PATH NY/NJ Yard Tractor Electrification Study

Andrew Kotz, Ken Kelly,
Doug Gagne, Brett Oakleaf

NATIONAL RENEWABLE ENERGY LABORATORY

NREL at a Glance

2,050

Employees,
plus more than
400
early-career researchers and visiting scientists

World-class
facilities, renowned technology experts

nearly 820

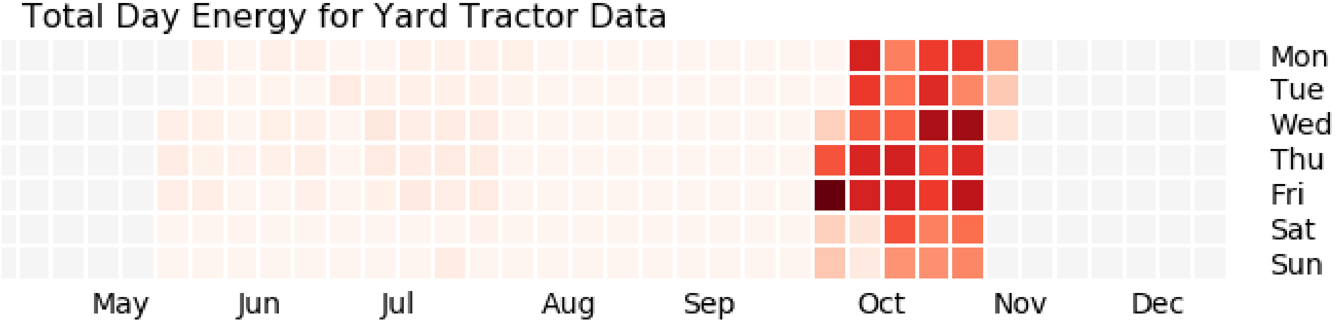
Partnerships
with industry, academia, and government

Campus
operates as a living laboratory

Project Overview

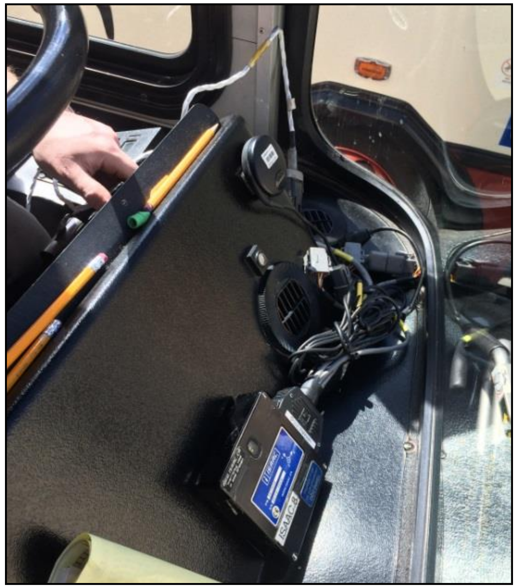
- Analyze Yard Operations
  - Usage characteristics
  - Vehicle performance
- Data Collection
  - Oct. 9th to Nov 15th
  - 36 Vehicles
    - 14 @ APM
    - 14 @ GCT NY
    - 8 @ Redhook
  - 1Hz ~ 50 parameters

Parameter	Miles of Data	Gallons Used	Hours of Operation	Vehicle Days
Value	21,219	6,898	7,389	609



Average Daily Energy: 948.4 kWh

Max Daily Energy: 3,684.0 kWh (28 vehicles)

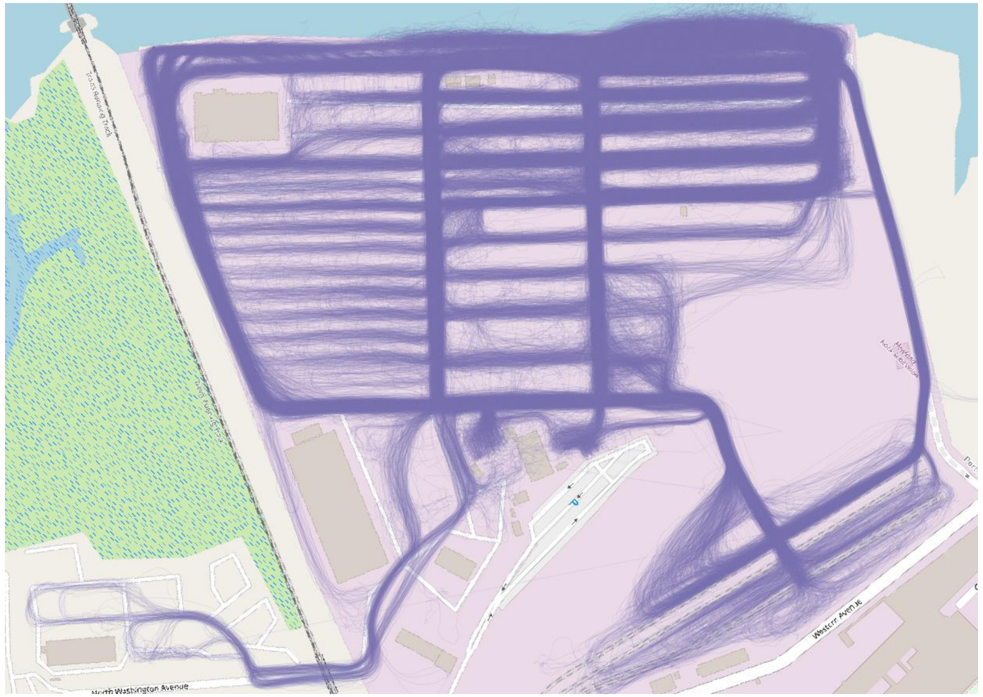


Vehicle Heat Maps

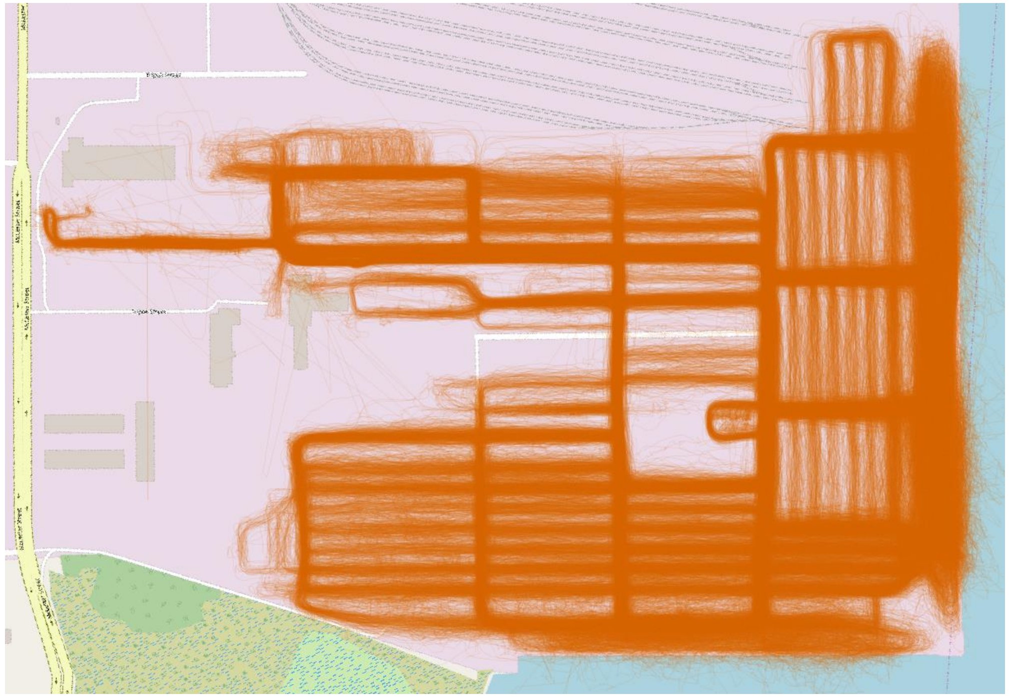
- GPS Traces of 36 vehicles
- 1Hz Refresh Rate
- 19,767,600 data points
- Darker lines = more frequent trips

Redhook Terminal (RHCT)

Global Container Terminal (GCT NY)



APM Terminals (APM)

