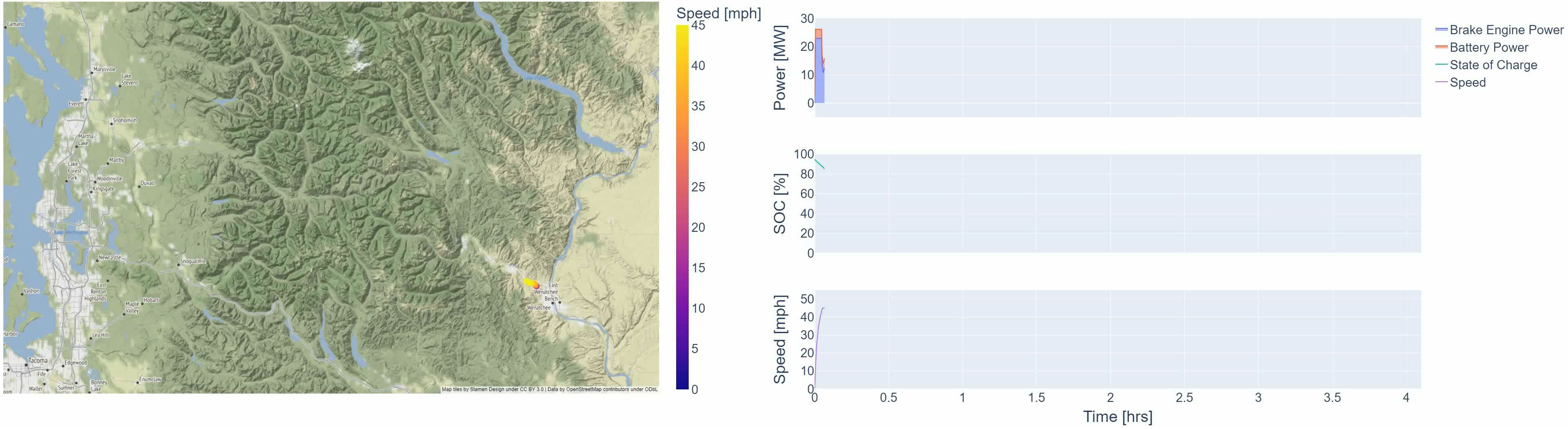
Example ALTRIOS Application

- Route within BNSF Scenic Subdivision
  - Subdivision spans from Seattle, WA to Wenatchee, WA
  - Contains Cascade Tunnel
- Route Statistics:
  - Distance: 185 km
  - Max. Elevation: 860 m
  - Trip Duration: ~4 hours





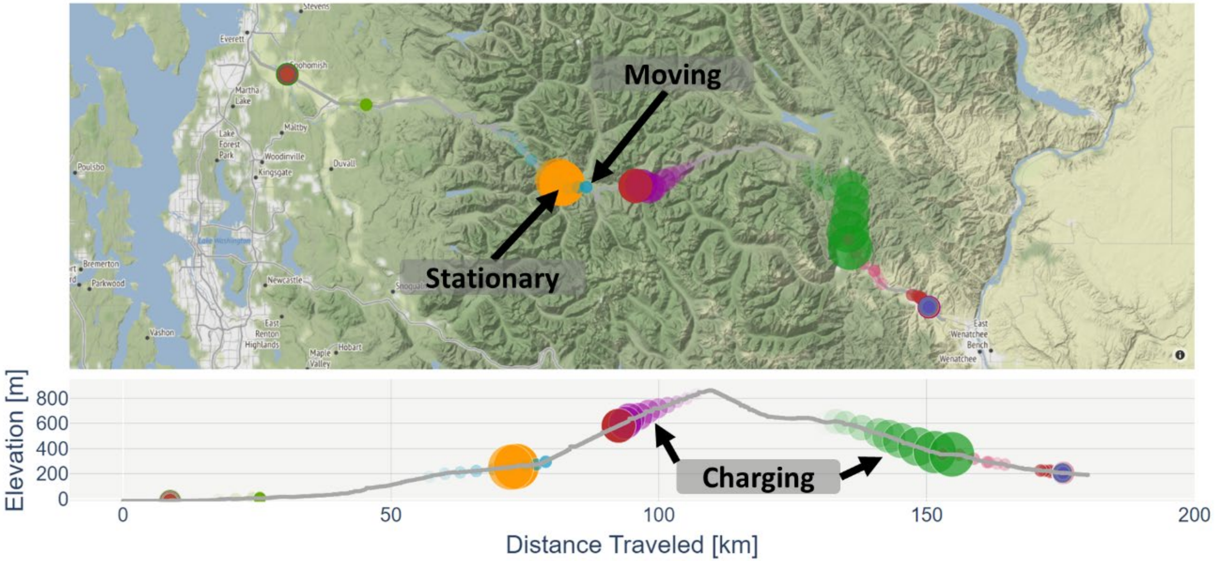
Example Application: Single Train with Hybrid Consist



