Project ID: VAN051

2024 DOE Vehicle Technologies Office Annual Merit Review

Regional Optimization of Application and Infrastructure Architecture in Heavy Duty Vehicle Electrification

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National Transportation Research Center

Oak Ridge National Laboratory

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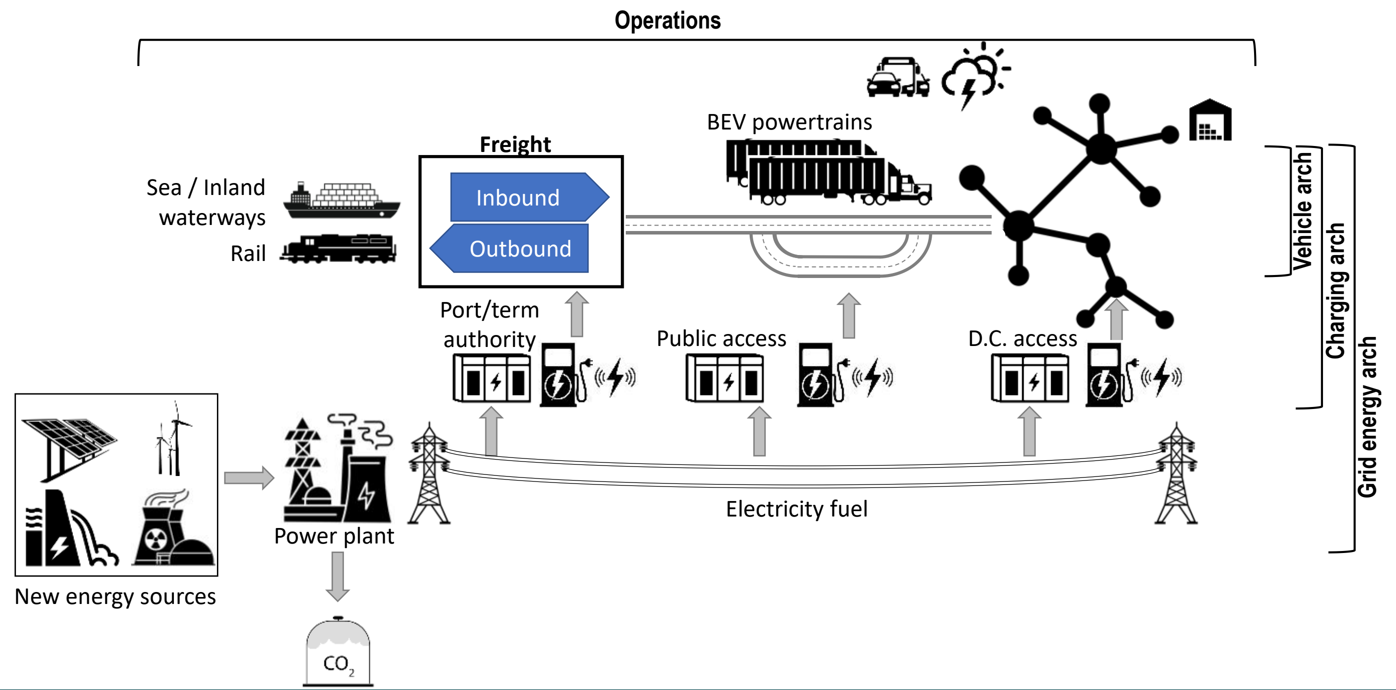
This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project goal

Motivation

- Most goods (95%) move in containers; 67% of U.S. freight trucking is short-haul (<250 mi/day).
- Drayage is essential for intermodal freight movement (ports, rail, trucking terminals, warehouses)
- Local freight mobility (like port transportation) accelerates energy technology adoption without requiring a national strategy
- **Diverse freight energy sources strengthen U.S. energy resilience, stabilize costs, and secure supply chains**



Optimizing a future or emerging highly electrified freight transport network considers three primary layers – Vehicle (+ODS), Charging, and Electric Grid

Goals

- **Goal 1: D**evelop an instrument that integrates the battery electric Heavy Duty Trucks (HDT) **powertrain architecture**, **charging infrastructure**, **grid architecture,** and **Operating Domain** into a common analytical framework
- **Goal 2: A**pply to electrified HDT systems technology deployment roadmaps for freight movement within **~250 miles**, centered on **major US shipping ports**

- **Major accomplishment (BP3)**: Developed an integrated framework for ***alternative power*** MHDT deployment, analyzed three major ports, assessed interconnected port drayage networks, and initiated tools for a national charging infrastructure blueprint.

https://ardentx.com/drayage/

Project Overview

Timeline

- Project start date: 10/1/2022
- Project end date: 09/30/2025
- Percent complete: 83%

Budget

- Total Project Funding: $1,500,000
  DOE share: 100%
- Funding for FY 2023: $500,000
- Funding for FY 2024: $500,000
- Funding for FY 2025: $500,000

Partners

- Project lead: ORNL
- Partners: SLAC/Stanford
  Ohio State University
- Informal collab: NREL, LBNL, INL
- Industry: Cummins, Walmart, UPS, TVA
  FedEx, Volvo, ExxonMobil, GTI

Technical Targets and Barriers

(from Vehicle-Mobility Systems Analysis Tech Team roadmap Feb 2020)

- ***Future scenario visioning*** *– To determine the impact of HD freight vehicle electrification on energy consumption and mobility system architecture associated with freight ports*
- ***Reconsidering operational scenarios*** *– To determine the impact to electrified HD freight vehicle systems technical specifications under the Operational Design Domain (ODD) of full year operations at freight ports*
- ***Barrier*** *– Detailed freight mobility data that classifies and assimilates*
  - *Origin – Destinations (OD) coordinates*
  - *Truck tour and weights of trucks*
  - *Truck routing (road grade, speed) and traffic implications*
  - *Weather or seasonal changes*
  - *Vehicle energy consumption variations and losses*
  - *Accurate real-world and evolving costing*

This is being overcome with industry collaboration, a new set of integrated data, and analytical tools developed in this project

Potential Impact and Relevance

Project targets

- Integrated systems analytics tool chain development
  - Interconnected systems electrification optimization considering vehicle powertrain, local charging infrastructure, and regional electric grid architectures
  - OR-AGENT
- Systems assessment for primary US shipping ports drayage applications
- Demonstrate roadmap to BEV parity with Diesel HD Drayage Trucking
- Demonstrate >50% TCO reduction over BAU electrification pathways
- Demonstrate >75% emissions reduction pathways

Potential Impact

- **Comprehensive Unique Analytical Framework:** integrate competing aspects of electrified HDT, infrastructure architecture, and ODS
  - Under deployment with industry stakeholders: Cummins, Walmart, UPS, GTI, Volvo, Prologis
- **Scalable & Replicable Solutions**: Process to drive no-/low-regret investments for deployment roadmaps
  - prioritize tech investments and inform research portfolios for OEMs/fleets.
- **Maximize System Efficiency**: Enhanced TCO, asset utilization, and emission reduction metrics to improve system-wide operational effectiveness
- **Accelerate resilient Smart-Grid solutions**: Including DER for eHD Port Drayage application
- **Develop future R&D needs:** Replicable/Scalable multi fuel problems

Successful execution enables electrified trucking systems bottom-up analysis, architecture optimization, value assessment, and replicable/scalable tools deployment.

Milestones

FY 24 Accomplishments

- **OR-AGENT**: Developed an integrated framework for *alternate power* MHDT deployment and national infrastructure planning (3 architecture layers – vehicle, dispensing, energy back bone)
- **Ports**: Completed deep-dive EV analyses of Houston, Savannah, and Seattle-Tacoma port ecosystems
- **Networks**: Assessed drayage networks to identify priority EV charging locations (preliminary)
- **Tools**: Delivered analytical tools for scalable infrastructure and technology roadmaps
- **BP2:** Task 2 completed
- **BP3**: Accelerated plans with expanded scope

Go/No-Go decision

- Critical gaps in models were identified:
  - Detailed freight mobility data
  - Detailed grid power capacity/carbon intensity modeling
- **Go decision**: Gaps have been addressed:
  - Freight data integration (Streetlight OD data, FAF, TMAS)
  - ORNL NAERM + Powerflow + EIA + ORSAGE
  - Phased deployment approach(es) established

Project Management

Key Milestones

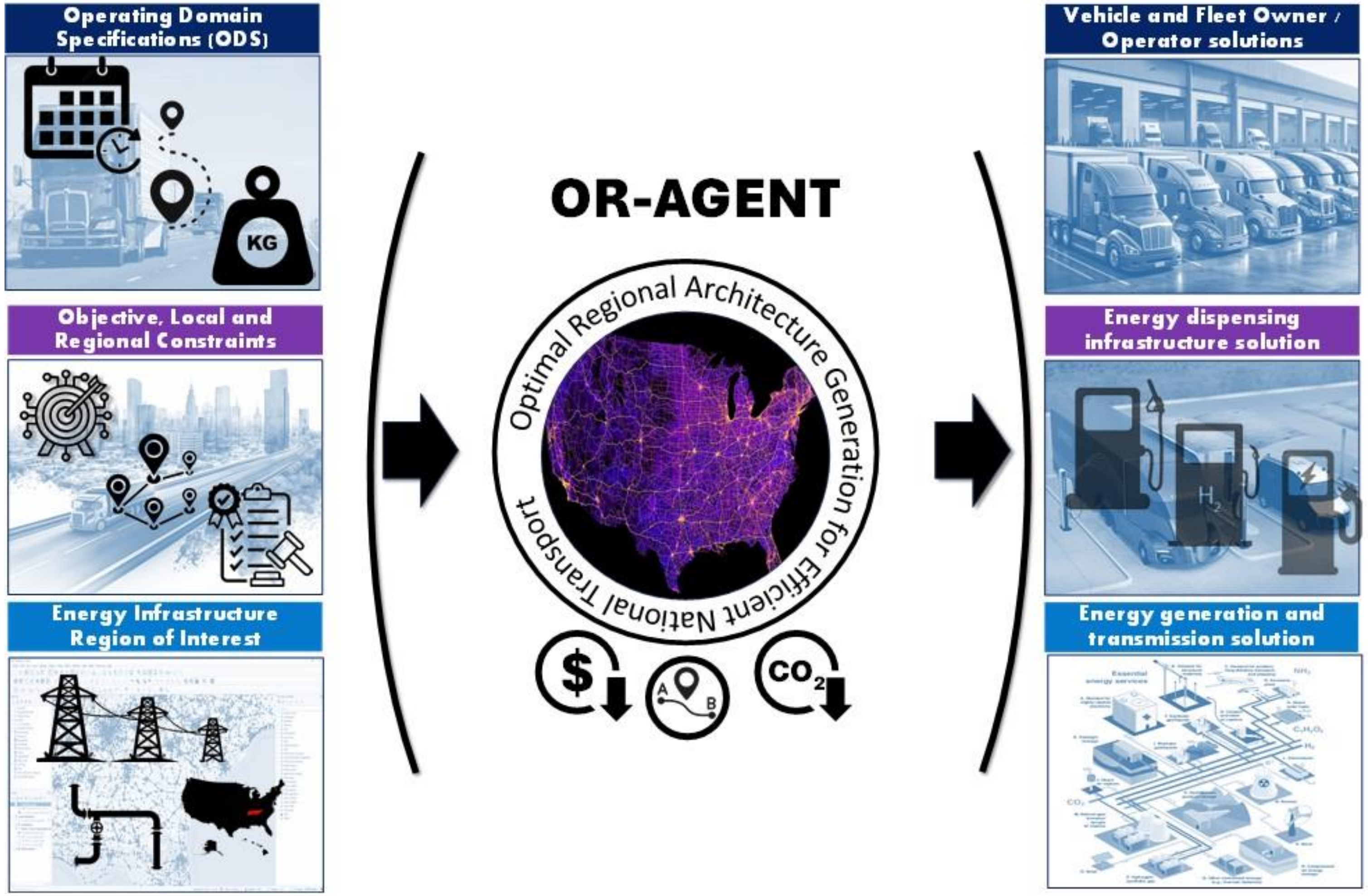
Years	1	2	3
Months	2, 4, 6, 8, 10, 12	14, 16, 18, 20, 22, 24	26, 28, 30, 32, 34, 36
SMART Milestone	**Q1:** Complete assimilating Class 8 freight vehicle and battery models capable of seasonal energy needs & life impact	**Q1:** Establish integrated co-opt. model and process with clearly defined cost fn/assumptions/ gaps. Define gap closure plan.	**Q1:** Complete assessment of model and data gaps for expansion studies beyond single port
	Q2: Complete developing charging infrastructure models integrated into private and public roads.	**Q2:** Validate integrated co-opt. model and process on simple test cases of synthetic freight flow data. Identify data gaps.	**Q2:** Identify key ports (US), data sources. Establish critical data streams to calibrate model. Define simulation variations.
	Q3: Complete assimilation key US port freight flow data into a common scalable freight deployment framework	**Q3:** Identify first port and data sources. Establish critical data streams to calibrate model. Define simulation variations.	**Q3:** Execute simulation studies for individual and integrated models for key ports (US). Present variation results.
	Q4: Complete grid capacity, cost, and carbon intensity model of TVA grid. Complete first risk assessment of models.	**Q4:** Execute simulation studies for individual and integrated models for single port. Present variation scenario results.	**Q4:** Project close out with roadmaps, gaps assessments, updated FMEAs, and documentation completed
Go/No-Go	Task 1: Decision to continue development based on key modeling/data gaps		
	Task 2: Decision to continue based on single port freight flow opt. viability		
Quarterly Progress Reports	Q 1.1, Q 1.2, Q 1.3, Q 1.4	Q 2.1, Q 2.2, Q 2.3, Q 2.4	Q 3.1, Q 3.2, Q 3.3, Q 3.4
Tasks	Task 1	Task 2	Task 3
Budget	$500K	$500K	$500K

