Perspectives on Charging Medium- and Heavy-Duty Electric Vehicles

May 15, 2025

Presented to MWCOG Regional EV Deployment Working Group

Brennan Borlaug, Alicia Birky, & Andrew Kotz

Focused on fundamental research and scaled deployment of ***renewable energy*** *and* ***energy efficiency technologies***

U.S. Department of Energy National Laboratories

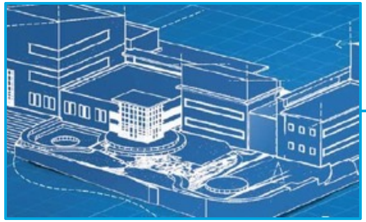
The DOE's **17** national laboratories have served as the leading institutions for scientific innovation in the United States for more than 90 years.

NREL Brings **Distinct Capabilities**

Foundational Science	Accelerated Technology Scale-Up	Market/Systems Analysis	Commercialization

Bench-scale- discovery → Scaling R&D and Process Engineering → R&D with Industry Partners

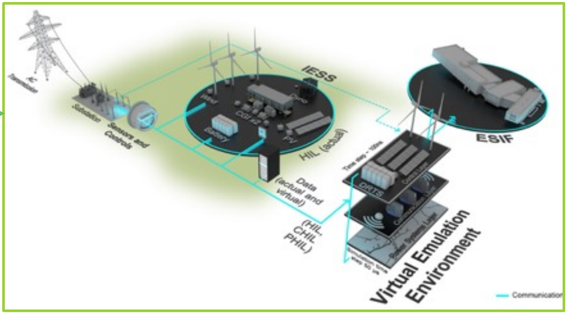
Solar Energy Research Facility
Science and Technology Facility
Field Test Laboratory Building



Energy Materials and Processing at Scale (Completion 2027)

Energy Systems Integration Facility (ESIF)

- Clean hydrogen
- Grid & security tech
- Products from electrochemical processes and CO_2
- Advanced batteries
- PV, wind, water, geothermal
- New buildings and industrial materials, manufacturing and systems



Advanced Research on Integrated Energy Systems (ARIES)

High-Performance Computing, Simulation, and Visualization

Commercial Vehicles R&D

Ground Vehicles

- Extensive on-road data collection and analysis
- **Fleet DNA** and **FleetREDI**
- Innovative analysis tools
- Duty cycles - **DriveCAT**
- Total Cost of Ownership – **T3CO**
- Multi-modal freight tools
  - **FAMOS**
  - **INFORMES**
- Infrastructure requirements
- Fleet technology assessments

Aviation

- Airport ground support vehicle data and analysis – shuttles, GSE, fleet vehicles, TNCs, freight movement
- Airport ZEV Blueprints
- **Athena ZEV** / Digital Twins
- **AeroSim**
  - Vertical Takeoff and Landing (VTOL) simulation tools
  - Electrified fixed wing aircraft, both battery and H2

Rail

- **ALTRIOS** – Advanced Locomotive and Rail Infrastructure Optimization System -- an opensource software tool to evaluate strategies for deploying advanced locomotive technologies and associated infrastructure
- Applying **ALTRIOS** with partners to understand technology benefits and costs

Maritime

- Over 12 years of experience with port electrification
- Support of electrification blueprints
- Data collection and electrification analysis
- ALFA fishing boat hybridization
- **MARINESim** vessel powertrain energy model

Contents

1 Background

2 Modeling Tools

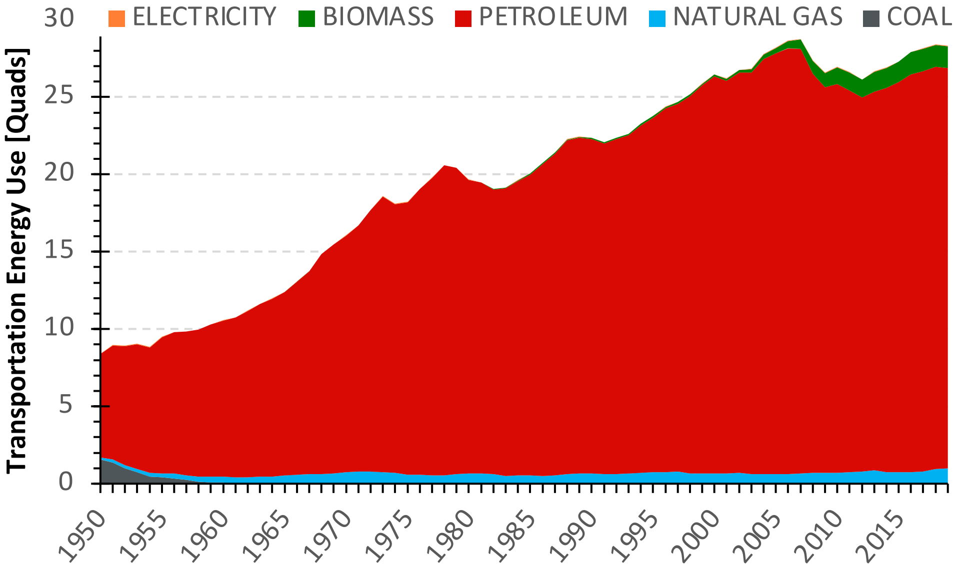
3 Commercial EV Charging Concepts

4 Key Studies

5 Summary & Next Steps

Transportation Systems are Petroleum Dependent

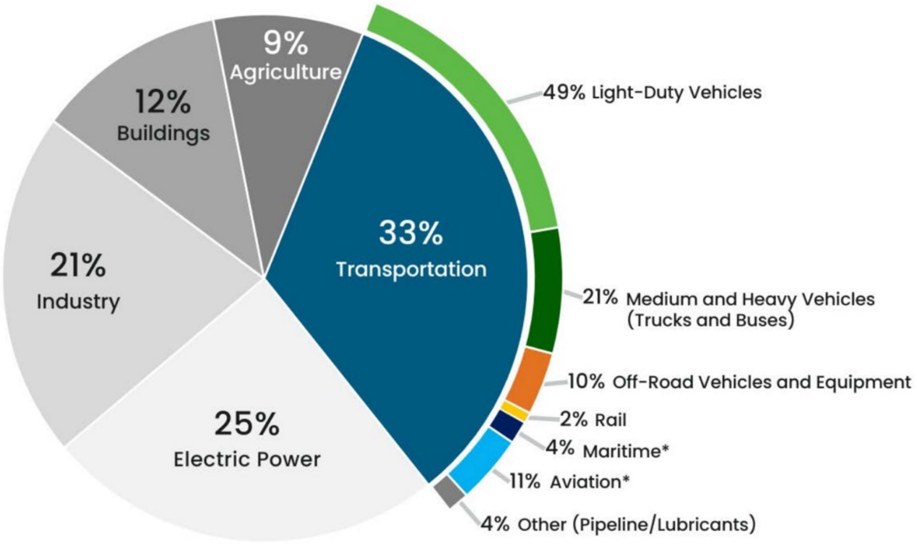
For >75 years, petroleum has been the dominant transportation energy source in the United States. **Today, petroleum products account for ~90% of the total U.S. transportation sector energy use**.



Source: NREL; Data: EIA

MHDVs: Major Source of U.S. Energy Demand

Total 2022 U.S. GHG emissions with transportation and mobile sources breakdown



*Aviation and marine include emissions from international aviation and maritime transport. Military excluded except for domestic aviation.

Source: DOE; Data: EPA (U.S.)

- **Transportation is a major source of U.S. energy demand and emissions**.
- **Medium and heavy-duty vehicles (MHDVs**) are the **2nd largest source of transport-related CO_2 emissions.**
- MHDVs are also a **major source of local air pollution**.
- **Battery electric vehicles (EVs) are a promising technology for MHDVs** as battery performance improves and costs decline.

Heavy-Duty Trucks: 22% of MHDVs, 66% of Energy Use

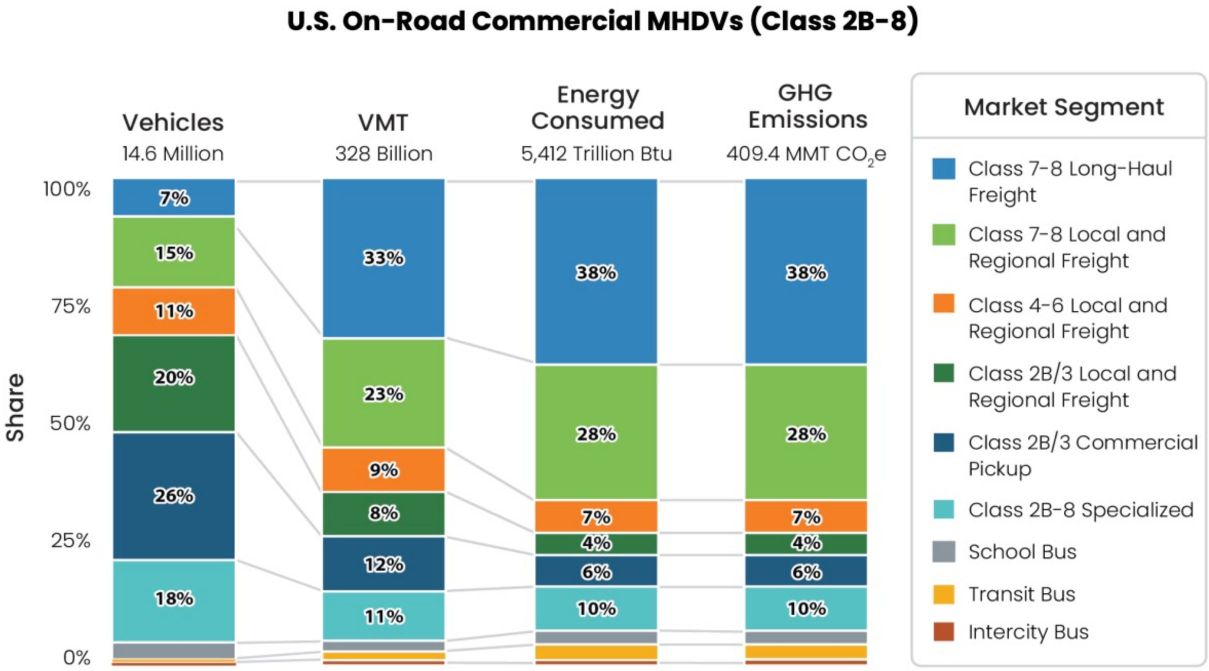
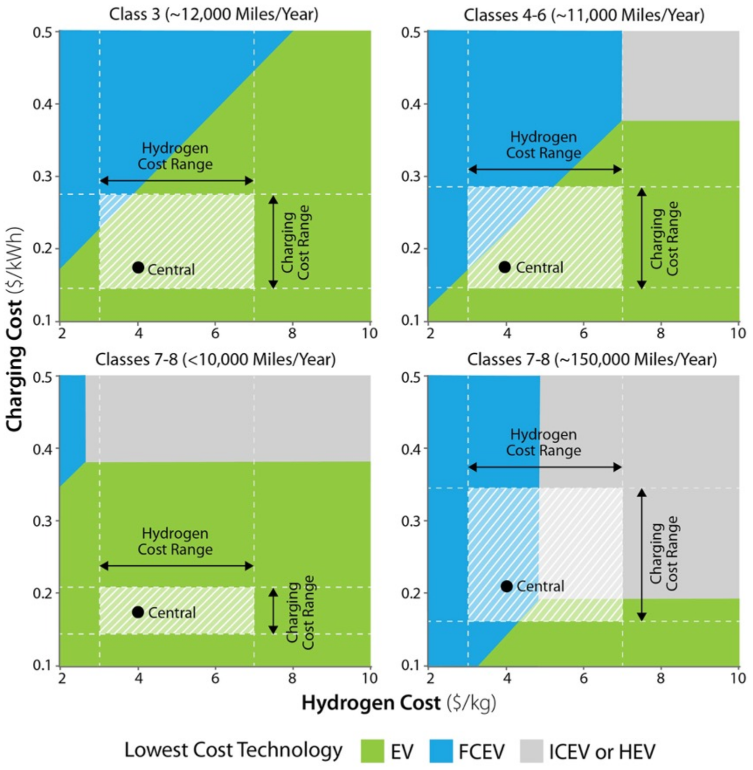


Figure ES-1. MHDV market segmentation by vehicle class—vehicles, vehicle-miles traveled (VMT), energy consumption, and GHG emissions. A small fraction of heavy-duty vehicles accounts for the majority of GHG emissions. Sources: National Renewable Energy Laboratory analysis using the Transportation Energy and Mobility Pathway Options (TEMPO) model based on data from the Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI),[6] the Vehicle Inventory and Use Survey,[7] the National Transit Database,[8] the 2023 School Bus Fleet Fact Book,[9] and the American Bus Association.[10]

Commercial EVs are Increasingly Attractive

TEMPO



Ledna et al. (2024)

Commercial EV Advantages:

- EVs are becoming **increasingly cost competitive on an upfront basis** as battery costs decline.
- EVs are more efficient than internal combustion engine vehicles (ICEVs) and may provide significant **operating cost savings**.
- EVs offer **performance advantages** that can improve safety, reliability, and driver retention.

United States Example:

Medium-duty EVs could reach total cost of driving (TCD) parity w/ ICEVs **within 5 years, assuming upfront cost and fuel price targets are met**.

For **heavy-duty EVs**, cost parity could be achieved **within 10 years, assuming upfront cost and fuel price targets are met**.