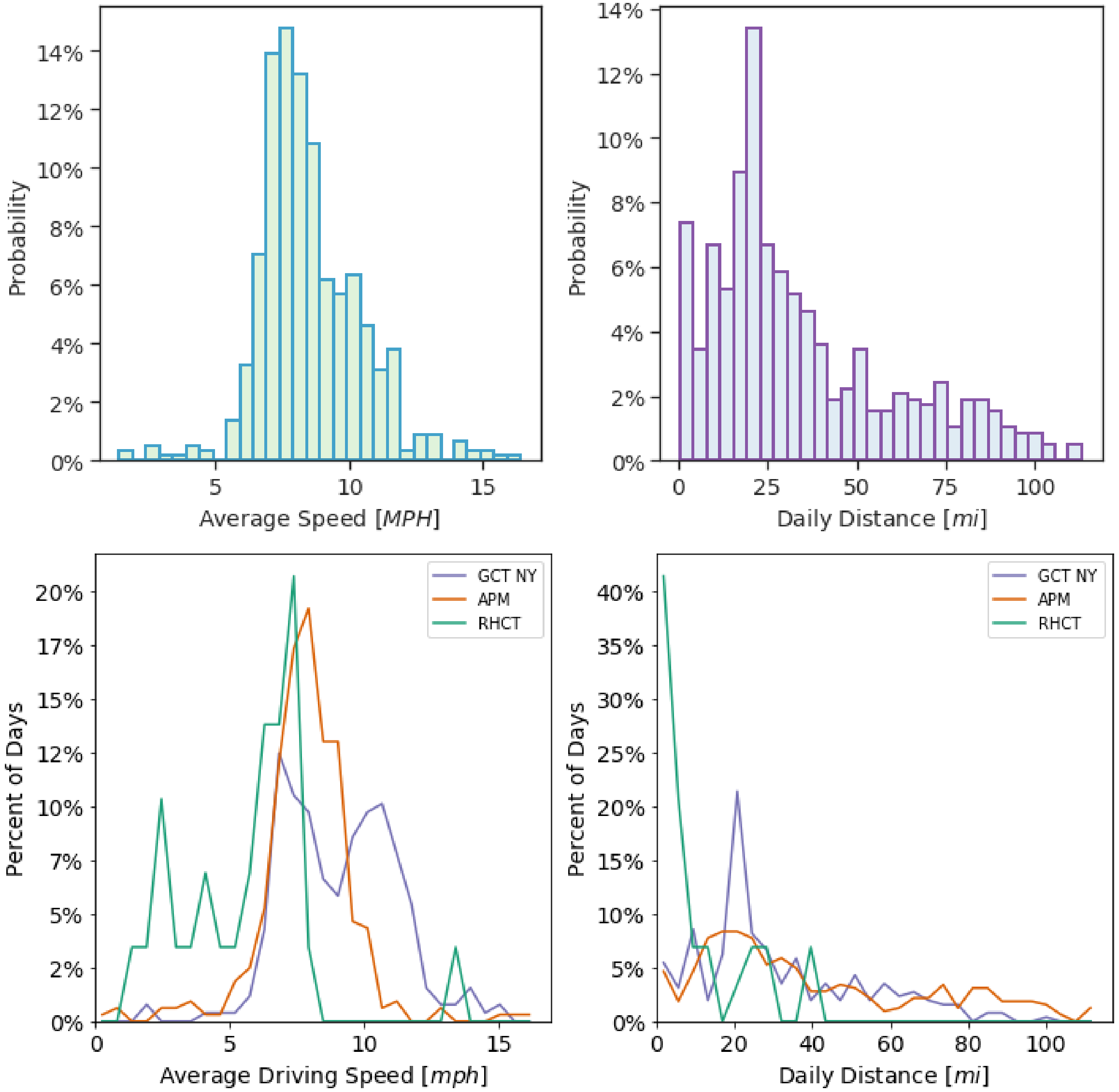


Duty Cycle Analysis

Understanding duty cycle or operating requirements are essential when evaluating a vehicle fleet for electrification.

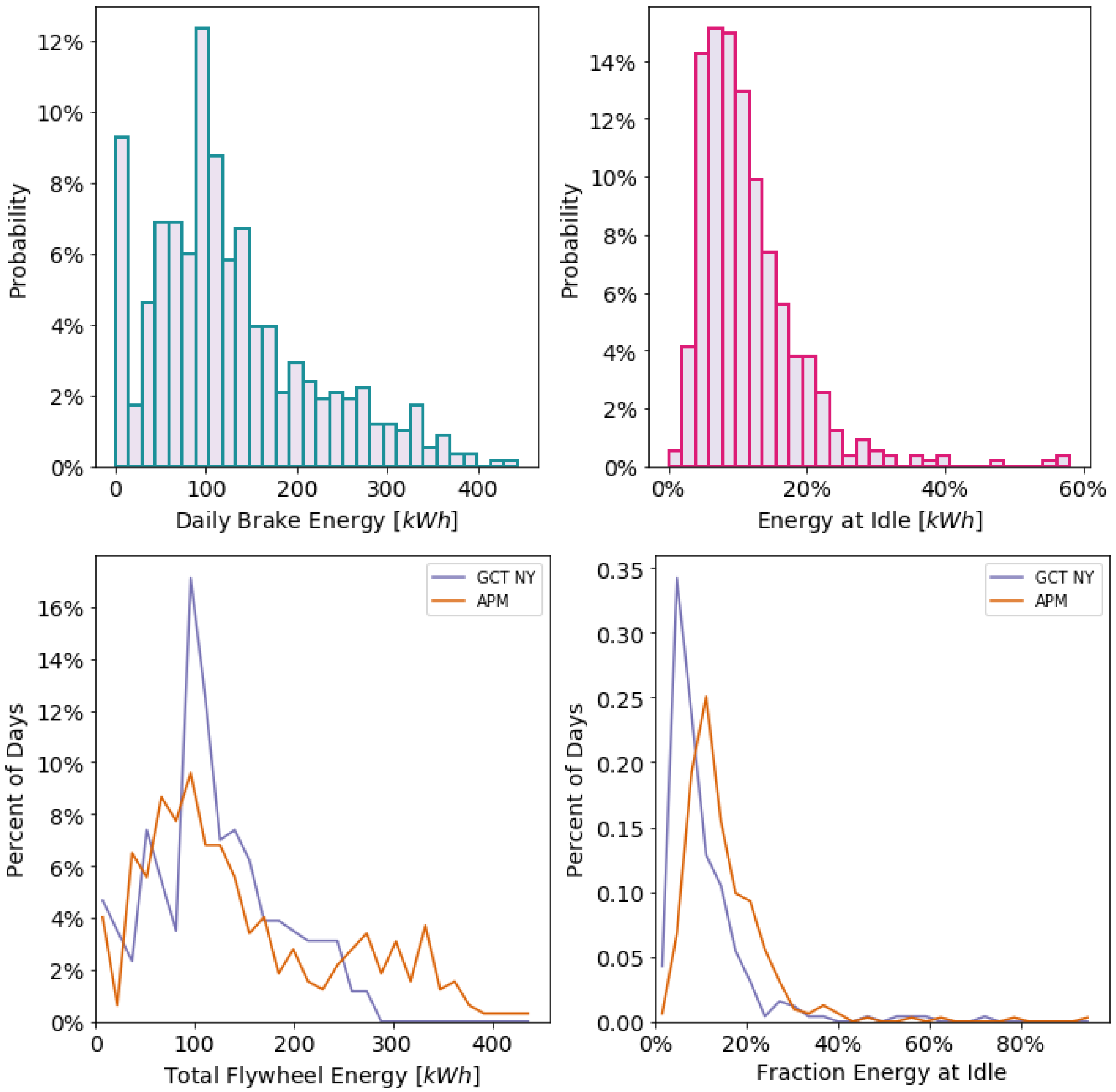
Duty Cycle

- Low speeds and short distance are conducive to electrification
  - Most less than 50 miles/day
- RHCT had lowest Millage
  - Only 8 days of data because battery died
- GCT NY next lowest
- APM had longest days
  - Multiple shifts



Engine Energy

- Statistics
  - Average Brake Energy: 127 kWh
  - Average Idle Energy: 14 kWh
  - % Energy Spent at Idle: 11.5%
- APM used more energy
  - Up to 450 kWh
  - multiple shifts
- GCT NY had majority below 200 kWh
  - BYD has 220 kWh tractor
- Still need to consider full charging and discharge cycle



Available Technology

- Multiple Commercially Available Products
  - Model Data: Kalmar T2E – 220kWh Battery & 70kW Charging

Vehicle Manufacturer	Vehicle Type	Vehicle Model	Battery Capacity (kWh)	OEM Estimate Range	EVSE Type	Maximum Charging Rate (kW)
BYD	Yard Tractor	8Y	217		BYD Proprietary/ J1772 CCS	40 AC / 120 DC
Capacity of Texas	Yard Tractor	PHETT				
Kalmar Ottawa	Terminal Tractor	T2E	132	**8-20 hours**	**J1772, CHAdeMO , J3068**	**70**
Kalmar Ottawa	Terminal Tractor	T2E	176			
Kalmar Ottawa	**Terminal Tractor**	**T2E**	**220**			
Orange EV	Terminal Tractor	T-Series	80	50 miles	J1772, J1772 CCS	10
Orange EV	Terminal Tractor	T-Series	160	100 miles		80

Model Development

A component-level vehicle model was developed using NREL's Future Automotive Simulation Tool (FASTSim) to account for the complex system interactions.