NOAA – National Oceanic and Atmospheric Administration
FAF – Freight Analysis Framework
TMAS – Traffic Monitoring and Analysis System
HPMS – Highway Performance Monitoring system
BTS – Bureau of Transportation Statistics
ATRI – American Transportation Research Institute

Any proposed future work is subject to change based on funding levels

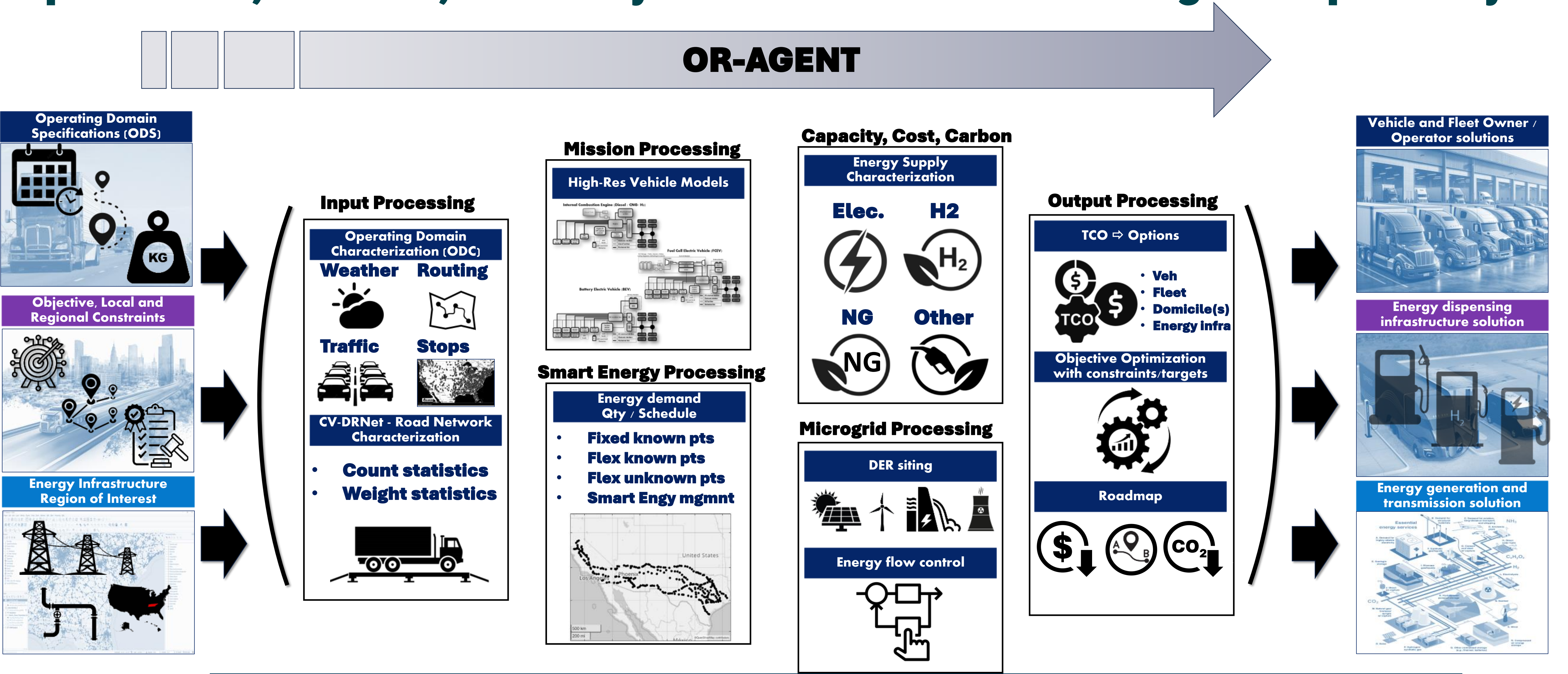
Approach and Technical Accomplishments (following slides)

- **Challenge**
  - Need to co-optimize vehicle specifications, usage, refueling/recharging infrastructure, and supporting energy sources
- **OR-AGENT development**:
  - Multi-agent optimization of an interconnected systems architecture considering
    - Multiple fuel types / options
    - Seasonal/Operational variations
    - Powertrain tech, Veh types, operations
    - Reg / Local / domicile constraints
    - Energy / DER infrastructure constraints
  - Assessment of model fidelity needs through sensitivity studies and impact analysis
  - **Outputs (spatial / temporal)**
    - **Vehicle powertrain specs / fleet mix**
    - **Local / depot energy dispensing infra**
    - **Region energy augmentation**



Optimum Regional Architecture Generation for Efficient National Transport

OR-AGENT is a **multi agent-based** framework for co-developing vehicle powertrain, domicile, and utility infrastructure with local/regional specificity



- OR-AGENT – Modular interconnected vehicle systems analysis framework
- Bottom-up approach to develop blueprints for commercial vehicle system energy resiliency
- Integrated workflow can be applied to inter-modal, mixed modal, and modal shift assessments

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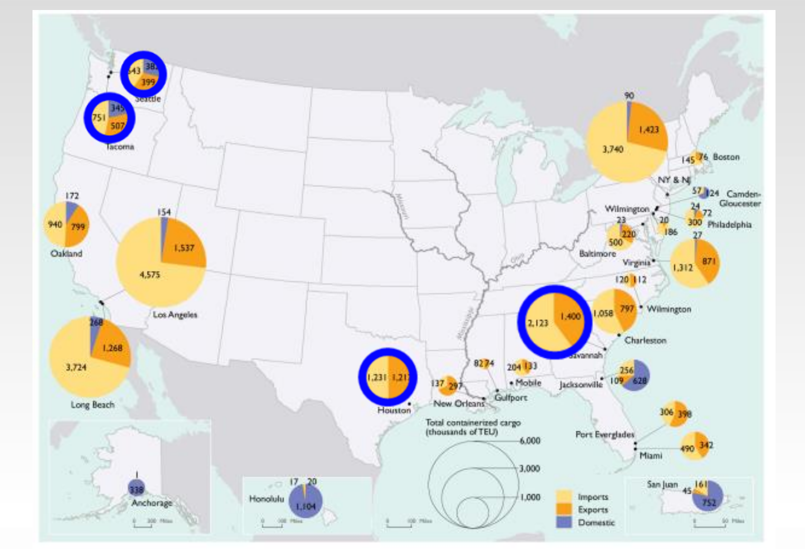
Operational flexibility will necessitate interconnected systems solutions

with flexibility on regions, constraints, and energy domains

Key US Ports



KEY: TEU = twenty-foot equivalent unit.

SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, based on 2019 data provided by the U.S. Army Corps of Engineers, Waterborne Commerce Statistics Center, special tabulation, accessed November 2020.

Current focus on:

- **Port of Savannah, GA**
- **Port of Houston, TX**
- **Port of Seattle/Tacoma, WA**

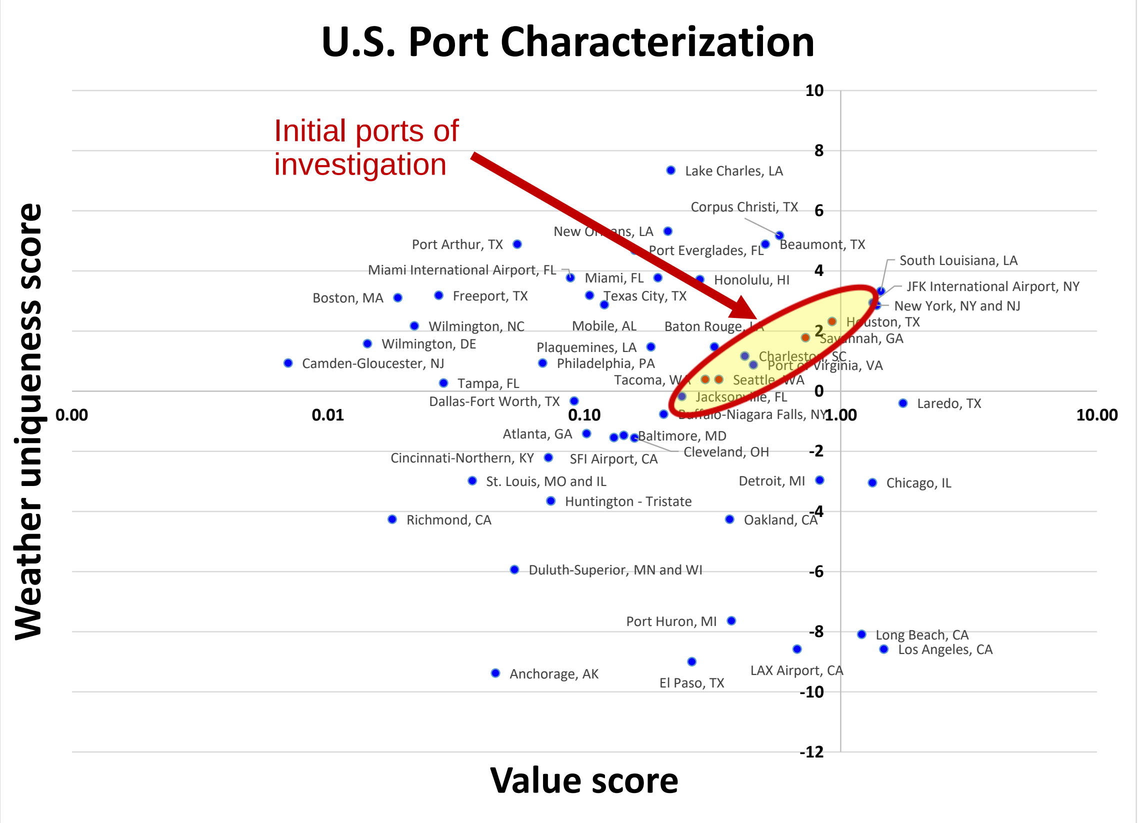
Next:

- **Port of LA/Long beach, CA**
- **Port of Oakland, CA**
- **Port of New York/New Jersey**
- **Port of Miami, FL**
- **Port of Jacksonville, FL**
- **Port of Charleston, SC**
- **Port of Virginia, VA**
- **Port of Baltimore, MD**
- **Port of Chicago, IL**
- **Port of DFW, TX**

Selecting the initial ports of investigation

Ports classified based on value and weather uniqueness

- Value: normalized weighted aggregate of port economics factors
- Uniqueness: weighted aggregate of weather factors deviation from average



- Economical energy transition of drayage applications is dependent on the unique characteristics of each port and supporting regional network
- Networks may interact, necessitating advanced mobility systems analysis
- Multiple options exist and must be cross compared for capability and best value
- Collaboration between government and industry research to assess key paths

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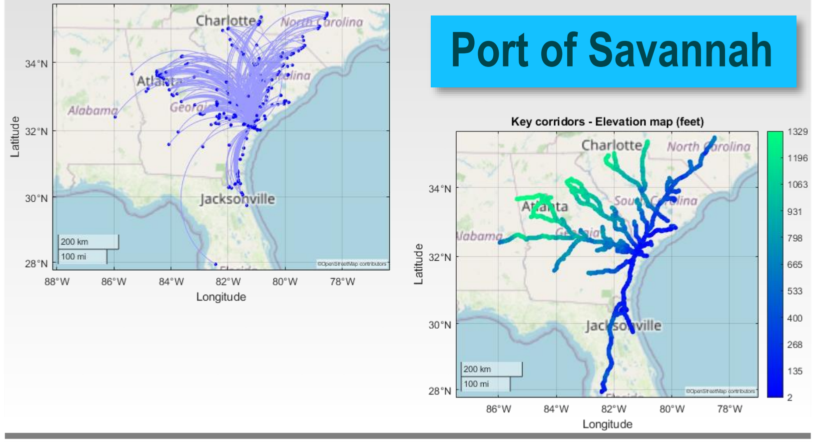
Operating Domain Specification/Characterization

Workflow – OD, weights, seasonal factors, vehicle counts, road speed/grade, traffic, etc.