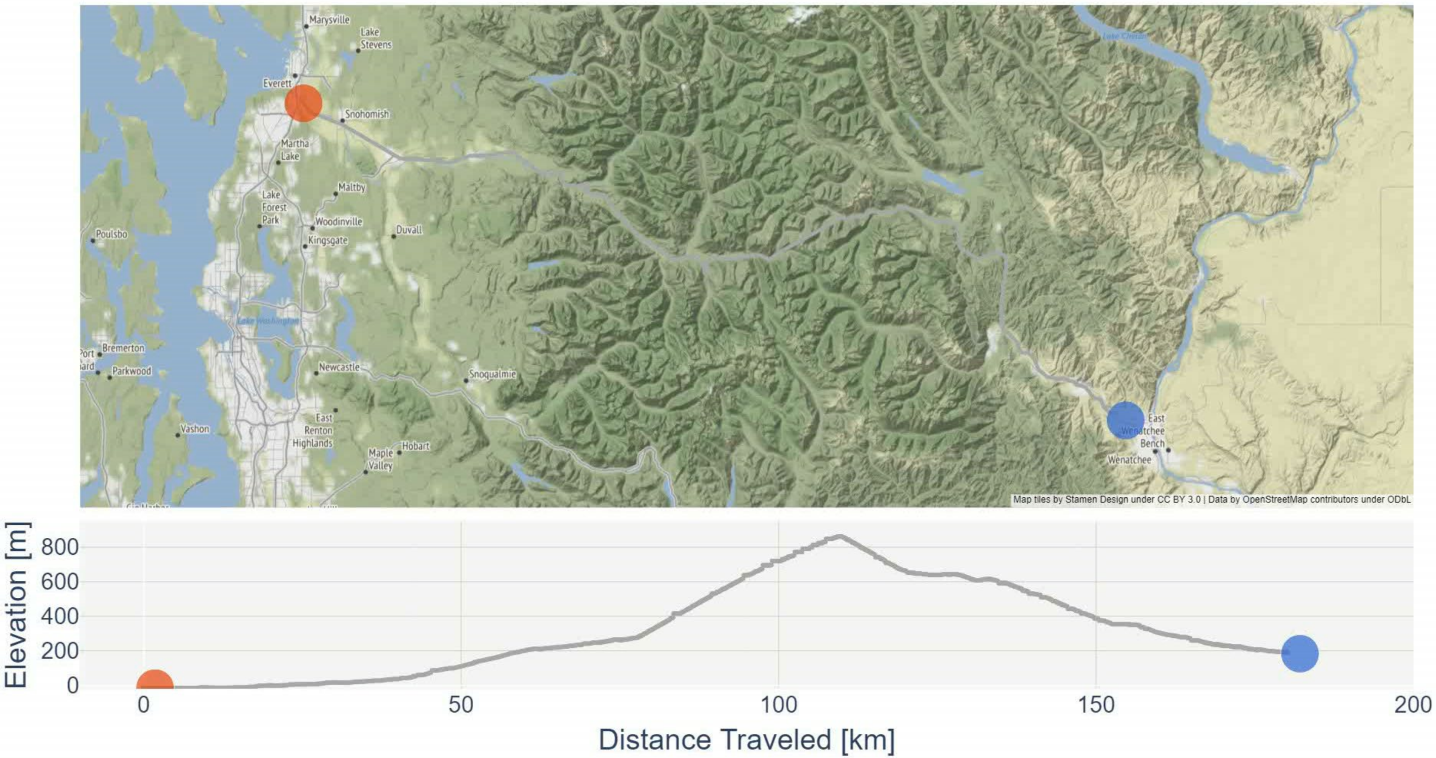
Example Application: Multiple Train Simulation Manager