TCD = total cost of driving

Modeling Tools

- FleetREDI
- HEVII
- T3CO
- EVI-X

FleetREDI

Fleet Research, Energy Data, and Insights

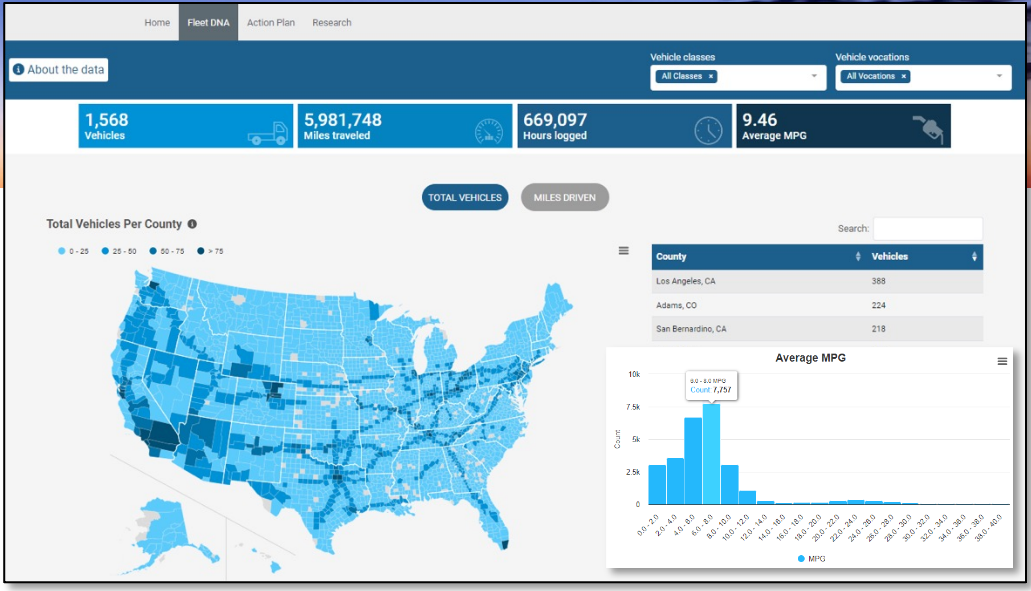
FleetREDI is an interactive online portal for sharing, discovering, and analyzing integrated commercial vehicle data and energy insights.

Learn More | Get Insights

https://fleetredi.nrel.gov

FleetREDI

FleetREDI Action Plan



Provides research community with ***updated, integrated, and comprehensive commercial vehicle data and intelligence*** for strategic planning, R&D portfolio development, and current and future R&D projects.

FleetREDI Analysis Framework

Analysis Methodology

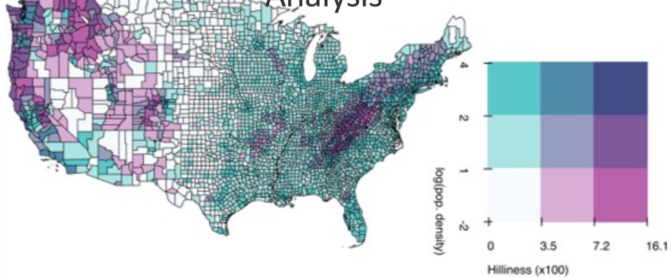
Data gaps identification

Capture of 1Hz data (second by second)

Automated analysis & rapid reporting

Framework to meet future needs

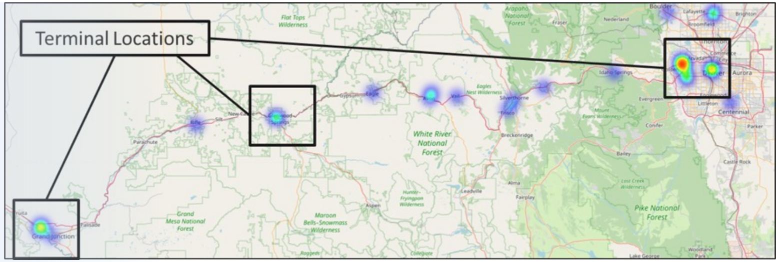
Data Categorization & Gaps Analysis



EVI-Pro T3CO Fleet DNA RouteE BLAST

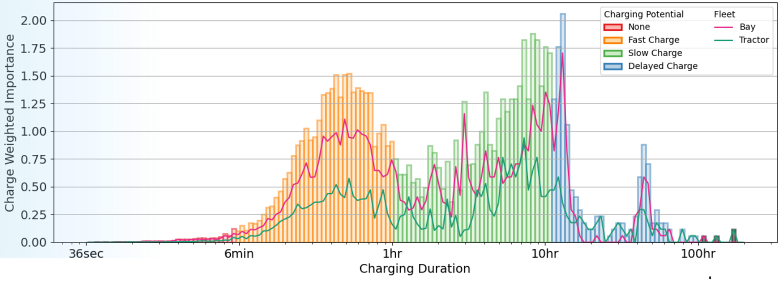
Data Capture Categories

GPS and Route Data
- Latitude / Longitude
- Elevation
- Route Profiles
- Time / Speed
- Ambient Conditions



Vehicle and Engine CAN
- Engine Speed / Torque
- Engine Fuel Rate
- NOx Sensor
- Exhaust Temperatures
- Engine Coolant Temps…

Electric Drive Data
- Battery SOC
- Voltage
- Current
- Temperatures
- Component Temps



FleetREDI **Insights**

https://fleetredi.nrel.gov/#/insights

NREL Transforming ENERGY

Electrification Analysis: All Aboard America!

Cory Sigler, Polina Alexeenko, Alicia Birky, Andrew Kotz, Jason Lustbader, Matt Jeffers, and Mike Lammert

Key Takeaway

An interregional express bus service can use a currently available battery capacity option (676 kWh) at a charge rate of 125 kW to immediately electrify part of its fleet for routes up to 200 miles in moderate climates, but the range of current market options limits full electrification.

Figure 1. A Bustang fleet. *Photo by Cory Sigler, NREL*

Ace Express Coaches is an All Aboard America Holdings Inc. portfolio company that offers interregional public transportation bus services across Colorado through its Bustang-branded fleet of motorcoaches in partnership with the Colorado Department of Transportation. The National Renewable Energy Laboratory collected operational data on nine 45-foot Bustang motorcoaches from May through August 2022. The deployment statistics are summarized in Table 1.

Table 1. Deployment Overview

Location	Number of Vehicles	Type	Vocation	Duration	Miles
Colorado	9	Motorcoaches	Interstate bus	May–Aug. 2022	33,942

NREL Transforming ENERGY

Electrification Analysis: Container Ports' Cargo Handling Equipment

Katerina Polemis, Andrew Kotz

KEY kWh: kilowatt-hour • TEU: twenty-foot equivalent unit

Figure 1. Estimating port terminal loads. *Illustration Cameron Nelson, NREL*

Maritime decarbonization is an integral part of reducing emissions from freight transportation. The Electrification Analysis of Container Ports' Cargo Handling Equipment developed by the National Renewable Energy Laboratory (NREL) in partnership with the Electric Power Research Institute provides a scalable solution to model energy demand per container moved (kilowatt-hour [kWh]/twenty-foot equivalent unit [TEU]) for an all-electric cargo handling equipment fleet.

Container Movements (Equipment Used)	Energy Consumed Per Container
Vessel to Dockside (Ship-to-Shore Crane)	6.5–12 kWh/TEU
Dockside to Container Stack (Yard Tractor)	2.1 kWh/TEU
Yard Tractor to Container Stack (Reach Stacker)	2.5–2.8 kWh/TEU
Container Stack to Drayage Truck (Reach Stacker)	2.5–2.8 kWh/TEU
Forklifts: Light, Medium, and Heavy Duty	0.6–0.7 kWh/TEU
Personnel Vehicles: Light Duty	0.4 kWh/TEU

Table 1. Energy Demand per Container Moved for Each Equipment Type

National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401
303-275-3000 • www.nrel.gov

NREL Transforming ENERGY

Estimating Electrification Potential for Class 8 Regional-Haul Trucks

Andrew Kotz, Setayesh Fakhimi, Catherine Ledna, and Jason Lustbader

Key Takeaway

Simulated Tesla trucks, with an average efficiency of 1.8 kWh/mi and daily driving distances ranging from an average of 445 to 1,100 miles, face challenges on longer routes and struggle to achieve full operational coverage with the current battery and charging configurations. However, where ubiquitous charging exists, 100% EV coverage is possible for the given drive cycles.

Figure 1. A row of Tesla semitrucks. *Photo from North American Council for Freight Efficiency*

In September 2023, the North American Council for Freight Efficiency collected data on Class 8 regional-haul tractors for approximately 2 weeks at various depots, such as the United Parcel Service, Frito-Lay, and PepsiCo.

As part of the Run on Less depot data workshop, the National Renewable Energy Laboratory (NREL) sought to understand how Tesla semitrucks would perform in real-world regional-haul applications.

NREL constructed a vehicle model to simulate the Tesla trucks in PepsiCo's fleet using the Future Automotive Systems Technology Simulator (FASTSim™) tool and NREL's Fleet Research, Energy Data, and Insights (FleetREDI) data analysis platform. Deployment statistics for each dataset are shown in Table 1.

Table 1. Fleet Overview for PepsiCo Tesla and FleetREDI Diesel Class 8 Trucks

	Number of Class 8 Trucks	Types	Calendar Days	Vehicle Days	Miles
PepsiCo Tesla	3	Regional haul	17	46	27,606
FleetREDI Diesel	49	Regional haul	61	494	219,870

NREL Transforming ENERGY

Electrification Analysis: Manhattan Beer

Polina Alexeenko, Cory Sigler, Alicia Birky, Andrew Kotz, Jason Lustbader

Manhattan Beer Distributors is a beverage delivery company operating in Manhattan and the Bronx. Logging devices were installed in seventeen vehicles and operational data was collected between August 2022 and October 2022. Two types of vehicles were included in data collection: seven tractors and ten bay trucks. The deployment statistics are summarized in Table 1.

Location	Number	Types	Vocation	Duration	Miles
New York City, NY	17	Tractors, Bay Trucks	Beverage Delivery	Aug–Oct 2022	7,889

Table 1: Deployment Overview

Duty Cycle Analysis

In this section, we discuss the duty cycle characteristics of the Manhattan Beer fleet. Figure 1 illustrates the distributions over vehicle speed and distance disaggregated across the two vehicle types. Although bay trucks are slightly faster than tractors on average, driving speeds and distances are generally low across the fleet. Low speeds and short travel distances suggests the fleet is amenable to electrification, as commercially available batteries and charging infrastructure are capable of meeting the fleet's energy needs.

Figure 2 depicts the distributions over engine run time and idle time for vehicles in the fleet. Engine run times are short, averaging 3 hours per day, and vehicles spend nearly half their time at idle. This suggests that vehicles have substantial charging flexibility and that potential for idling emissions and energy expenditure reduction is meaningful. Table 2 provides further information on the fleet's duty cycle characteristics, listing statistics for various duty cycle parameters for each type of fleet vehicle.

Figure 1: Distributions over driving speed (left) and daily distance (right), disaggregated across vehicle types.

Figure 2: Distributions over engine run time (left) and time at idle (right)

Charging Analysis

In this section, we discuss the fleet's electrification potential. Figure 3 shows the distribution over charging opportunities for vehicles in the fleet, while Figure 4 shows the number of vehicles whose mobility needs can be satisfied given various choices of battery size and charging rate. We find that the majority of vehicle stops exhibit some charging potential, and that there are reliably opportunities for delayed or slow charging. Furthermore, even modest infrastructural choices (e.g., a battery size of 220kWh and a charger with an output power of 70kW) are sufficient to satisfy vehicle mobility needs.

Figure 3: Charging opportunities

Figure 4: Electrification potential

Conclusion

The fleet shows substantial electrification potential, as daily driving distances (below 50 miles) and short and average speed is low (below 22mph). Such duty cycle needs can often be met by even modestly sized battery and charging infrastructure. Furthermore, vehicles spend nearly half of their time at idle and fuel efficiency is low (2 mpg on average), suggesting that electrification can improve energy efficiency. Lastly, these vehicles operate in vulnerable communities where reductions in tailpipe emissions due to electrification may be particularly impactful.

Acknowledgment

The authors would like to thank Manhattan Beer Distributors and the National Renewable Energy Laboratory communications team for their assistance in creating this report. This work was authored 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.

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Future Insights

- Low-Cost Logging Tools
- Joint Office School Bus Cold Weather
- National Parks Service – Doing 3 parks in bold
    - **Acadia**, **Glacier**, Sequoia, Grand Canyon, **Zion**, Bryce, Yosemite

Photo Credit: Mark Kotz

Adaptable **Fleet Evaluation Process**

Step 1 – Vehicle Inventory and Fleet Coordination

Step 2 – In-use Vehicle Data Collection

Step 3 – Duty Cycle Analysis

FleetREDI, Fleet DNA, DRIVE, DriveCAT

Step 4 – Assessment of Advanced Technology and Efficient Operations

FASTSim, RouteE

Step 5 – Infrastructure Requirements and Charging Strategies

EVI-InMotion, EVI-Pro

Step 6 – Total Cost of Ownership

T3CO

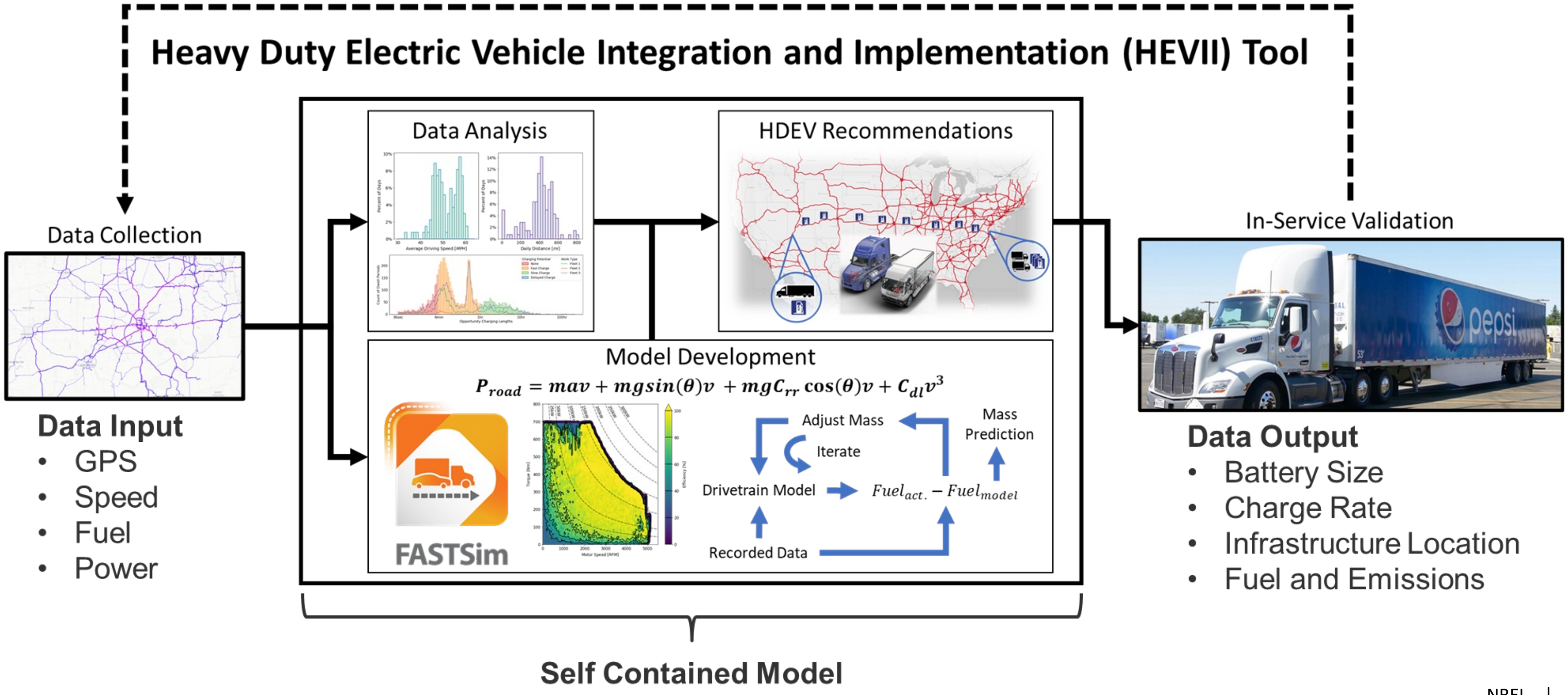
Step 7 – Detailed Charging Infrastructure Requirements

