# Modeling personal vehicle energy consumption for electrification and decarbonization

ZACH NEEDELL

DISSERTATION DEFENSE, 8/14/2018

Civil and Environmental Engineering

Trancik lab ENERGY MODELING

# U.S. $CO_{2eq}$ Emissions

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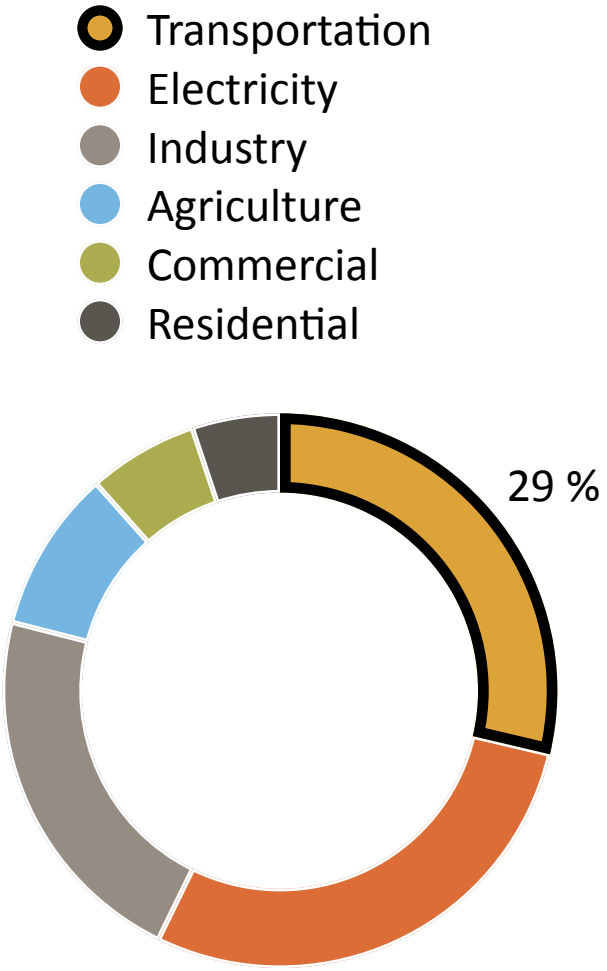

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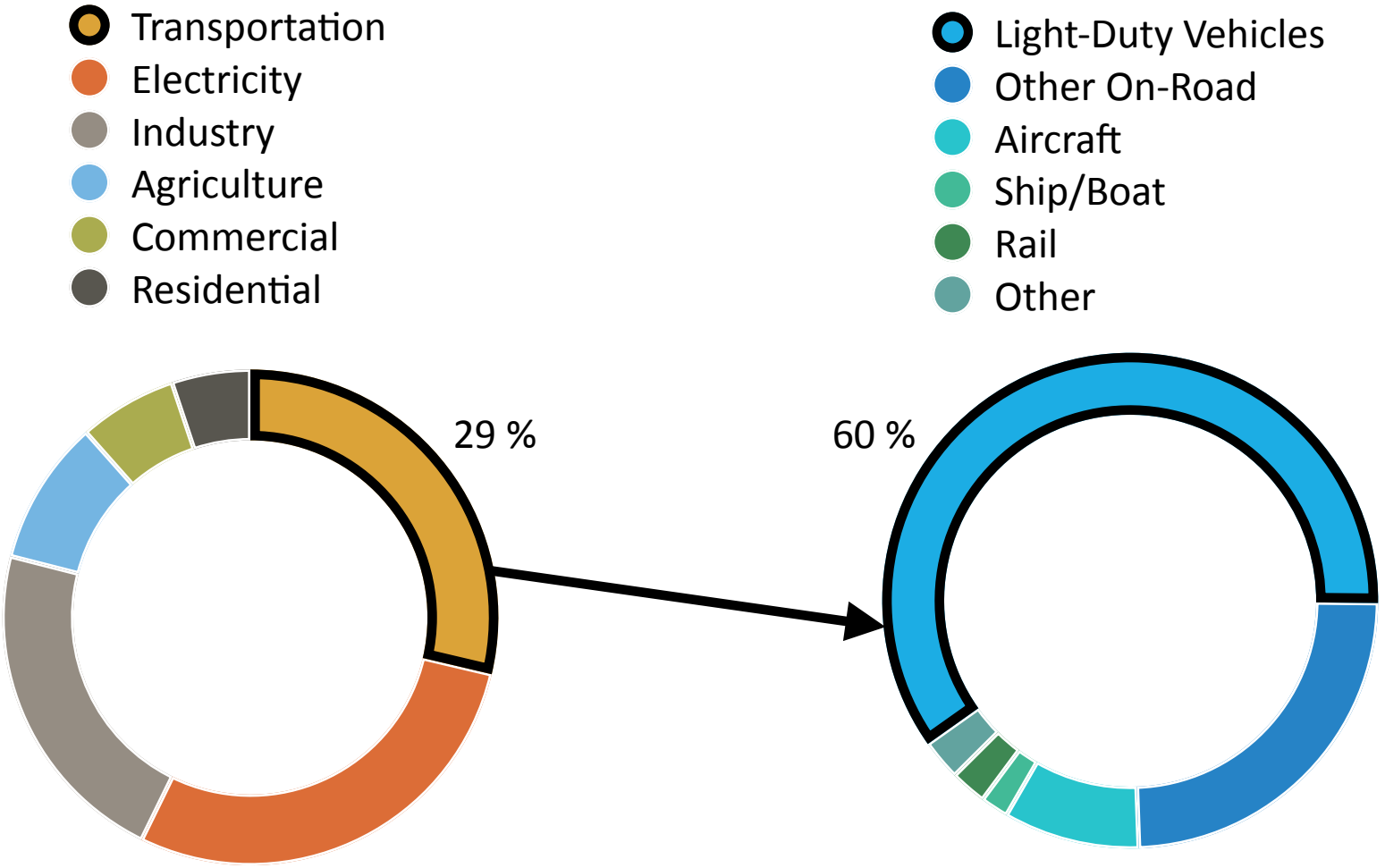

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Identify and evaluate technological and policy solutions to ease emissions reductions from the transport sector

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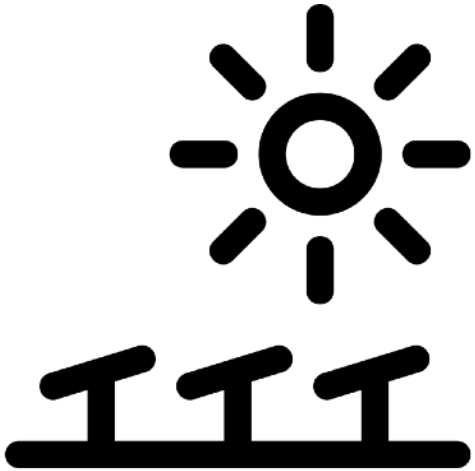