Model Development

$$P_{road} = mav + mg\sin(\theta)v + mgC_{rr}\cos(\theta)v + C_{dl}v^3$$

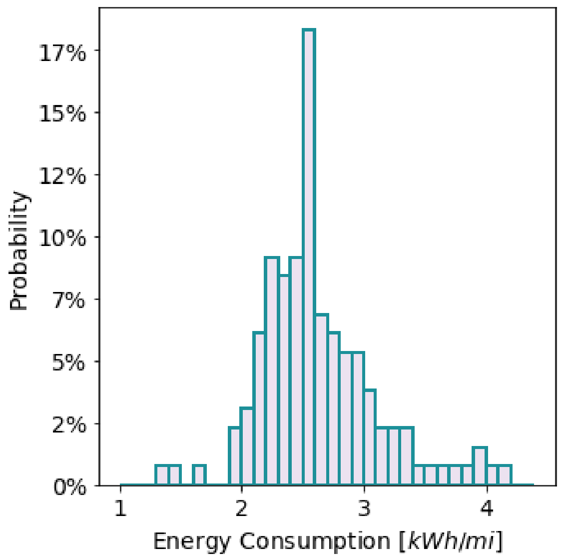
$$\omega_{axle} = \frac{v}{r_{tire}} \quad \omega_{diff} = \omega_{axle} * \beta_{diff} \quad \omega_{trans} = \omega_{diff} * \beta_{trans}$$

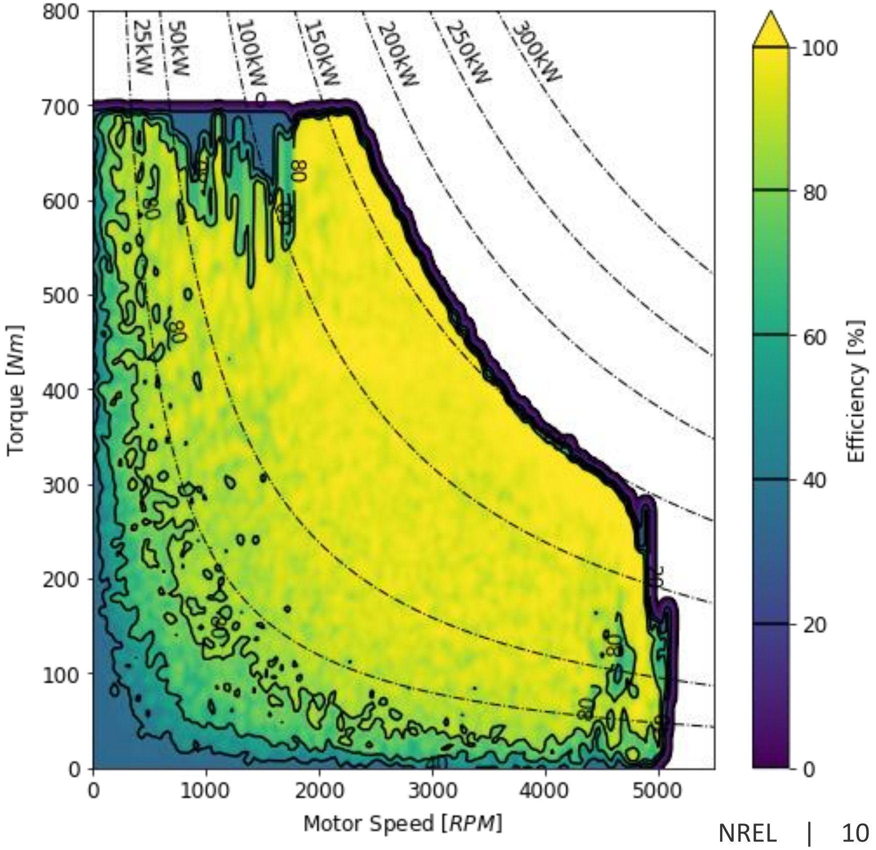
$$T_{axle} = \frac{P_{road}}{\omega_{axle}} \quad T_{diff} = \frac{T_{axle}}{\beta_{diff}} \quad T_{trans} = \frac{T_{diff}}{\beta_{trans}}$$

Backward-Looking Model

1. Start with knowledge of:
   - Vehicle Speed(v)
   - Mass(m)
   - Rolling Resistance (C_{rr})
   - Drag (C_{dl})
   - Road Grade (θ)
2. Calculate backwards from the wheels for rotational speed (ω) and torque (T) along the drivetrain,
3. Mimic the logic of transmission to choose gear ratio (β_{trans})
4. Motor efficiency from In-Use EVYT Data
   - Transpower Partnership
   - 300 days of data

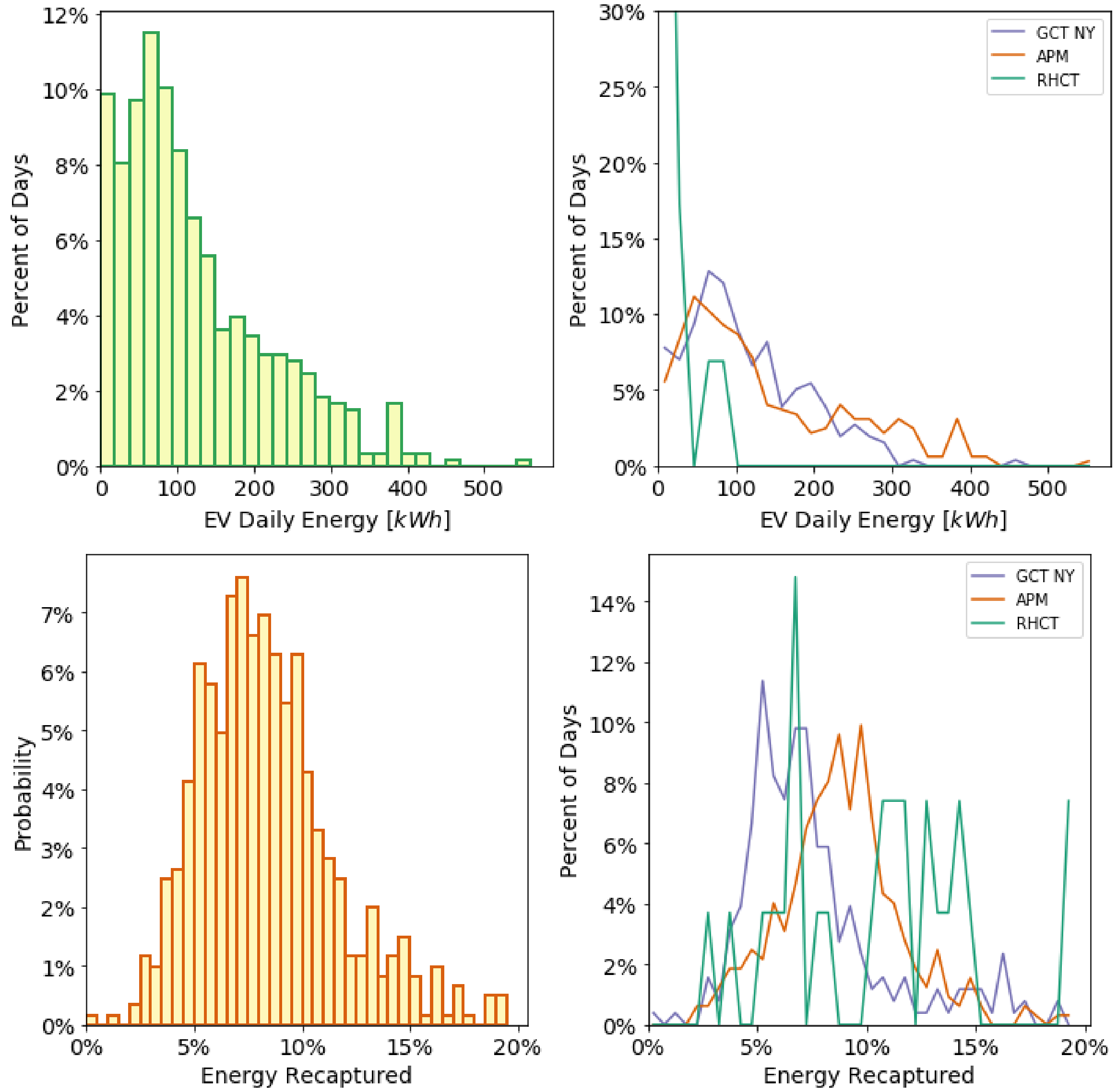
Physics based model used to estimate energy consumption