Step 8 – Results / Reporting

Heavy Duty Electric Vehicle Integration and Implementation (HEVII) Tool

HEVII

Leverages multi-fidelity in-use vehicle data to provide owners with customized electrification requirements

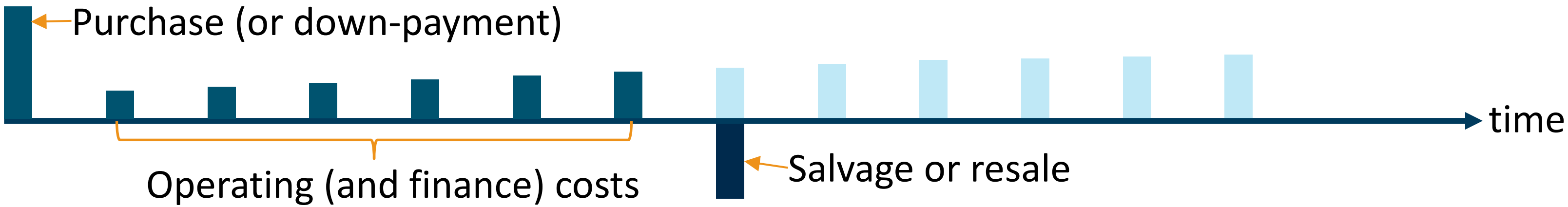


T3CO: Motivation

Commercial vehicle purchases are financial decisions - *within specific functional requirements* and with consideration of soft costs including corporate environmental goals

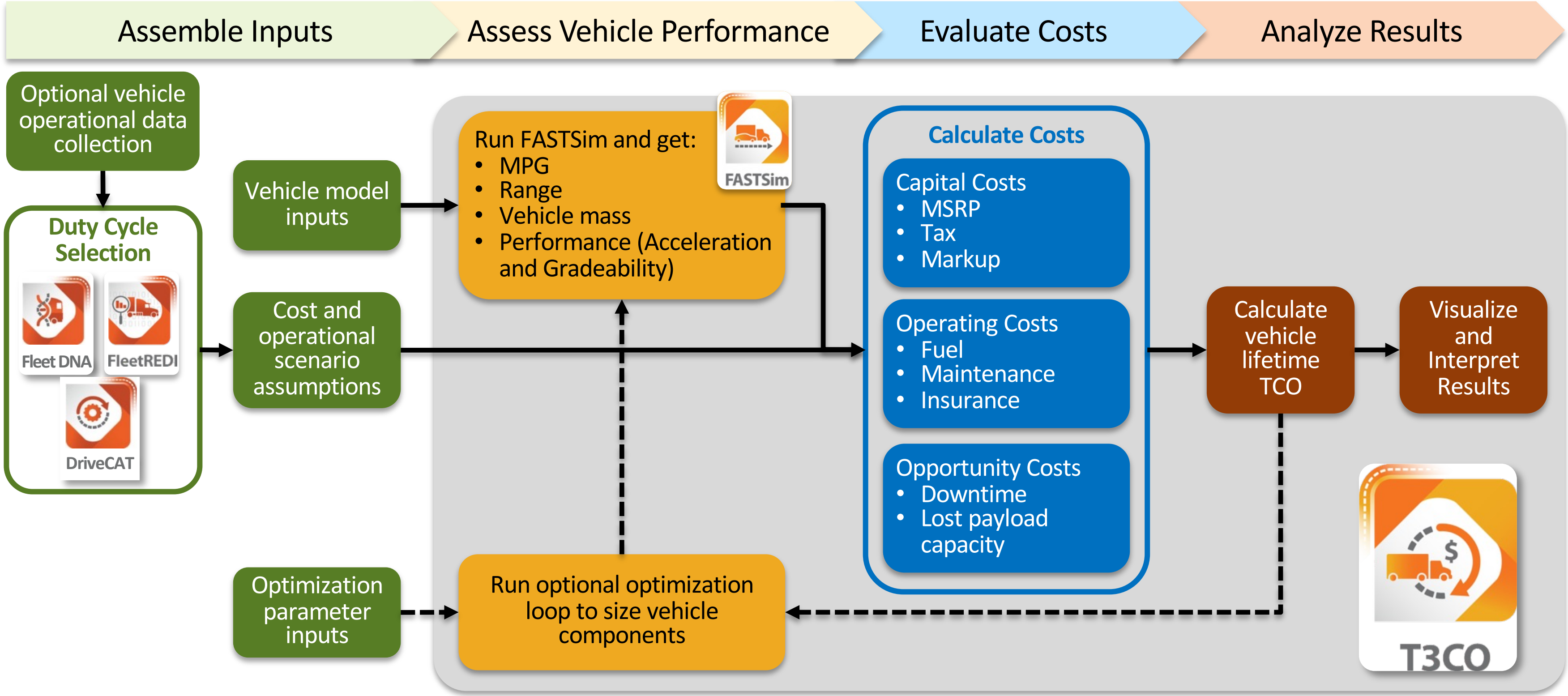
Parity analysis is often used to assess the affordability and uptake of advanced powertrains and establish technical targets, such as battery cost/kWh

- These analyses often overlook ***non-fuel operating costs and "soft" (opportunity) costs*** such as due to payload capacity impacts and the time required to refuel / recharge



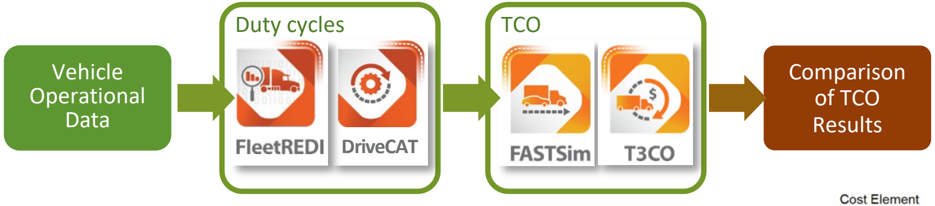
- **Total cost of ownership (TCO)** is the net present value of payments over the ownership period or lifetime, often levelized to \$/mile or \$/ton-mile
- TCO is conceptually straightforward, but often complex and difficult in practice
  - Appropriate discount rate?
  - What costs are important?
  - Data availability
  - Time period / lifetime?
  - How to monetize opportunity costs?
  - Variability day-to-day, fleet-to-fleet

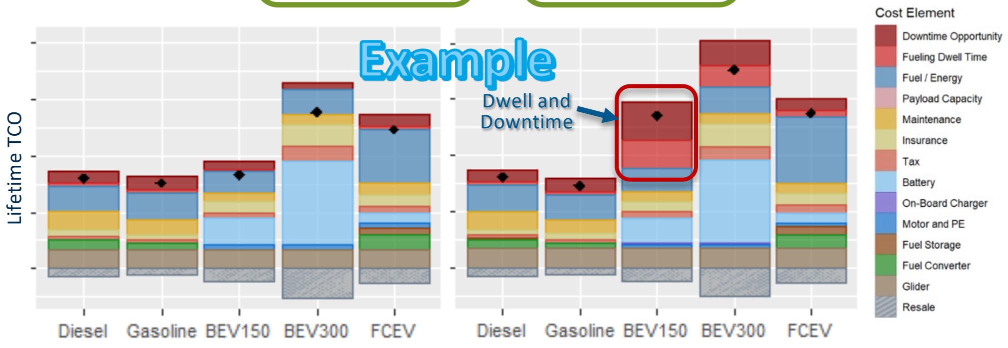
T3CO: Analysis Workflow



https://www.nrel.gov/transportation/t3co.html

T3CO Analysis of **Duty Cycle Variability**





- Hypothetical results for vehicle-level analysis assuming average duty cycle (left) versus statistical combination with inclusion of high energy days (right)
- Fueling dwell time represents driver wages paid while charging the vehicle during the workday
- Downtime represents cost of lost productivity or revenue during charge time and maintenance
- 150-mile BEV is significantly impacted by charge time for duty cycles / days with high energy demand

- T3CO values the cost of dwell time (driver wages to charge during the work period) and downtime (lost opportunity to work / generate revenue)
- T3CO can evaluate large sample data covering the full range of operations
  - Variations in total daily distance and energy intensity (kWh/mi)
- Results can be statistically combined to provide a more realistic vehicle- or fleet-level TCO compared to an average day

EVI-X: Modeling Tools for Forward-Looking EV Analysis

Electric Vehicle Charging Infrastructure Analysis
NREL's EVI-X Modeling Suite

Lite Version Available Online

Network Planning Tools
How many ports are needed in my area? What kind? Where?

Site Design Tools
What is the optimal configuration for my site? What is the expected load profile? Would I benefit from storage?

Network Planning

EVI-Pro
Charging infrastructure projection based on typical daily travel

EVI-OnDemand
Charging infrastructure demand modeling for ride-hailing services

EVI-RoadTrip
Charging infrastructure analysis for long-distance travel

EVI-Connect
Transportation expenditures and infrastructure accessibility

NEVI U-Finder
Charging infrastructure networking data

Site Design

EVI-Ratio
Planning the ratio and type of chargers to vehicles in a fleet

EVI-InMotion
Dynamic and quasi-dynamic charging infrastructure design

EVI-EnSite
Charging infrastructure energy estimation and site optimization

HEVII
Multi-fidelity telematics-enabled vehicle and infrastructure design

EVI-EDGES
Techno-economic evaluation of behind-the-meter storage

Financial Analysis

EVI-FAST
Charging infrastructure financial analysis (free to download)

EVI-LOCATE
Charging station installation design analysis and cost estimation

These financial analysis tools can integrate with any of the tools above.

Financial Analysis Tools
What does it cost to charge? How can this be reduced?

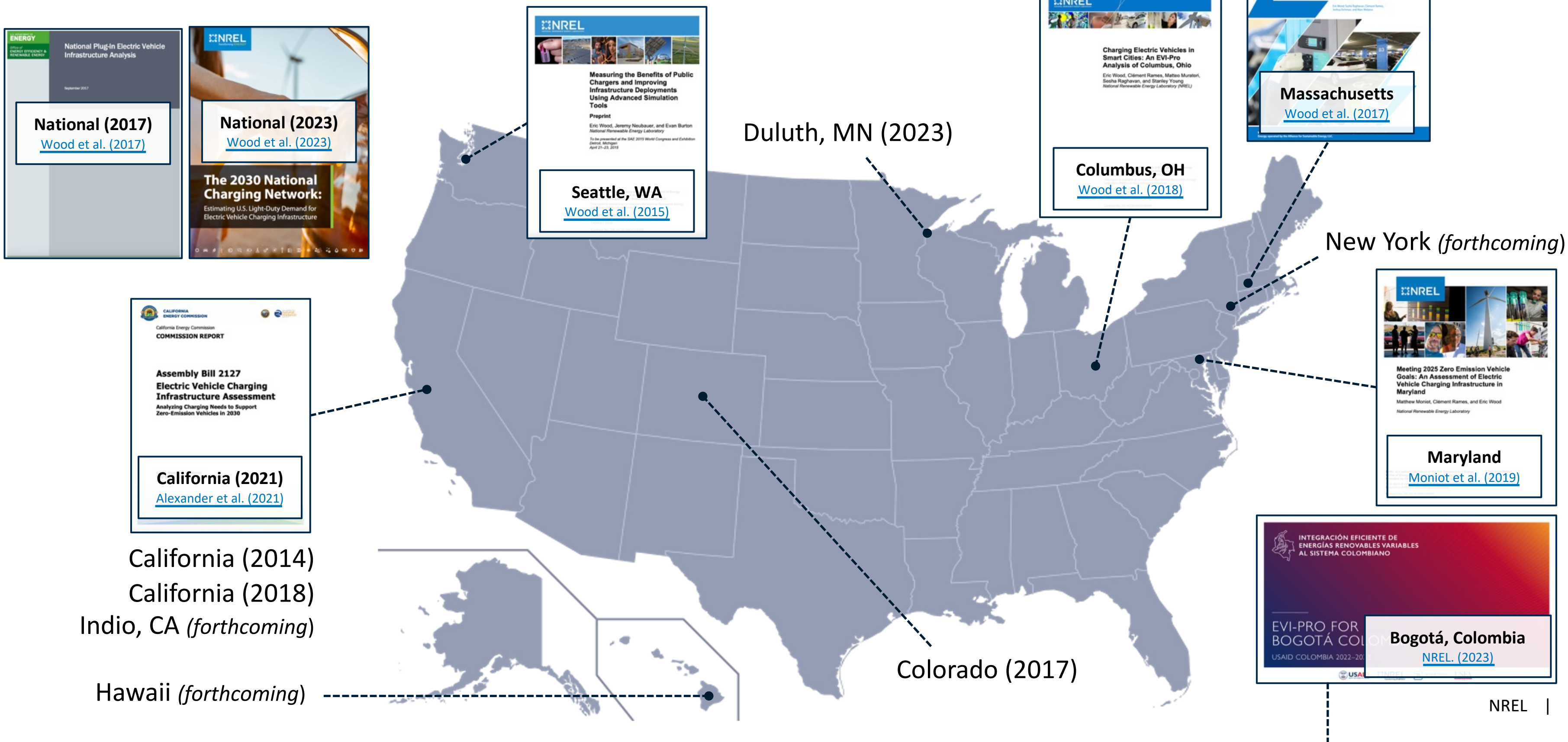
https://www.nrel.gov/transportation/evi-x.html