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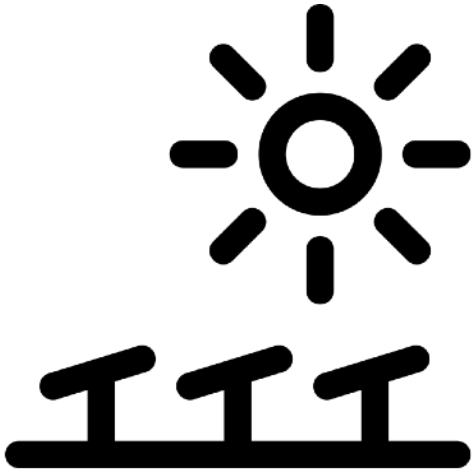

**Barrier:**

Limited range

Grid integration

# Gap in the literature

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Existing research addresses these topics by focusing on set of determinants or the other

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Existing methods either:

- Assume fixed per-mile energy use
- Rely on unrepresentative travel patterns

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**How effectively can battery electric vehicle (BEV) technology meet the range requirements of typical driving?**

**When in the transitions to BEVs and renewables will harmful impacts occur, and how can positive interactions be maximized?**

# Methods

## TRIPENERGY MODEL FRAMEWORK

# Model needs

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This model should:

- Capture realistic variability in travel behavior, technology performance, and the ways in which they are related
- Work efficiently, use available data

# Data needs

**Behavior**

**Technology**


Map from Azevedo, Carlos Lima, et al. "Simmobility short-term: An integrated microscopic mobility simulator." *TRR* 2622 (2017): 13-23.

# Data needs

**Behavior**

**Technology**

***Comprehensive travel patterns***

***Detailed driving behavior***


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Photo by AdamNavrotny - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31745770
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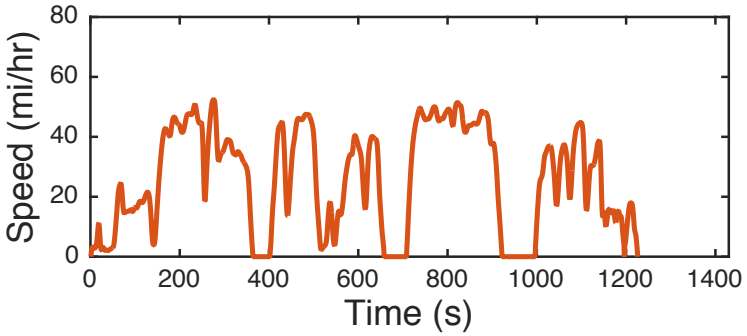



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***Detailed driving behavior***

**Technology**

- EPA CAFE test data
  - Drag coefficients
  - Fuel economy test results

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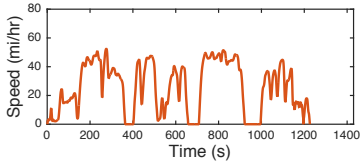
# Modeling energy use patterns

Comprehensive behavior

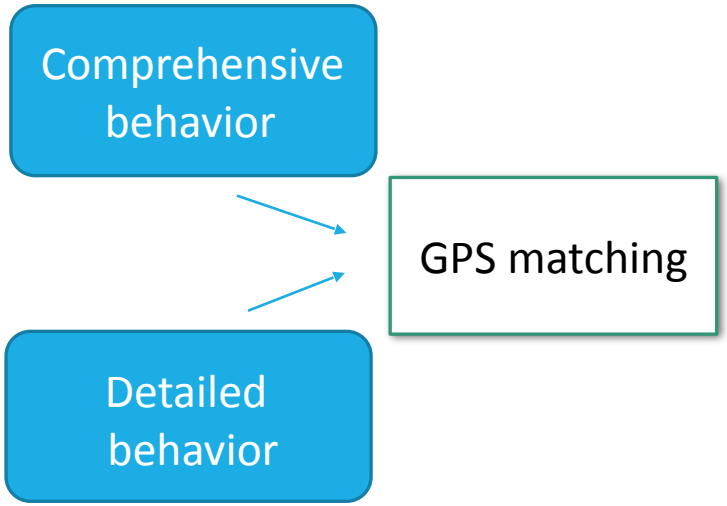
NHTS
U.S. Department of Transportation
Federal Highway Administration

Detailed behavior



# Modeling energy use patterns

- Match lower-resolution data that captures collective travel patterns with second-by-second GPS data



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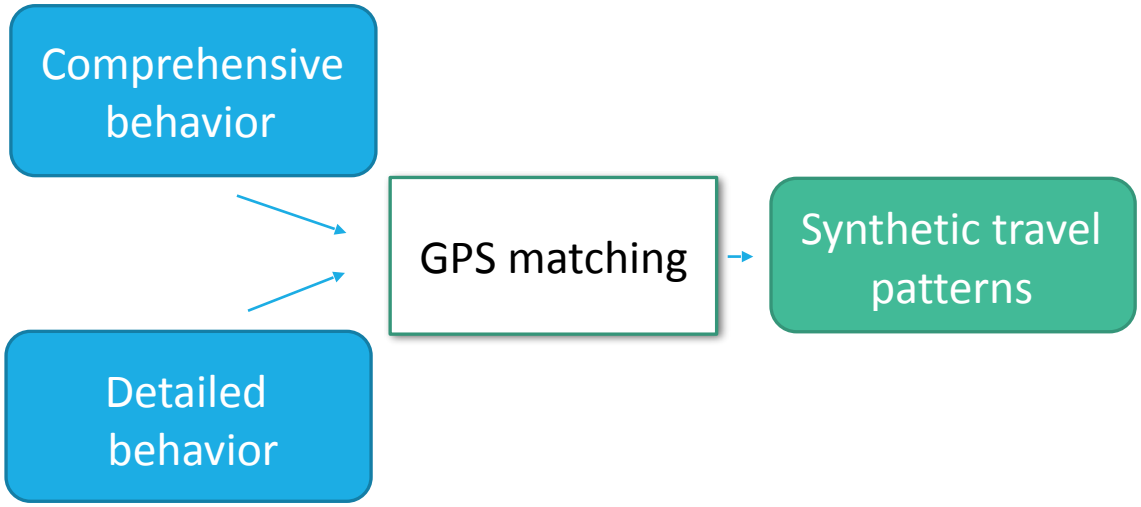
- Match lower-resolution data that captures collective travel patterns with second-by-second GPS data
- Produce a representative synthetic picture of driving behavior