ODS/ODC - Routing

Origin-Destination road grade/speed

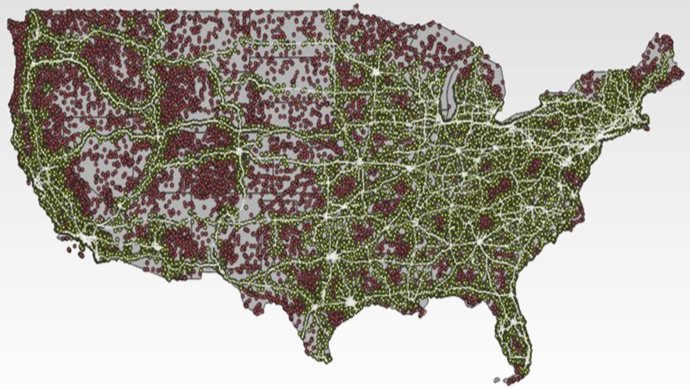


Attributes

- Operating Domain Specification effects are classified into road and weather characteristics where the dominant energy sinks are databased and modeled
  - **Grade**: US Census road network (US/States) + Nokia HERE + USGS
  - **Road speed limits**: FAF + HERE
  - **Curvature/Heading**: US Census road network (US/States) + HERE + Google
  - **Traffic flow**: HERE + RITIS + BTS/ATRI

ODS/ODC - Weather

Weather station data curation

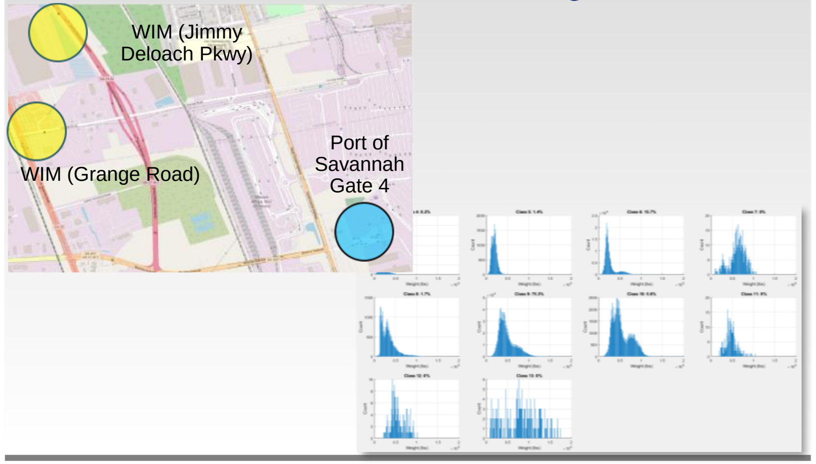


Attributes

- Weather and seasonality charges are critical to estimating energy needs and constraints
  - Over 50K NOAA weather stations with down to 1 min sample time
  - **Temperature:** impact battery and vehicle TM
  - **Wind:** impact to vehicle aero
  - **Air density:** impact to aero
  - Seasonal changes impact vehicle energy consumptions (up to 10% due to ρ alone)

ODS/ODC - Distributions

Vehicle class, count, weight



Attributes

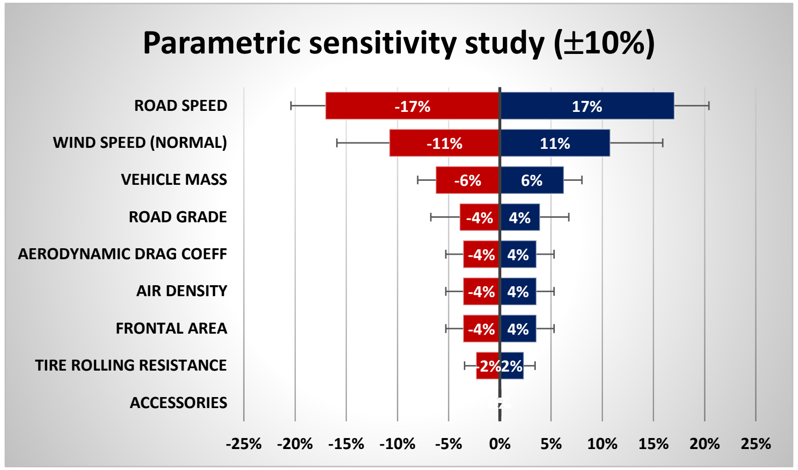
- **FAF** provides a key road network basis for freight movement
- **HPMS** data provides improved type count not limited to freight movement but limited network
- **TMAS** data provides details on count, type, and weight but limited number of stations
- **CV-DRNET** fuses this information to yield truck type, count, weight distr. by hour on each FAF segment (uncertainty defined)

Similar assessments completed for Ports of Houston and Seattle-Tacoma

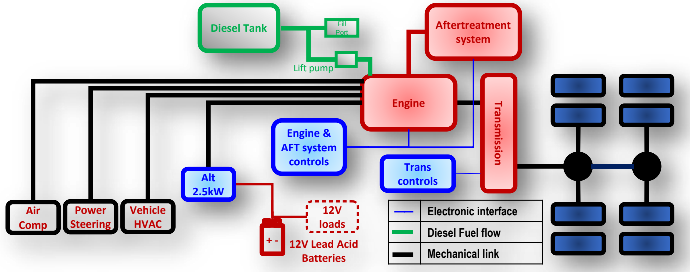
Detailed vehicle models for application characterization within established ODS

Integrated vehicle models immersed in real world ODS including driver, road, and ambient conditions

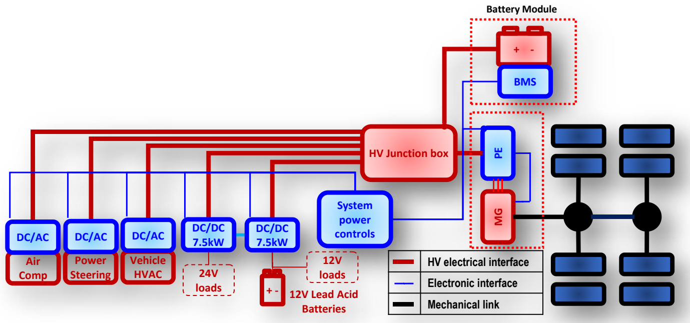
- **Diesel, CNG, H2ICE, BEV, FCEV, Diesel-HEV, H2-HEV, NG-HEV**
- **Enhanced driver model:** driver aggressiveness modifies vehicle target velocity (prior OSU research)
- **Real-world tire model:** tire and road thermal characteristics (through existing literature models/data)
- **HVAC / Auxiliary loads**: seasonal loads due to HVAC, power steering, coolant, electricals, brakes
- **Integrated battery and charger model**: electric, thermal, degradation, for commonly used Li-ion battery chemistries and charger types
- **Sensitivity analysis to identify critical factors**



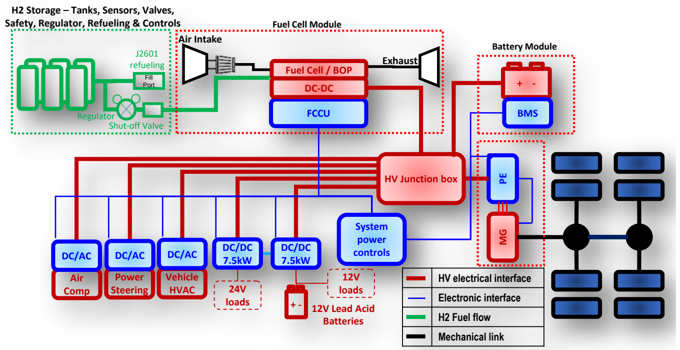
Internal Combustion Engine (Diesel / CNG/ H2)

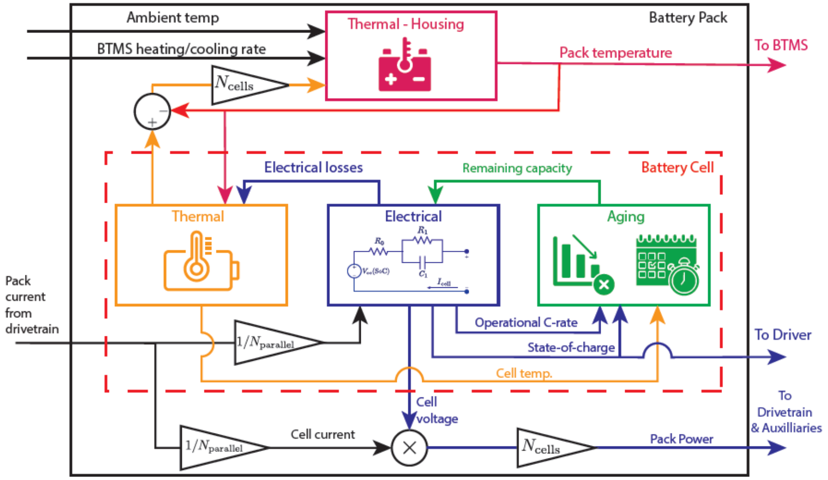


Battery Electric Vehicle (BEV)



Fuel Cell Electric Vehicle (FCEV)





Vehicle systems analysis to create mission energy signature

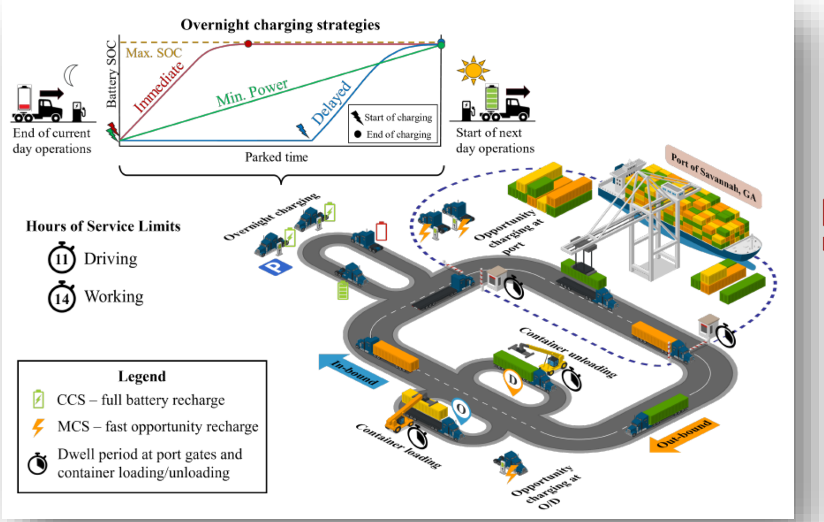
Vehicle count/OD: 12 months ops based on StreetLight data

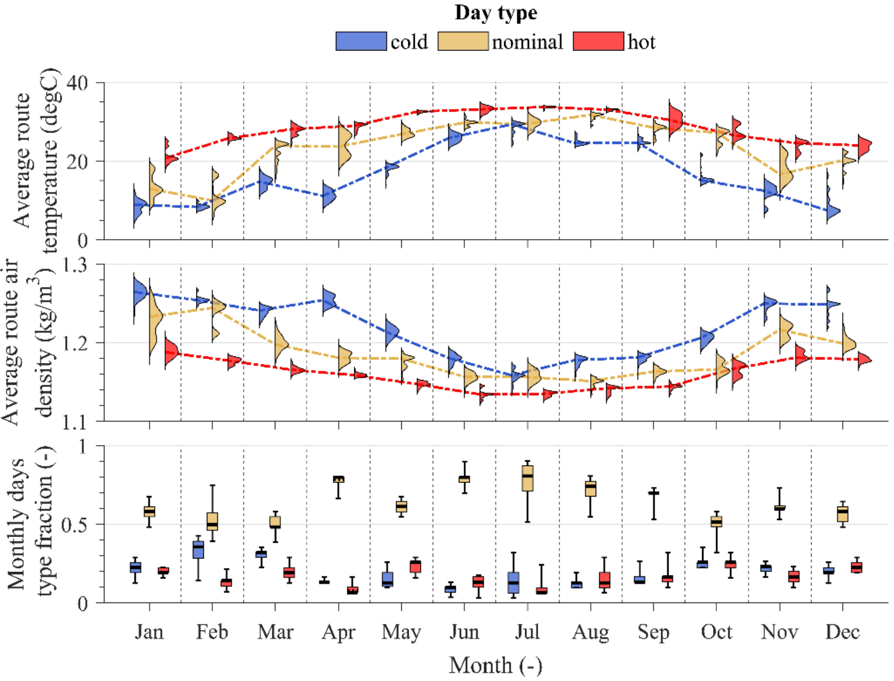
Port of Savannah: 1611 OD's ➔ **550k truck missions**