- Planned 88 trains from origin/destination demand and simulated energy use for Wenatchee-Seattle
- The 88, 4-hour long train trips span 7 days, plus 14 days for warm start and cool-down
- This simulation runs end-to-end in 23 seconds on a laptop ("wall clock" computer time)

Simulated route map :
Each marker is a hybrid consist train simulation, marker size indicates SOC, opacity shows time



Example Application: Multiple Train Simulation Manager

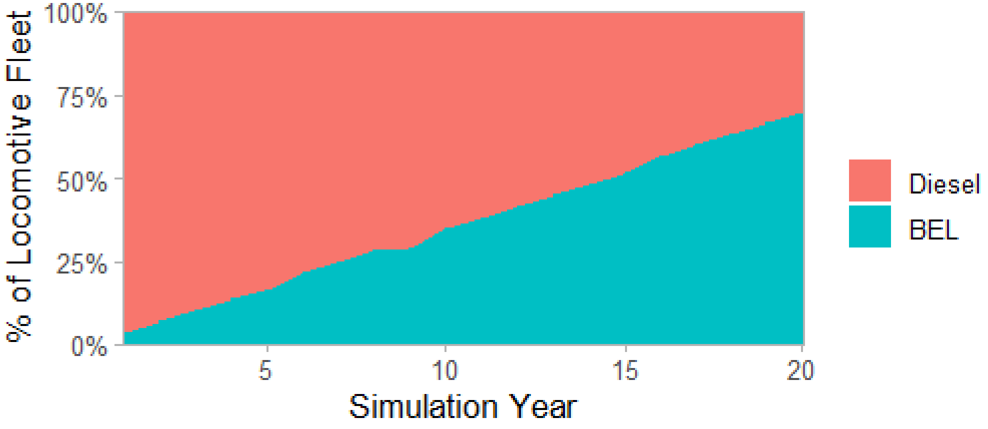


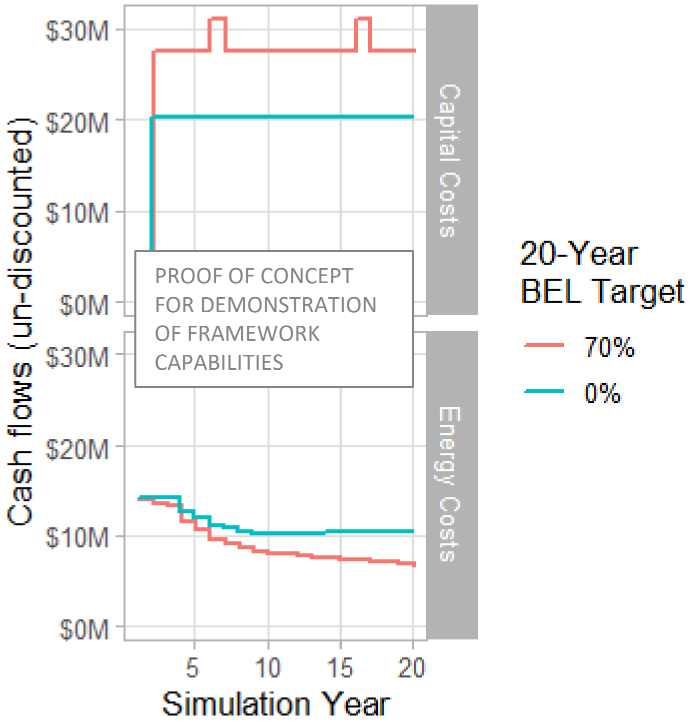
Each marker is a hybrid consist train simulation, marker size indicates SOC