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- Match lower-resolution data that captures collective travel patterns with second-by-second GPS data
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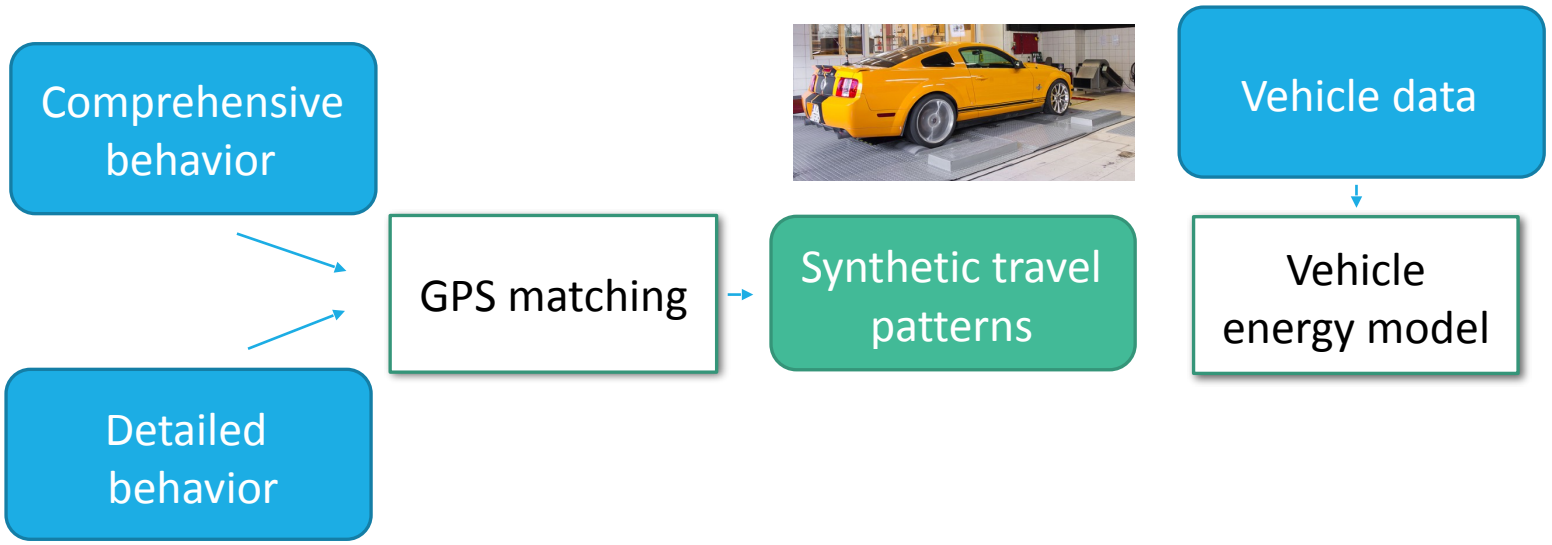
- Calibrate vehicle-specific energy model



# Modeling energy use patterns

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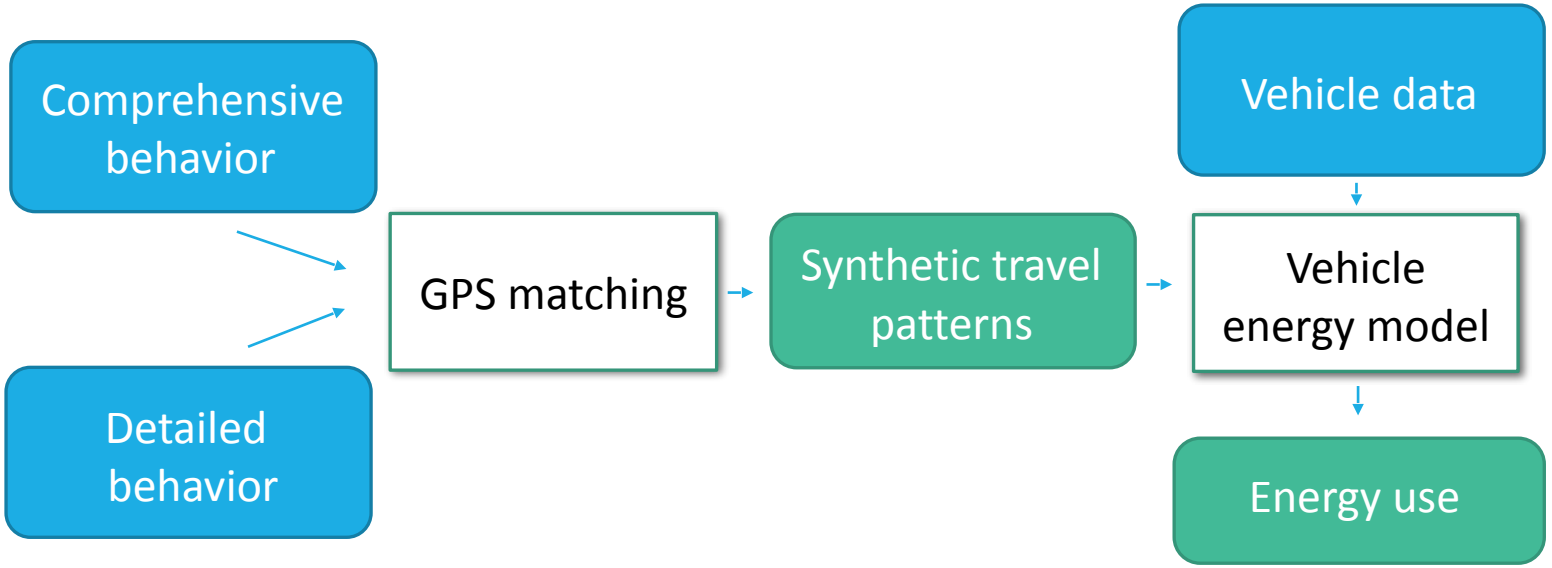
- Produce a representative synthetic picture of driving behavior
- Calibrate vehicle-specific energy model
- Produce energy estimate



# Vehicle model

$$E_{tr} = \int F_{tr}(t)v(t)dt$$

# Vehicle model

**Tractive energy:**

Drag coefficients

$$F_{tr}(v) = a + bv + cv^2 + (1+q)m\frac{dv}{dt}$$

Rotational inertia

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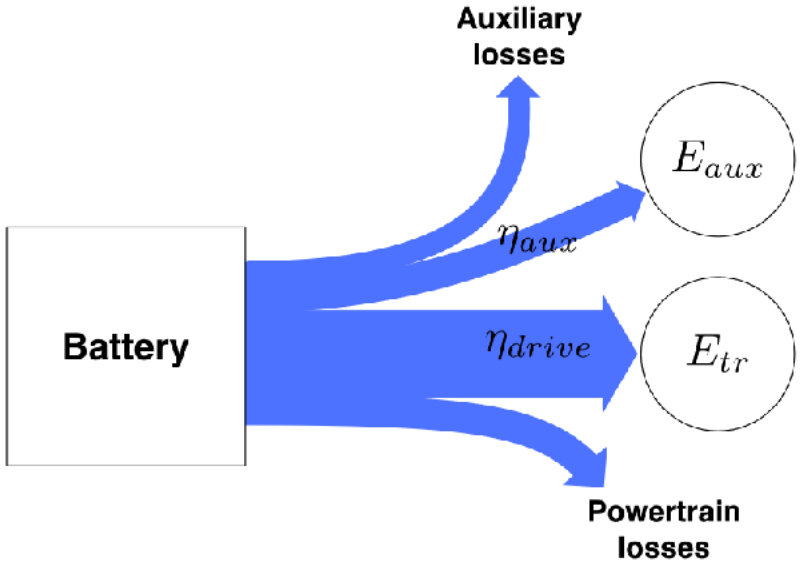