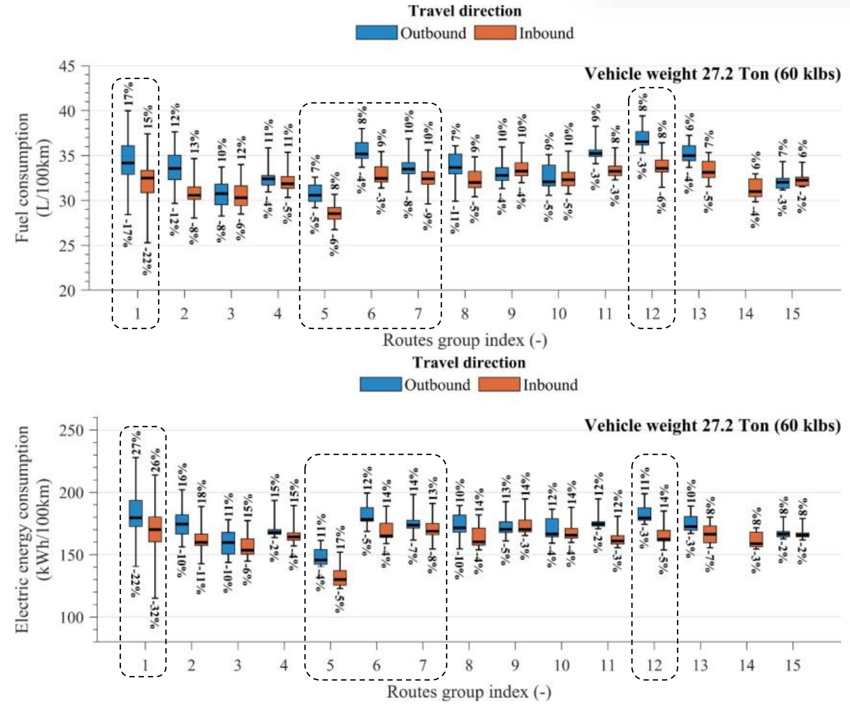
Port of Houston: 2002 + 1449 + 2078 + 2211 + 1884 OD's ➔ **799k truck missions**

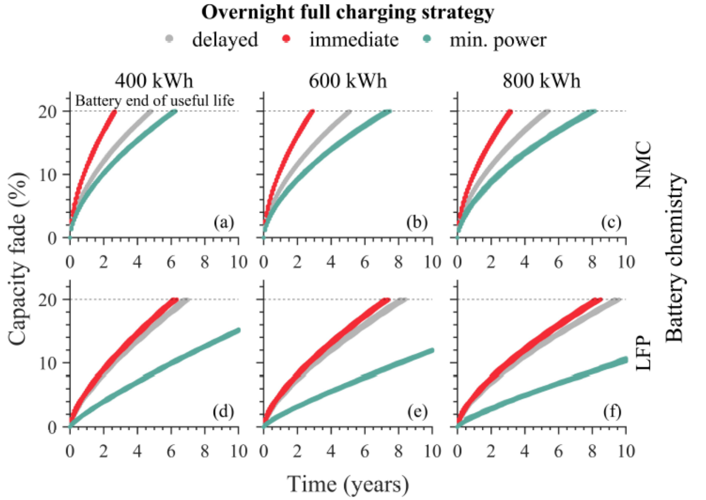
Port of Seattle/Tacoma: 1879 + 1069 + 4430 OD's ➔ **500k truck missions**

Vehicle simulations (and partial validation) using synthetic truck tours: seasonal energy impacts, battery aging, charging strategies and power levels









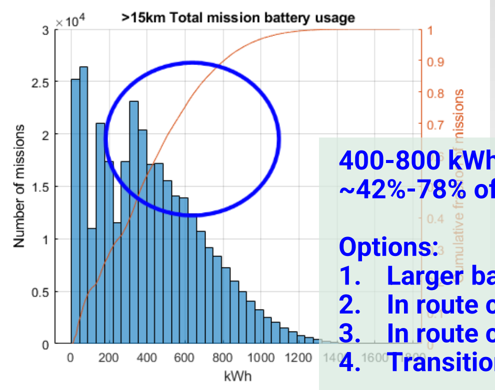
Exploring more validation data

Smart Energy Processing – Fixed Stopping Points

Assessing energy demand and schedule

Vehicle / domicile energy demand

Port of Savannah – Drayage trucks



400-800 kWh battery will cover ~42%-78% of missions

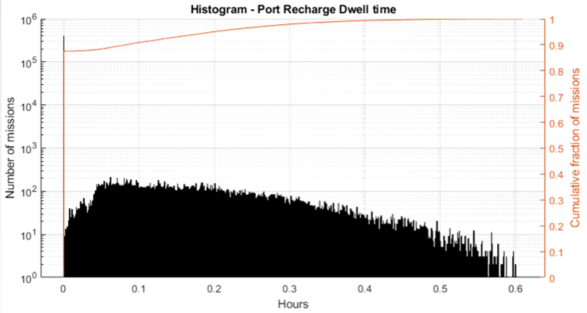
Options:
1. Larger batteries
2. In route charging (plug-in)
3. In route charging (eRoad)
4. Transition to H_2

Attributes

- Individual domiciles/ports/hubs analyzed to determine expected “8760” energy demand
  - **Electricity**: Dispensing options range from DC fast to MCS. Limits such as 2 options applied
  - **Diesel**: Mixed fleet considerations
  - **Individual sites (port and off-port):** are collectively studied for schedule, power demand, charger count/type
  - **Overnight** slow (managed) charging and **In-mission** opportunity fast charging

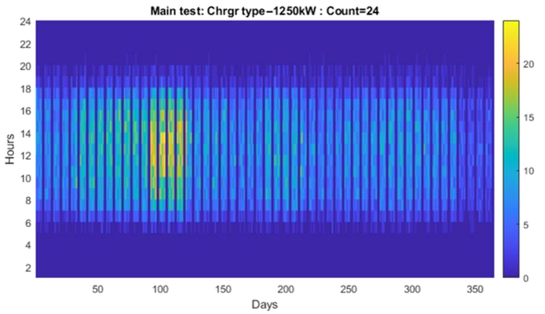
Port of Savannah - BEV demand with Smart Charging

Daytime dwell



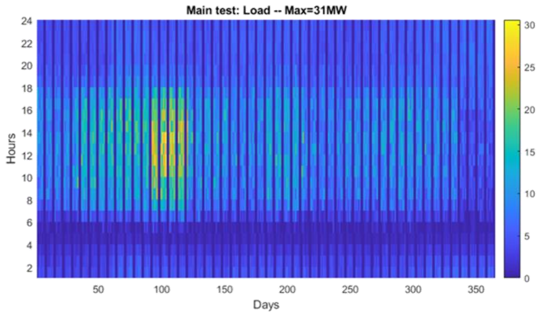
< 45mins

Daytime charging



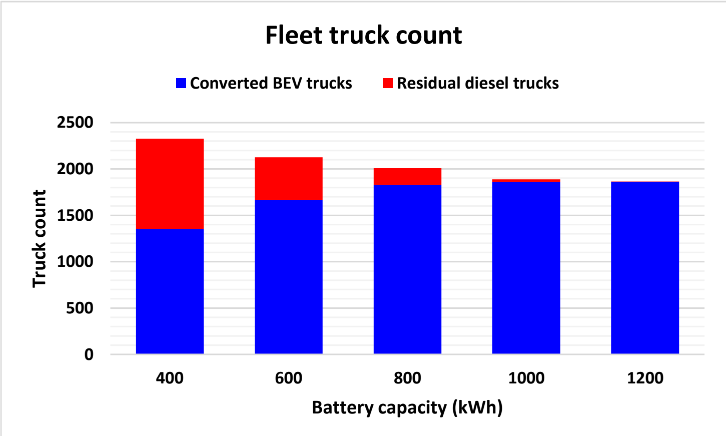
150kW: 33
1250kW: 24

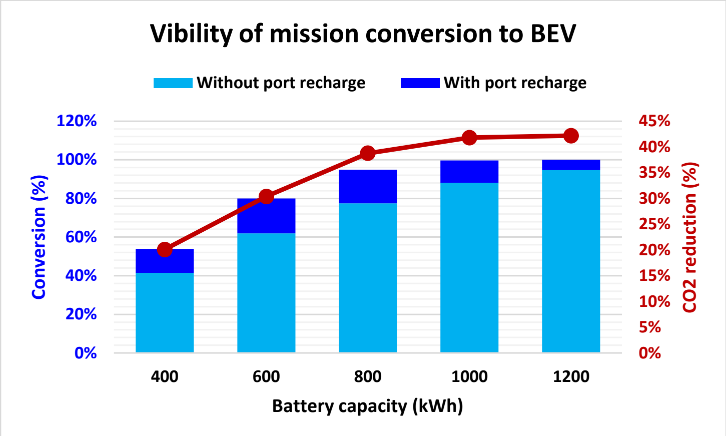
Grid demand



Port peak: 31MW

Example: 1 of 180 scenarios at the port (additional resources at off-port sites)





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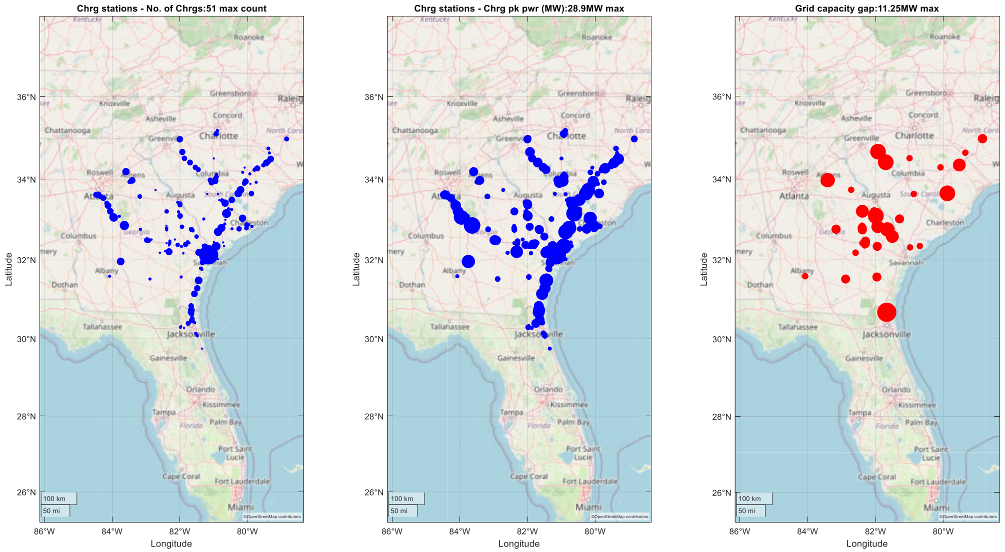
Similar assessments completed for Ports of Houston and Seattle-Tacoma

Smart Energy Processing – Fixed Stopping Points

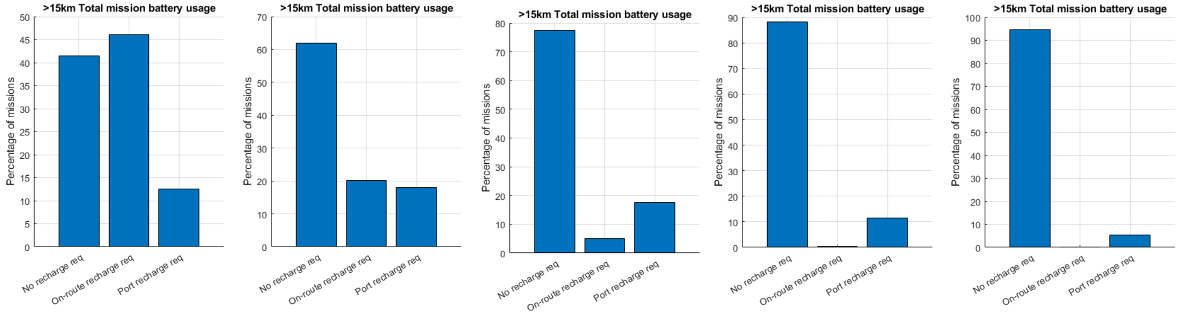
Charging siting requirements

- **Multiple configurations**
  - **Options**: Fixed and Flexible (known, unknown) stopping points
  - **Scope:** Fixed known points (Hub-to-hub operations)
- **Scenario analysis**
  - Vehicle powertrain type: 400 – 1200kWh
  - Charger options: CCS (150kW, 350kW) + MCS (440kW, 720kW, 1250kW)
  - Depot/domicile infrastructure: consolidation 0 – 25 miles
  - Grid capacity
  - Constraints

800kWh - Consolidation radius: 0 miles (max grid gap ~11 MW)

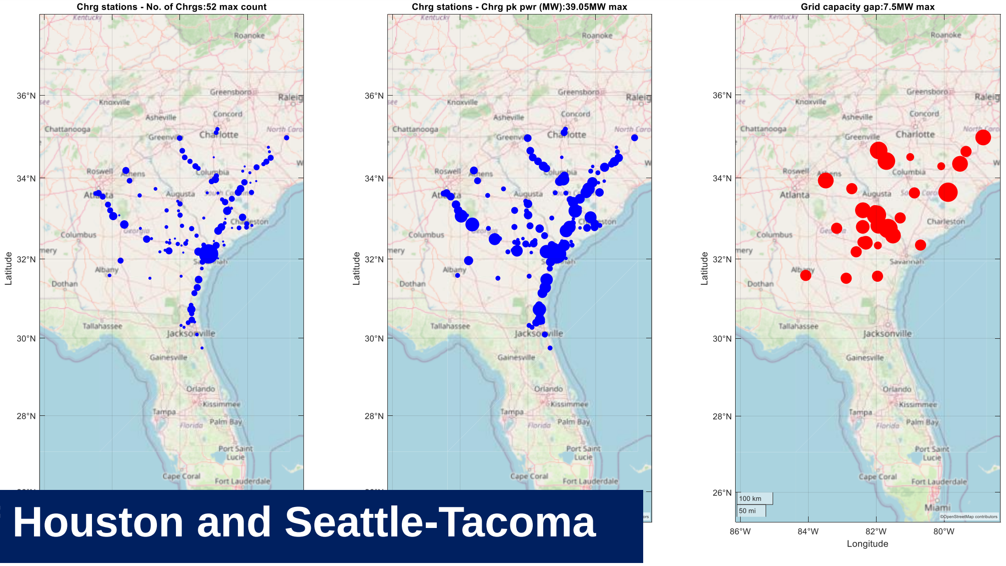


Impact on charging requirements based on battery capacity



(a) 400kWh (b) 600kWh (c) 800kWh (d) 1000kWh (e)1200kWh

800 kWh - Consolidation radius: 5 miles (max grid gap ~7.5MW)