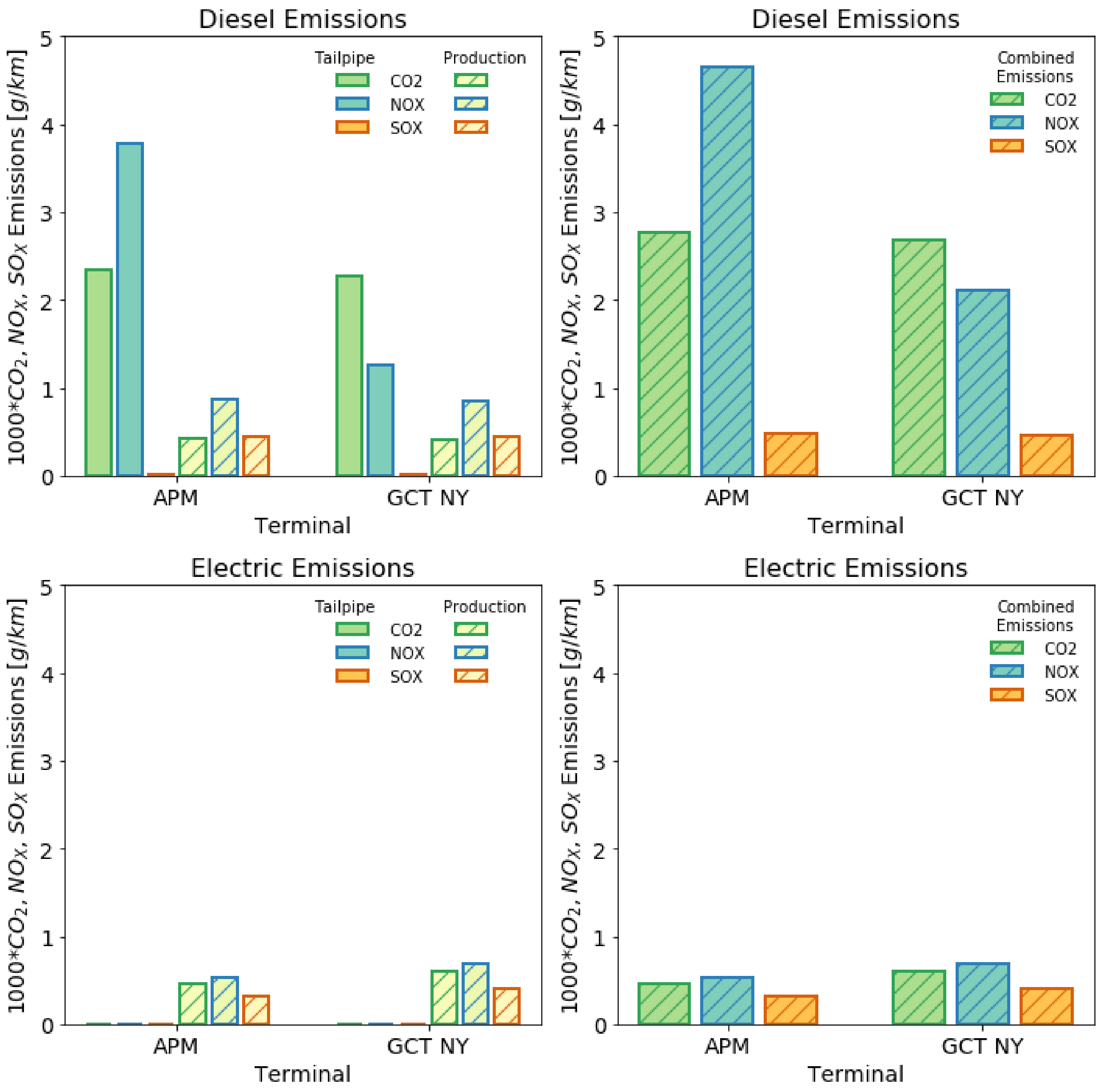
Model Results

- Daily energy use is key to EVYT feasibility
  - Ensure adequate battery size
  - RHCT is new result – only have speed information for this terminal so all results are modeled
- GCT NY and APM have days greater than 220 kWh which is beyond currently available technology
- All days by RHCT less than 220 kWh
- Low regen rates
  - 6% energy recapture on average
  - Likely due to rolling resistance losses



Emissions

- Tailpipe Emissions
  - CO_2 & SO_X – Calculated from fuel consumption
  - NO_X – Quantified from sensors
- GCT NY Emissions Benefit:
  - 77% reduction in CO_2
  - 67% reduction in NO_X
  - 8% reduction of SO_X
- APM Emissions Benefit:
  - 86% reduction in CO_2
  - 90% reduction in NO_X
  - 44% reduction of SO_X



Yearly Fuel Consumption and Total Emissions Reduction

GCT NY Yearly Stats:

- 170,966 gal Diesel
- 1,575,579 kg CO_2
- 1,073 kg NO_X
- 28 kg SO_X

APM Yearly Stats:

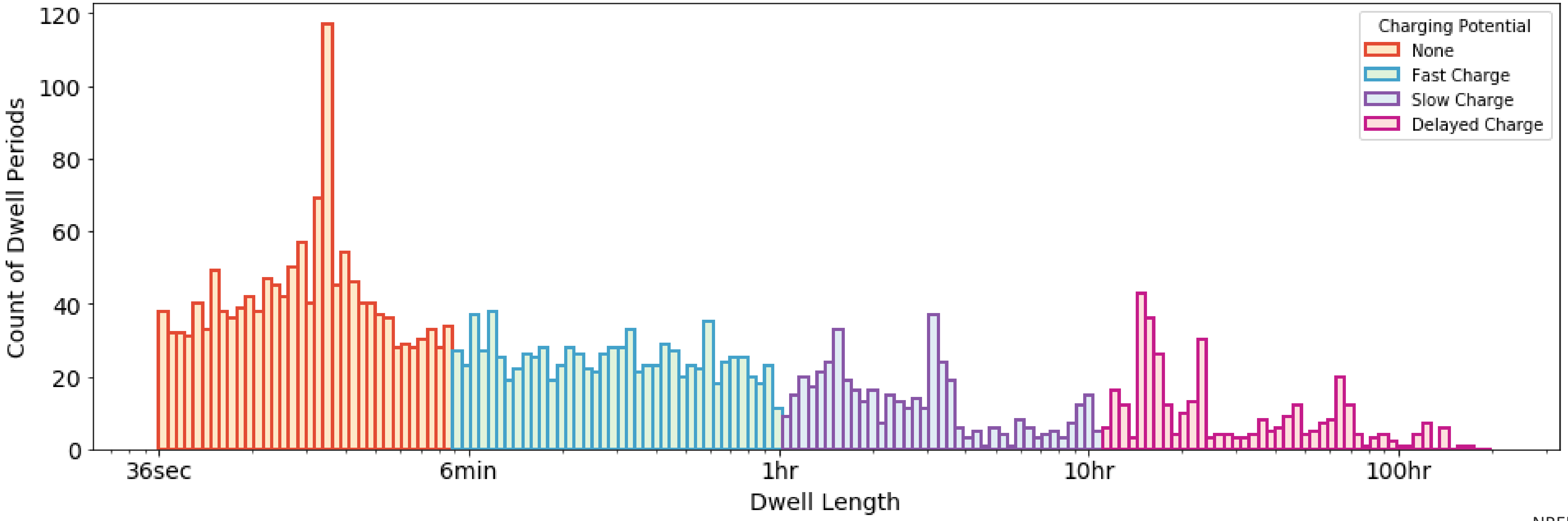
- 817,528 gal Diesel
- 8,400,849 kg CO_2
- 14,980 kg NO_X
- 729 kg SO_X

Charging Analysis

Identify charging opportunity and optimal charging locations based on vehicle dwell times.