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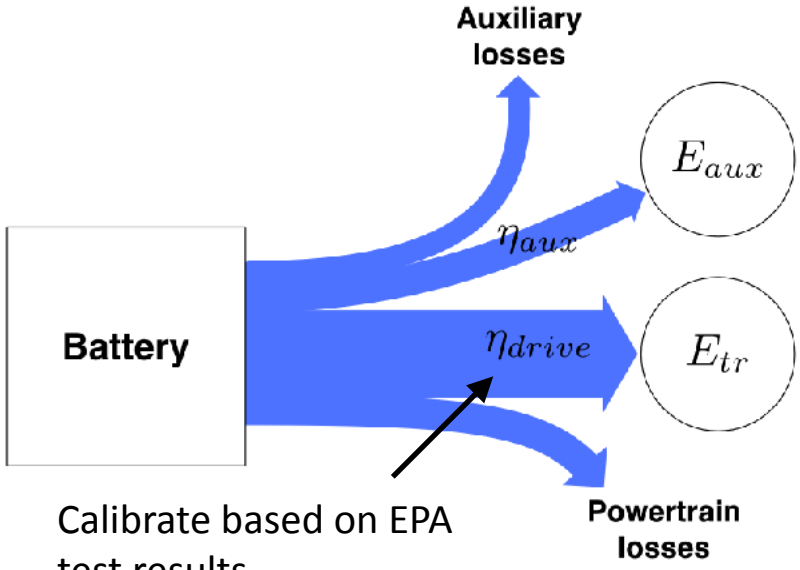


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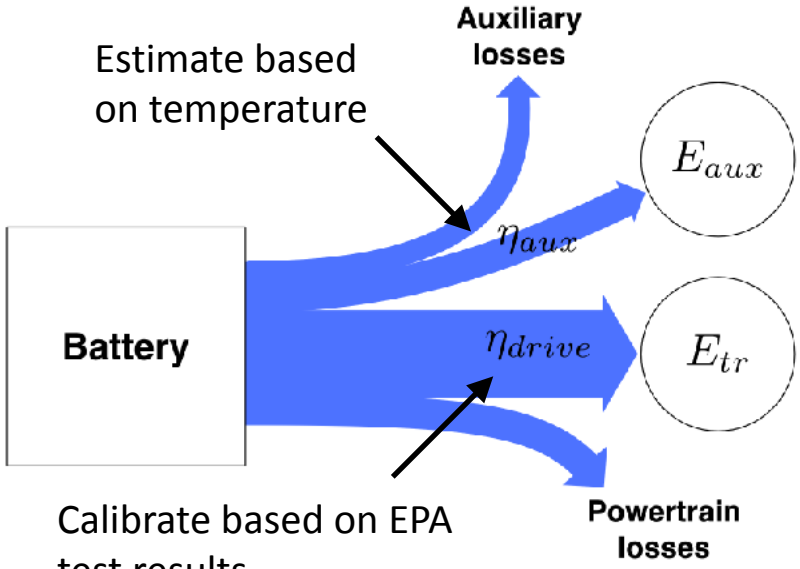
**Losses:**

Estimate based on temperature

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**Comparison**: TripEnergy vehicle model, given full-resolution GPS trajectory

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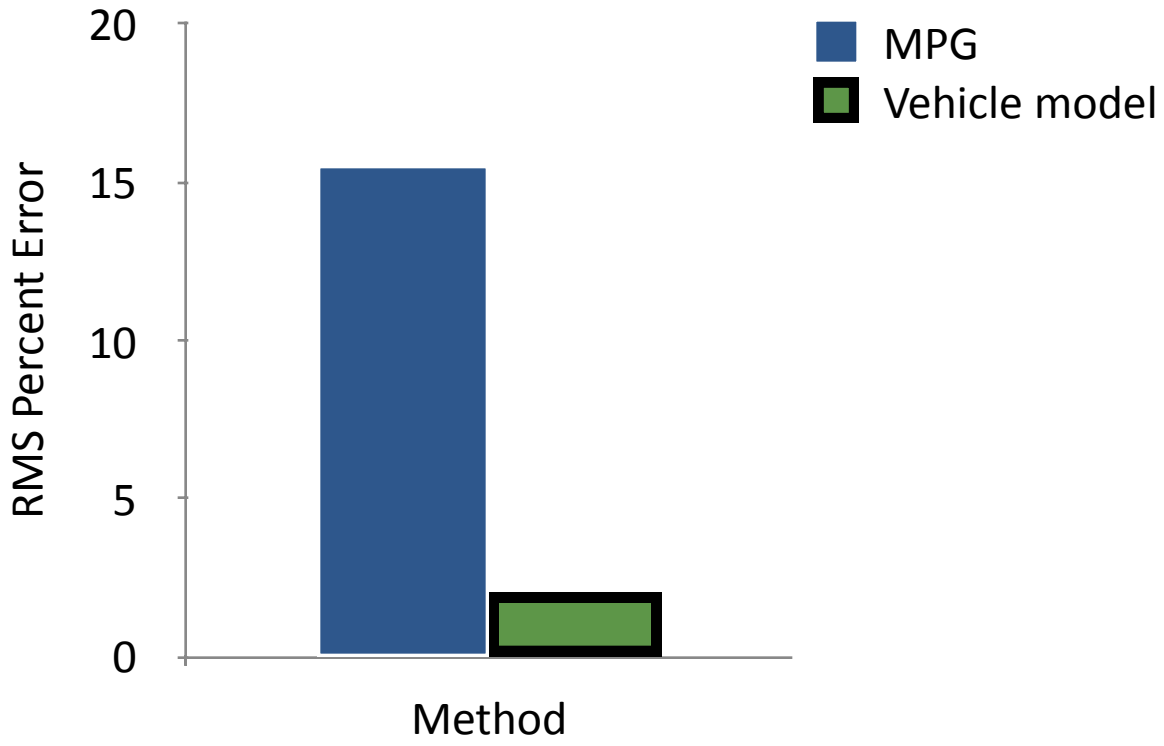

