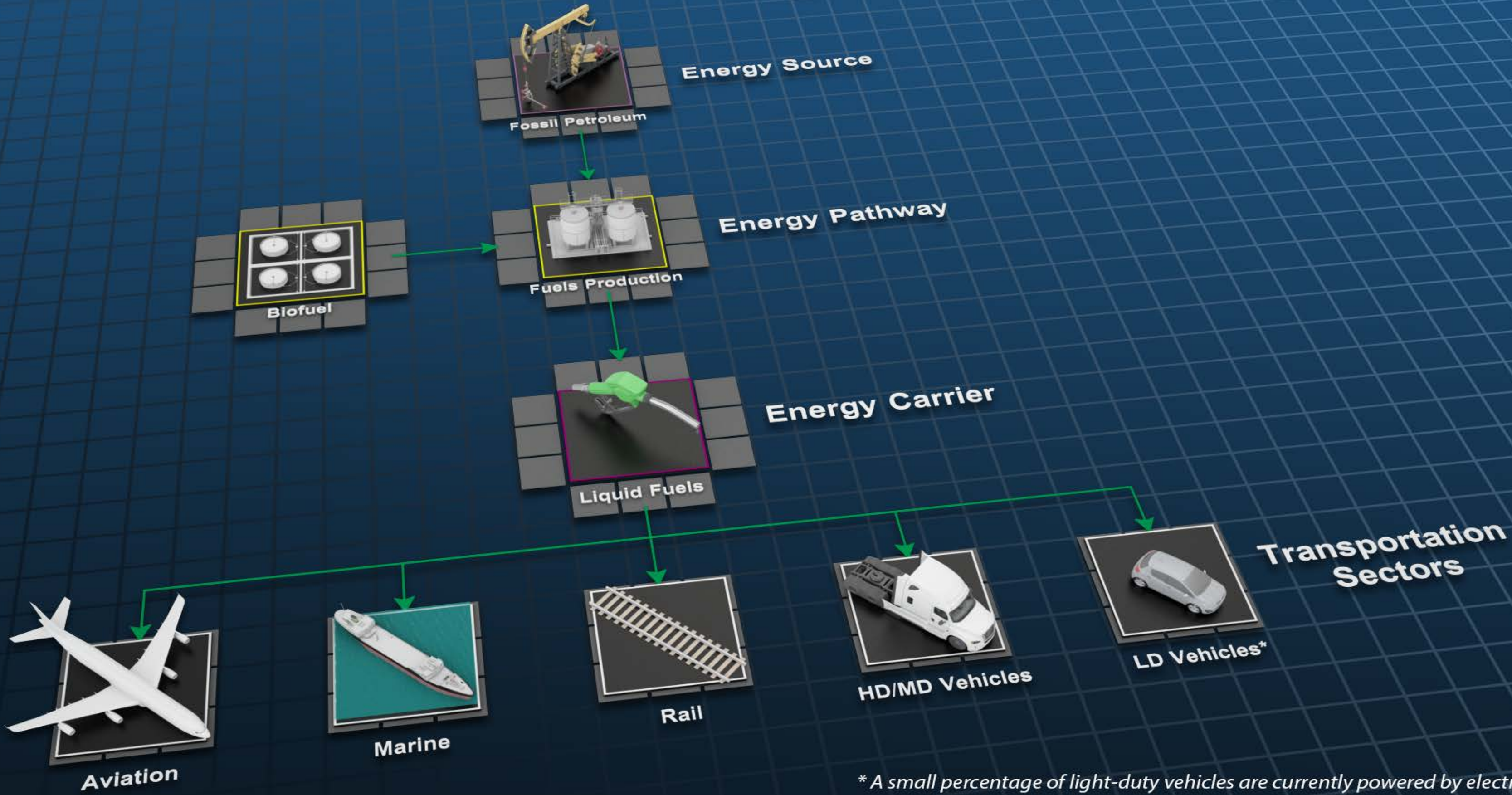
ALTRIOS - Advanced Locomotive Technology and Rail Infrastructure Optimization System