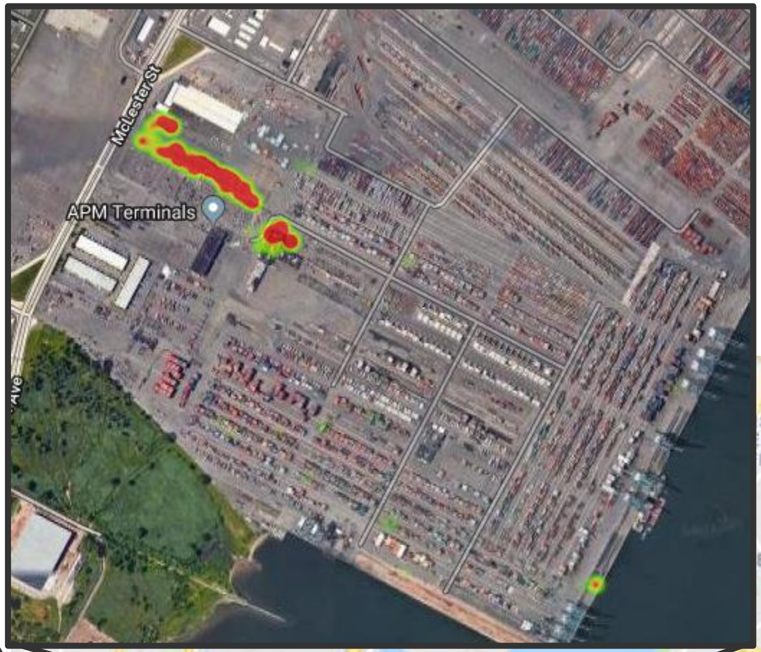
Charging Opportunities

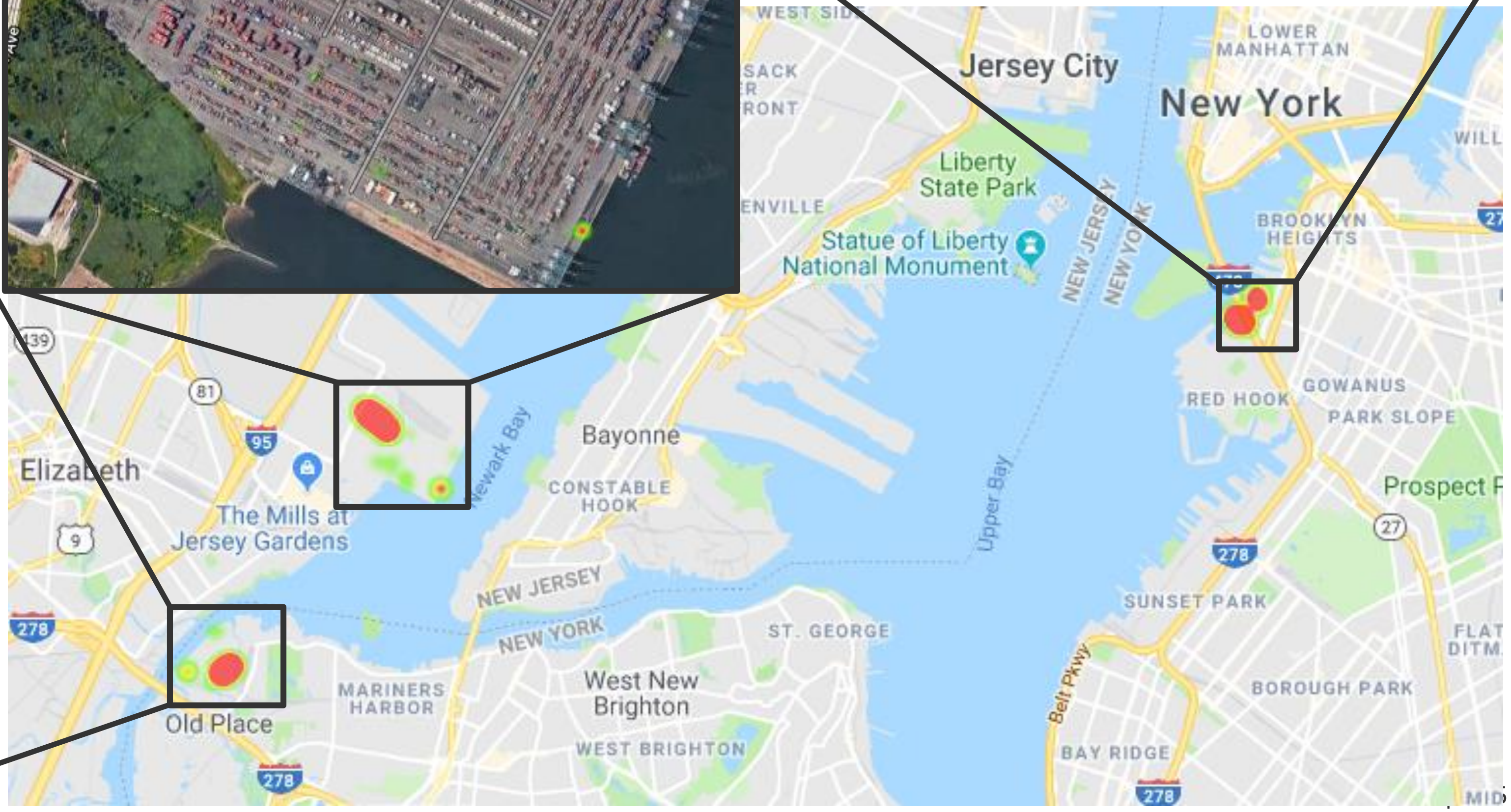
- Charging Opportunities Exist Throughout the Day
  - Majority are short stops with no potential
  - Fast charging may be an option
  - Slow/overnight charging opportunities exist, but may be limited (**current technology**)



Charge Locations

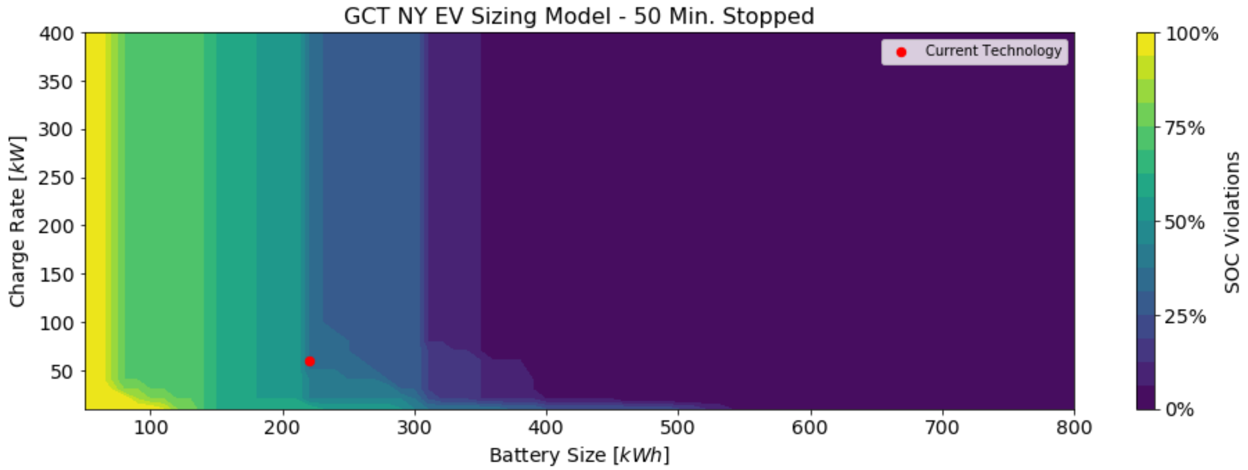
- Hotspot Analysis on Stop locations > 60min
- Parking Location
- Coffee/Break Location