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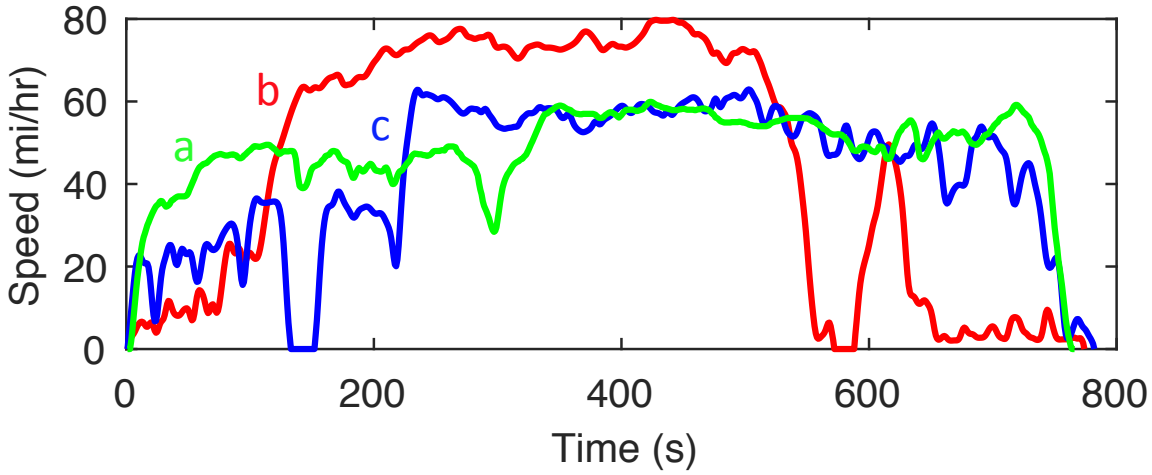

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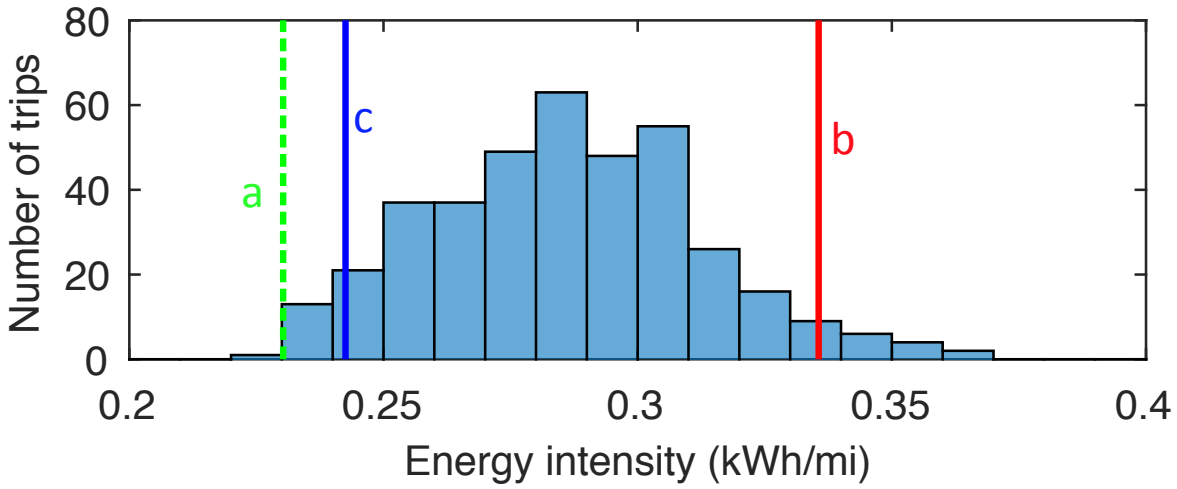

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**Ground truth**: Microsimulation with ADVISOR of full GPS trajectory

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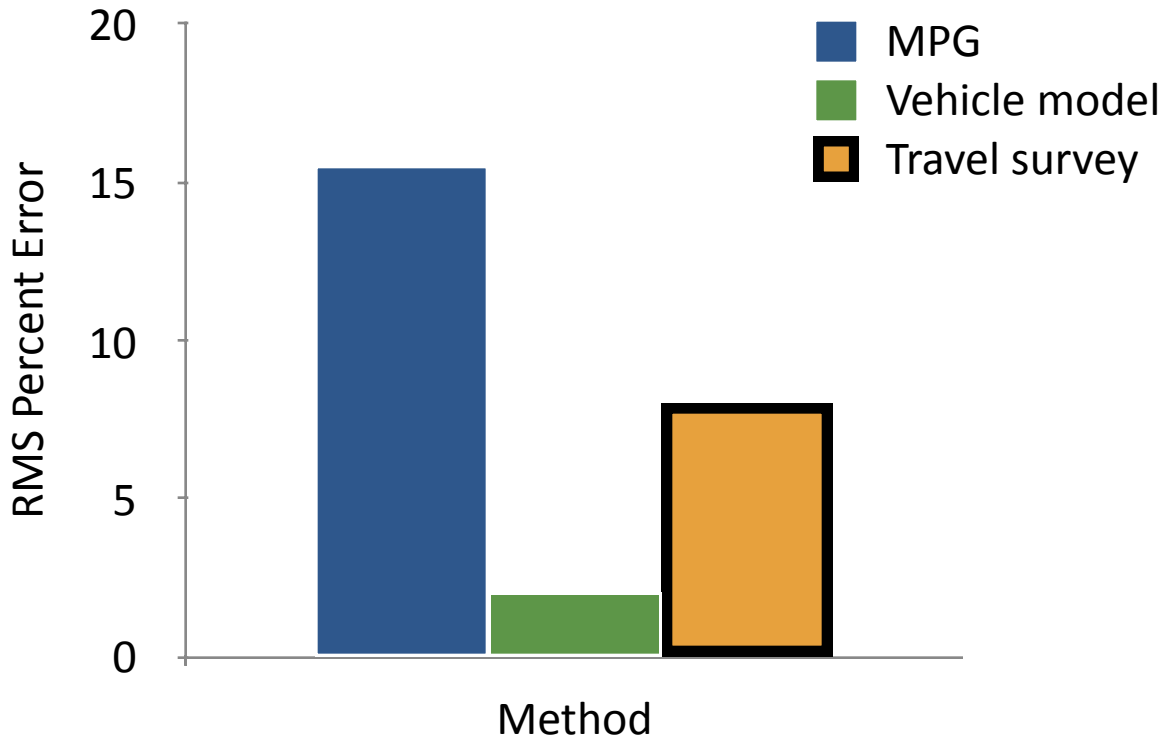