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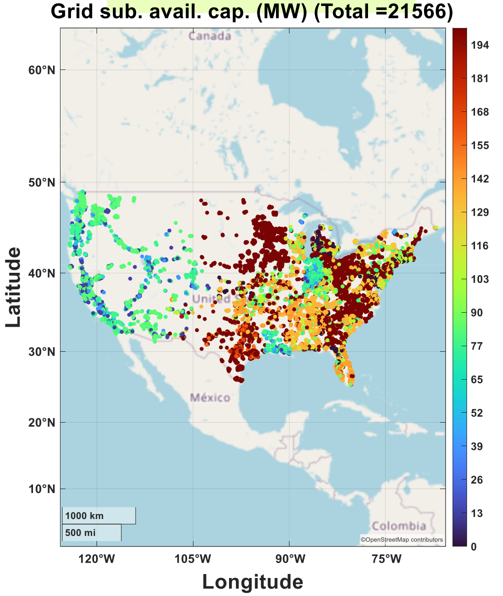
Similar assessments completed for Ports of Houston and Seattle-Tacoma

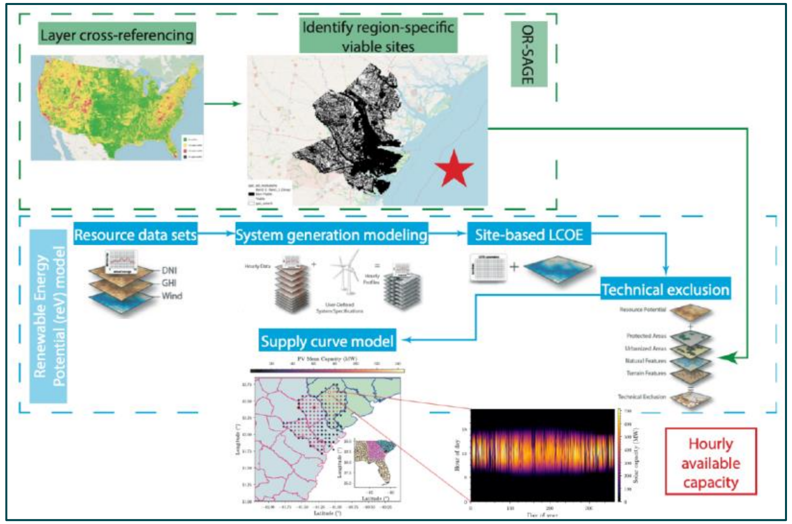
Energy Supply and Microgrid Deployment for BET systems

- **Grid issues**
  - Power limits, Supply and Emissions gaps ➔ grid resiliency
- **DER asset feasibility**
  - **System: Grid + Storage + DER generating assets**
  - Find dispatch schedules for each resource through optimization
  - Name plate capacity: **Solar, Nuclear (SMR), Wind**, Hydro
  - Long duration storage: BESS, others (TBD)
  - Seasonal variation, demand signal, optimal control
- **Site specific opportunity ➔ LCOE and LTCO**

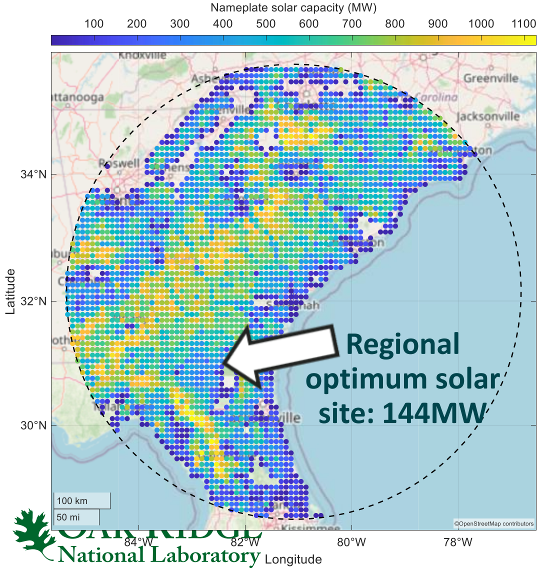
Grid capacity



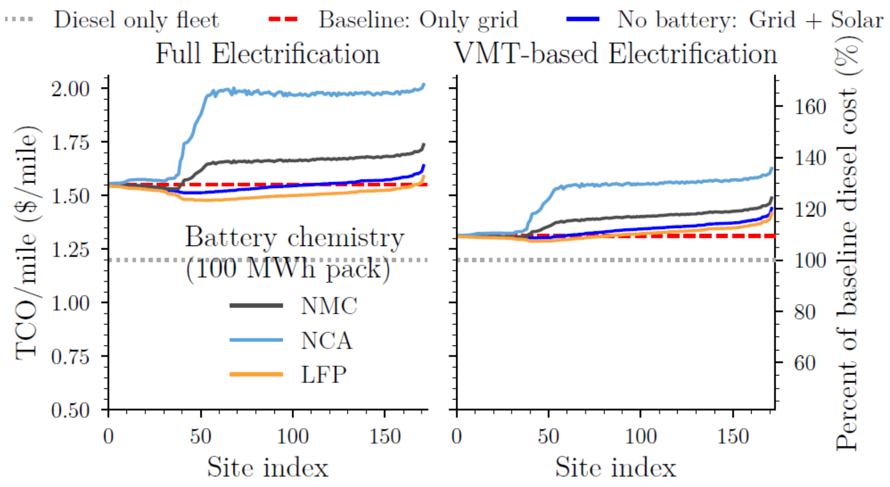
DER site capacity assessment



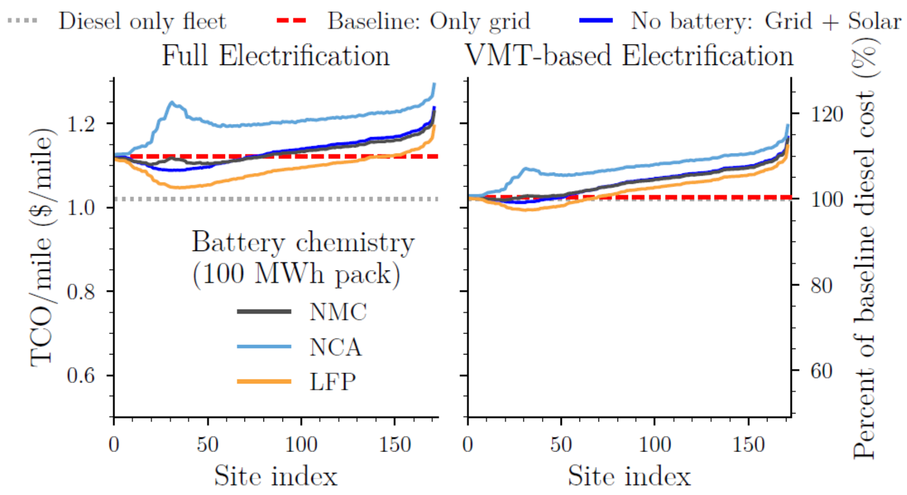
Optimal system siting



2023 LCOE



2030 LCOE

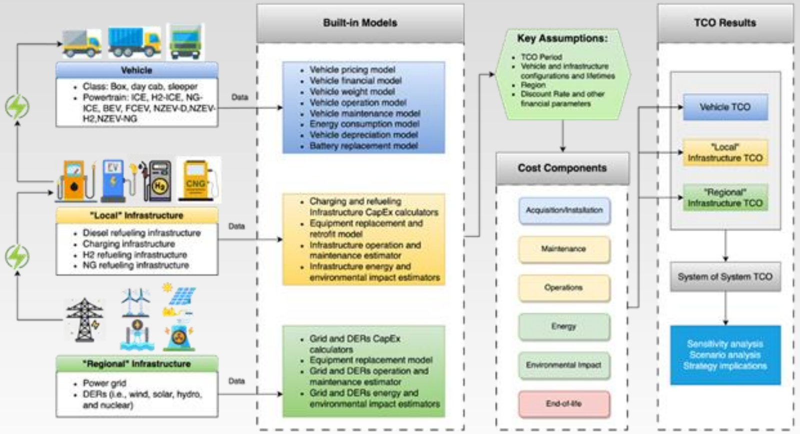


21CTP + ICCT assumptions: TCO parity early 2030's

Optimization based on an integrated TCO approach

Multilayered approach that is being refined

System of Systems TCO



Attributes

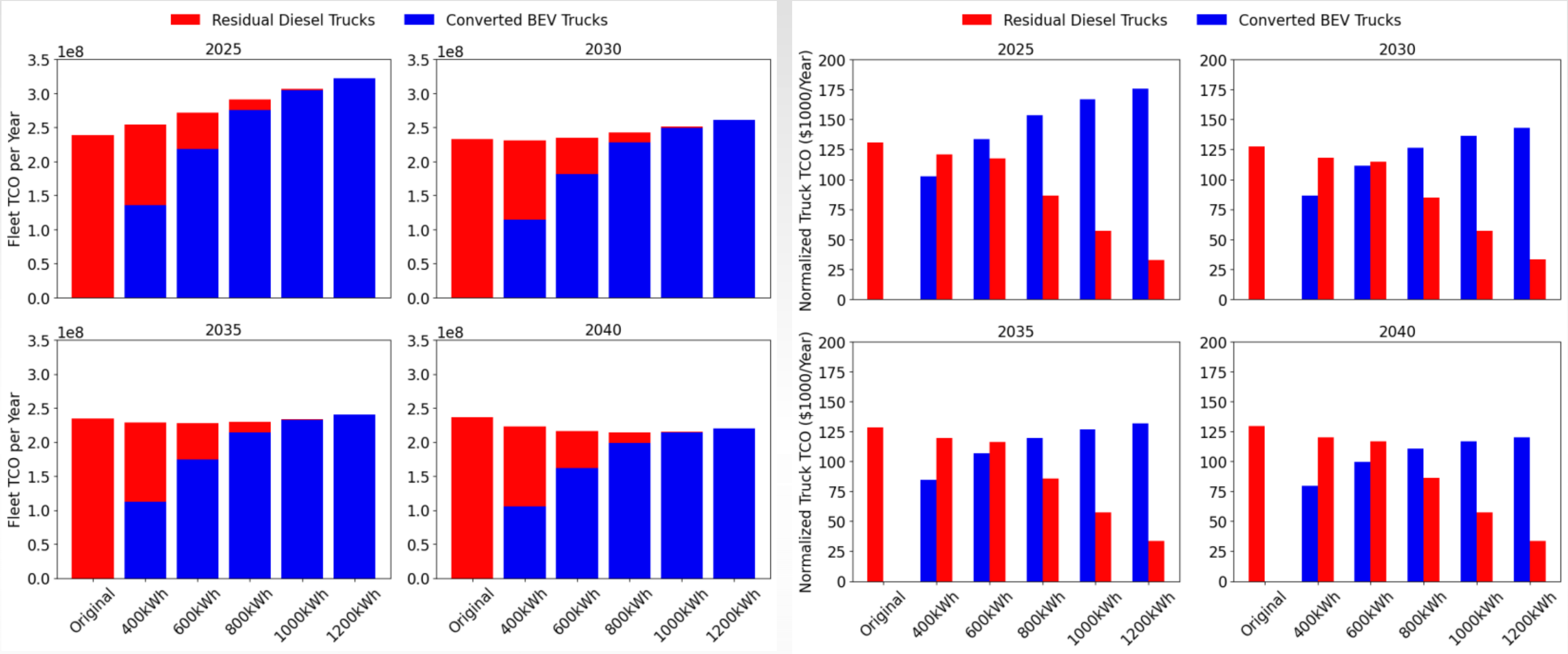
- Individual vehicle / domiciles (ports/hubs) analyzed to determine expected "8760" TCO over 30 years
  - **Considers**: Acquisition, maintenance, operations, energy, end-of-life, environment
  - **Powertrain:** ICE (Diesel, NG, H2), Plug-in hybrid (diesel, NG, H2), BEV, FCEV
  - **"Local" infra.:** Diesel, NG, Electricity, H2
  - **"Regional" infra.:** DER + Grid