Railroad Environmental Conference
ARPA-e LOCOMOTIVES Project
November 2nd, 2022

- 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, and Matthew Duncan

Today's Transportation System

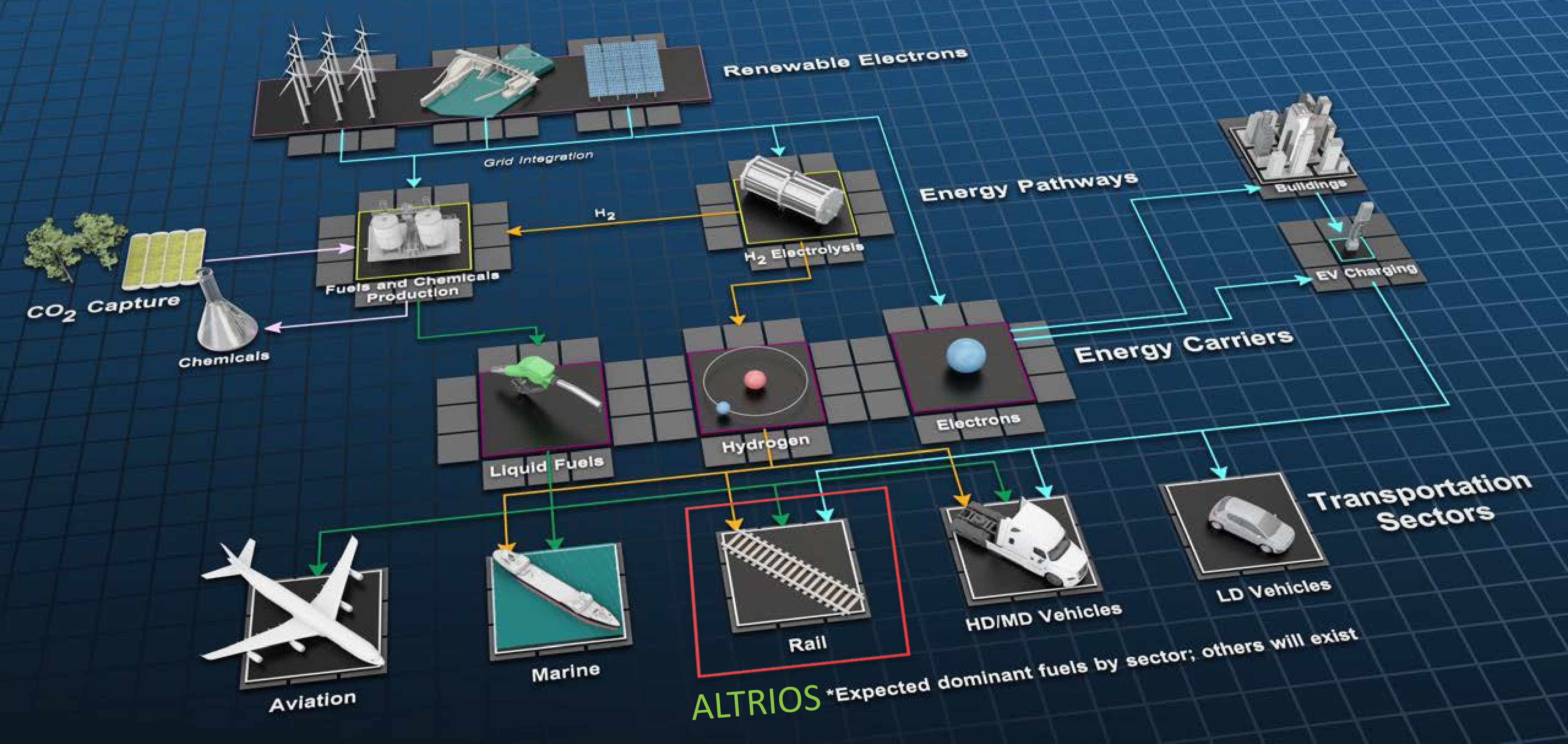
Illustration by Josh Bauer, NREL



** A small percentage of light-duty vehicles are currently powered by electricity.*

NREL's Vision for Decarbonizing the Transportation Sector

Illustration by Josh Bauer, NREL



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

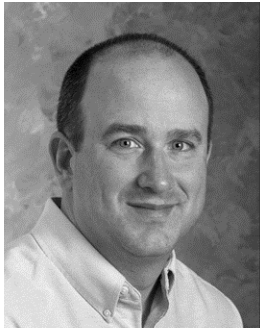
- NREL: Deep experience in energy efficient transportation technologies, energy storage/conversion, and developing and deploying open source software
- RAILTEC: Expertise in railroad operations, train dynamics, and train energy modeling
- SwRI: Locomotive powertrain expertise and performance data.
- BNSF: 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

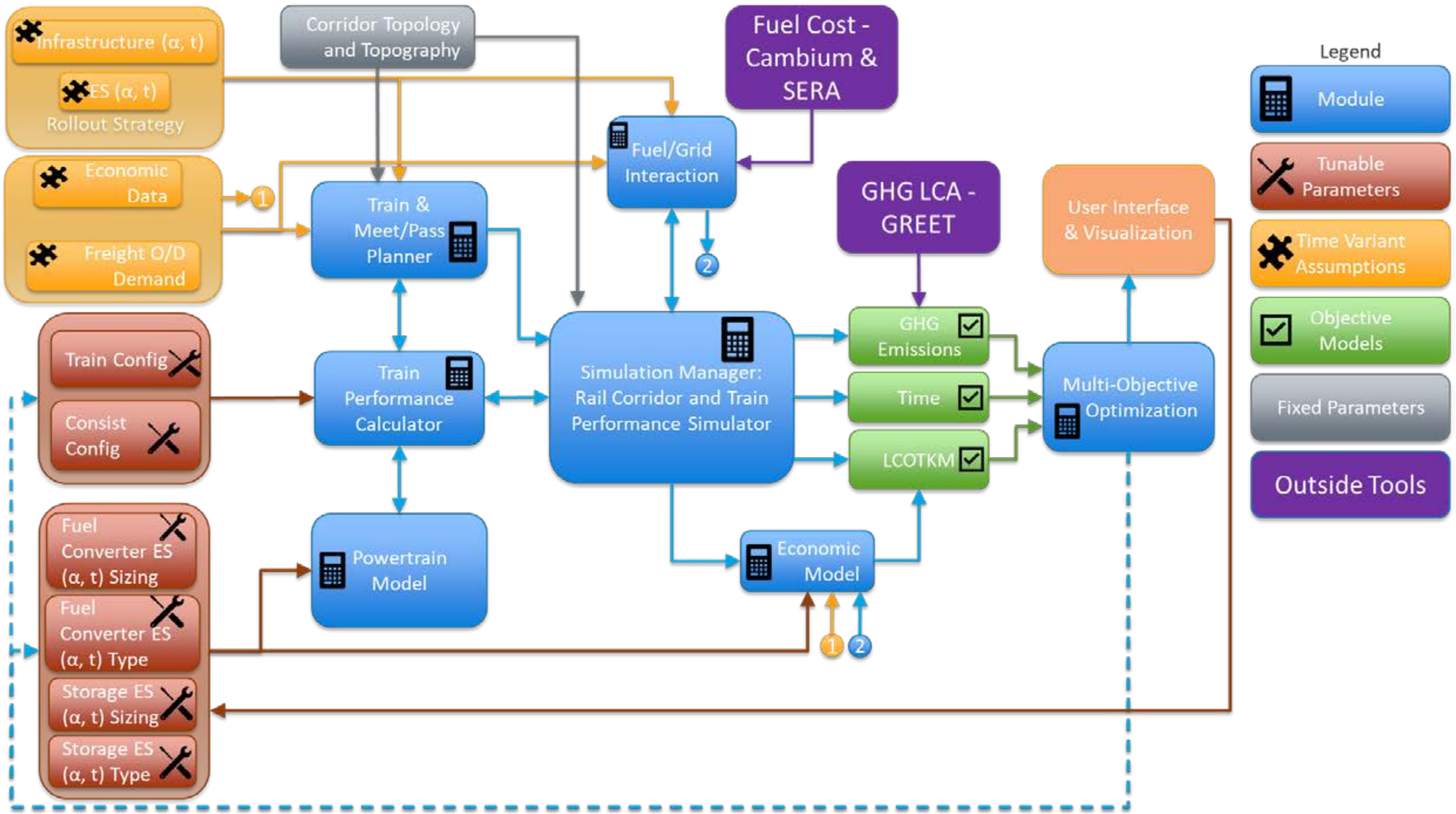
UIUC RailTEC (co-PI)
C. Tyler Dick



SwRI:
Steven Fritz

BNSF (Industry):
Mike Swaney

Framework: Overview
ALTRIOS Modeling Framework



ALTRIOS: Train Corridor Simulator

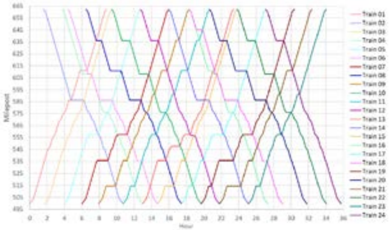
Train Consist Planner

Pool ID	Engine_Number	Type	Capacity_Cars	Capacity_Tonnage	Refill_Time
0	2000.0	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