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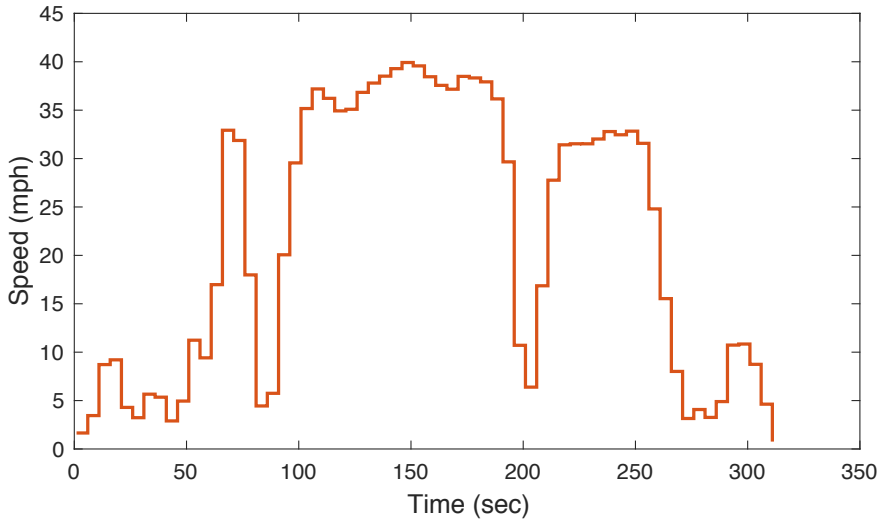

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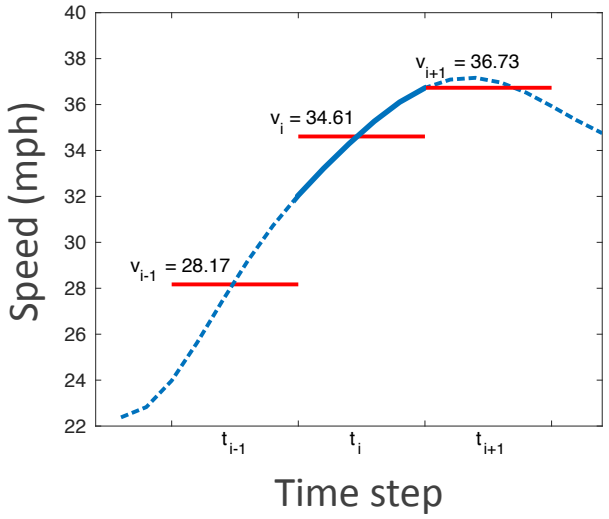

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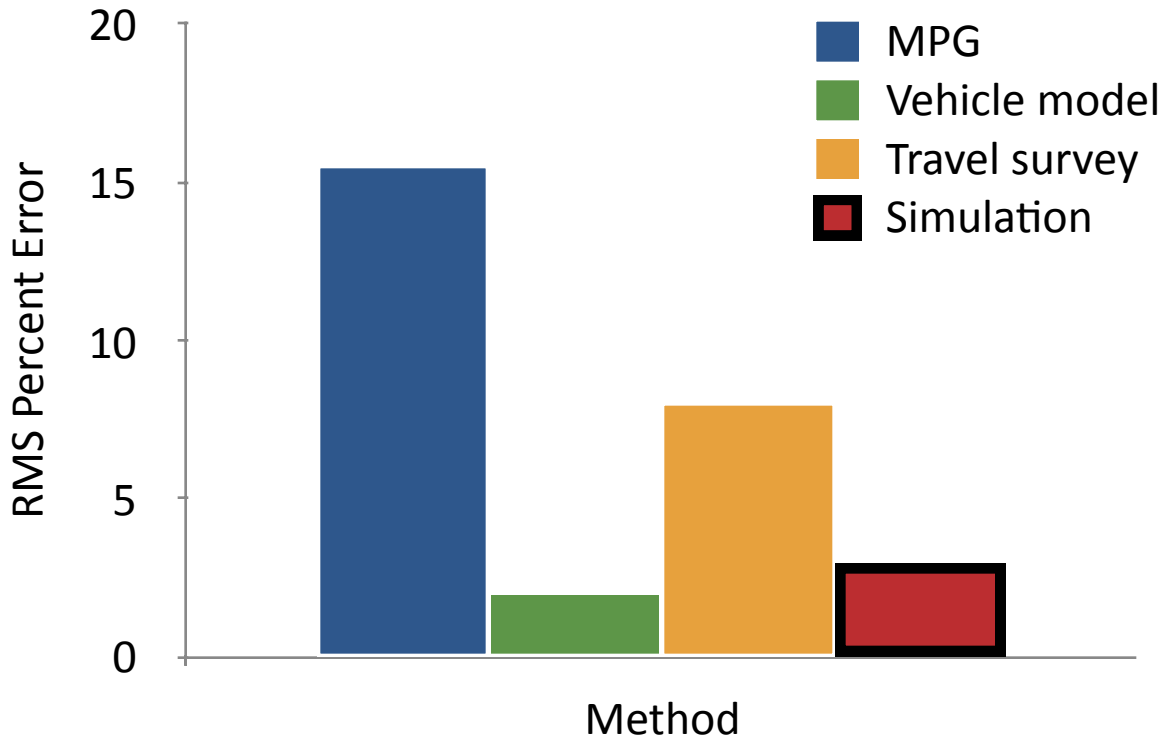
**Ground truth**: microsimulation with ADVISOR of full GPS trajectory

**Comparison**: TripEnergy, given medium-resolution simulated trajectory



# Model performance

kW per meter →

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- Estimating vehicle-specific energy from a drive cycle to within 2% does not require extensive data collection
- Half of trip-by-trip variability in energy consumption can be captured by just vehicle type, and trip distance and duration
- Trajectories from mesoscopic simulations (if accurate) can determine energy consumption to within 3%

# TripEnergy applications

Areas where a more comprehensive picture of energy consumption can bring new insight into tools to reduce emissions

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***Survey-based model***

- Evaluate specific vehicle's performance under representative demand
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***Survey-based model***

- Evaluate specific vehicle's performance under representative demand
- Estimate aggregate impacts of vehicle use

***Simulation-based model***

- Understand situations where technology performance affects travel behavior
- Design and implement personalized tools

# Model applications

EVALUATING TOOLS TO REDUCE EMISSIONS

# Research questions: BEV range

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**How effectively can battery electric vehicle (BEV) technology meet the range requirements of typical driving?**

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- Would improved battery technology solve this problem?

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# Performance measures

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**Daily adoption potential (DAP):**

What percentage of vehicles on a given day could be replaced by an electric vehicle without requiring mid-day charging?

**Gasoline substitution potential (GSP):**

What percentage of total gasoline use do these ‘replaceable’ vehicle days represent?