ICCT assumptions: TCO parity early 2030's

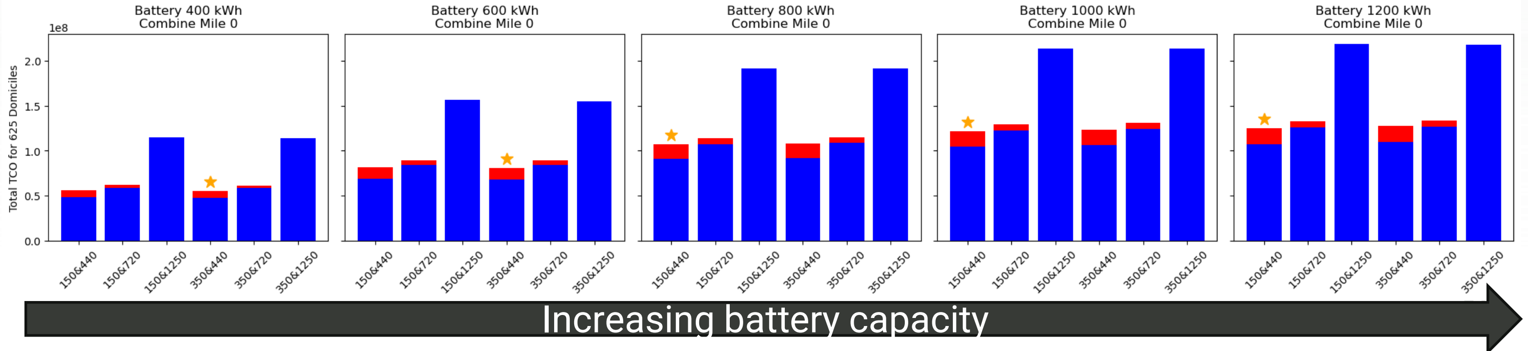
Similar assessments completed for Ports of Houston and Seattle-Tacoma

Port of Savannah - Vehicle / Domicile TCO (with dwell time costs)

Vehicle TCO (1863 vehicles)



Combine domicile TCO (625 hubs) – 150kW / 350-440kW charger solutions are preferred

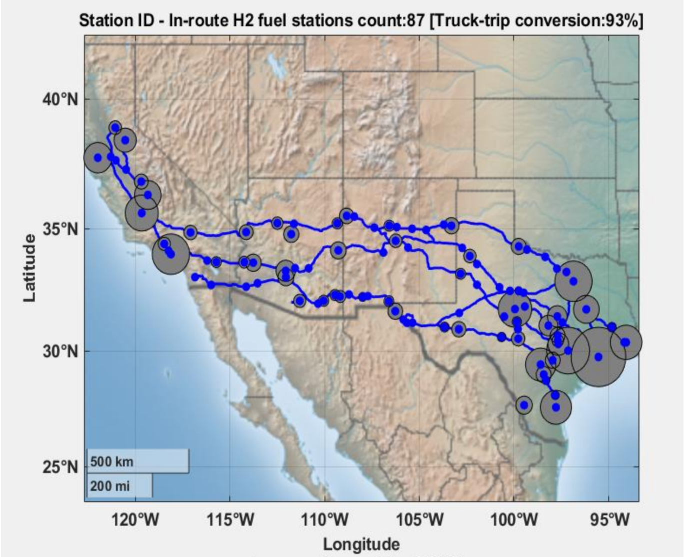


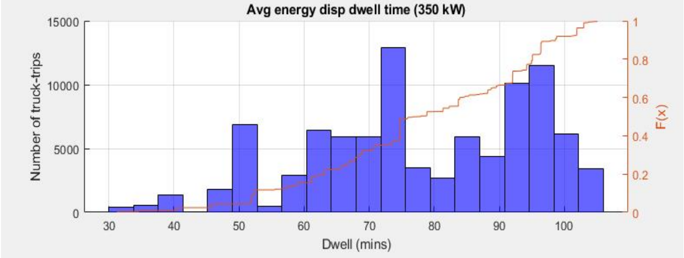
Ongoing work - Phased transitions: Ports as Gateways to more reliable and cost-effective freight transit

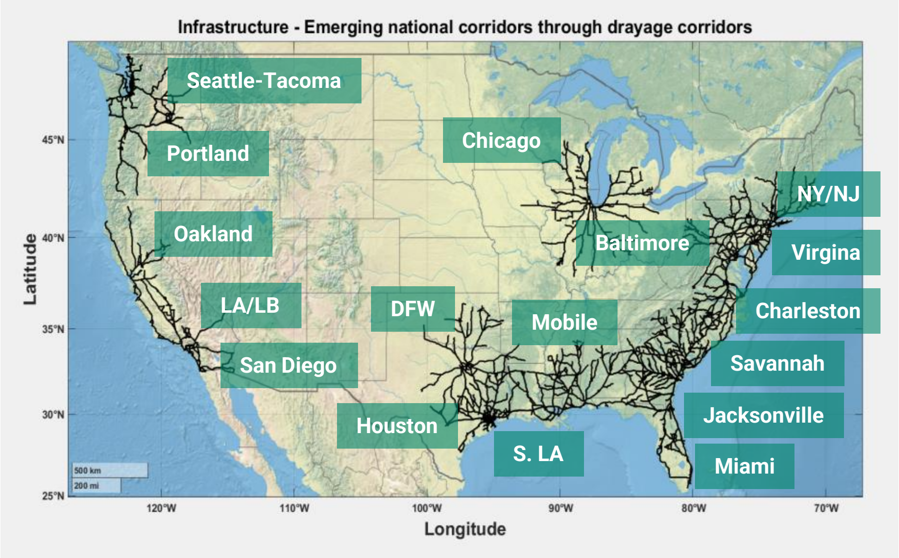
- **Why:** Diversifying freight energy sources enhances U.S. energy resiliency, stabilizes fuel costs, reduces supply chain disruptions—ensuring more reliable cost-effective goods movement.
- **Strategic Phased Deployment:** Introducing a stepwise energy transition strategy, beginning with ports to establish foundational charging hubs.
- **Corridor Emergence:** Initial port-based truck conversions naturally extend into early-stage freight corridors.
- **Next steps: Optimize Truck & Infrastructure Co-Evolution:** Aligned vehicle deployment with infrastructure readiness to maximize efficiency and investment impact
- **Data-Driven Decision Making (Fleets and Agencies):** OR-AGENT is replicable/scalable to identify high-value deployment zones and optimize investment timing & roadmaps

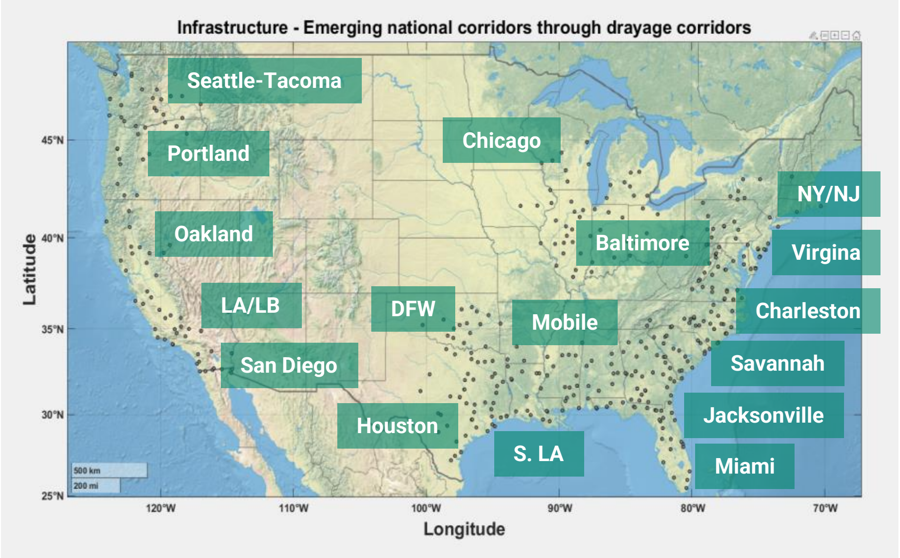
Phased infrastructure siting

Extract from DOE EE0010650 H2LA Project leveraging OR-AGENT









Response to Previous Year Reviewers' Comments

- **This is the year 3 review**
  - **No reviewer comments from previous year (poster board).**
  - **This project started in FY23.**

Collaborations and Coordination with Other Institutions

Partners

- **SLAC / Stanford**, development of battery cell, pack, and system models that capture electricals, thermals, aging, and cost characteristics of different cell chemistries
- Advanced charger model development to reflect system interactions with the grid and the vehicle, including efficiency, power flow, and thermals

- **Ohio State University**, development of integrated vehicle powertrain models capturing major influences of ambient and road conditions
- Integration of powertrain, tractor, trailer, battery, and charging system, and studies conducted on energy consumption, limits, and costs.
- Develop energy impact studies based on regions of interest

Collaboration

- **National Renewable Energy Laboratory**, data share on adoption predictions from US macroscopic view and distribution grid capabilities
- **Lawrence Berkeley National Laboratory**, data share on public charging infrastructure expectations for general freight haul (using ORNL data on energy needs)
- **Idaho National Laboratory**, data share on battery cell/packs for model development / calibration

Consultancy (Industry Advisory)

Cummins
Volvo
Walmart
FedEx
ExxonMobil
GTI
TVA

- **Cummins/Volvo**, advice on powertrain characteristics, market adoption factors, and vehicle performance requirements
- **Walmart/FedEx/ExxonMobil/GTI**, advice on end-user mission expectations, driver/operator constraints, and 1st mile delivery profiles
- **Tennessee Valley Authority**, support electricity pricing based on asset requirements

Challenges and Barriers

Truck freight mobility

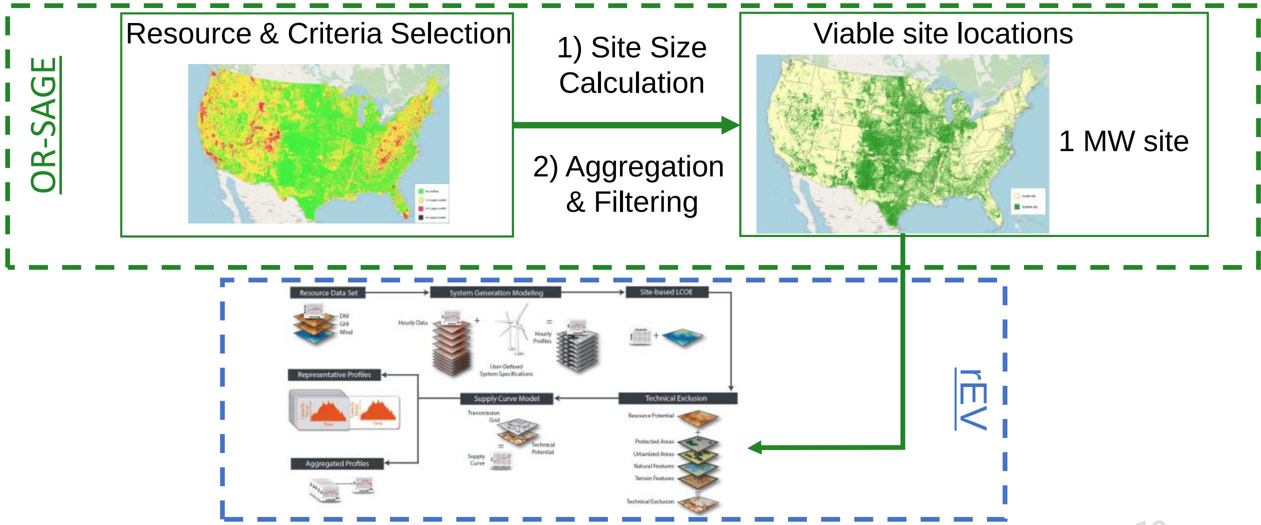
- Freight mobility data (OD, schedule, weight, route, idle time) is business-sensitive and not fully available in a single dataset.
- No single dataset provides statistically complete freight mobility information.
- This project integrates multiple disjointed datasets (StreetLight, Google/HERE, FAF, TMAS, HPMS) for a clearer view of freight operations.
- **Scaling to a national level requires integrating larger datasets (RITIS, BTS), presenting a future challenge.**

Operating Domain Specs.