NREL EV Infrastructure Studies

https://www.nrel.gov/transportation/evi-x.html

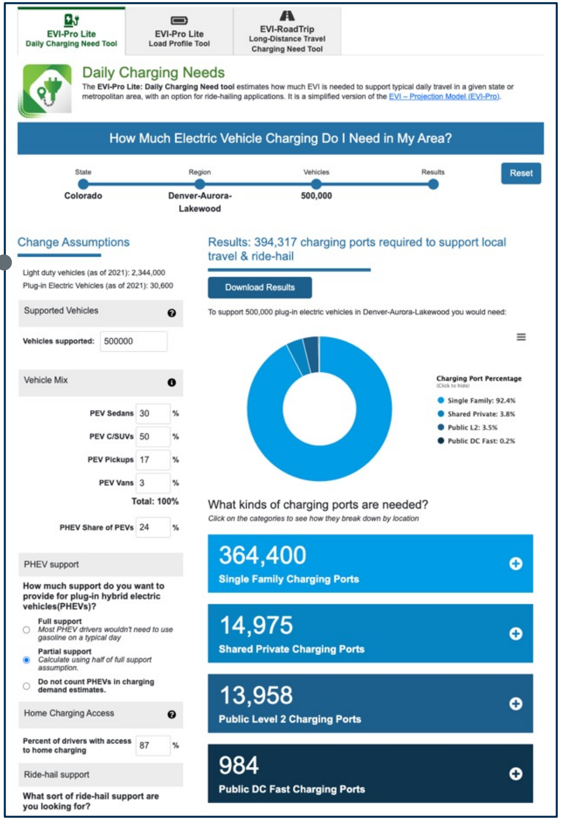
EVI-X

NREL Track Record: >10 studies spanning a decade



Public EV Planning Tools

- **NREL Tools**
  - FleetREDI: Interactive online portal for sharing, discovering, and analyzing integrated commercial vehicle data and energy insights.
  - EVI-Pro Lite: Interactive web tool for estimating regional charging needs and associated electricity demands based on user-defined scenarios.
  - EVI-LOCATE: Interactive web tool for developing comprehensive EV station deployment plans.
  - EVI-FAST: Financial analysis tool for EV charging infrastructure.
- **Non-NREL Tools**
  - AFDC Station Locator: Displays publicly accessible alternative fueling stations in the United States, Canada, and soon-to-be Mexico.
  - EPRI eRoadMap: Mapping tool that estimates the power and energy needs for electrifying transportation at the local level.



https://afdc.energy.gov/evi-x-toolbox#/evi-pro-ports

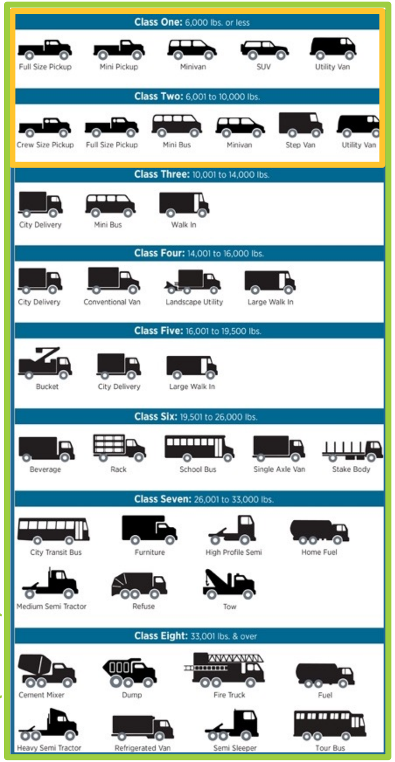
Commercial EV Charging Concepts

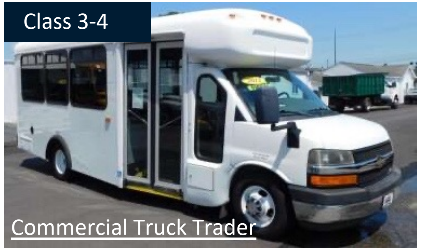
Commercial Vehicles Come in **All Shapes & Sizes**

Personal vehicles (Class 1-2)

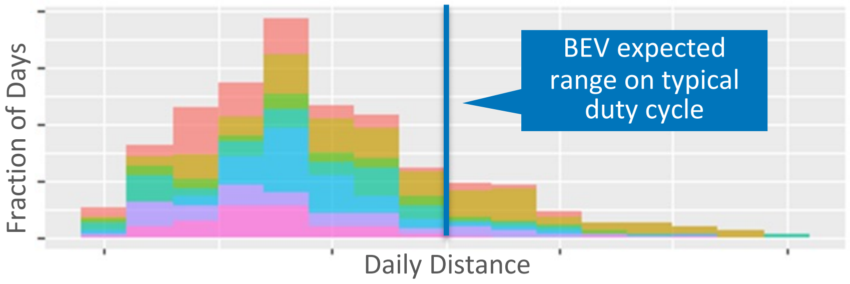
Commercial vehicles (Class 1-8)

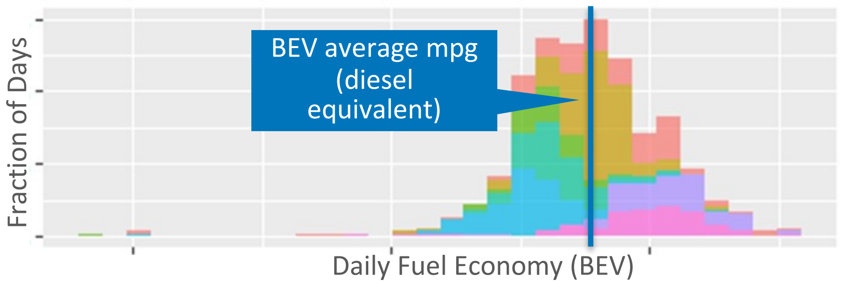
U.S. FHWA Classifications

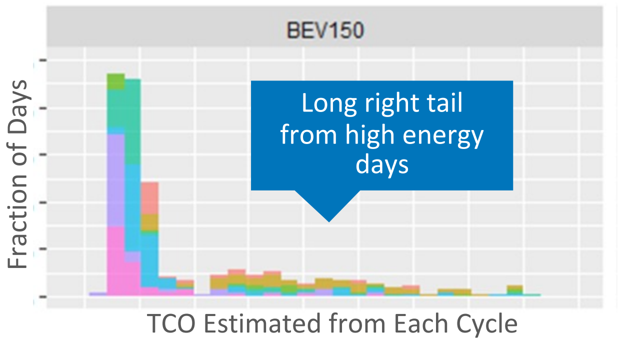




Average ≠ Max Requirements





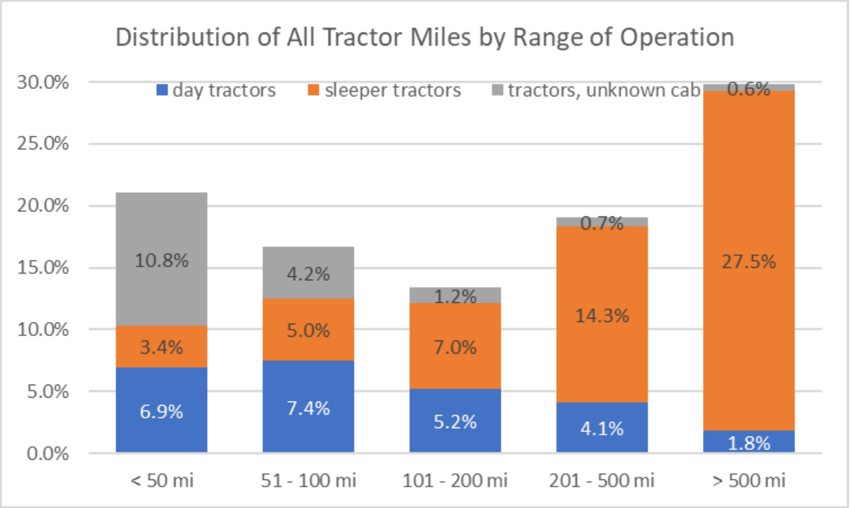


- While vehicle range may seem sufficient to cover average trip distance or even most daily trips, days with longer distances or higher energy intensity (lower mpg) can result in the need for mid-shift refueling / charging
- Previous research shows that including high energy days can alter conclusions about best-fit technology
- These results can also inform charge power requirements to minimize cost or productivity impacts

Freight Operations **Evolve Over Time**

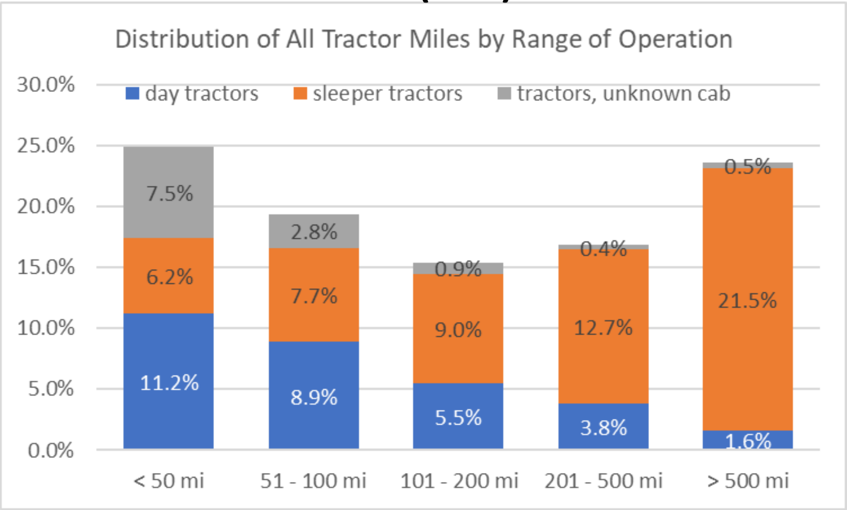
U.S. freight operations have shifted over time, driven by the growth of e-commerce, supply chain localization, and efforts to improve driver retention.

2002 (U.S.):



21% 17% 13% 19% 30%

2021 (U.S.):



25% 19% 15% 17% 24%

+8% vs. 2002 *-8% vs. 2002*

Source: NREL analysis of 2002 & 2021 VIUS

Commercial vs. Personal EV Charging

EV Charging Expectations:

More vehicles with **lower electricity demands**

Charging is **geographically distributed**

Power level: several kW to **hundreds of kW per vehicle**

Spend **95% of the time parked** (opportunity for managed charging)

Personal Vehicles

VS.

Commercial Vehicles

Fewer vehicles with **higher electricity demands**

Charging is more **geographically concentrated**

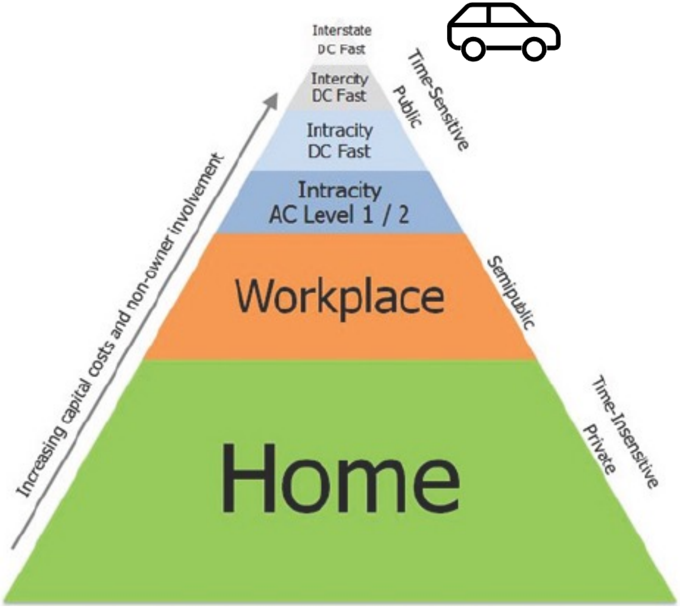
Power level: tens of kW to **1+ MW per vehicle**

Spend **less time parked**, but **may have more predictable operations** enabling managed charging

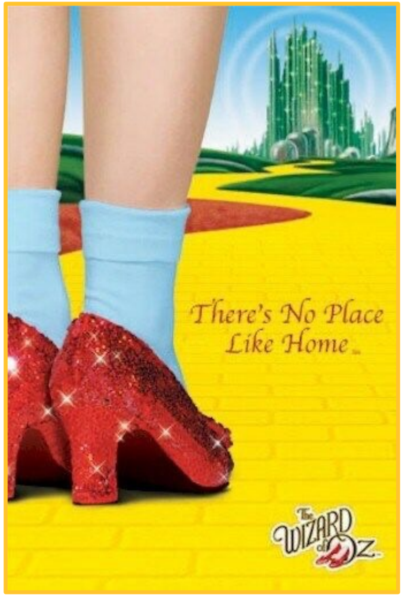
Personal LDV Charging: *"There's No Place Like Home"*

Home charging is the **most convenient and preferred LDV charging option today** and represents the majority of EV electricity demand in most countries.