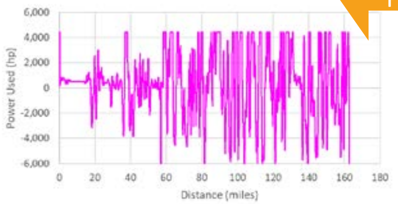
Meet/Pass Planner



Generates target speed profiles for multiple trains using simplified physics with tunable parameters for acceleratio n/deceleration

C++

Train Performance Calculator



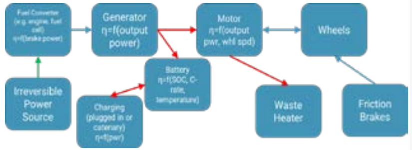
Physics-based model calculates detailed train resistance, speed and tractive power required to achieve target speeds

Rust

Avail. Power

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

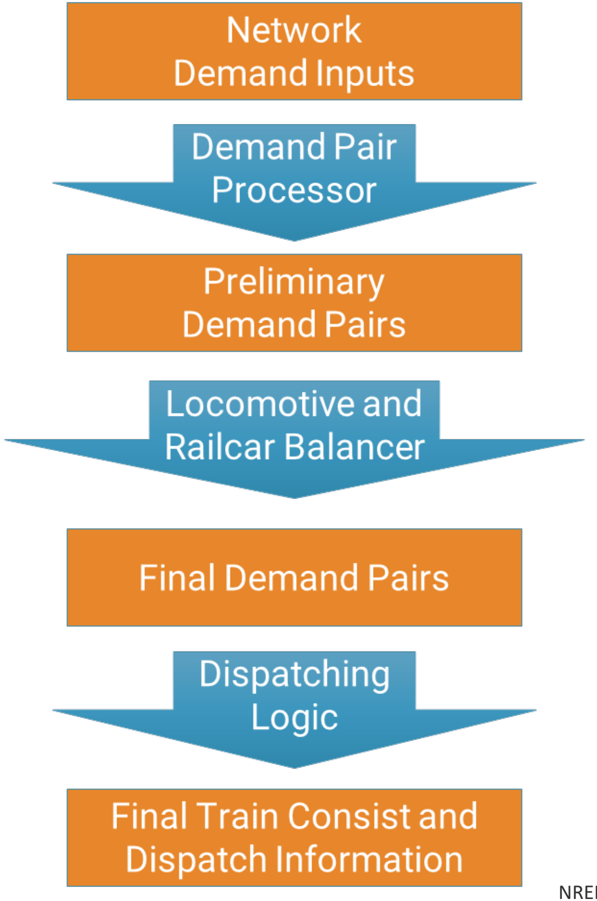
Train Energy

Performance Metrics

Simulation Manager - **Python**

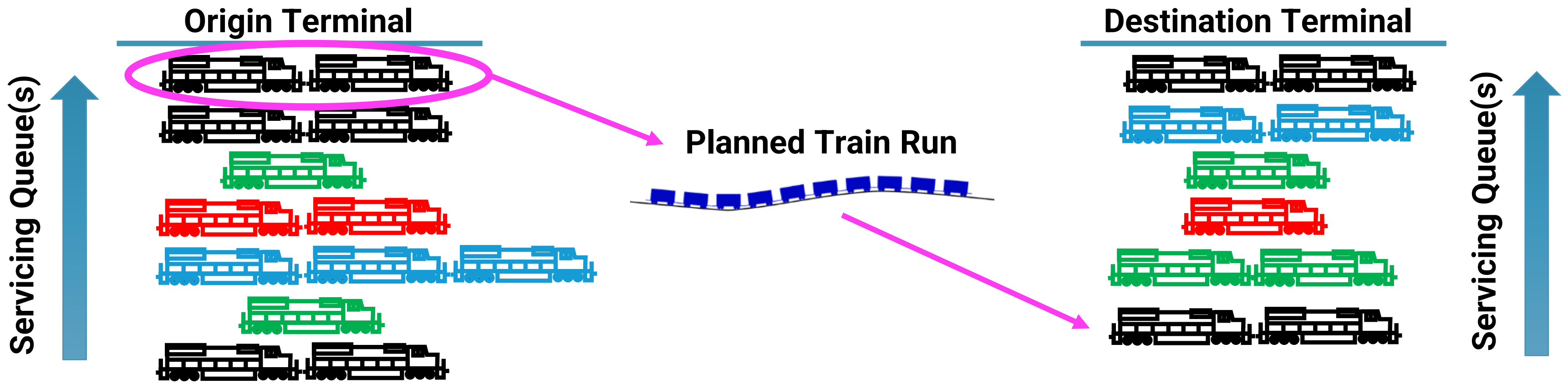
Train Consist Planner, Overview

- Train consist planner builds a train plan including:
  - Locomotive ID,
  - Type of train
  - Origin and destination on simulated network
  - Number of empty and loaded railcars
- Periodic locomotive and railcar rebalancing algorithm used to avoid unbalanced distributions caused by unbalanced demands
- 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



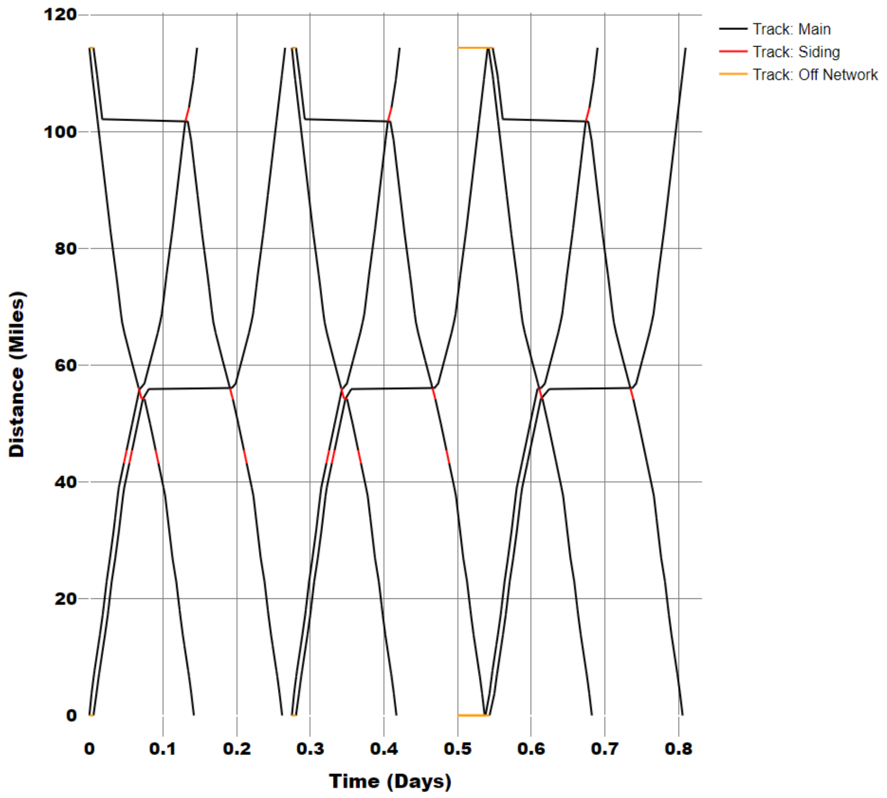
Train Consist Planner: Locomotive Tracking

