ACN-Data
Analysis and Applications of an Open EV Charging Dataset

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Why care about EV charging?

**EV30@30 Scenario**

Charging demand in 2030: 640 TWh

Source: IEA analysis developed with the IEA Mobility Model.
Why care about EV charging?

10 kWh daily
7 kW

29 kWh daily
1.2 kW*

* Average power consumption over day
Why care about large-scale EV charging?

Parking lot: 100 EVs

1 MWh daily
700 kW
Adaptive Charging Network
Framework for large-scale smart charging networks
Real-time monitoring and control of EV charging
User interaction through app
ACNs around the country
What is ACN-Data?

32,000+ EV charging sessions
Publicly available
Growing daily – 90 sessions a day
What can I do with this dataset?

**Machine Learning and Statistical Modeling**
- Understand, model, and predict user behavior
- Apply reinforcement learning to smart charging

**Algorithm Design and Evaluation**
- Accurately evaluate online scheduling algorithms

**System Design and Grid Impacts**
- Inform charging system design and planning
- Demonstrate grid impacts and opportunities
- Evaluate the potential of charging + renewable energy sources
Data-Driven Research

What can we learn from data about user behavior?

How can we use data to model user behavior?

How can we use models to design better charging systems?

How can we use models to understand grid impacts?
What can we learn from data about user behavior?
How is the system used?

<table>
<thead>
<tr>
<th>Sessions per Day</th>
<th>Energy per Day (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free</td>
<td>$0.12 / kWh</td>
</tr>
</tbody>
</table>

Sessions per Day:
- Free: 11
- $0.12 / kWh: [Graph showing data]

Energy per Day (kWh):
- Free: [Graph showing data]
- $0.12 / kWh: [Graph showing data]
When is the system used?
How much flexibility to users have?

\[ \text{LAX}(i) := \text{session duration} - \text{minimum charging time} \]

80% of sessions have laxity > 1 hour
How much flexibility does the system have?

**Caltech**

- Uncontrolled: 3.78x
- Optimal Scheduling: 3.41x

**JPL**

- Uncontrolled: (Graph shows network capacity vs. proportion of days feasible)
- Optimal Scheduling: (Graph shows network capacity vs. proportion of days feasible)
How can we use data to model charging behavior?
Individual model

Gaussian Mixture Model!

Normal Behavior

Other Modes

User 334

Arrival time
Individual model

Gaussian Mixture Model!

Normal Behavior

Other Modes

User 334

Arrival time
Individual Gaussian Mixture Model

Arrival Time

Session Duration

Session Energy

User 334
Population Gaussian Mixture Model

Testing Accuracy (9/1/18 – 11/1/18)

- Modeled Arrivals
- Modeled Departures
- Actual Arrivals
- Actual Departures

Evaluation Set Accuracy (12/1/18 – 5/1/19)

- Modeled Arrivals
- Modeled Departures
- Actual Arrivals
- Actual Departures
Predicting User Behavior

User 334

Session Energy

Session Duration

8:30 AM
Predicting User Behavior

- Duration MAE (hours)
- Energy MAE (kWh)

- GMM Prediction
- User Input
- Mean
How can these models help us design better charging systems?
Right-sizing on-site solar
Problem Formulation

Optimal Cost Schedule
\[ c^*(\alpha, \mathcal{V}) := \min_{\mathcal{R}} C_{\text{sol}}(\alpha, \mathcal{V}) \]

Cost of Solar
\[ C_{\text{sol}} := c_s \alpha \sum_t s(t) \]

Energy Cost (grid)
\[ + \sum_t c_e(t) \left[ \sum_i r_i(t) - s(t) \right] + \Delta \max_t \sum_i r_i(t) \]

Demand Charge

Solar Curve (TMY)
\[ s(t) := \]

\[ \alpha^* := \arg \min_{\alpha} \mathbb{E}_\mathcal{V}[c^*(\alpha, \mathcal{V})] \approx \arg \min_{\alpha} \frac{1}{S} \sum_{j=1}^{S} C_{\text{sol}}(\alpha, \mathcal{V}_j) \]