LDV Paradigm:



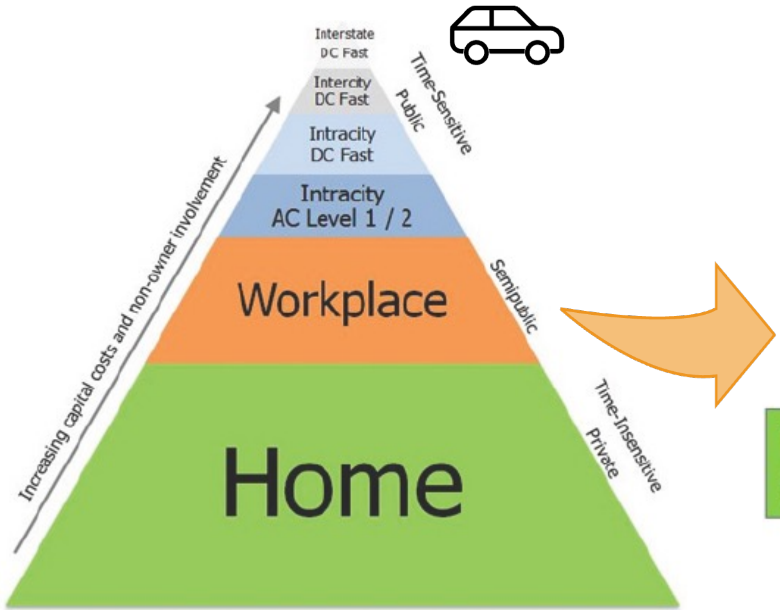
National Research Council (2015)



MHDV Charging: *"There's No Place Like ~~Home~~ the Depot"*

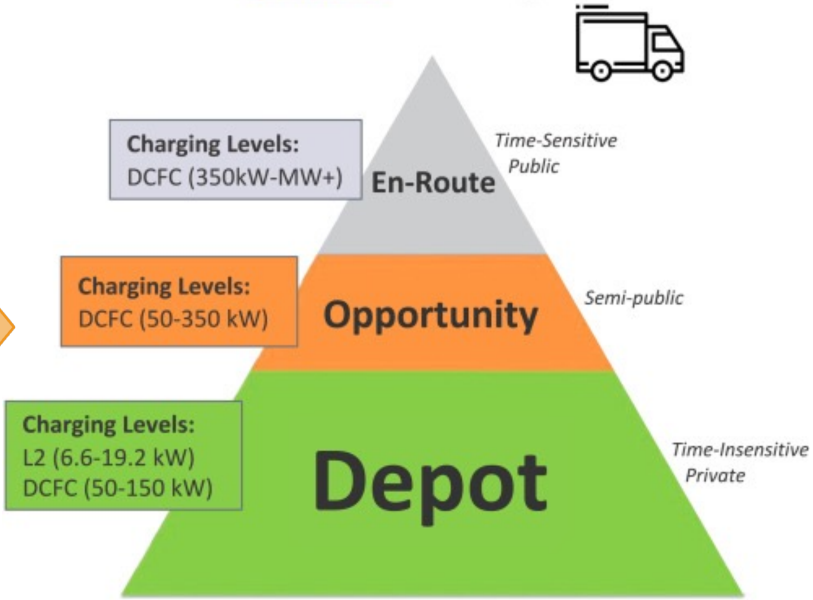
For commercial vehicles, private depot charging could play a similar role, representing the majority of EV electricity demands for limited-range operations.

LDV Paradigm:



National Research Council (2015)

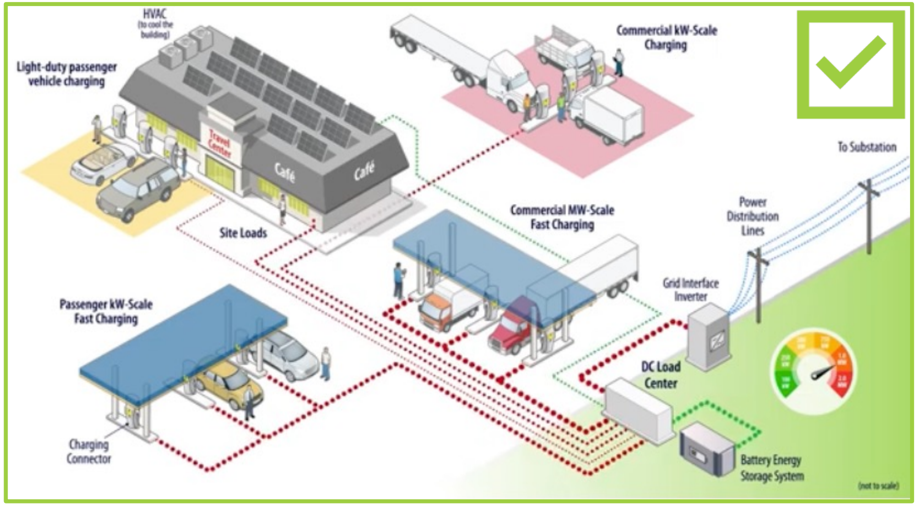
MHDV Paradigm:



Muratori et al. (2023)

MHDV Charging: **Maneuverability Constraints**

Electric semi truck blocking IONITY chargers (source: Elektrotrucker)



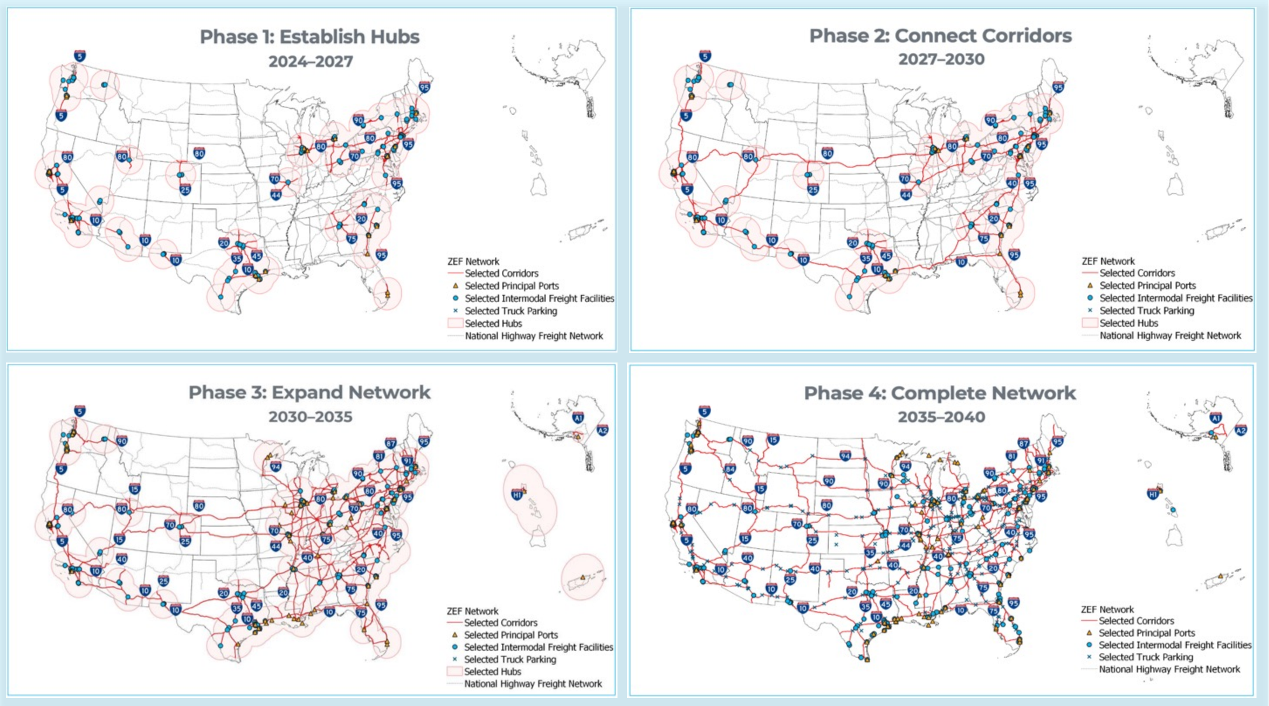
"Charging plaza of the future" can charge a variety of vehicles at different rates depending on the application.

Smaller Commercial Vehicles May Be Able to **Leverage Established Passenger Vehicle Charging Networks**

Electrek

Phased Rollout of MHDV Charging Network

Costly and time-consuming commercial EV charging infrastructure installations can be **phased in over time**, with an initial prioritization around favorable launch areas.



***Targeted & strategic** <u>not</u> everything everywhere all at once*

Key Studies

FleetREDI **Electrification Analysis**

In partnership with Manhattan Beer Company and All Aboard America Holdings, NREL identified pathways for electrification using FleetREDI

Duty Cycle Analysis:

- **Beverage Delivery –** 17 vehicles total: 6 tractors and 11 bay trucks
  - Low speeds and short distance conducive to electrification: 11 MPH & 22 mi avg
  - Engine run times less than 5 hours for 90% of days with about 50% of time at idle
- **Charter Bus –** 9 intrastate motorcoaches(~34,000 mi of travel)
  - Considerable difference in requirements for I-70 routes vs I-25 routes:
    - I-70 corridor daily median – 278 mi & 715 kWh engine energy
    - I-25 corridor daily median – 192 mi & 482 kWh engine energy
  - Market options may be insufficient for more intensive days

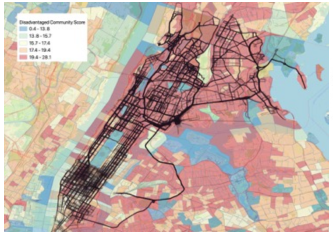
Key Takeaways:

- Manhattan Beer fleet has great electrification potential: with 220 kWh batteries and 70kW charging power, all vehicles can be charged during 2 hour stops
- About 78% of AAA's fleet observed could be satisfied with current EV market options, however, high grade and longer distances of I-70 routes provide additional electrification challenges.

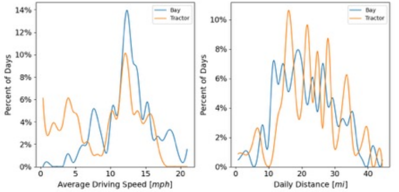
Significance & Impact

- Manhattan Beer vehicles operate mostly in densely populated areas, so electrification would reduce the impact of criteria pollutants in these communities
  - High idle fuel consumption and energy costs could be reduced
- Vehicle/route candidates identified for near-term electrification and target vehicle requirements determined for more demanding operations in AAA's fleet

Left: Manhattan Beer Tractor; Right: AAA Charter Bus Motorcoach

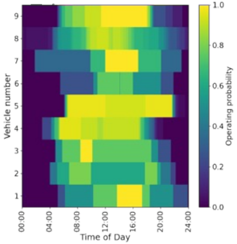


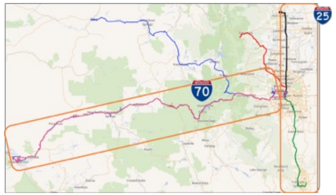
Beverage Delivery



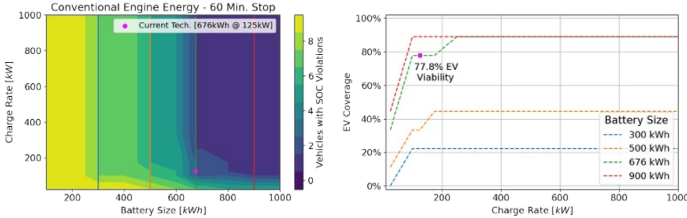
Beverage Delivery Duty Cycle Analysis

AAA Operating times heatmap





AAA Routes



AAA Electrification Viability Model

Drayage Electrification Analysis

In partnership with the Port Authority of New York & New Jersey, NREL has identified pathways for drayage electrification for the studied fleets using NREL's advanced analytics.

Duty Cycle Analysis:

- 46 diesel vehicles across 3 fleets ~ 36 million data points (120,000 miles)
- 86% of days below 250 miles of operation
- Diesel Tractors: 5.4 MPG, 2.7 gal/hr, 26 gallons per day average
- 338 kWh day average mechanical energy with 8.9% spent at idle
    - Some days up to 1,680 kWh
    - 375 kWh batteries currently available
- FASTSim, hotspot, dwell period, and emissions analysis performed in this study

Key Takeaways:

- Partial Electrification possible today with 375 kWh battery – battery size increase will be the main driver of future electrification potential
- 75% reduction of CO_2 with current grid (76 $MTCO_2$ per year per vehicle)
- Fleets will switch to industrial pricing with addition of single charger > 150 kW
- Electric trucks will be cost-competitive with diesel at $3/gal and $0.21/kWh

Significance & Impact

- PANYNJ has goal to achieve net-zero carbon emissions by 2050 and *electrifying the studied fleets will remove 24,100 $MTCO_2$ each year*
- Drayage trucks are significant contributors of port-related NO_X pollution – *>75% reduction expected from electrification in NY/NJ non-attainment zone*

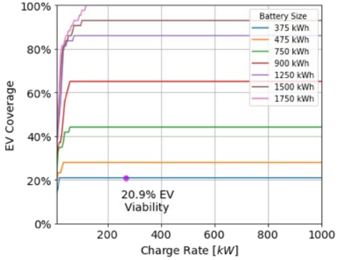
Dollar-per-Mile Savings From Electrification [$/mi]

Fuel Price [$/gal] \ Electricity Price [$/kWh]	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
6.00	1.06	0.94	0.82	0.70	0.58	0.46	0.34	0.22	0.10
5.50	0.96	0.84	0.72	0.60	0.48	0.36	0.24	0.12	0.00
5.00	0.86	0.74	0.62	0.50	0.38	0.26	0.14	0.02	−0.10
4.50	0.76	0.64	0.52	0.40	0.28	0.16	0.04	−0.08	−0.20
4.00	0.66	0.54	0.42	0.30	0.18	0.06	−0.06	−0.18	−0.30
3.50	0.57	0.45	0.33	0.21	0.09	−0.03	−0.15	−0.27	−0.39
3.00	0.47	0.35	0.23	0.11	−0.01	−0.13	−0.25	−0.37	−0.49
2.50	0.37	0.25	0.13	0.01	−0.11	−0.23	−0.35	−0.47	−0.59
2.00	0.27	0.15	0.03	−0.09	−0.21	−0.33	−0.45	−0.57	−0.69

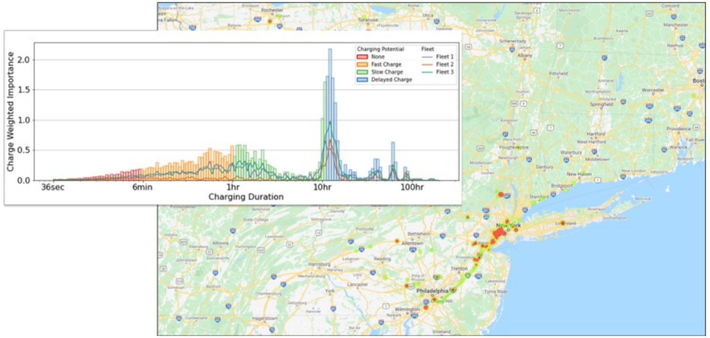
Electrification Trade-off Analysis

Diesel Drayage Truck

Vehicle Charging Potential



Charging Opportunity and Placement Analysis



School Bus Electrification Analysis

With support from the Joint Office of Energy and Transportation, NREL is collecting and analyzing detailed duty cycle data from several school bus fleets that have begun operating electric school buses (ESBs).