- Departing trains
  - After each train departure is planned, the pool of locomotives is updated with the departing locomotives removed from the origin pool
  - As each train is planned, the origin pool runs a pre-check to determine the locomotive(s) to assign to the train based on train size/weight and power requirements, and available locomotive charge and fuel refill status, etc.
- Arriving trains
  - Arriving locomotives added to the back of the queue in a first-in-first-out (FIFO) order



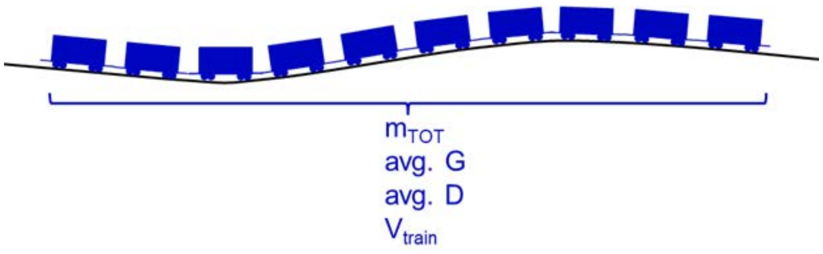
Meet/Pass Planner

- Develops a complete plan for the path each train will take through the track network along with estimated times for traversing each segment
- 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
- Aerodynamic resistance
  – Function of square of speed and air density
  – Air density will be estimated from front of train elevation
- Curve resistance
  – To be implemented using tabular approach from the AAR Train Energy Model



Locomotive Powertrain Architectures

Conventional, hybrid, and battery locomotives

Legend

FC — fuel converter -- e.g. engine, fuel cell

Gen — Generator/alternator

RES — reversible energy storage -- e.g. battery

E-Drivetrain — electric drivetrain – motors and power electronics

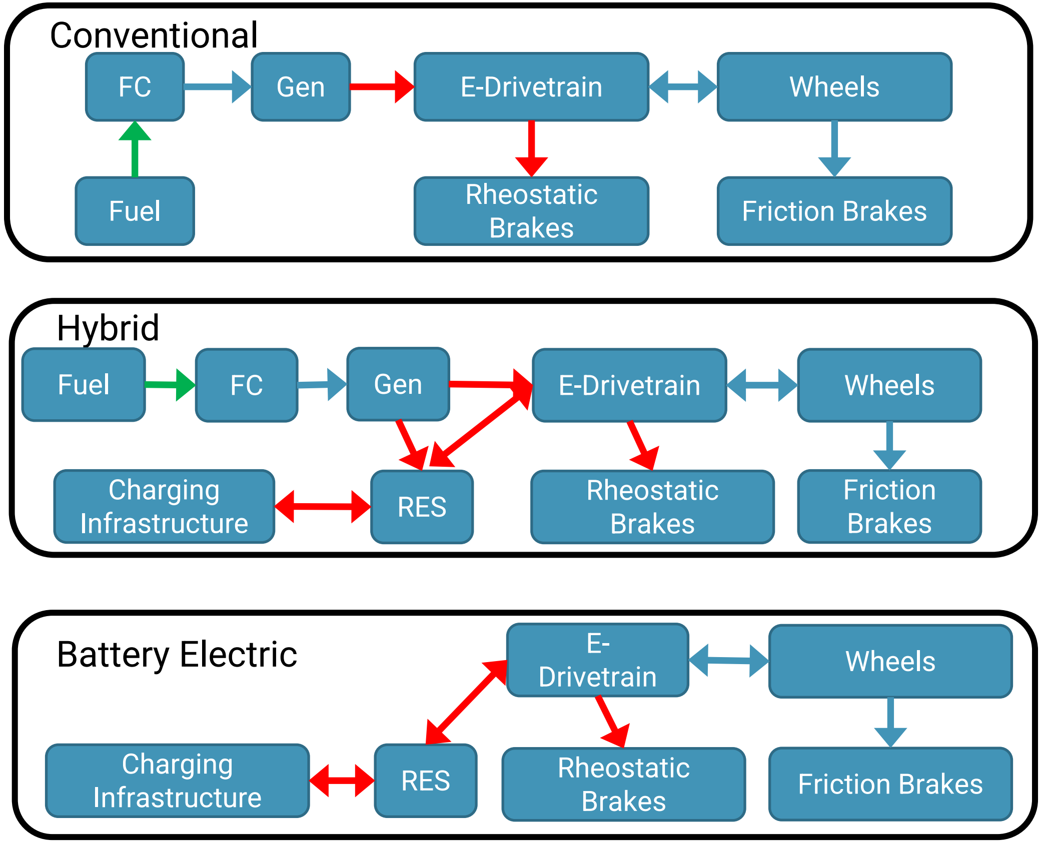
irreversible chemical energy flow

irreversible electrical energy flow

reversible electrical energy flow

irreversible mechanical energy flow

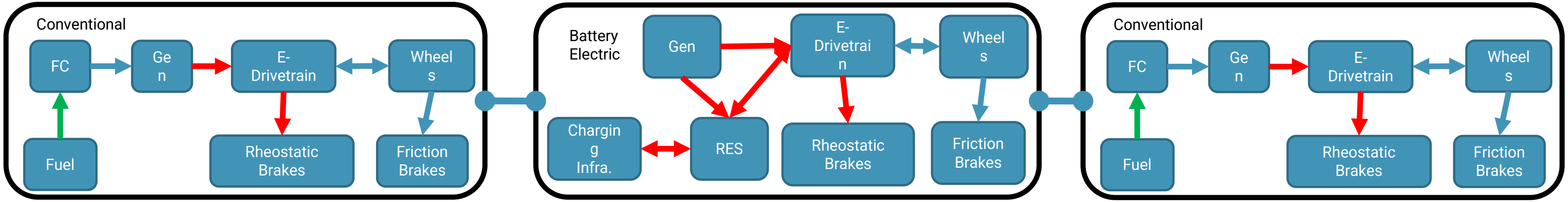
reversible mechanical energy flow



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.