Wenatchee-Seattle, Hybrid Consist, 88 trains, 7 days

Example Application: Multi-Year, Multi-Train Roll-Out Estimates Electrification Costs

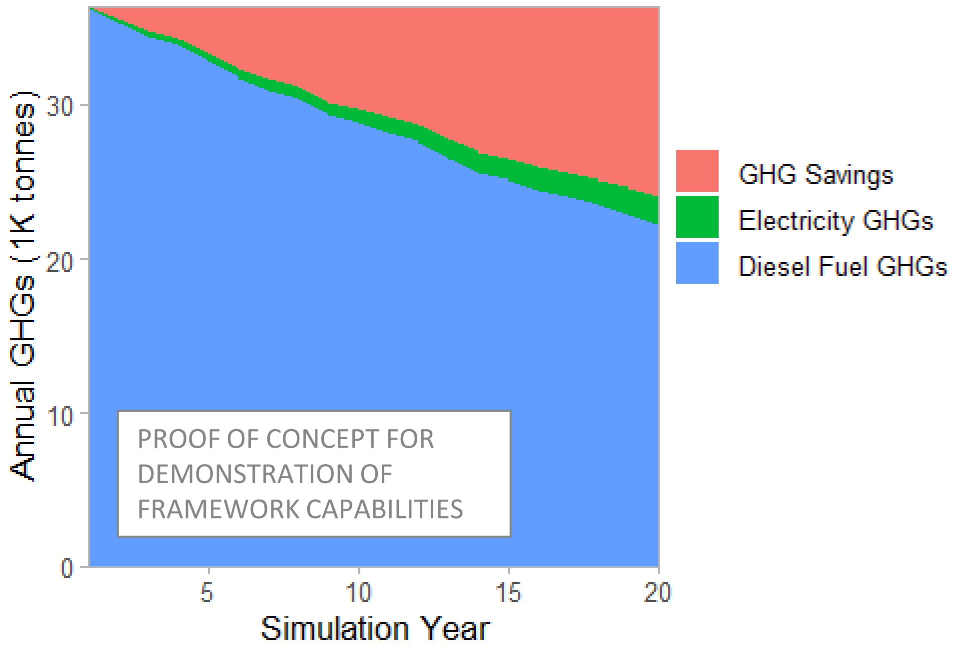
- Set of 20-year prescribed rollouts using 2.4 MWh BELs to meet electrification targets (total fleet size approx. 120 locomotives)
  - Initial proof of concept uses static, present-day cost assumptions for Li-ion batteries (NREL ATB), diesel (EIA), and electricity (EIA)
  - Freight demands and locomotive pool sizes are assumed and may not represent actual operations within that subdivision
  - 20-year locomotive life-span assumed (5% annual turnover)