Goals

- Understand ESB efficiencies and range compared to other baseline conventional bus technologies
- Develop lessons learned on transitioning a school bus fleet to electric through collection and analysis of ESB route and vehicle performance data

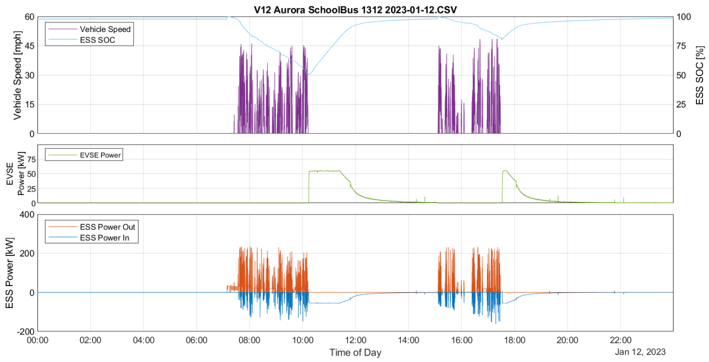
Data Collection and Analysis:

- 70+ school buses across 3 fleets—25 electric, 22 diesel, 16 propane, 8 gas
  - School districts in CO and OR, expanding to other locations
  - Summer and winter data collection periods
  - Multiple ESB OEMs
- Evaluating standard duty cycle metrics to compare across fuel types, as well as developing ESB-specific analyses
- Investigating cold weather impacts to energy consumption rates and range, charging performance, etc.

Significance & Impact

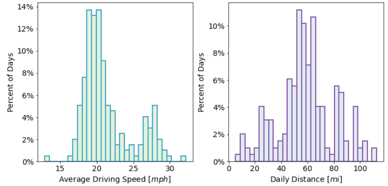
- FleetREDI highlights current ESB performance to support Joint Office electrification program and enable broader deployment of ESBs nationally
- Provides new data for cold weather and V2G applications

ESB Daily Operating and Charging Profiles

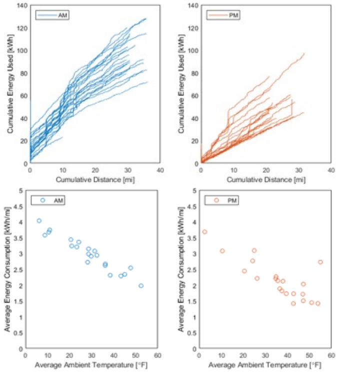


Aurora, CO ESBs

Duty Cycle Analysis

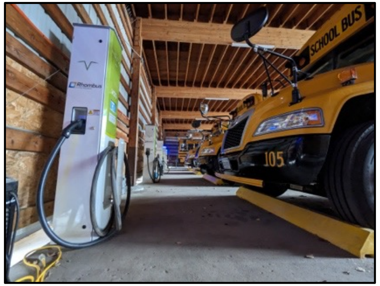


Cold Weather Energy Impacts



Joint Office of Energy and Transportation

Steamboat, CO ESBs

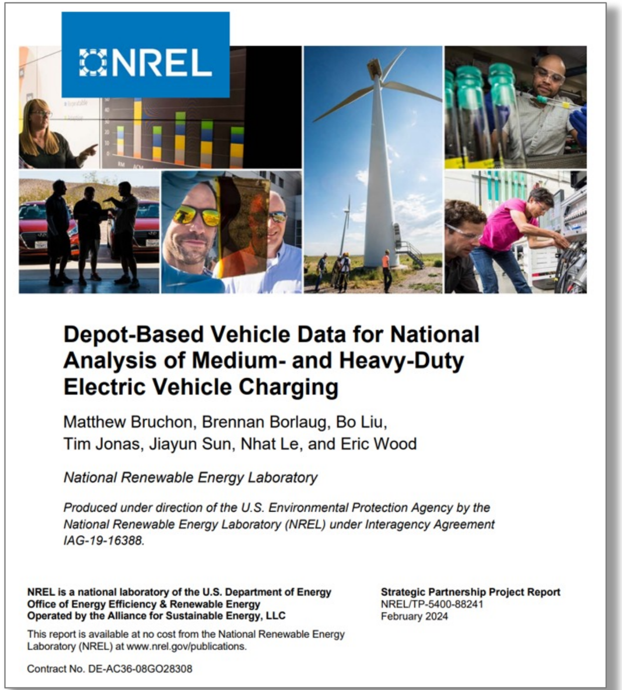


MHDV Operating & EV Charging Requirements

Challenge:
Many outstanding uncertainties around MHDV electrification…

- *How many MHDVs are "easily electrifiable"?*
- *How many MHDVs may be more challenging to electrify?*
- *How does this vary by vehicle type and vocation?*

Contribution:
Public dataset summarizing typical operations across various MHDV types.


NREL

Depot-Based Vehicle Data for National Analysis of Medium- and Heavy-Duty Electric Vehicle Charging

Matthew Bruchon, Brennan Borlaug, Bo Liu, Tim Jonas, Jiayun Sun, Nhat Le, and Eric Wood

National Renewable Energy Laboratory

Produced under direction of the U.S. Environmental Protection Agency by the National Renewable Energy Laboratory (NREL) under Interagency Agreement IAG-19-16388.

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Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Strategic Partnership Project Report
NREL/TP-5400-88241
February 2024

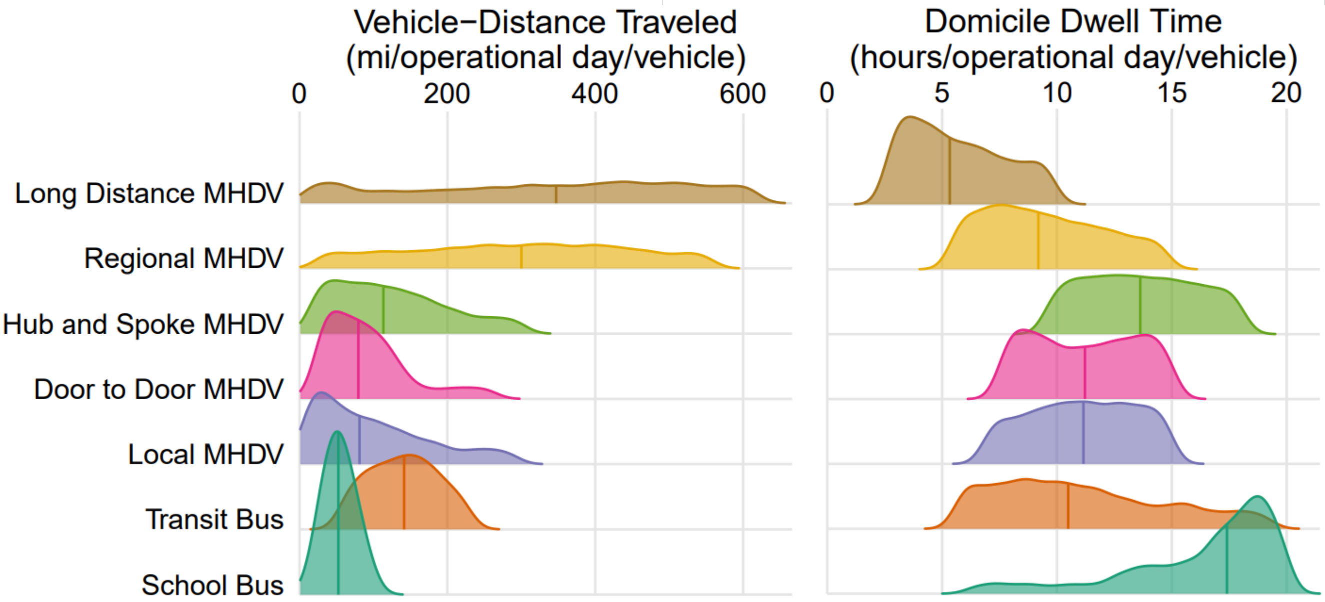
data.nrel.gov/submissions/231

MHDV Operating Distributions

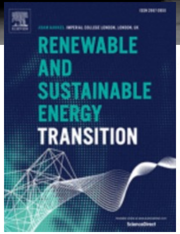
- Higher daily miles
- Shorter depot dwells

- Typically driven less than 200 miles/day
- More depot charging potential

Typical operations (10th-90th percentile)



Bruchon, Matthew, Brennan Borlaug, Bo Liu, Tim Jonas, Jiayun Sun, Nhat Le, Eric Wood. "Depot-Based Vehicle Data for National Analysis of Medium- and Heavy-Duty Electric Vehicle Charging". National Renewable Energy Laboratory. NREL/TP-5400-88241. February 2024.



ELSEVIER

Renewable and Sustainable Energy Transition

Volume 2, August 2022, 100038

Full-length article

Charging needs for electric semi-trailer trucks

Brennan Borlaug [a], Matthew Moniot [a], Alicia Birky [a], Marcus Alexander [b], Matteo Muratori [a]

Paper:

https://doi.org/10.1016/j.rset.2022.100038

Data:

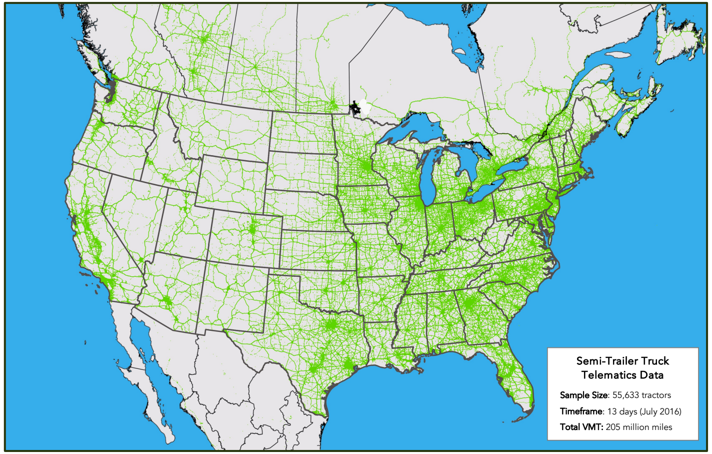
https://data.nrel.gov/submissions/198

Charging Needs for Heavy-Duty Trucks

Motivation:

Significant uncertainty regarding the charging needs for heavy-duty battery electric trucks (HDBETs):

- *How might they charge?*
- *…at what power levels?*
- *…and where?*



Telematics data used to simulate heavy-duty charging requirements

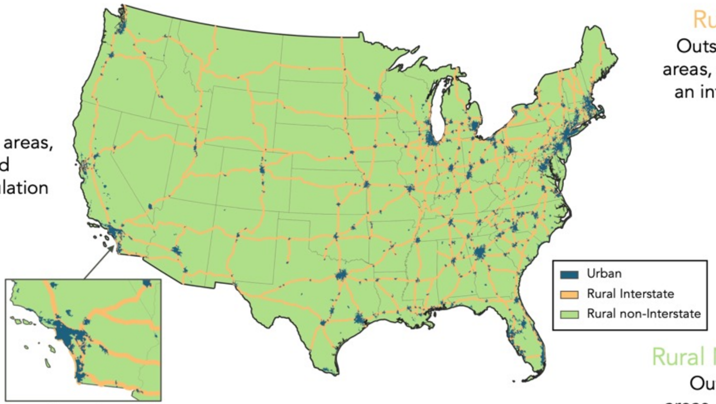
Objective:

Use **large-scale Class-8 telematics data** (~56k trucks) to **simulate heavy-duty battery electric truck (HDBET) charging** and empirically assess requirements for charging HDBETs with multiple battery ranges and across operating segments (local, regional, long-haul).

Off-shift Charging Can Supply the Majority of Electricity Demand for Heavy-Duty Trucks

Simulated charging events are assigned as either urban, rural interstate, or rural non-interstate based on their location and proximity to the U.S. interstate highway system.

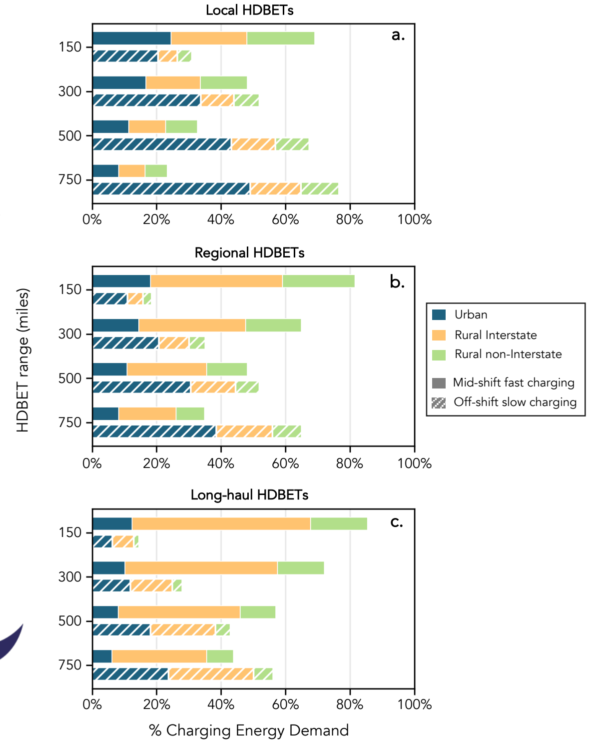
Urban
Census urbanized areas, densely developed regions with population ≥50,000.