Set of EVs

Infrastructure Constraints

Scenarios from learned distribution
Monthly Savings with Optimal Solar

- Monthly Optimal
- Yearly Optimal

<table>
<thead>
<tr>
<th>Savings ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
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<tbody>
<tr>
<td>On-Peak</td>
<td>$0.25 / kWh</td>
<td>$0.08 / kWh</td>
</tr>
<tr>
<td>Mid-Peak</td>
<td>$0.09 / kWh</td>
<td>$0.08 / kWh</td>
</tr>
<tr>
<td>Off-Peak</td>
<td>$0.06 / kWh</td>
<td>$0.07 / kWh</td>
</tr>
<tr>
<td>Demand Charge</td>
<td>$15.48 / kW/month</td>
<td></td>
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</tbody>
</table>

Assuming no net metering or alternative uses of solar
Sensitivity to LCOE of Solar

Solar Capacity (kW)

Percent Solar (%)

Cost Savings (%)

Solar Levelized Cost of Energy ($)

Assuming no net metering or alternative uses of solar
How can data help us understand the impact of EV charging on the grid?
Problem Formulation

Net demand trend

Avg. ramp
~8,643MW in 3 hrs.
Problem Formulation

Minimum Ramp Schedule

\[ \min_{r \in R} U_{ramp}(V) \]

\[ U_{ramp} := \sum_{t} -\left( \hat{d}(t) - \hat{d}(t - 1) \right)^2 \]

\[ \hat{d}(t) := \sum_{i \in V} r_i(t) - d(t) \]

\[ d(t) := \text{Net Demand Curve} \]
Qualitative Results

MW

0:00 5:00 10:00 15:00 20:00 25:00

Caltech

JPL

None 350,000 1.5 million 5 million

MW
Quantitative Results

- **Up Ramp**
  - Caltech
  - JPL

- **Down Ramp**
  - Caltech
  - JPL

- **Peak Demand**
  - Caltech
  - JPL

Graphs showing the comparison between Caltech and JPL for Up Ramp, Down Ramp, and Peak Demand as a function of the number of EVs.
Recap

Over 32,000 EV Charging Sessions

- Machine Learning and Statistical Modeling
- Algorithm Design and Evaluation
- System Design and Grid Impacts
- Your idea here...
Accessing the dataset

- Web Interface
- API
- Python Client
- ACN-Sim
More tools for EV research
**ACN Research Portal**

- **Phase 0**: ACN Testbed
- **Phase 1**: ACN-Data
- **Phase 2**: ACN-Sim
- **Phase 3**: Integration with OpenAI Gym
- **Phase 4**: ACN-Live (hardware-in-the-loop)
- **Phase 5**: Integration with grid simulator
ACN-Sim

A common environment to accelerate large-scale EV charging research.
Simulation Loop

run()

EventQueue Empty?

Yes

Simulation finished

No

Execute events in queue up to current timestep

Recompute Schedule?

Yes

Call scheduling algorithm

No

Send updated pilot signals to EVSEs

Update stored charging schedule

Pass pilot signal through EV to Battery

Collect actual charging rates

Update state and increment timestep
ACN-Sim + ACN-Data

![Graph showing demand met (%) vs. transformer capacity (kW) for different scheduling algorithms. The algorithms include First-Come First-Served, Earliest Deadline First, Least Laxity First, Round Robin, Adaptive Charging, and Offline Optimal.]
Oversubscribing
Unbalanced Three-Phase Infrastructure

Uncontrolled

Adaptive Charging

Line Current (A)

Time (periods)

0 100 200 300 400 500 600

150 200 250 300 350

A
B
C

Caltech
The Adaptive Charging Network

Accelerating Electric Vehicle Research @ Caltech and Beyond

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