# Performance measures

- Measured for the entire U.S.

| Vehicle | Daily adoption potential (DAP) | Gasoline substitution potential (GSP) |
|---|---|---|
| 2013 Nissan Leaf | 87% | 61% |
| 2016 Nissan Leaf | 93% | 76% |
| 2016 Tesla Model S | 96% | 86% |

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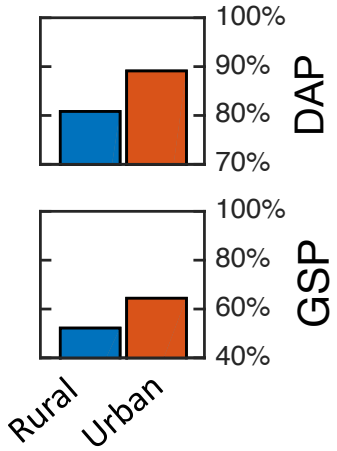


- Urban areas do better than rural areas in both measures

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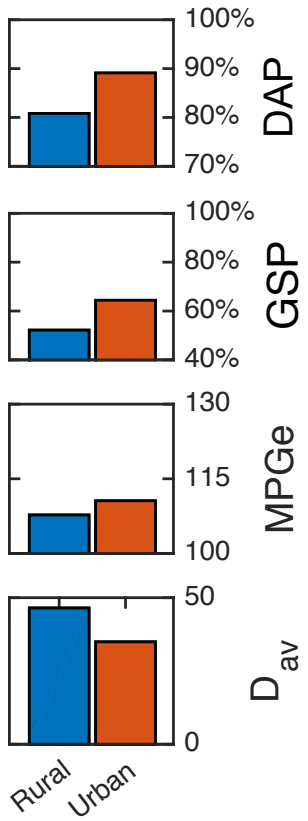
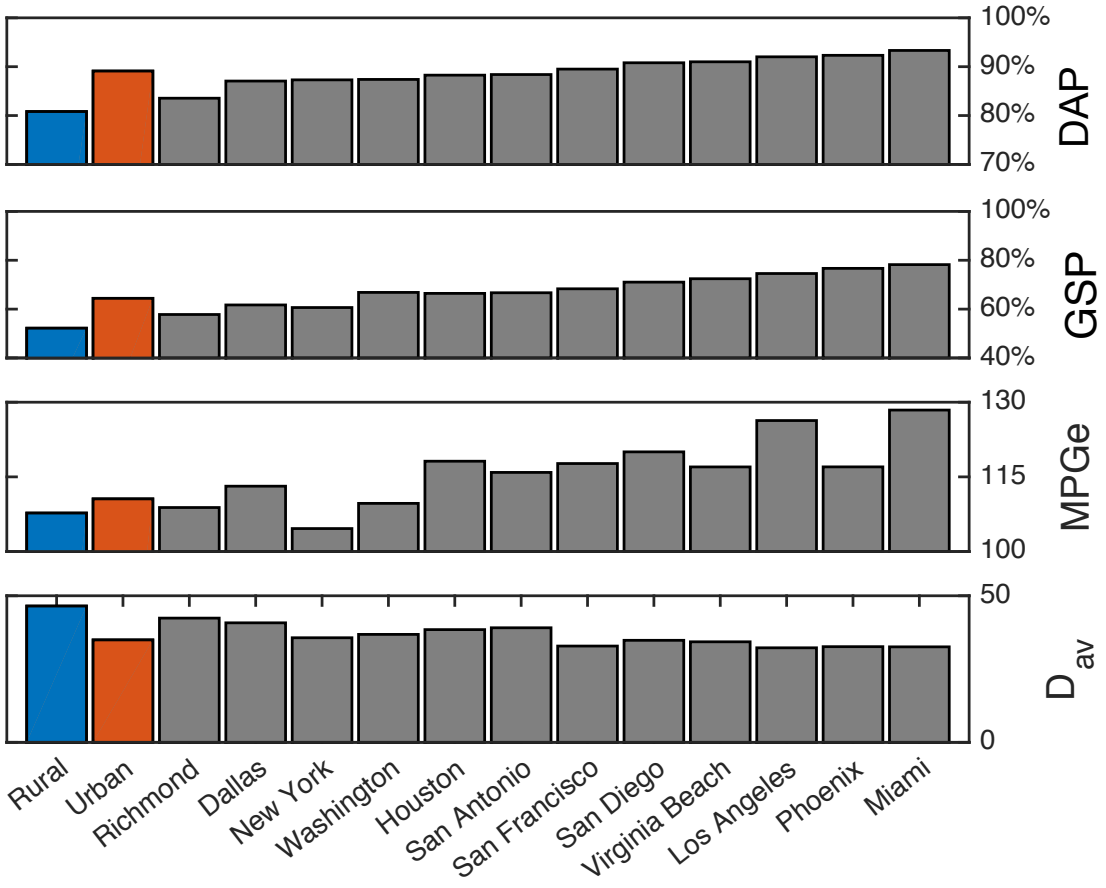



- Urban areas do better than rural areas in both measures due to:
  - Higher average fuel economy
    - *MPGe* — Miles per Gallon Equivalent
  - Shorter driving distances
    - $D_{av}$ — Average daily driving distance

# Performance measures



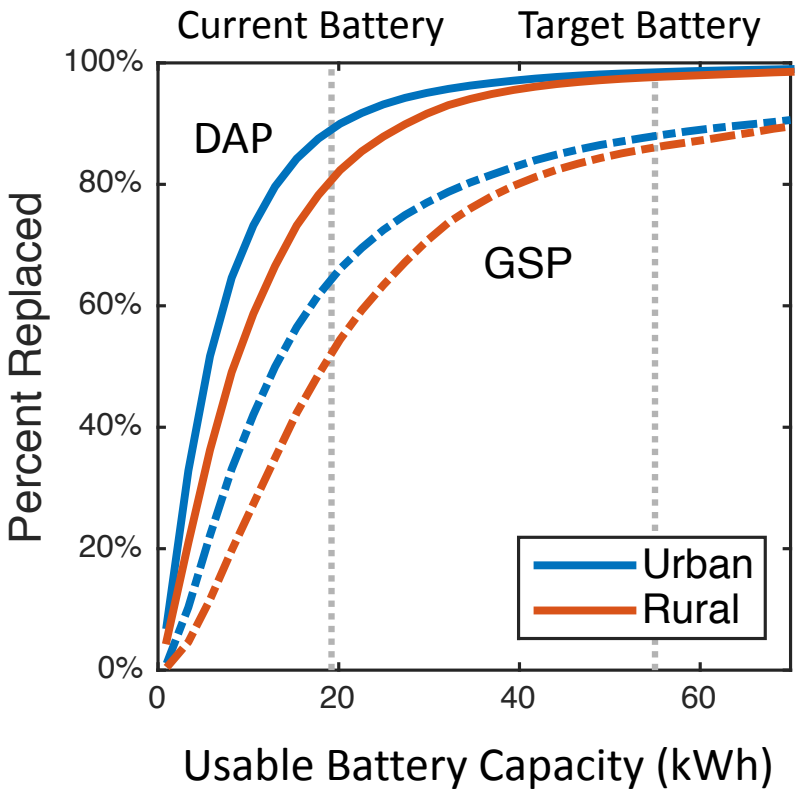

- Some individual cities do better than urban average
- No cities do as poorly as the rural average
- Best cities are in the sunbelt—LA, Phoenix, Miami

# Research questions: BEV range

How effectively can battery electric vehicle technology meet the range requirements of typical driving?