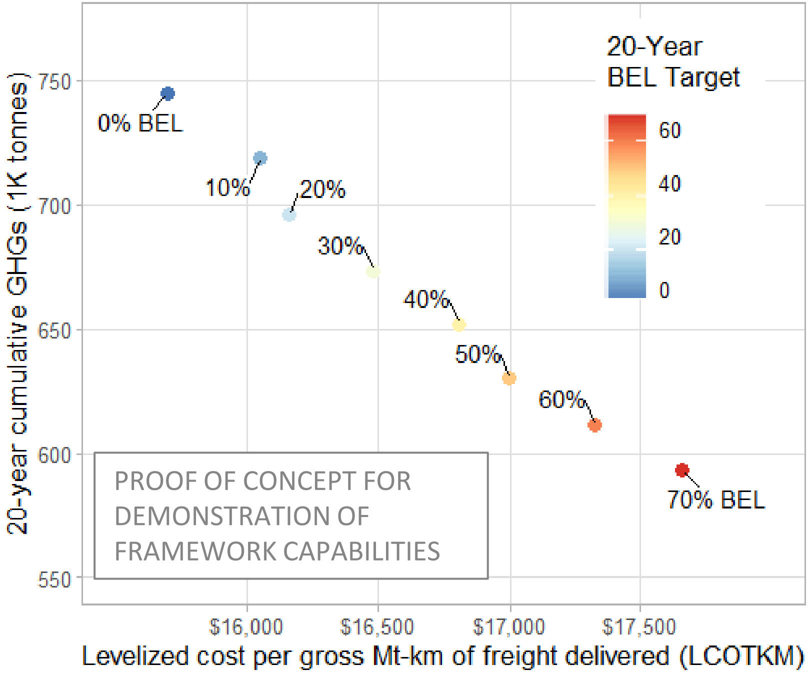


Example Application: Multi-Year, Multi-Train Roll-Out Estimates Cumulative GHG Savings

A 70% 2.4 MWh BEL fleet reduces annual GHGs by 12,000 tonnes

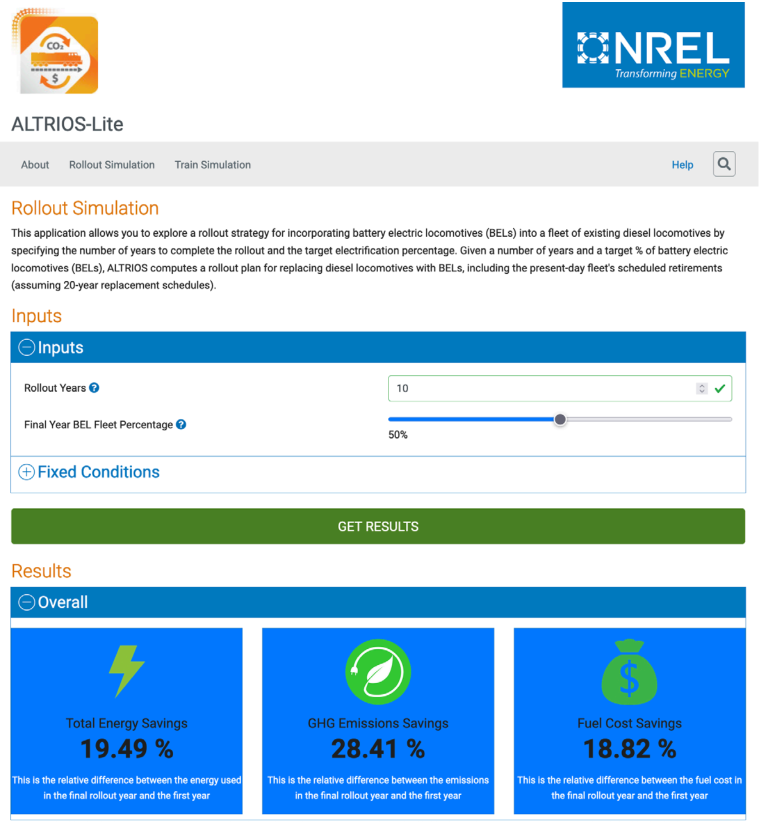


Cumulatively, a 20-year target of 70% BELs increases levelized costs 12% and reduces GHGs 22%



ALTRIOS-Lite Web Application

- Easy to use web-based application for running ALTRIOS simulations
- Includes features:
  - Single train simulation
  - A/B train simulation comparison
  - Simulate BEL fleet rollout
- Developed to be modular and expandable
- Meets Federal accessibility requirements defined by Section 508 (29 U.S.C. 794d) to ensure disabled employees and members of public access to infraction comparable to others.



Next Steps

- Complete Graphic User Interface (GUI) and release publicly
- Complete case study assumption definitions and conduct trade-off analysis of BELs.
- Publication of example analysis study using ALTRIOS
- Open source by June 2023

For the latest ALTRIOS news please see our website:
https://www.nrel.gov/transportation/altrios.html

Thank You

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Please email me if you would like to learn more about ALTRIOS

www.nrel.gov

Jason A. Lustbader
Advanced Vehicles and Charging Infrastructure Group Manager
National Renewable Energy Laboratory
Jason.Lustbader@nrel.gov

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