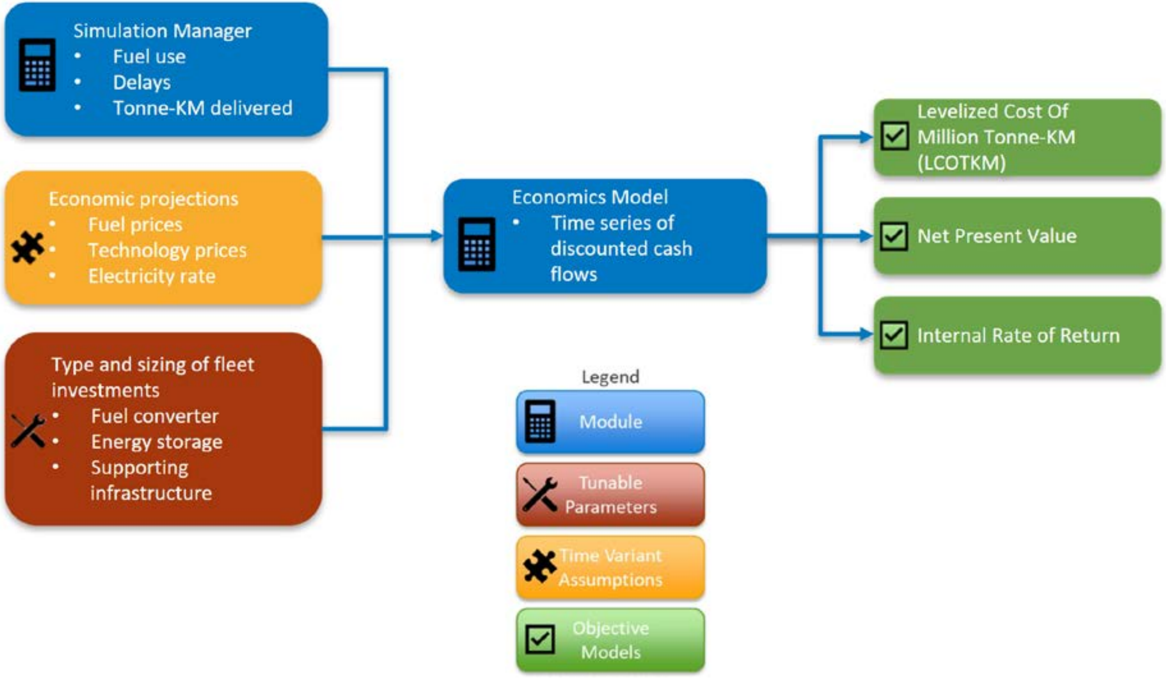
Example hybrid consist, including a BEL in 2nd position



Metric Calculators: Greenhouse Gas and Economics

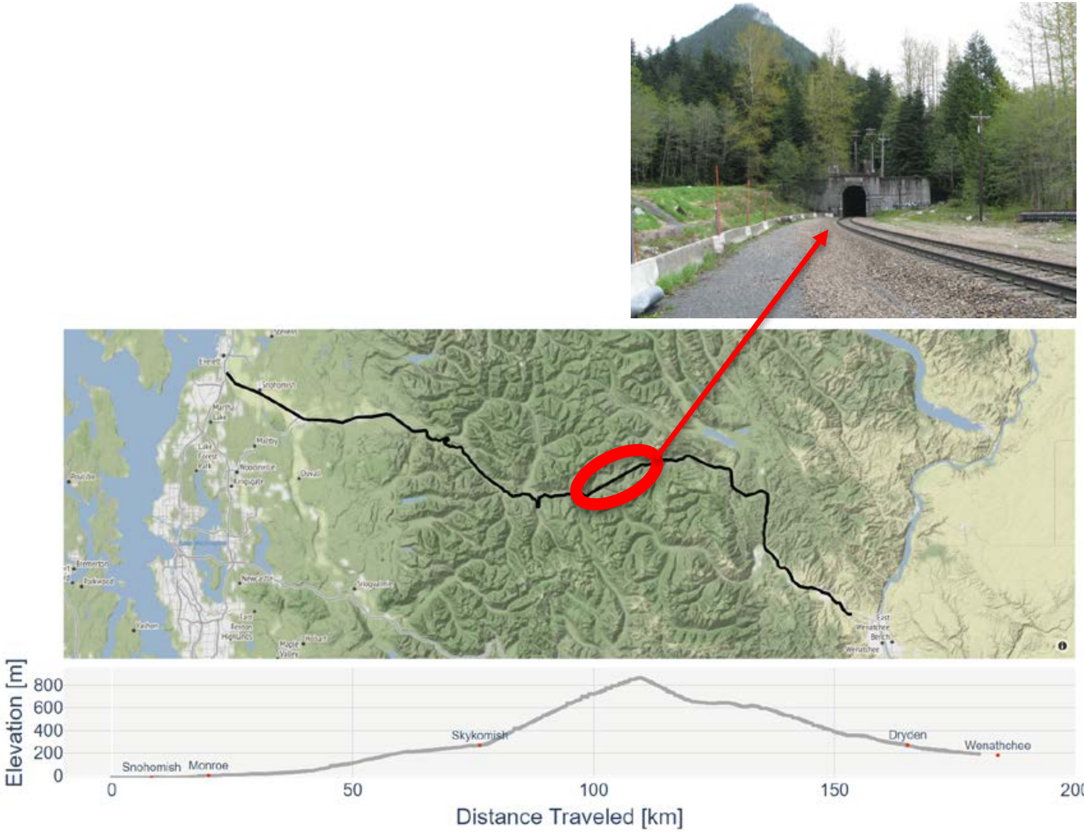
- Greenhouse Gas
  - Flexible input structure allowing for user defined fuel type, region, and time of day variation.
  - Default values being developed for common fuel types including
    - Ultra-low sulfur diesel
    - Soybean Biodiesel
    - Hydrogen
    - Electricity
- Economics Model
  - Levelized Cost of Million Tonne-Km
  - Net Present Value
  - Internal Rate of Return

