PATH NY/NJ Yard Tractor Electrification Study

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NREL at a Glance

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

World-class facilities, renowned technology experts

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Miles of Data</th>
<th>Gallons Used</th>
<th>Hours of Operation</th>
<th>Vehicle Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>21,219</td>
<td>6,898</td>
<td>7,389</td>
<td>609</td>
</tr>
</tbody>
</table>

Total Day Energy for Yard Tractor Data

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

Global Container Terminal (GCT NY)

Redhook Terminal (RHCT)

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

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

Backward-Looking Model

1. Start with knowledge of:
   - Vehicle Speed ($v$)
   - Mass ($m$)
   - Rolling Resistance ($C_{rr}$)
   - Drag ($C_{dl}$)
   - Road Grade ($\theta$)

2. Calculate backwards from the wheels for rotational speed ($\omega$) and torque ($T$) along the drivetrain,

3. Mimic the logic of transmission to choose gear ratio ($\beta_{trans}$)

4. Motor efficiency from In-Use EVYT Data
   - Transpower Partnership
   - 300 days of data

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

\[ \omega_{axle} = \frac{v}{r_{tire}} \quad \omega_{diff} = \omega_{axle} \beta_{diff} \quad \omega_{trans} = \omega_{diff} \beta_{trans} \]

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

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
  – CO₂ & SOₓ – Calculated from fuel consumption
  – NOₓ – Quantified from sensors
• GCT NY Emissions Benefit:
  – 77% reduction in CO₂
  – 67% reduction in NOₓ
  – 8% reduction of SOₓ
• APM Emissions Benefit:
  – 86% reduction in CO₂
  – 90% reduction in NOₓ
  – 44% reduction of SOₓ

Yearly Fuel Consumption and Total Emissions Reduction

GCT NY Yearly Stats:
• 170,966 gal Diesel
• 1,575,579 kg CO₂
• 1,073 kg NOₓ
• 28 kg SOₓ

APM Yearly Stats:
• 817,528 gal Diesel
• 8,400,849 kg CO₂
• 14,980 kg NOₓ
• 729 kg SOₓ
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
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. 9\textsuperscript{th} to Nov 15\textsuperscript{th}, 2018

FASTSim Vehicle Model to Predict EV Loads
• Current technology:
  – 220 kWh Battery & 70 kW charging
• RHCT – All vehicles \(\leftarrow\) First Candidate
• GCT NY – 10/14 vehicles
• APM – 2/14 vehicles

Yard tractors = 23% of landside port CO\textsubscript{2}
• BEYT\textsc{s} could reduce CO\textsubscript{2} by 85\% \(\sim\) 9,960 MTCO\textsubscript{2} per year
Questions?

www.nrel.gov
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

Use Kernel Density Estimation to Determine Final Drive Ratio

Develop Characteristics From Actual Vehicle

<table>
<thead>
<tr>
<th>Current Gear</th>
<th>Median Gear Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.556</td>
</tr>
<tr>
<td>2</td>
<td>4.125</td>
</tr>
<tr>
<td>3</td>
<td>2.514</td>
</tr>
<tr>
<td>4</td>
<td>1.587</td>
</tr>
<tr>
<td>5</td>
<td>0.997</td>
</tr>
</tbody>
</table>

Gather Gear Ratios
Mass Estimation

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

\[
P_{\text{road}} = m a v + mg \sin(\theta) v + mg C_{rr} \cos(\theta) v + C_d v^3
\]

\[
m = \frac{P_{\text{road}}}{a v + g C_{rr} v}
\]

Constrain mass to reasonable limits

![Graphs showing modeled and actual energy use](image-url)
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