Rural Interstate
Outside of urbanized areas, within 5 miles of an interstate highway

Rural Non-Interstate
Outside of urbanized areas, not within 5 miles of an interstate highway

Shares of Electricity Demand by HDBET Segment, Battery Range, and Location Type



Key Findings:

- Many **local applications** can be electrified with current/near-term battery electric trucks (500-mi battery range or less) and **off-shift charging (150 kW or less)**.
- Most **regional and long-haul applications** will require public **MW-level charging (1-2 MW)** which is not widely available in the United States.
- **Depot-based short-distance operations should be first to electrify** due to limited near-term battery ranges and lack of public high-speed (i.e., MW+) charging infrastructure. These fleets tend to operate near urban areas.

Summary & Next Steps

Summary

- **Commercial vehicles** encompass a wide range of vehicle types and operations, each with unique EV charging requirements.
  - **Local return-to-base operations** (e.g., school buses) may be easily electrified with depot charging alone.
  - **Long-distance operations** will likely require large batteries and MW-level charging (not yet widely available in the U.S.).
  - **Majority of MHDV charging can take place off-shift** at similar power levels to light-duty DCFC if charging infrastructure is installed at these locations.
- **EV charging networks** should provide sufficient coverage and capacity.
- **Commercial charging infrastructure deployments** may be phased in over time to reduce costs and improve network efficiency.
- **NREL has developed unique capabilities** to study the opportunities and impacts of MHDV electrification – EVI-X, TEMPO, FleetREDI, T3CO, etc.

Next Steps

Future Research Questions:

- What **charging infrastructure** is needed to support commercial EVs? By when, where, and at what cost?
- What are the **load profiles** and potential **grid impacts** of MHD EV charging? Can these loads be effectively managed through **passive and active management strategies** and at what cost?
- What are the **least-cost solutions** for **"hard-to-electrify"** segments like long-haul and off-road vehicles?
- How much **operational flexibility** do commercial vehicles have? How might operational requirements evolve as **new technologies** emerge?
- How can **emerging technologies** increase freight system efficiency, reduce costs, and strengthen supply chain resilience?

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NREL

Supplemental

Analysis to Inform a **Sustainable Mobility Future**

Evolving Mobility Options

Automation, mobility-as-a-service, telepresence, micromobility, urban air mobility, etc.

Efficient Travel Modes & Vehicles

Affordable, efficient solutions for all people and markets

Electrification & Sustainable Fuels

Next-generation powertrains with reduced environmental impact

Energy Systems Integration

Integrate transportation with energy systems and supply networks

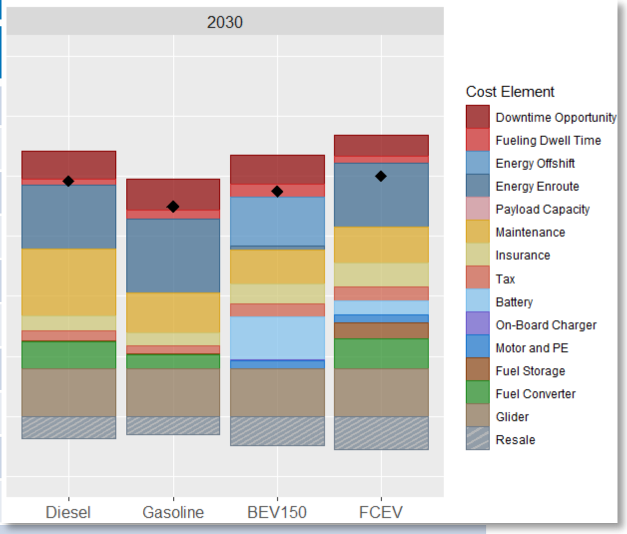
CVT Capabilities Overview

	Operational Data Collection and Analysis	Vehicle-level Simulation and Analysis	Infrastructure Analysis	Techno-economic Analysis	Integrated System Analysis
Tools	• Fleet DNA • FleetREDI • Fleet Chromosomes • DRIVE • DriveCAT	• FASTSim • RouteE • AeroSim • MarineSim • ALTRIOS • HEVII • CoolCalc • CoolSim	• HEVII • EVI Pro HD • EVI InMotion • SERA	• T3CO • VICE • HD ADOPT • TRUCK & HDStock • TEMPO	• FAMOS • ALTRIOS • INFORMES
Example Research	• Vehicle and infrastructure design requirements • Site and fleet level assessments: opportunities for advanced technologies and operational efficiency • Representative drive cycles • Load profiles	• Advanced technology component requirements • Advanced powertrain performance and benefits • Powertrain suitability • Advanced thermal systems	• Infrastructure requirements and design	• TCO comparison across powertrains; duty cycle impacts • Market adoption and dynamics • Component costs required to meet market needs • Technology benefits at market level	• Opportunities for / benefits of advanced powertrains and operational efficiency in freight systems • Fueling infrastructure requirements • Freight system efficiency and resiliency

- The 1 Hz operational data contained in Fleet DNA was identified by stakeholders as a primary need to support a wide range of commercial vehicle research and development
- Our suite of capabilities and tools encompass the spectrum from vehicle- to system-level analysis
- We continually work to integrate and enhance our tools to address research questions from a complex systems perspective
- CVT strives to maximize public access to data, tools, and analysis results

T3CO Cost Elements and Features

		Cost Element/Feature	Notes and sources
Cost Elements	Capital	Purchase cost (MSRP)	Vehicle listings, component assumptions
		Lease, Finance costs	Coming soon (v2.0)
		Sales / Excise Tax	Dependent on price paid
		Resale / Salvage	Used vehicle listings, literature review
	Operating	Insurance	MSRP - dependent on price
		Fuel / Energy	Enroute charging vs. overnight (v2.0)
		Maintenance	Literature review, fleet evaluations
		Labor	Coming soon (v2.0)
		Refueling Dwell Time	Labor costs
	Oppor-tunity	Refueling Down Time Opportunity	Lost productivity
		Maintenance Down Time Opportunity	Lost productivity
		Payload Capacity Loss	Cost of more vehicles (class 8 freight); cost of increasing weight class
Features		Dynamic power transfer	Fraction of energy from on-road charging; input value or estimate from FASTSim or EVI-InMotion; alters range and refueling time
		Batch Mode	Automates running a large set of drive cycles for variability analysis
		Parallelization/Multiprocessing	Ability to utilize multiple processors to run large scenario sets
		Results Visualization	R, Python; future web app
		Web-based interface	T3CO-Go



Future work is subject to change based on funding levels

T3CO Status and Future Work

	Powertrain Simulation	TCO Estimation	Variation in TCO / Fleet	Opportunity Costs	Free and Open Source	Fast	GUI
T3CO	✓	✓	✓	✓	✓	✓	✓ T3CO-Go

Applications (Past and Current Projects)

- DOE VTO Transportation Analysis
  - EEMS SMART 2.0 – BEAM Freight scenarios
- EPA – analysis to inform rulemaking and certification drive cycle development
- SuperTruck 3 – Ford MD FCEV
- EVs@Scale Wireless Power Transfer
- Federal Transit Administration – transit bus selection tool
- Electric School Bus evaluation
- VGI Toolkit Integration

Future Work

- ☑ Results visualization template
- ☑ Web API
- ☑ Web-based interface
- ☑ Decoupling from FASTSim for use with other simulation tools or exogenous inputs
- ☑ Annual cash flow
- ☑ Finance / lease costs
- ☐ Emissions calculation with regional resolution
- ☐ User feedback is identifying other high-value additions

Future work is subject to change based on funding levels

National Park Electrification Studies

NREL is assisting National Parks Service identify pathways for shuttle bus electrification using NREL's FleetREDI Platform

National Parks:

Zion, Bryce Canyon, Yosemite, Grand Canyon, Rocky Mountain, and Acadia National Parks

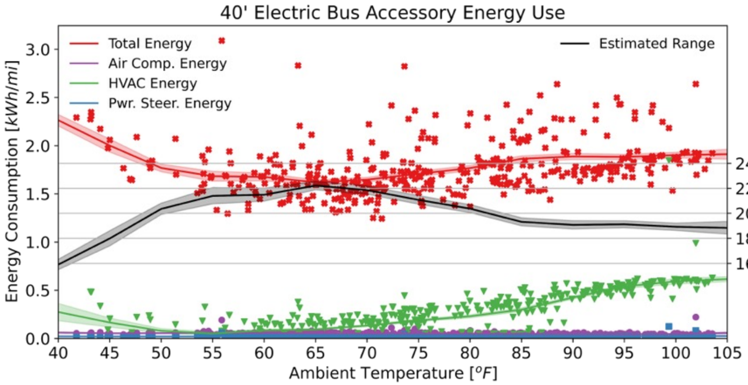
Collect in-use data to understand operational needs

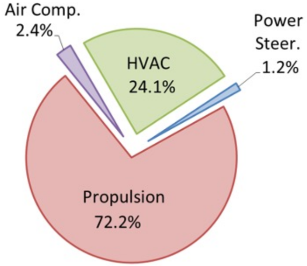
- 1Hz data, EV & conventional buses

Provide battery size, charge rate, and cooling needs

Key Findings:

- **HVAC nearly ¼ of the bus energy use**





EVI-X: Network Planning

Charging networks should provide sufficient coverage & capacity!

EVI-Pro is a simulation model that:

– Models **daily charging demands** for EVs

– Designs **supply of infrastructure** to meet demand

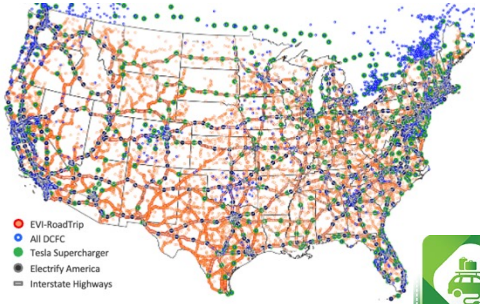
Models EV driver charging behaviors for a given set of assumptions around EVSE access and charging preferences.

Originally developed through a collaboration with the California Energy Commission, EVI-Pro has been applied in multiple city-, state-, and national-level studies

EVI-Pro

https://www.nrel.gov/transportation/evi-pro.html

EVI-RoadTrip estimates EV charging demands along highway corridors for long-distance travel (road trips).



EVI-RoadTrip

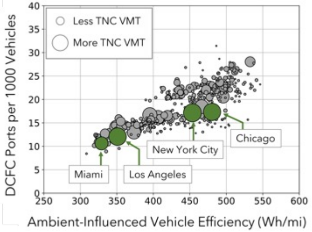
https://www.nrel.gov/transportation/evi-roadtrip.html

EVI-OnDemand estimates DC fast charging infrastructure requirements for ride-hail EVs considering:

– Local weather/driving conditions

– Typical driver shift lengths

– Home charging access for ride-hail drivers

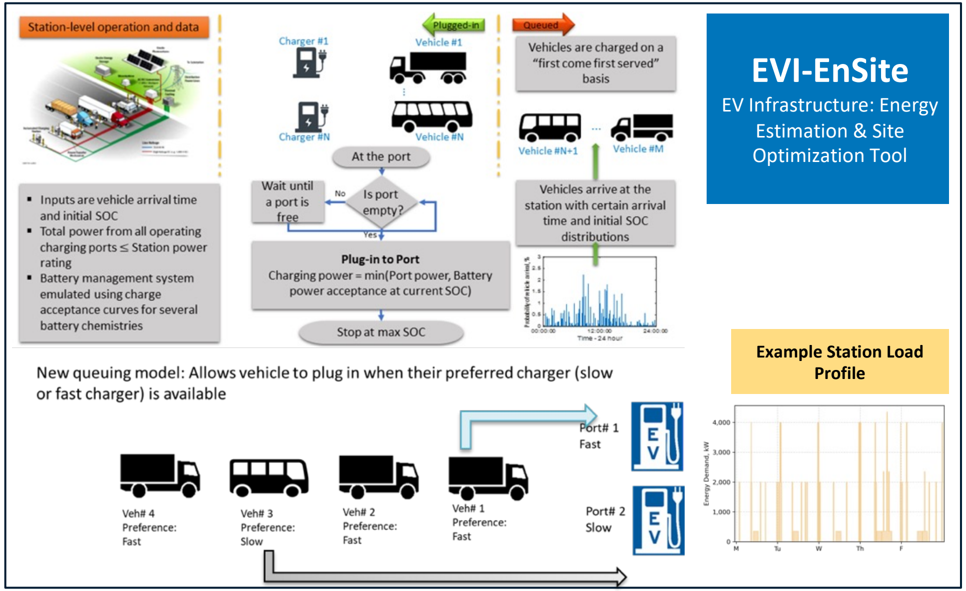


EVI-X: **Site Design**

EVI-EnSite – agent-based charging station modeling and analysis tool to investigate site operating requirements.

- **Charging Station design parameters**:
  - Station power capacity
  - Number of ports
  - Port power capacity
- **Used to answer questions such as:**
  - *How should EV charging stations be designed?*
  - *How much queuing is expected at a proposed station?*
  - *What site-level control policies can reduce grid requirements while limiting inconvenience?*
  - *What is the average utilization of a station?*
  - *What is the total power demand of a station?*

https://www.nrel.gov/transportation/evi-ensite.html



EVI-EnSite simulates EV station operations, producing site load profiles and performance metrics like station peak and average power demand, energy delivered by port type, and vehicle queuing statistics.