Economics Model Overview



Example Corridor Topology and Topography

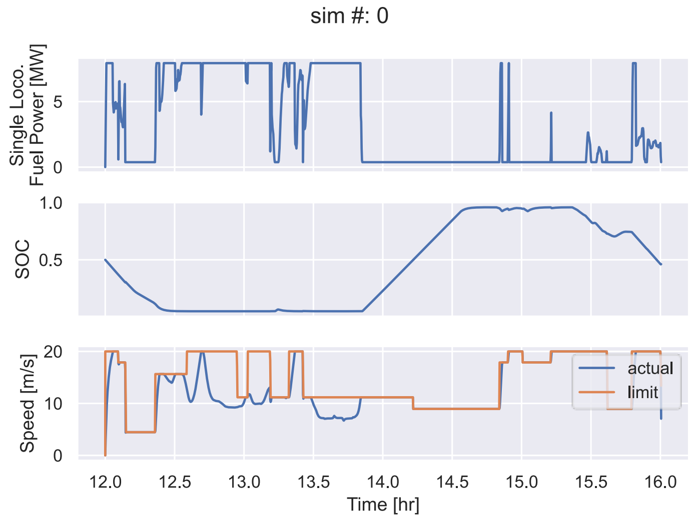
- Route within BNSF Scenic Subdivision
  - Subdivision spans from Seattle, WA to Wenatchee, WA
  - Contains Cascade Tunnel
- Route Statistics:
  - Distance: 185 km
  - Max. Elevation: 860 m
  - Trip Duration: ~4 hours



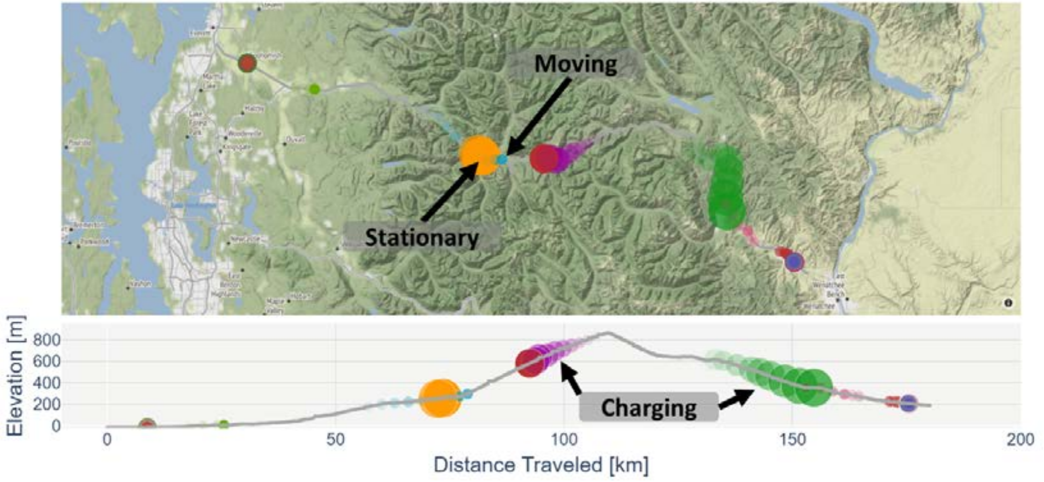
ALTRIOS Demonstration – Simulation Manager

- Planned 100 trains from origin/destination demand and simulated energy use from Wenatchee to Snohomish, WA
- Completed the 100, 4-hour-long train trips occurring over 3 days in 45 seconds of computer time
- Total fuel energy use over this time interval: 24,200 GJ ~= 146,000 gallons = 2,432 metric tons CO_2

Fuel, SOC, and Speed for 1 of 100 conventional locomotive trips

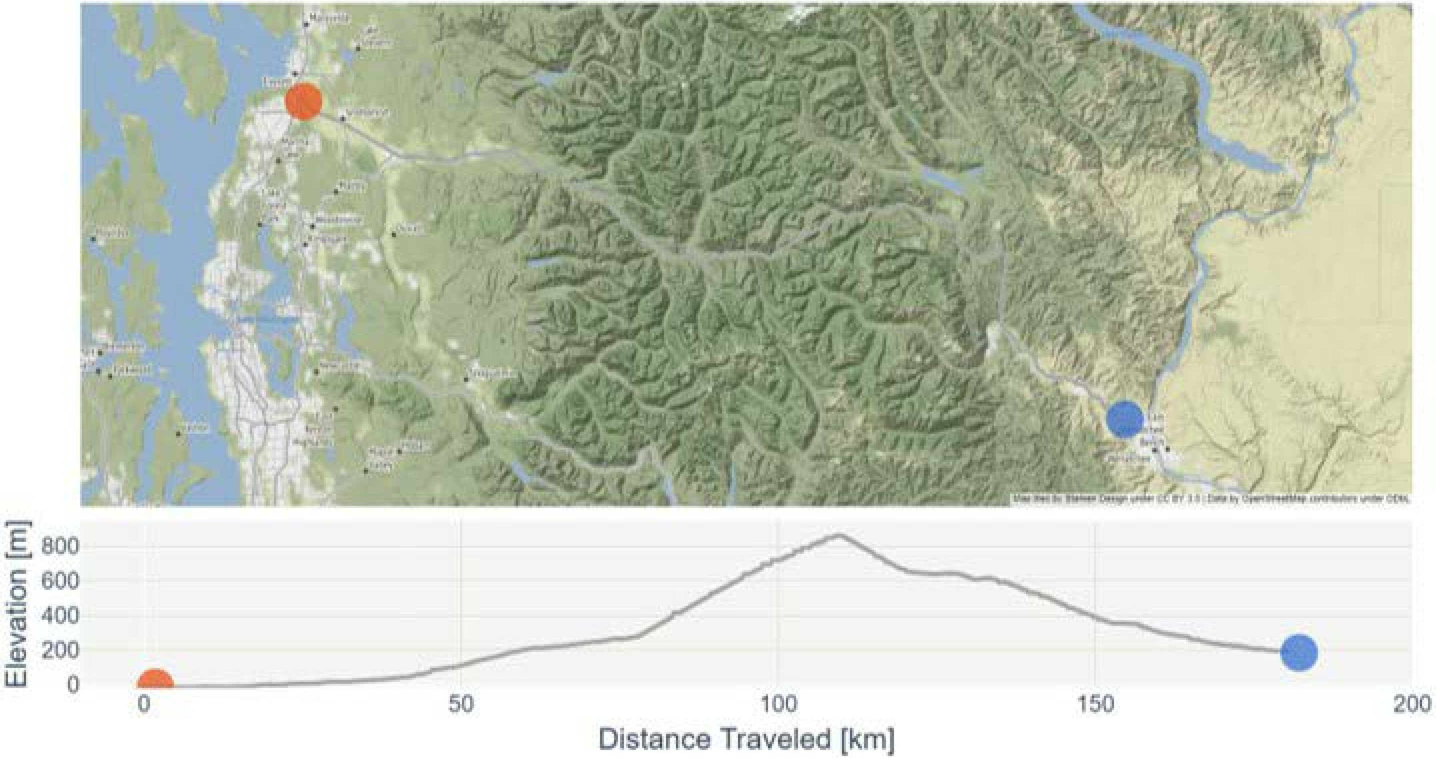


Simulated route map :
Each maker is a hybrid consist train simulation, maker size indicates SOC, opacity shows time