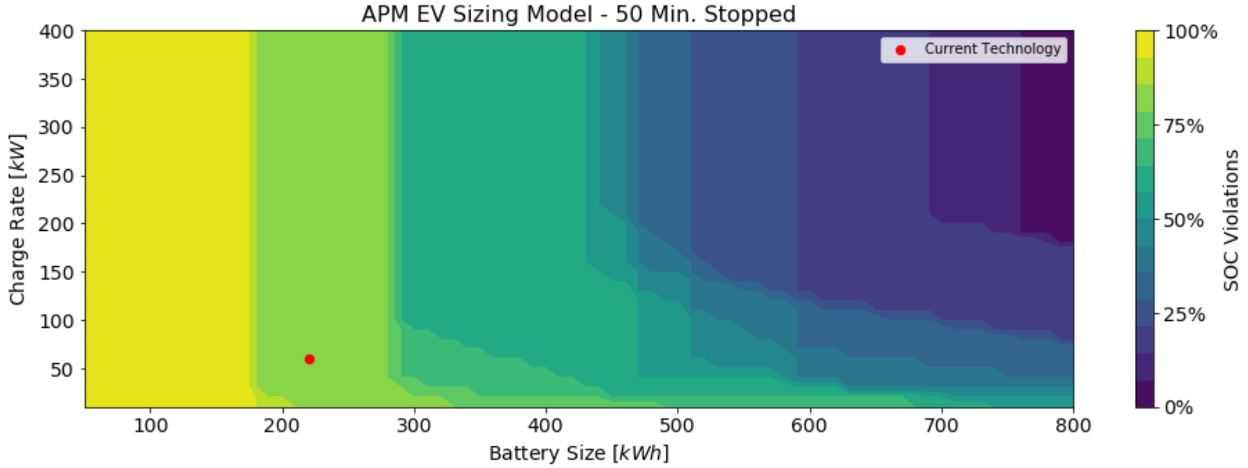




Scenario 1: Minimal Change

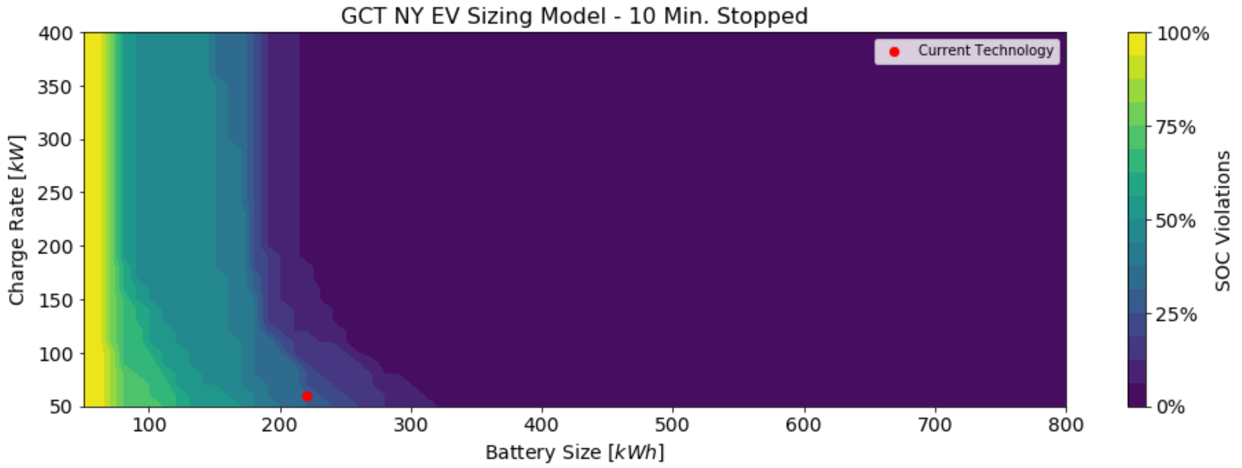
- Assumptions
  - Charges when stopped for > 50 min
  - 90% conversion eff.
  - No energy when stopped
  - No AC/Heating
  - Current tech: 220 kWh battery & 70 kW charging
- RHCT – All monitored vehicles
  - 1201, 1202, 1207, 1209, 1218, 1220, 1221, 1226
- GCT NY Vehicles:
  - T132, T135, T136, T137, T138, T140, T141, T141, T143, T146
- APM Vehicles: – Hardest Duty Cycle
  - 40350 and 40479

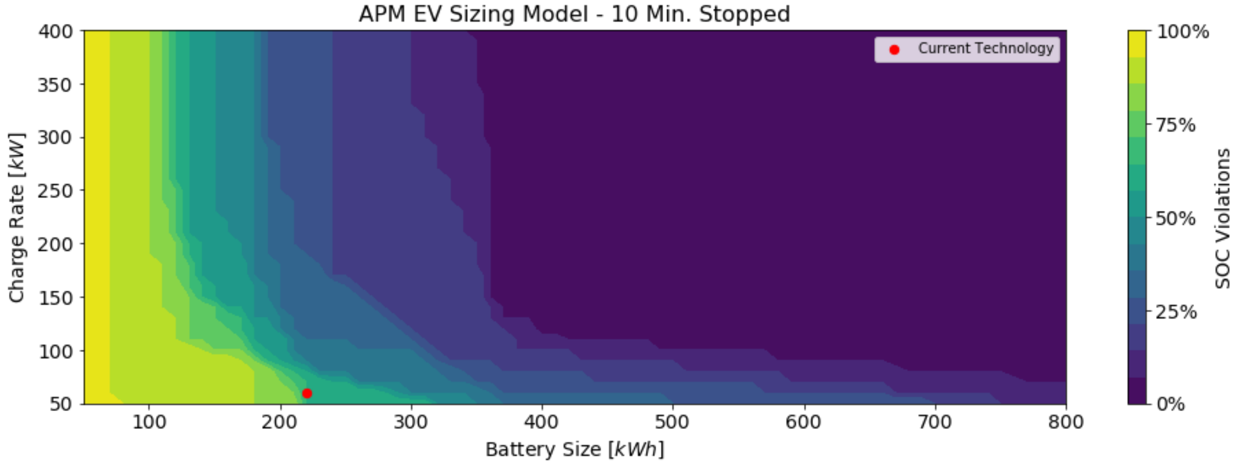




Scenario 2: Moderate Change

- Assumptions
  - Charges when stopped for > 10 min
  - 90% conversion eff.
  - No energy when stopped
  - No AC/Heating
  - Current tech: 220 kWh battery & 70 kW charging
- RHCT – All monitored vehicles
  - 1201, 1202, 1207, 1209, 1218, 1220, 1221, 1226
- GCT NY Vehicles:
  - T132, T135, T136, T137, T138, T140, T141, T141, T143, T146, T133, T134
- APM Vehicles: – Hardest Duty Cycle
  - 40350, 40479, 40330, 40366, 40476 – Rail





Infrastructure

$$\frac{Energy\ [kWh]}{Vehicle - Day} = Terminal\ Average\left(\frac{\sum Energy\ Used\ During\ Logging\ Period\ for\ Vehicle\ i}{Days\ of\ Data\ Logging\ for\ Vehicle\ i}\right)$$

Using average daily energy use of all terminal vehicles

- RHCT – 20.8 kWh/vehicle-day
  - 12.5 MWh/month
  - 1.4 MW of peak load
- GCT NY – 57.3 kWh/vehicle-day
  - 99.6 MWh/month
  - 4.1 MW of peak load
- APM – 105.9 kWh/vehicle-day
  - 476 MWh/month
  - 10.5 MW of peak load

Summary

NREL Collected Data on 36 Yard Tractors

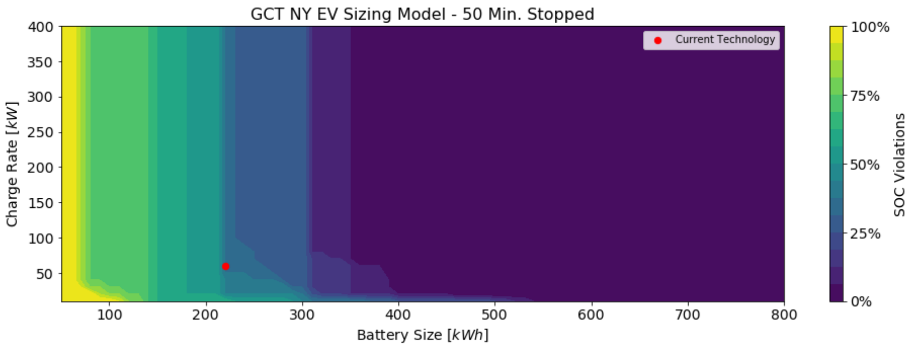
- RHCT, GCT NY & APM
- Oct. 9th to Nov 15th , 2018

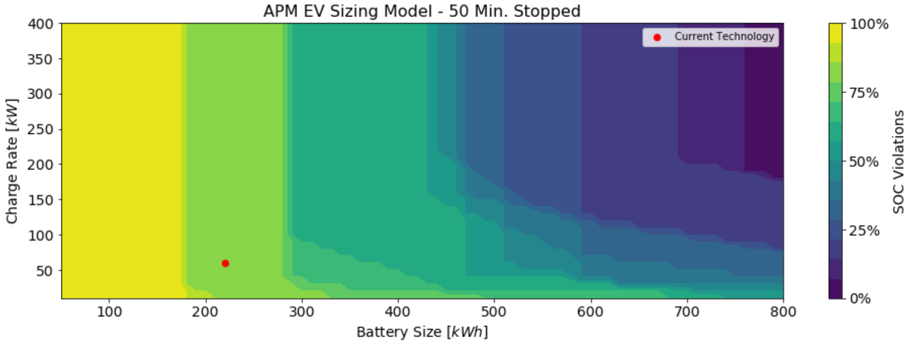
FASTSim Vehicle Model to Predict EV Loads

- Current technology:
  - 220 kWh Battery & 70 kW charging
- RHCT – All vehicles ← **First Candidate**
- GCT NY – 10/14 vehicles
- APM – 2/14 vehicles