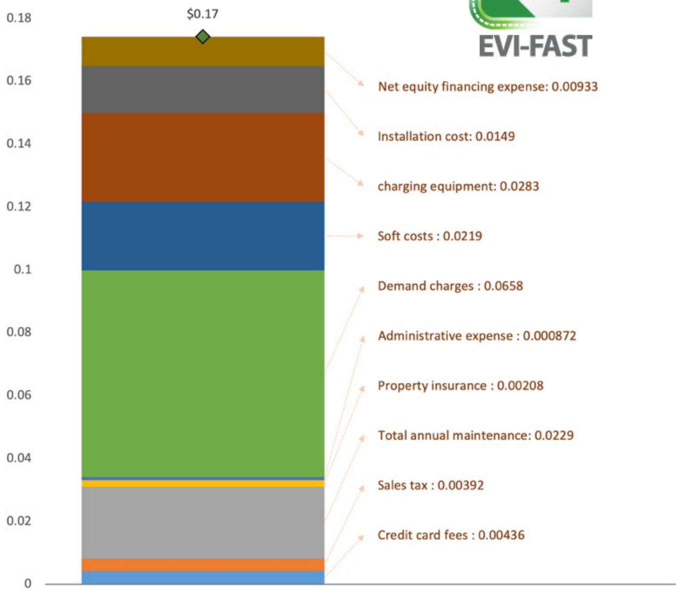
EVI-X: Charging Station/Network Economics

https://www.nrel.gov/transportation/evi-fast.html

EVI-FAST – EV station financial analysis tool

- **Publicly accessible** tool for in-depth financial scenario analysis of EV charging stations.
- **Highly configurable** – inputs include station design (power capacity), utilization, costs (equipment, installation, and operating), incentives, and financing assumptions.
- Calculates financial performance metrics including **investor payback period**, **net present value**, and the **levelized cost of charging** ($/kWh) for each station scenario.
- Used in multiple recent DOE analyses[1,2]

Breakdown of Station LCOC ($/kWh)



EVI-FAST estimates the levelized cost of charging (i.e., the breakeven cost of charging inclusive of capital expenses (e.g., EVSE), operating costs (e.g., electricity purchases), and financing assumptions) for EV charging stations.

[1] Borlaug et al., 2020, "Levelized Cost of Charging Electric Vehicles in the United States"

[2] Bennett et al., 2022, "Estimating the Breakeven Cost of Delivered Electricity to Charge Class 8 Electric Tractors"

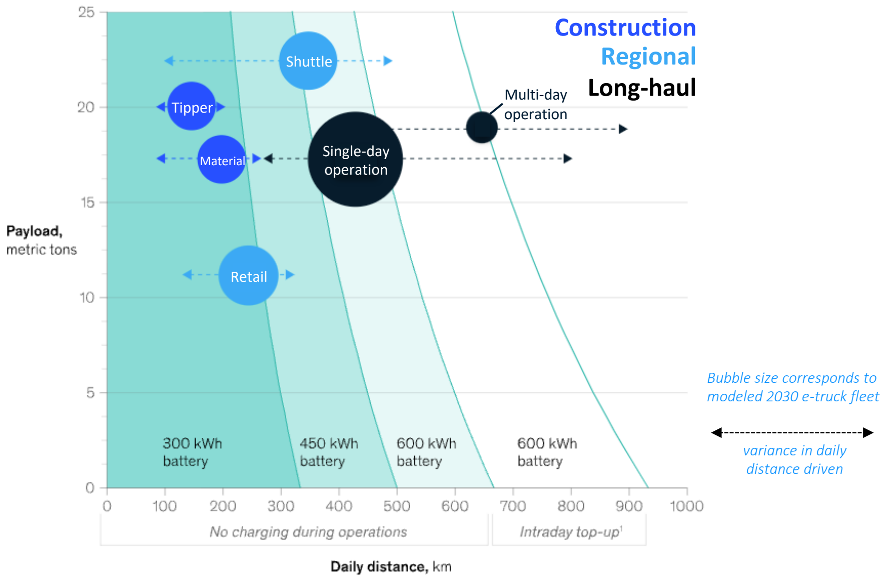
Commercial Vehicles: **Varying EV Requirements**

Bigger Payloads:
More charging or larger batteries required

Higher daily distance:
More charging or larger batteries required

Charging infrastructure, driving patterns, and battery sizes have to be optimized in concert to efficiently electrify truck operations.

2030 view, use cases



[1]Assumes charging during mandatory break of 45 minutes at 400 kW DC charger.

McKinsey & Company

adapted from:
Herlt & Hildebrandt (2024)

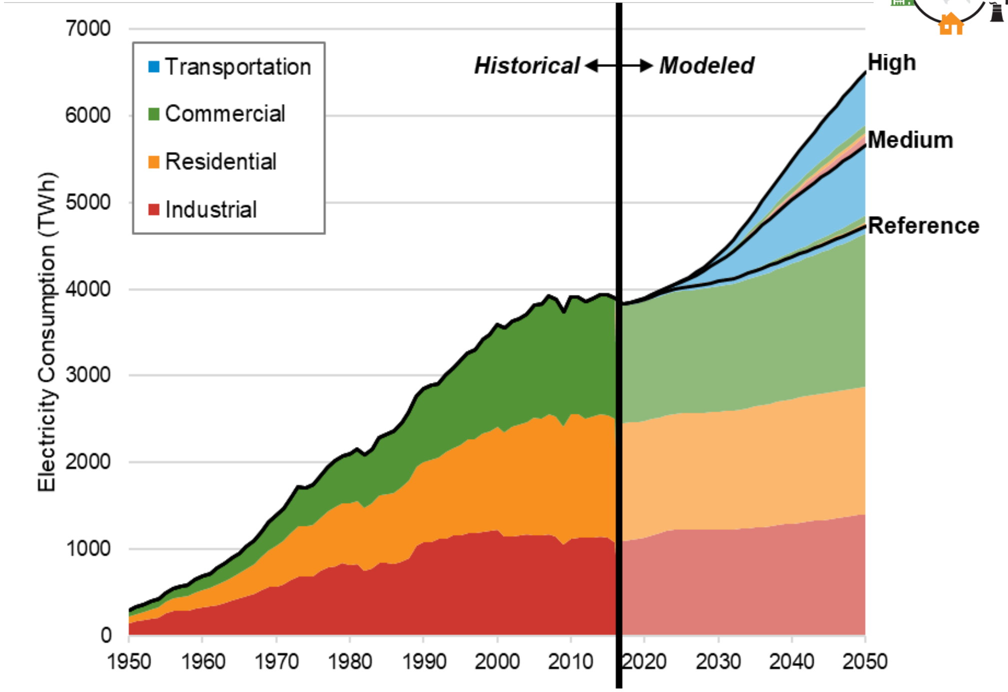
EV-Grid Integration

EV-Grid Integration: *Why is it important?*

- U.S. electricity demand has been flat for nearly 20 years.
- **Electricity demand growth expected to resume** as all major end use sectors transition from fossil fuels to electricity.
- **Transportation electrification** is expected to be one of the **main contributors to future electricity demand growth**.

EFS High scenario, 2050:

Transport share of electricity use increases from **0.2% in 2018 to 23% in 2050** (1,424 TWh/yr increase), and more recent net-zero studies show even more significant growth.

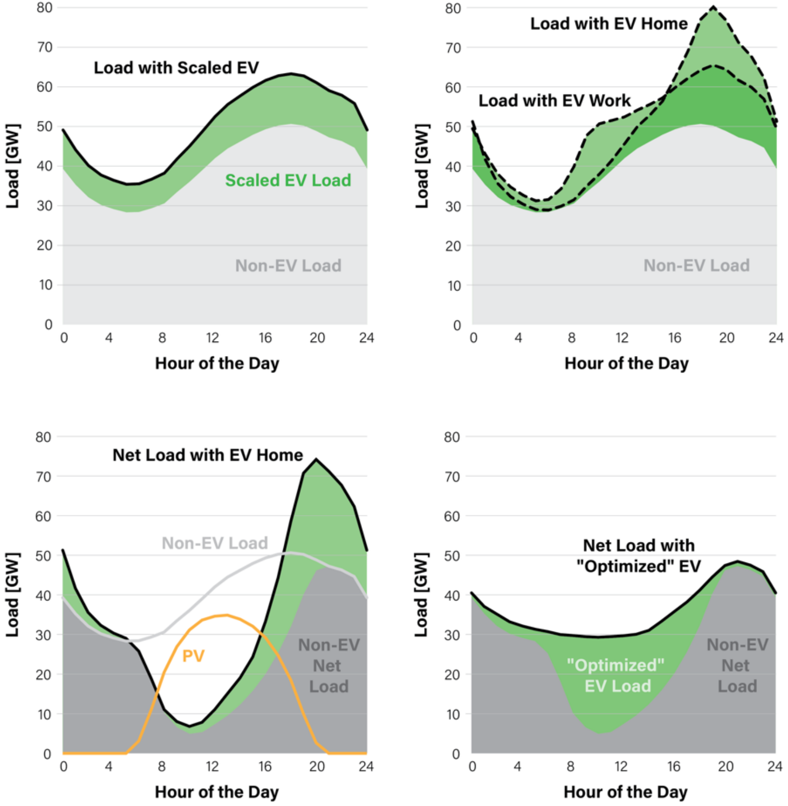


Source: NREL's Electrification Futures Study

EVs Can Be Flexibly Charged

a) ASSUMPTION:
EV charging is often assumed to simply scale up electricity demand.

b) COMPLEXITY:
Future EV charging could change the shape of demand, depending on when and where charging occurs.



c) INTEGRATION:
EV charging can impact power system planning and operations, particularly with high shares of variable renewable energy.

d) FLEXIBILITY:
Optimizing EV charging timing and location could add flexibility to help balance generation and demand.

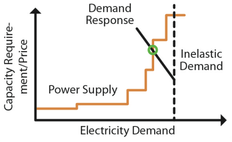
When, where, and how EVs charge will be as critical as how much electricity is demanded.

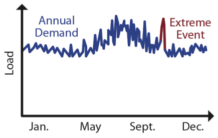
Source: Muratori & Mai (2020)

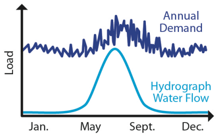
EVs Can Provide Multiple Benefits for the Grid

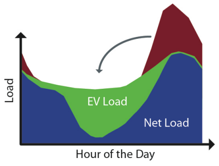
Smart electric vehicle-grid integration can provide flexibility – the ability of a power system to respond to change in demand and supply – by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales

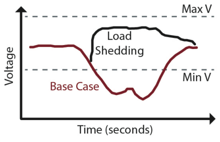
Power System Application	Generation Capacity and Transmission/ Distribution Planning	Resilience To Extreme Events	Seasonal Planning (Hydro/Long-Term Storage Dispatch)	Commitment and Dispatch Decisions	Balancing and Power Quality	Support End Consumers
Time scale	*Multi-year*	*Years (planning), hours (real-time response)*	*Months*	*Days to Hours and Sub-Hours*	*Seconds to sub-seconds*	*Years (planning), hours (real-time response)*
Vehicle-Grid Integration value	Ability to reduce peak load and capacity requirements and defer distribution systems upgrades if reliable EV charging flexibility is available	Load response to natural events (heat waves, tornados) or human-driven disasters, load postponement over days, and support microgrid management and grid restoration (V2G)	No role for EVs	Leverage EV charging flexibility to support supply dispatch and load-supply alignment (tariff management), variable renewables integration, operating reserves, energy arbitrage (V2G)	Provide voltage/frequency regulation and support distribution system operations	Tariff management (e.g., mitigate retail demand charges), complement other distributed energy resources (smart load, generation and storage), and minimize equipment aging/upgrades

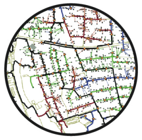












Source: Anwar et al. (2022)

Critical to Understand Charging Loads and Prepare for Effective Grid Integration (Distribution Upgrades?)

Higher energy demands increase the likelihood for upgrades further upstream in the distribution system which are **more expensive** and **take longer** to complete

Approach: Review of 10 public data and literature sources, supplemented by internal expert elicitation by industry co-authors

Table 1 | Summary of electricity distribution system upgrades for depot charging

Component category	Upgrade	Typical cause for upgrade	Typical cost[a]	Typical timeline (month)[a]
Customer on-site	50 kW DCFC EVSE	EVSE addition	Procurement, U$20,000–36,000 per plug; installation, U$10,000–46,000 per plug[b]	3–10
	150 kW DCFC EVSE		Procurement, US$75,000–100,000 per plug; installation, US$19,000–48,000 per plug[b]	
	350 kW DCFC EVSE		Procurement, US$128,000–150,000 per plug; installation, US$26,000–66,000 per plug[b]	
	Install separate meter	Decision to separately meter	US$1,200–5,000	
Utility on-site	Install distribution transformer	200+ kW load	Procurement, US$12,000–175,000	3–8
Distribution feeder	Install/upgrade feeder circuit	5+ MW load[c]	US$2–12 million[d]	3–12[e]
Distribution substation	Add feeder breaker	5+ MW load[c]	~US$400,000	6–12[f]
	Substation upgrade	3–10+ MW load[g]	US$3–5 million	12–18
	New substation installation	3–10+ MW load[g]	US$4–35 million	24–48[h]

[a]Cost and timeline ranges include procurement, engineering, design, scheduling, permitting and construction and installation; estimates are project-specific and vary greatly. [b]Costs reflective of 2019 and expected to continue to fall in future years; EVSE installation includes upgrading or installing service conductors and load centres; per-unit installation costs are reduced as the number of installed units increase. [c]Feeder extensions or upgrades (including new feeder breakers) are typically required for new loads >5 MW, especially for voltages <20 kV; new loads >12 MW may require a dedicated feeder. [d]Feeder extensions or upgrades tend to be more expensive in urban areas than in rural areas. [e]Timeline for feeder extensions includes jurisdictional permitting for construction, obtaining easements and right-of-way, and procurement lead times. [f]Timeline for adding a new feeder breaker depends on substation layout and the time required to receive clearance for construction. [g]The decision to upgrade an existing substation versus to build a new one is largely dependent on the layout of the existing substation and whether there is sufficient room for expansion. [h]Additional time may be required for regulatory approval for the transmission line construction. DCFC, direct current fast charging.