ALTRIOS Demonstration – Simulation Manager

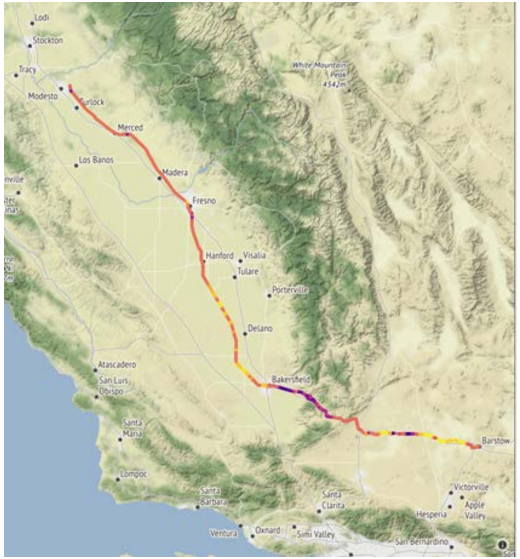
Wenatchee, WA to Snohomish Hybrid Consist Simulation, 100 trains, 3 days

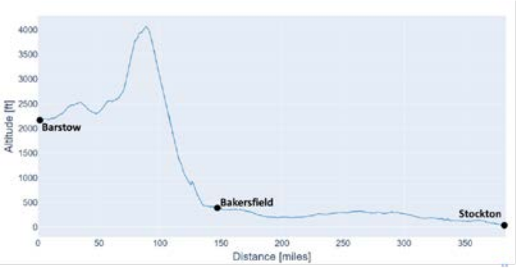


Each maker is a hybrid consist train simulation, maker size indicates SOC

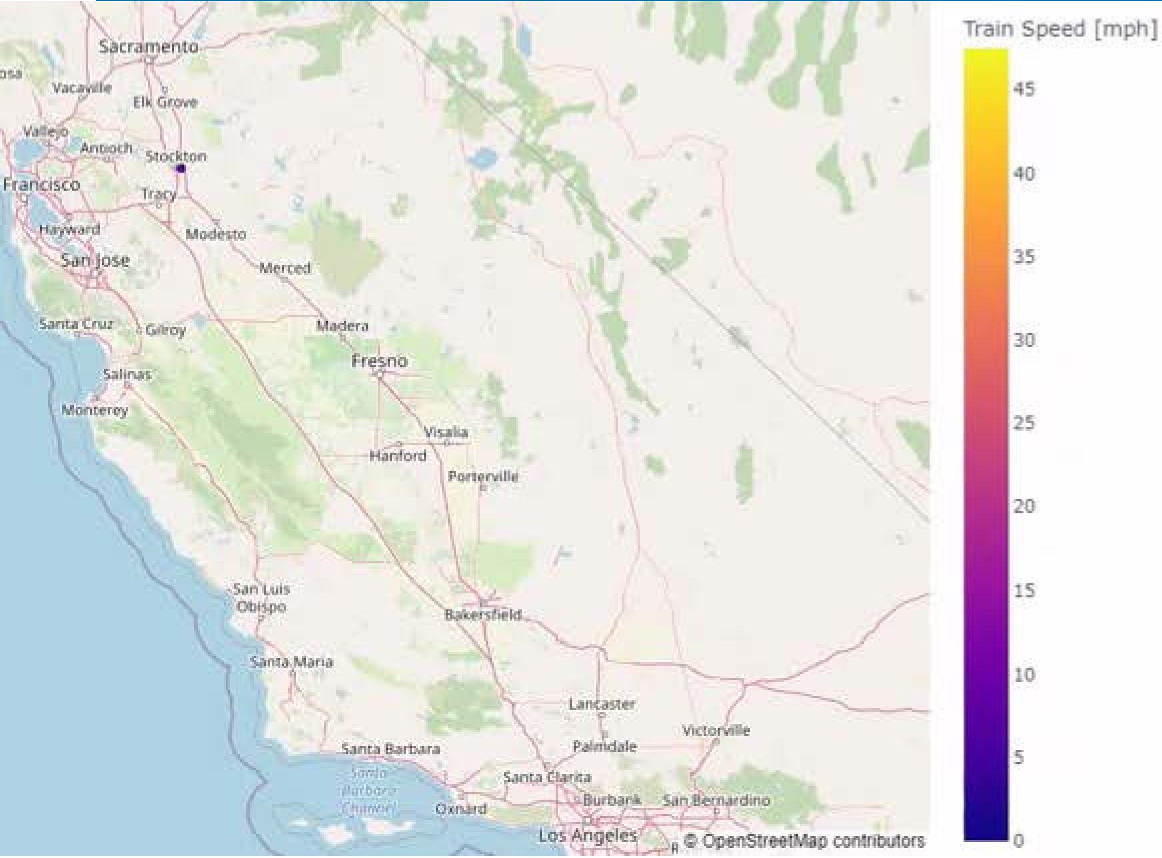
Data Collected for Validation

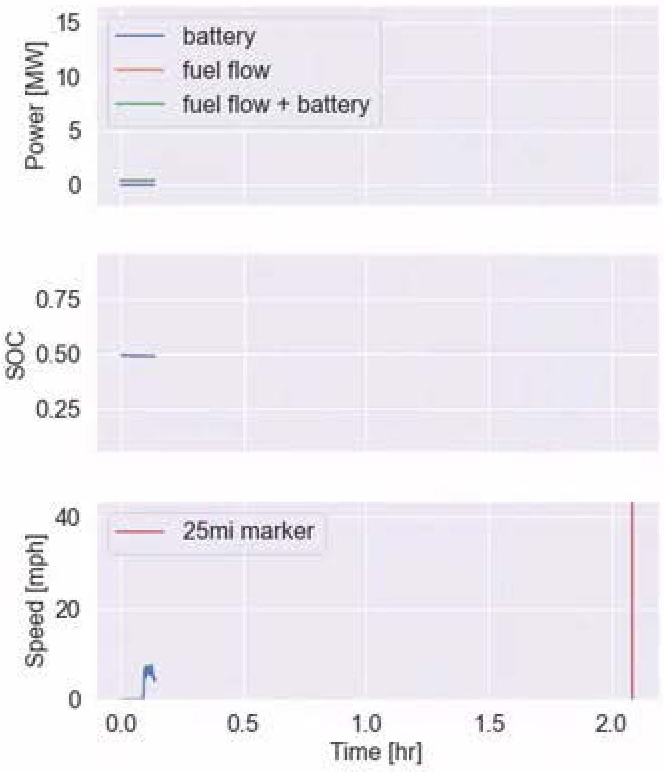
- ~ 375-mile route between Barstow and Stockton, California
- Detail data for 1 BEL & 2 Wabtec Tier 4 ET44C4 diesel locomotives used for complete route
- 17 round trips, with a total of 6,375 miles traveled. The total duration of the data recorded is 900 hours.
- Geography well suited for validation
  - 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.