Yard tractors = 23% of landside port CO_2

- BEYTs could reduce CO_2 by 85% ~ 9,960 $MTCO_2$ per year





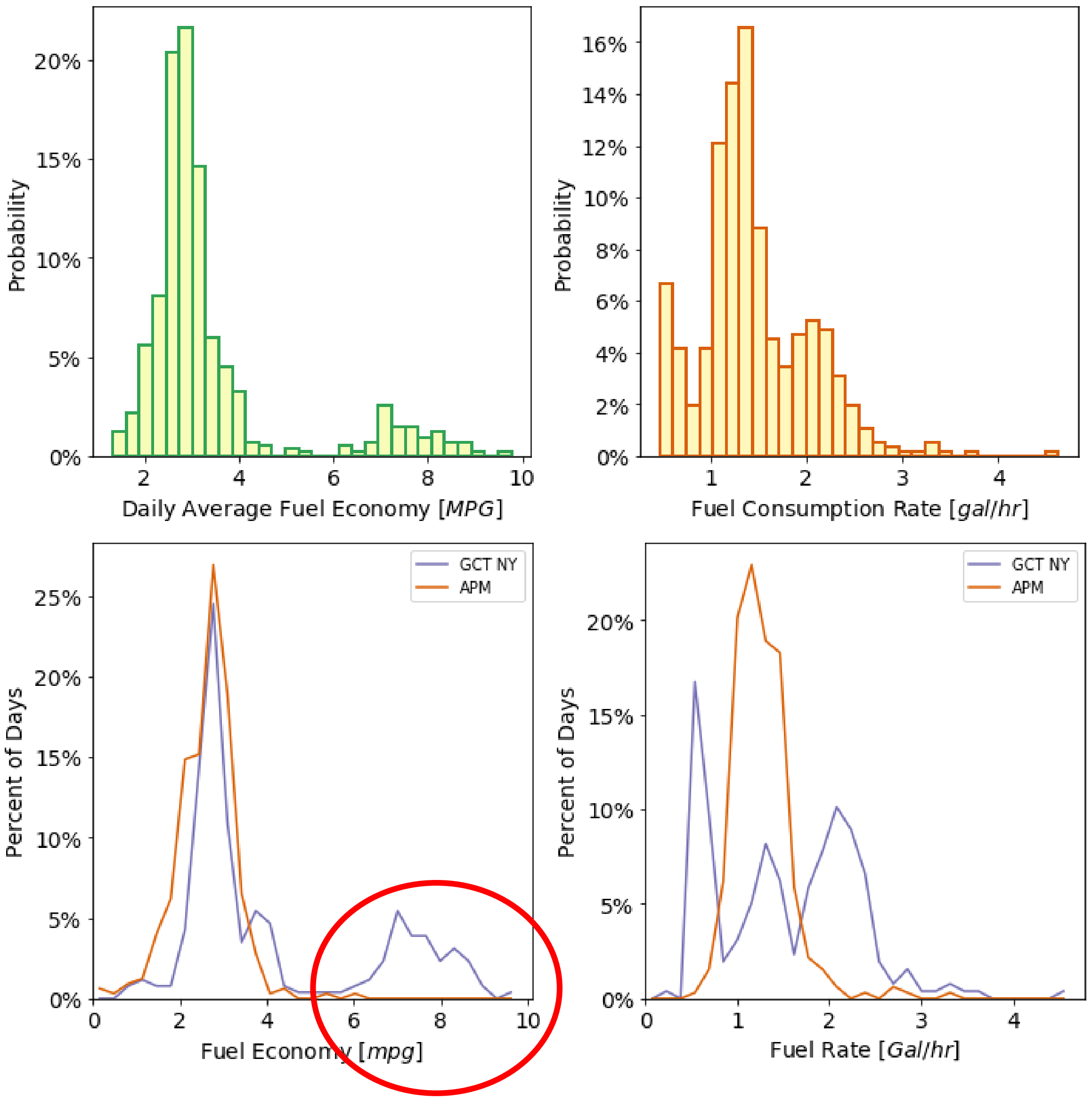
Questions?

www.nrel.gov

NATIONAL RENEWABLE ENERGY LABORATORY

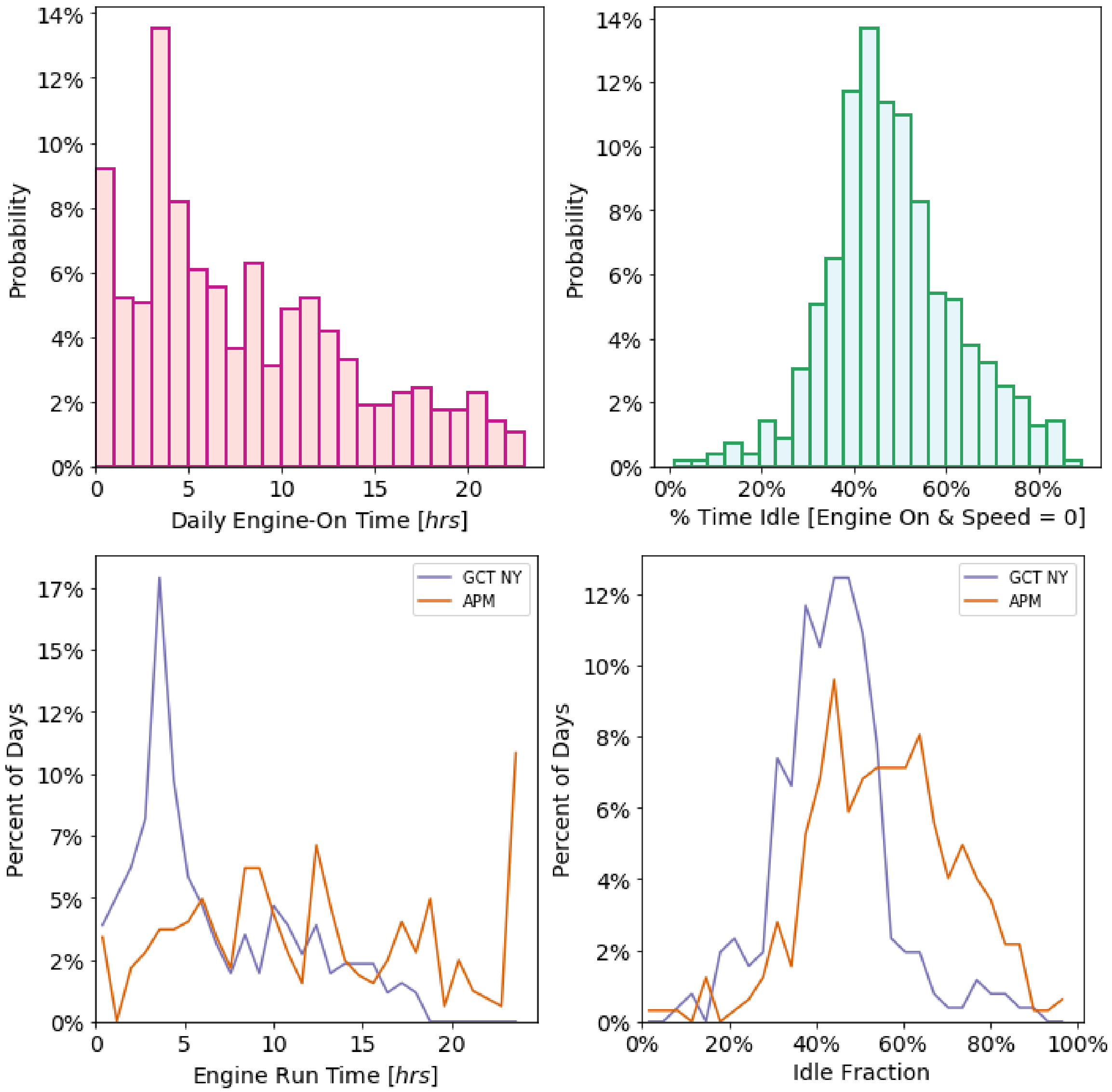
Current Fuel Economy

- Statistics
  - Fuel Economy: 3.4 MPG
  - Fuel Rate: 1.5 gal/hr
  - Daily Fuel Used/Vehicles [gal]: 11.2
  - Thermal Efficiency: 34.4%
  - Average Brake Energy: 127.2 kWh
- Similar fuel economies between terminals
  - Odd high fuel economy at GCT NY – Suspect empty trailer moving