- Freight energy use depends on road and ambient conditions.
- Analysis shows strong weather dependency on freight volume using NOAA and StreetLight data.
- **Expanding to micro seasonal/diurnal/traffic impacts requires more data and model development.**

Grid capability / resiliency

- Grid models exist up to the distribution substation level, capturing multi-bus power limits
- **Limited last-mile energy data introduces uncertainty in power flow analysis**
- DER siting (Solar, Wind, Nuclear) via OR-SAGE & rEV requires layered land-use exclusions.
- **Integrating TCO with microgrids, VGI, and SCM unlocks critical system and customer opportunities Requires careful synthesis of multi-domain models.**



Proposed future research

BP3 / FY 25

- HDT infrastructure needs through multi-port network assessment
- Micro-grid architecture optimization scalable tool completion
- Parametric **TEA and optimized options** studies of vehicle architecture, charging solutions, grid capacity, and DER requirements across the key large ports

FY 26

- 3-year project concludes in FY25
- Next steps being discussed to address critical agency challenges including
  - National scale grid resiliency assessment
  - Integrated commercial vehicle transport corridor architecture

10/1/2022 – 9/30/2023
BP1 - Model generation and early optimization of 1 port

10/1/2023 – 9/30/2024
BP2 - Model extensions and TEA optimization on multiple ports

10/1/2024 – 9/30/2025
BP3 - Model refinements and optimization on primary US ports

- MQ1.3 – Freight mobility using FAF5 est.
- MQ2.1 – Vehicle model parametric sensitivity study
- MQ2.3 – Grid capacity model for Port of Savannah
- MQ2.4 – Data imputation for truck weight, volume, OD
- MQ3.3 – Battery/vehicle integration for TM and aging complete
- MQ4.3 – Parametric TEA for Port of Savannah complete
- BP1 – Go/No-Go: Decision to continue development based on key modeling/data gaps
- MQ5.1 – Integrated ODD characterization and models across nation
- MQ6.1 – Parametric TEA and optimization for single port complete
- MQ7.1 – Integrated freight mobility / grid data and models across nation
- MQ8.1 – Parametric TEA and optimization for multiple diverse ports complete
- BP2 – Go/No-Go: Decision to continue based on port freight flow characterization. viability
- MQ9.1 – Air quality impact models developed
- **MQ10.1 – Multi-port freight network infra. cross impact assessment**
- MQ11.1 – Parametric TEA and optimization for national ports complete
- MQ12.1 – Project close out with roadmaps, gaps assessments

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Any proposed future work is subject to change based on funding levels

Summary

Takeaways

- Strategic short-haul freight electrification strengthens U.S. energy resilience and supply chain stability through fuel cost control, reduced disruptions, and faster tech adoption
- But there are challenges…
- **Accomplishments:**
  - **OR-AGENT** - Integrated Analytical Framework roadmaps to Scalable HDT energy transition and deployment
  - **Ports**: Savannah, Houston, Seattle-Tacoma & *challenges*
  - Preliminary broader infrastructure network analysis
  - Tools deployment initiated with industry stakeholders

Approach:

- **OR-AGENT** developed for multi-fuel and application assessments
- Systematic integration and development of critical **data**, tools, and models
- Assessment of model fidelity needs through sensitivity studies and impact analysis
- Parametric study and optimization to assess fleet customer value propositions

Collaborations and Coordination:

- Project team: **ORNL, OSU,** and **SLAC/Stanford**
- Collaboration: **NREL**, **LBNL**, and **INL** on data share
- Consultancy/industry stakeholders: **Cummins, Walmart, FedEx, Volvo, ExxonMobil, GTI,** and **TVA**

Next steps:

- **TCO sensitivity** - Expand scenario-based economics sensitivity analysis to inform vehicle/infrastructure architecture trade-offs.
- **Energy transition** - Phasing in through route priority assessment
- **Network growth** - Assess HDT infrastructure needs through multi-port network assessment

Thank you for your attention.

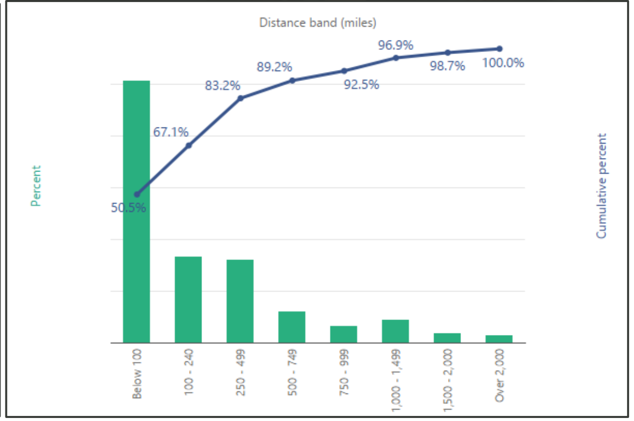
Questions?

Technical Backup Slides

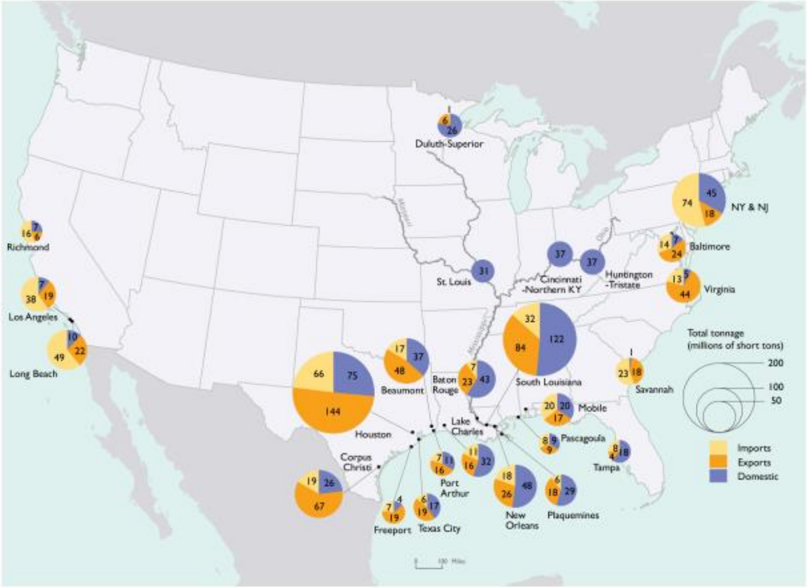
Background

Trucking freight characteristics

- Up to 95 percent of all globally manufactured goods travel in a container at some point
- Drayage is critical in moving containers from intermodal hubs (shipping ports, harbors, rail terminals, trucking terminals, and warehouses)
- 67% of freight trucking in U.S. is Short haul operations (<250 miles per day)
- **Local mobility does not necessitate a national strategy execution ➔ accelerates adoption path for clean energy technology to move goods**



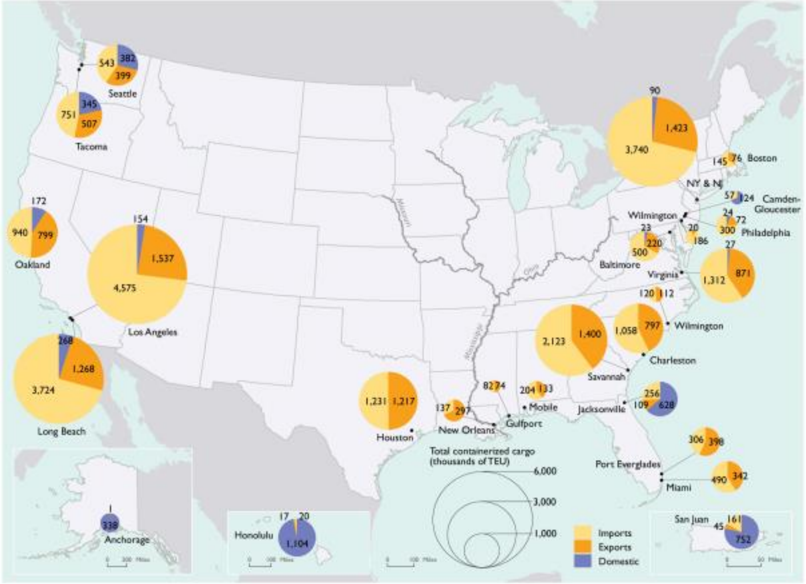
Water ports ranking by tonnage



NOTE: 1 short ton = 2,000 pounds.

SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, based on 2019 data provided by the U.S. Army Corps of Engineers, Waterborne Commerce Statistics Center, special tabulation, accessed November 2020.

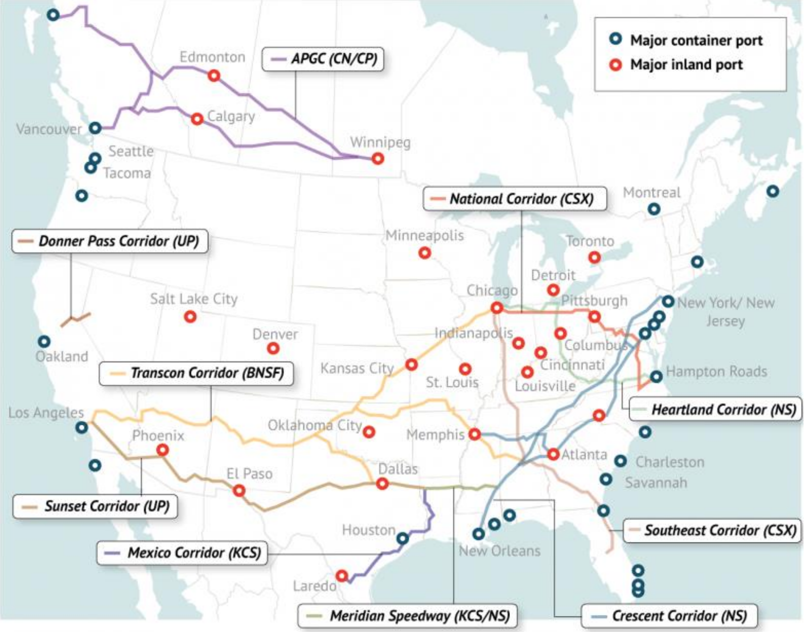
Water ports ranking by TEU



KEY: TEU = twenty-foot equivalent unit.

SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, based on 2019 data provided by the U.S. Army Corps of Engineers, Waterborne Commerce Statistics Center, special tabulation, accessed November 2020.

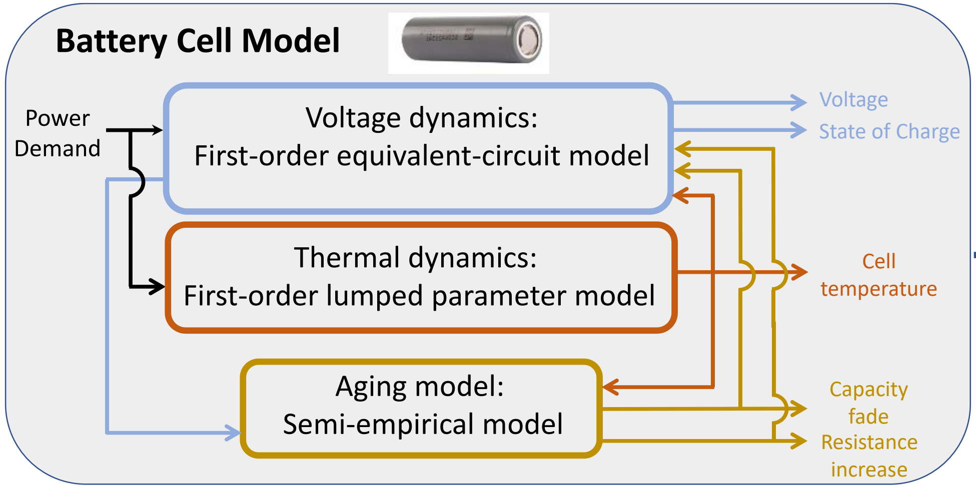
Major inland rail ports



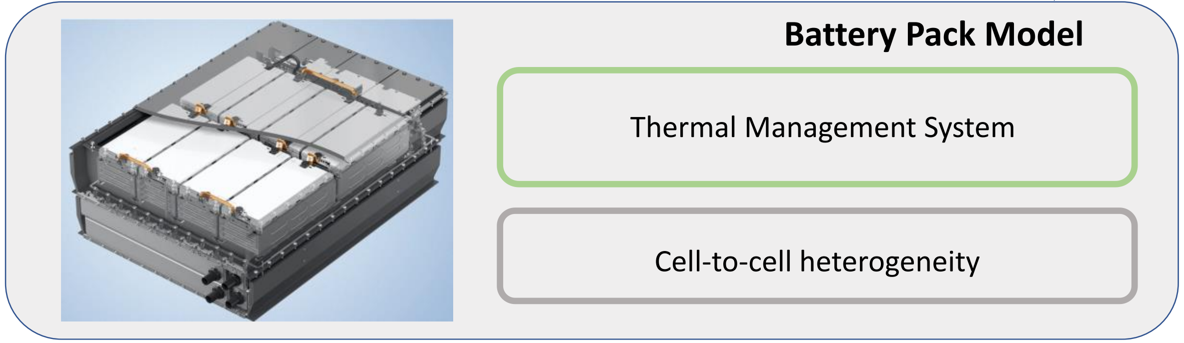
Sources: Dr.Jean-Paul Rodrigue, Dept. of Global Studies & Geography, Hofstra University

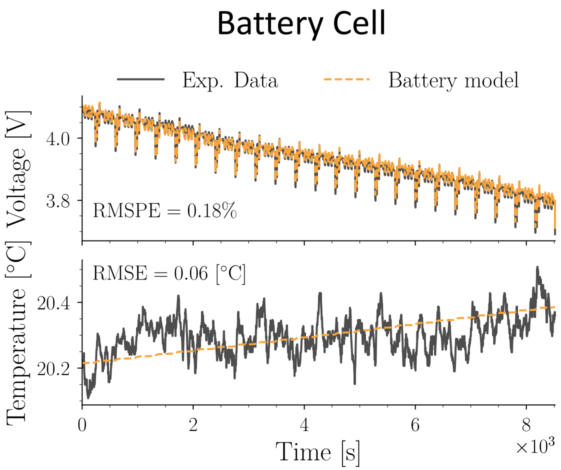
Established multiple chemistries battery pack models
with sensitivity to environment conditions (temperature, charging, calendar life)