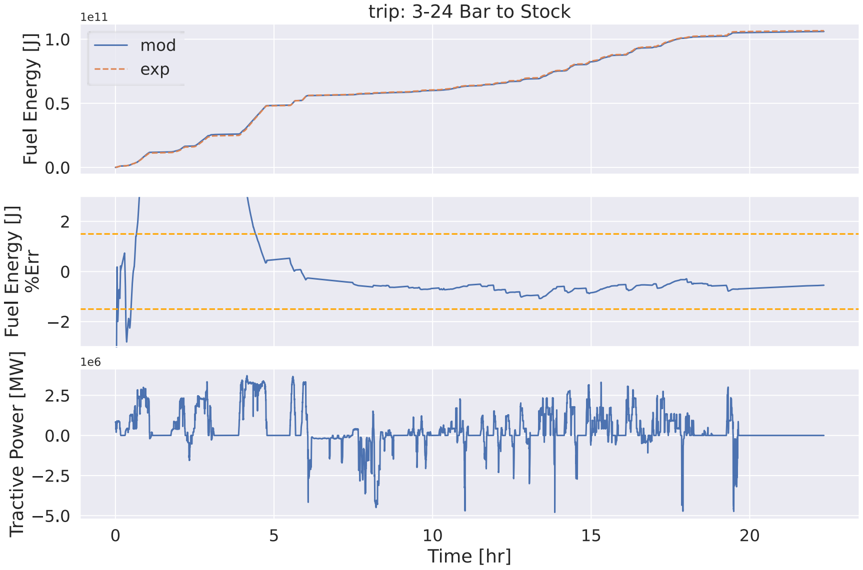


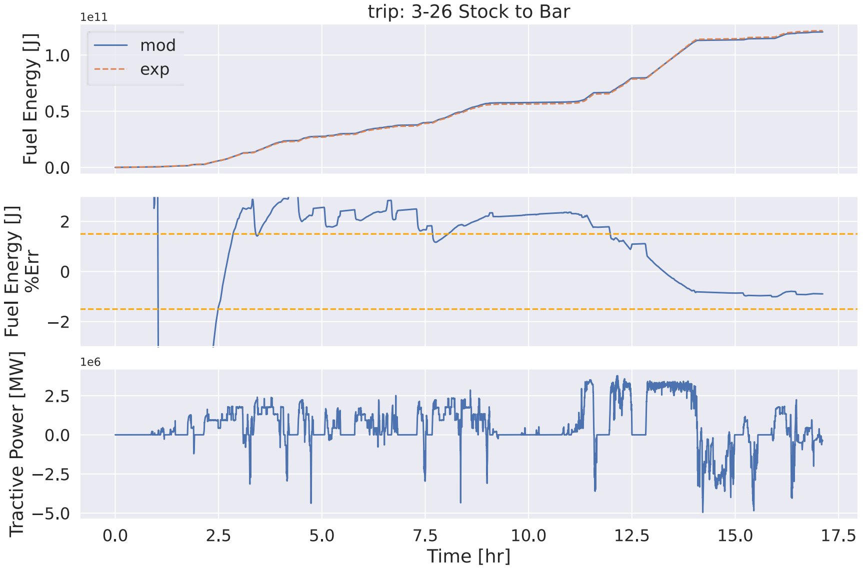
ALTRIOS Initial Results Over Validation Route Barstow to Stockton – *Train Speed*





Example Powertrain Validation Results

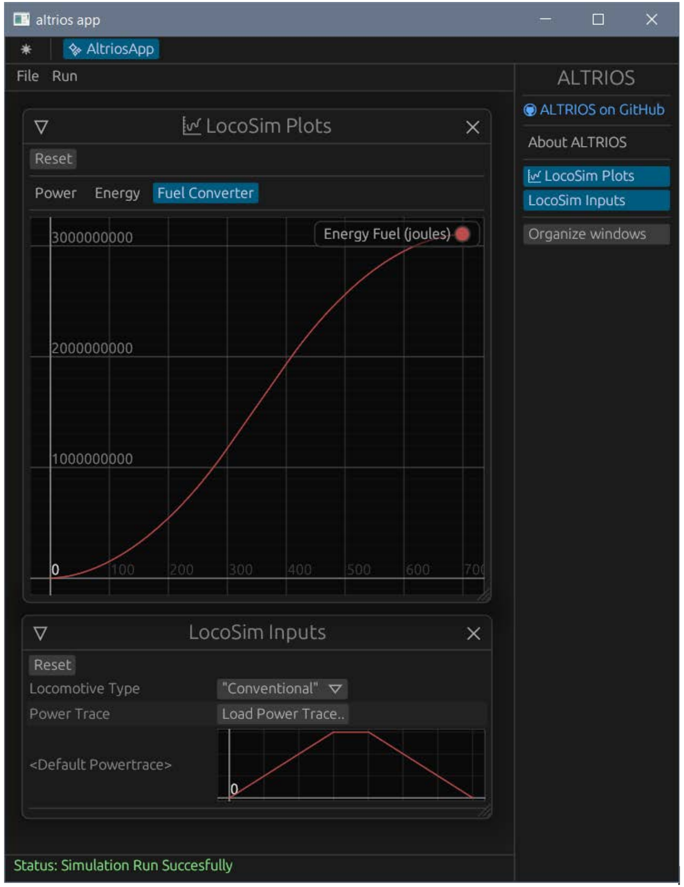




Full train validation in process

Next Steps

- Complete validation
- Tighter integration of metric calculators for GHG and levelized cost per Mt-km (LCOTKM)
- Implementation of Rollout Analysis Module
- Graphic User Interface (GUI)
- Publication of example analysis study using ALTRIOS
- Open source by March 2023



Thank You

www.nrel.gov

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

NREL/PR-5400-84507

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Advanced Research Projects Agency-Energy. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL
Transforming ENERGY