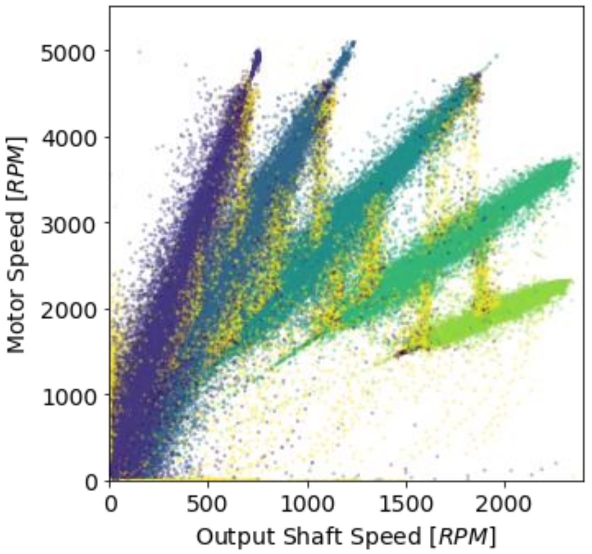
Run Time

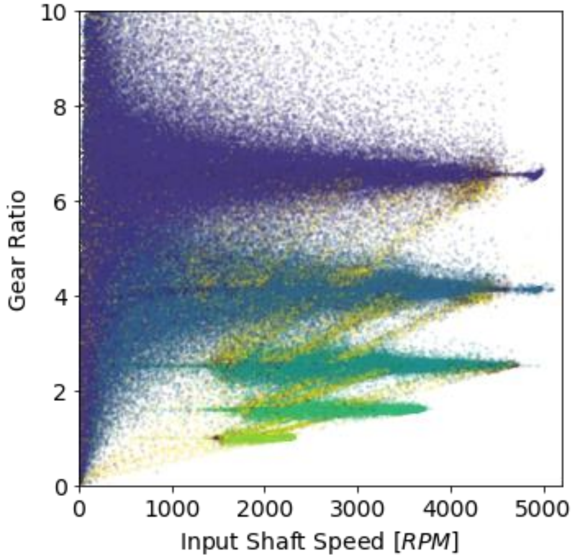
- Statistics
  - Average Run Time: 8 hrs
  - Max Run Time: 24 hrs/day
    - Analysis cuts at midnight
  - Average Idle Time: 4.7 hrs
- Long hours may be hard for currently available electric vehicles
- Large portions of idle
  - Electric vehicles use less energy at idle than conventional vehicles



Analysis of EVYT Data

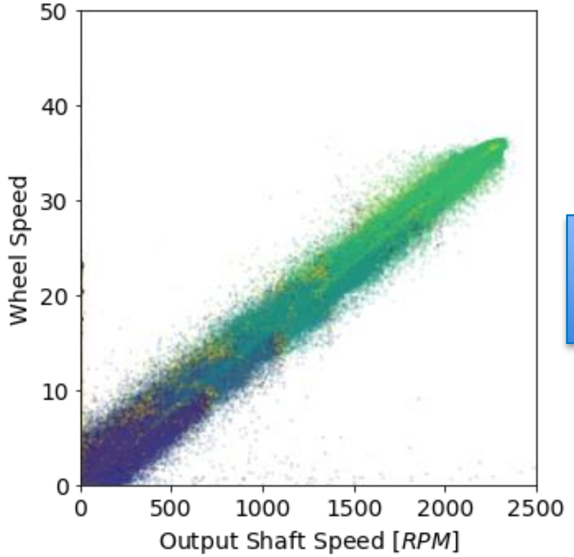
Develop Characteristics From Actual Vehicle



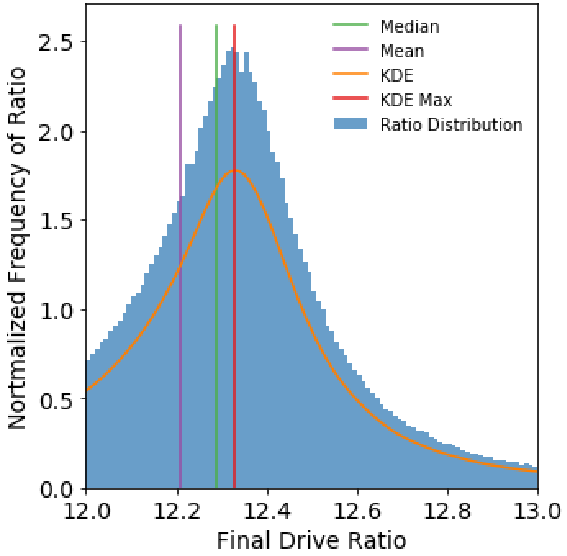


Gather Gear Ratios

Current Gear	Median Gear Ratio
1	6.556
2	4.125
3	2.514
4	1.587
5	0.997



Use Kernel Density Estimation to Determine Final Drive Ratio



Mass Estimation

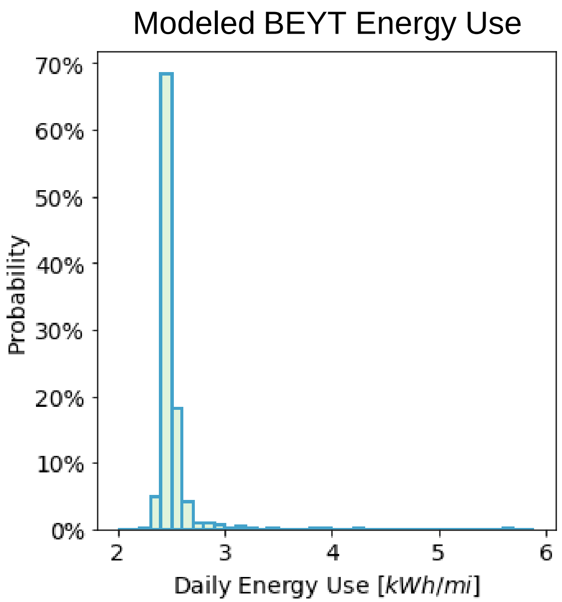
- Help Improve Energy Estimates by Introducing Mass Variation
- Simplifying Assumptions
  - Drag is minimal due to speed <25mph
  - Zero grade within port

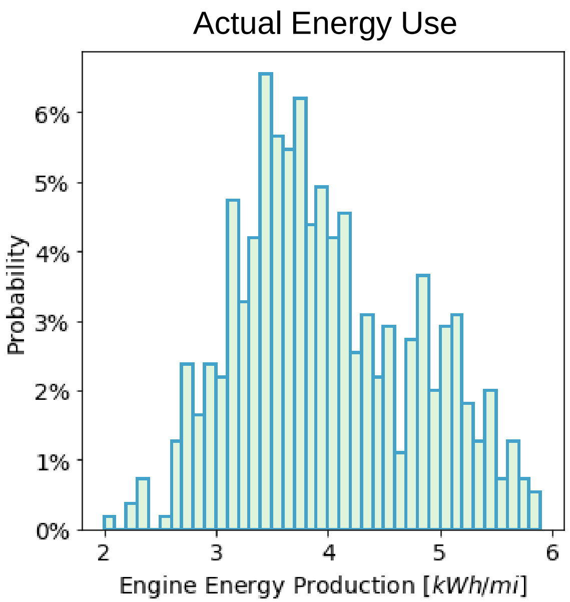
θ=0

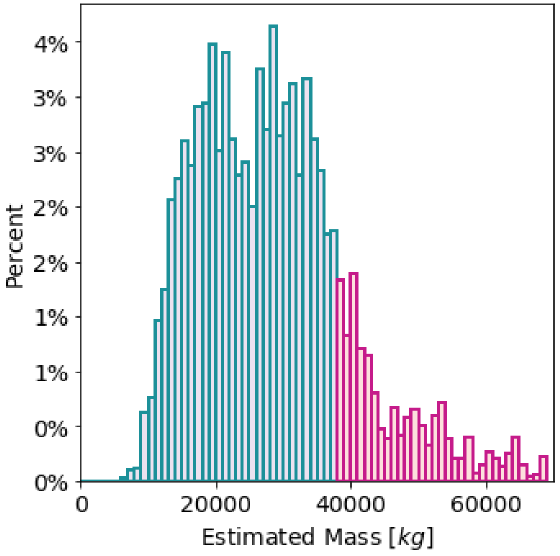
$$P_{road} = mav + mg\sin(\theta)v + mgC_{rr}\cos(\theta)v + C_{d}v^3$$

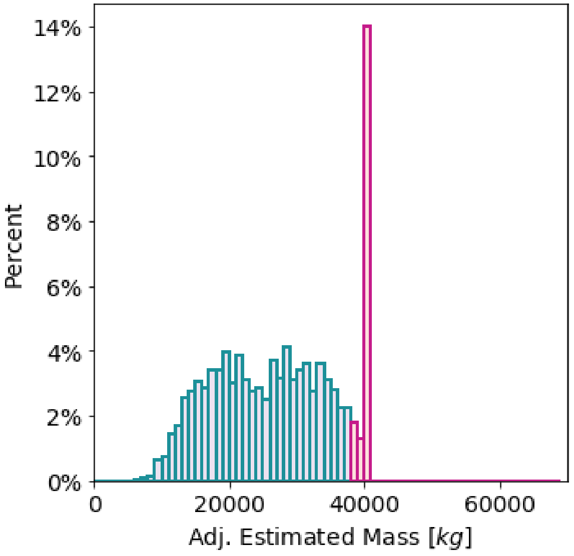
$$m = \frac{P_{road}}{av + gC_{rr}v}$$

Constrain mass to reasonable limits









Model Results

- Compared EV efficiency to engine energy production in kWh/mi
  - Validates modeled results
- First modeled results show similar energy production profiles
  - Confirms modeled results
    - Diesel Engine: 3.9 kWh/mi
    - EV Efficiency: 3.7 kWh/mi
  - Slightly better efficiency of EV due to regenerative braking
  - Further model refinement will show improved efficiency of EV