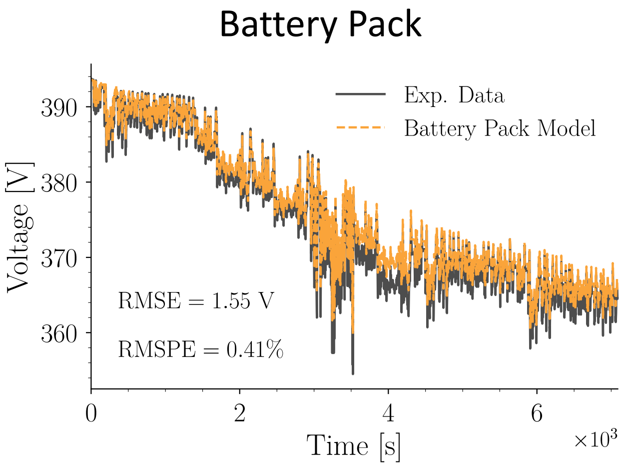
- Develop comprehensive battery models (electric, thermal, degradation), for commonly used Li-ion battery chemistries, to be integrated into a HDEV simulator to evaluate the capabilities (range & life) of these vehicles
- **Battery cell model**: Electrical, Thermal, Aging
  - Different levels of fidelity (throughput to detailed FEA/CFD considered)
  - Experimental data (INL) validates our identified model at the cell level
- **Battery pack model**: Extend cell models to pack models w/ TM that are integrated into a HDEV simulator
  - Homogenous vs Heterogenous assumptions
  - TM pack housing temperature and kicks on the cooler or the heater if the temperature is outside the acceptable range



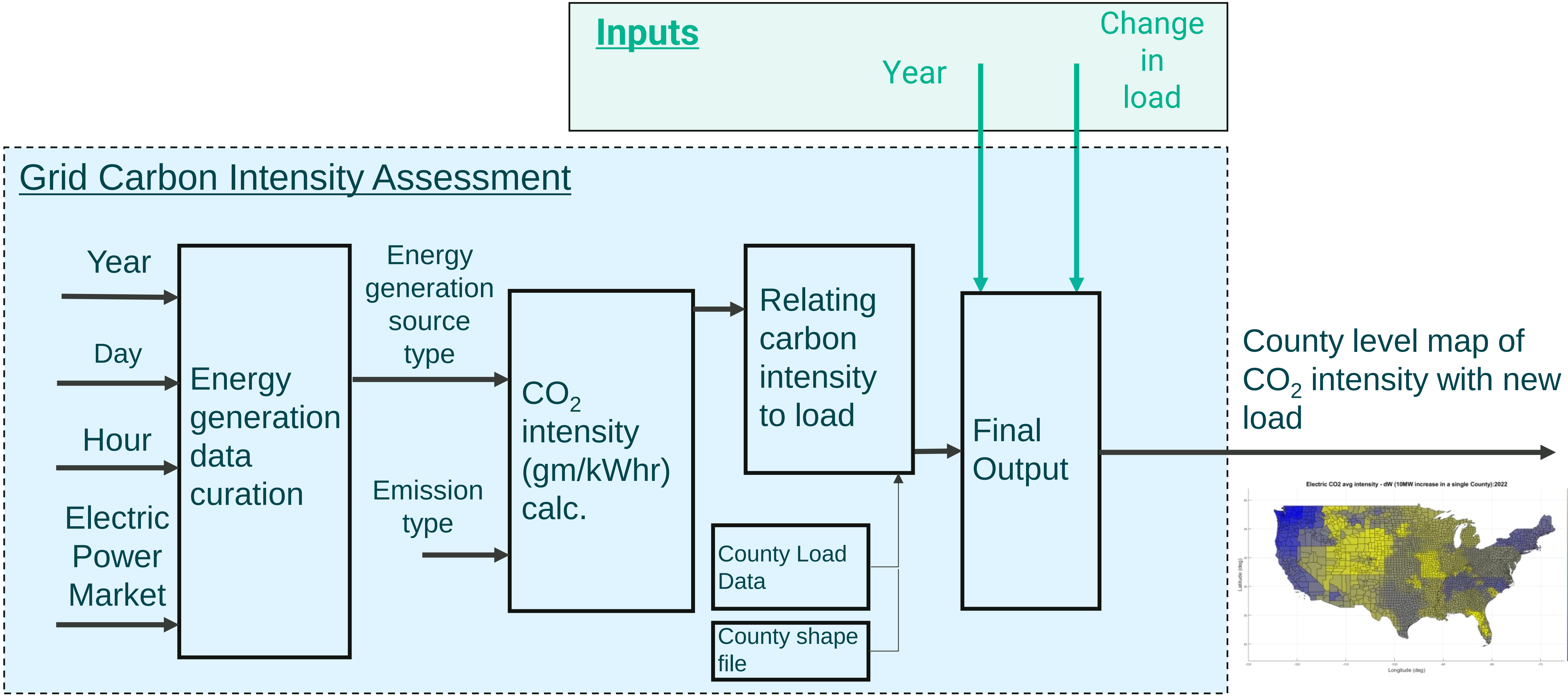
Upscaling from cell to pack





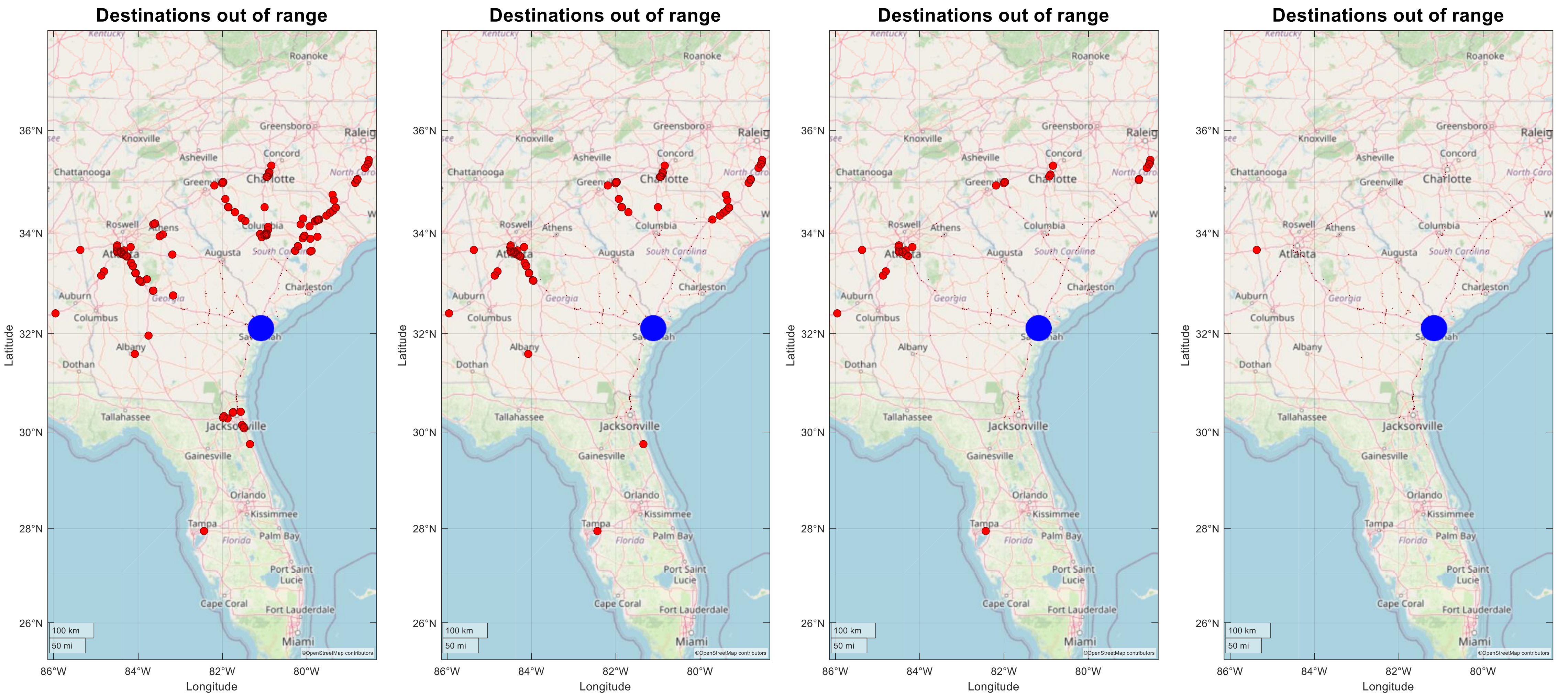


Estimating The Grid Carbon Intensity With Increased Electric Load From HDCV Electrification



Electric vehicle range and mission viability assessment

(a) 400kWh	(b) 600kWh	(c) 800kWh	(d) 1000kWh



Similar assessments completed for Ports of Houston and Seattle-Tacoma

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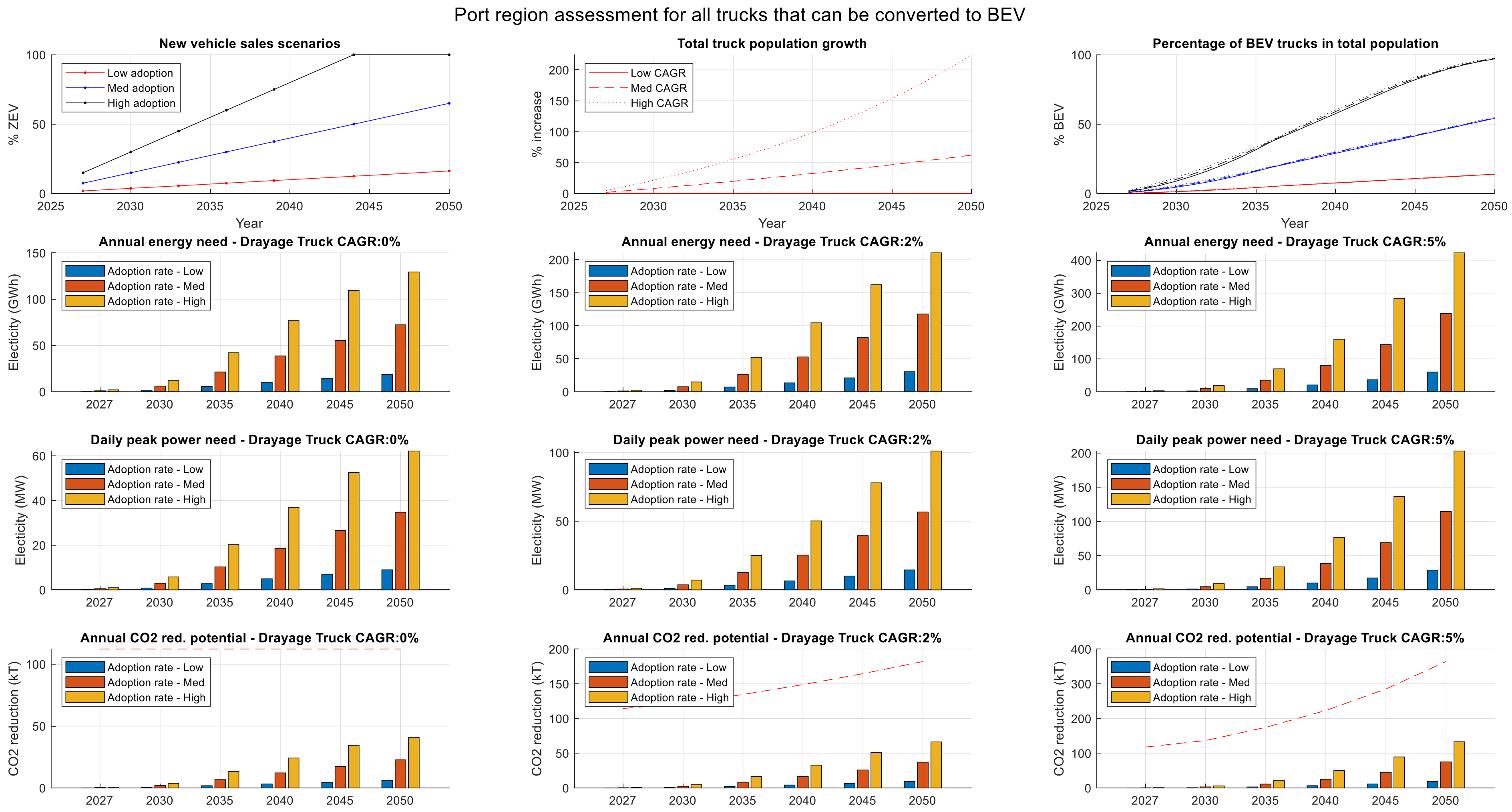
Port of Savannah region drayage transport – projected energy usage

- **Key notes**
  - New vehicle sales scenarios come from 21CTP
  - Only vehicles that can be converted to BEV are considered here
  - Example shown: 800kWh batt pack capacity
  - Results are shown are aggregated for the entire region supported by port drayage
  - Given the earlier results this growth us expected to be quite manageable



Similar assessments completed for Ports of Houston and Seattle-Tacoma

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