- How much of a technological constraint does current BEV range provide on electrification across the U.S.?
- **Would improved battery technology solve this problem?**

# Effects of improved batteries



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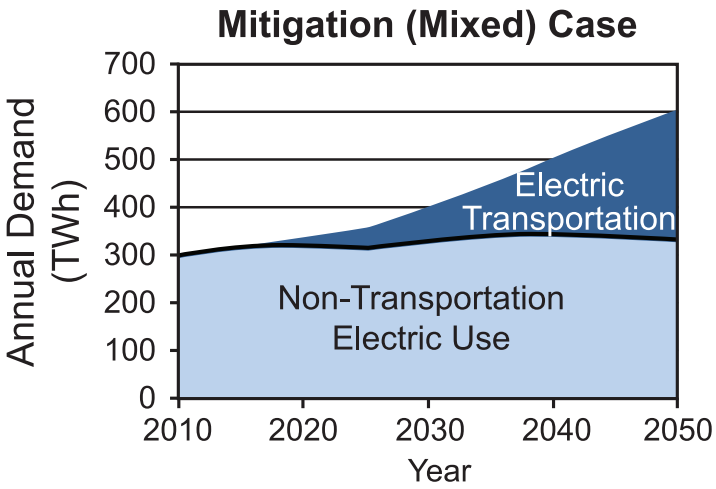
    - Suggests focus switch from extending range to promoting adoption, covering extreme days, and managing effects

# BEVs and PV




- BEVs a plausible candidate for widespread adoption

Williams, James H., et al. "The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity." *Science* 335.6064 (2012): 53-59. Haegel, Nancy M., et al. "Terawatt-scale photovoltaics: Trajectories and challenges." *Science* 356.6334 (2017): 141-143.

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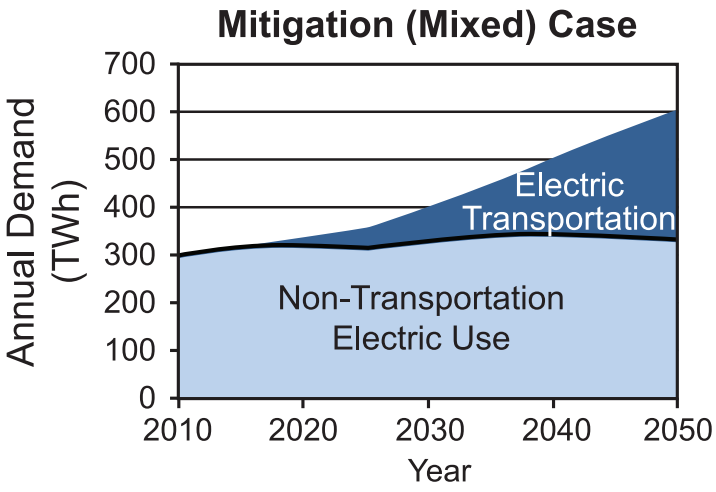


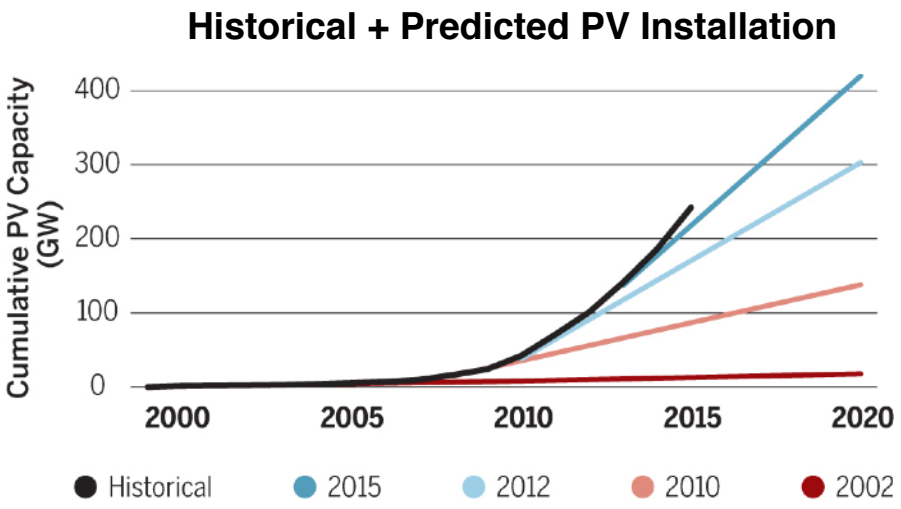


- BEVs a plausible candidate for widespread adoption
- Solar photovoltaic (PV) installation has consistently outpaced predictions
- Transitions likely to coincide. Interactions are poorly understood

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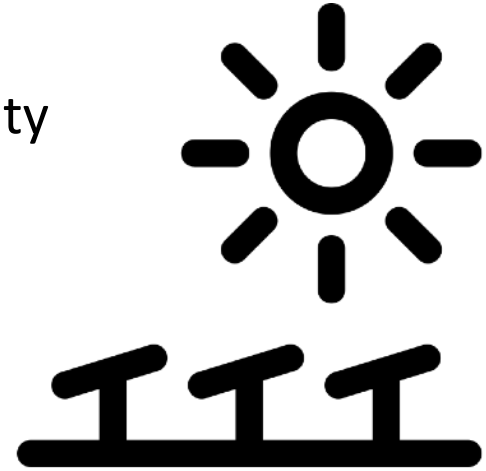
# Research questions: BEVs and PV

**Transition:**

Low-carbon electricity to power EVs

**Barrier:**

Grid integration



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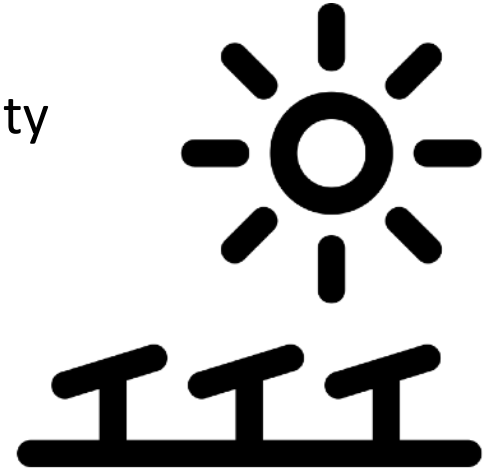

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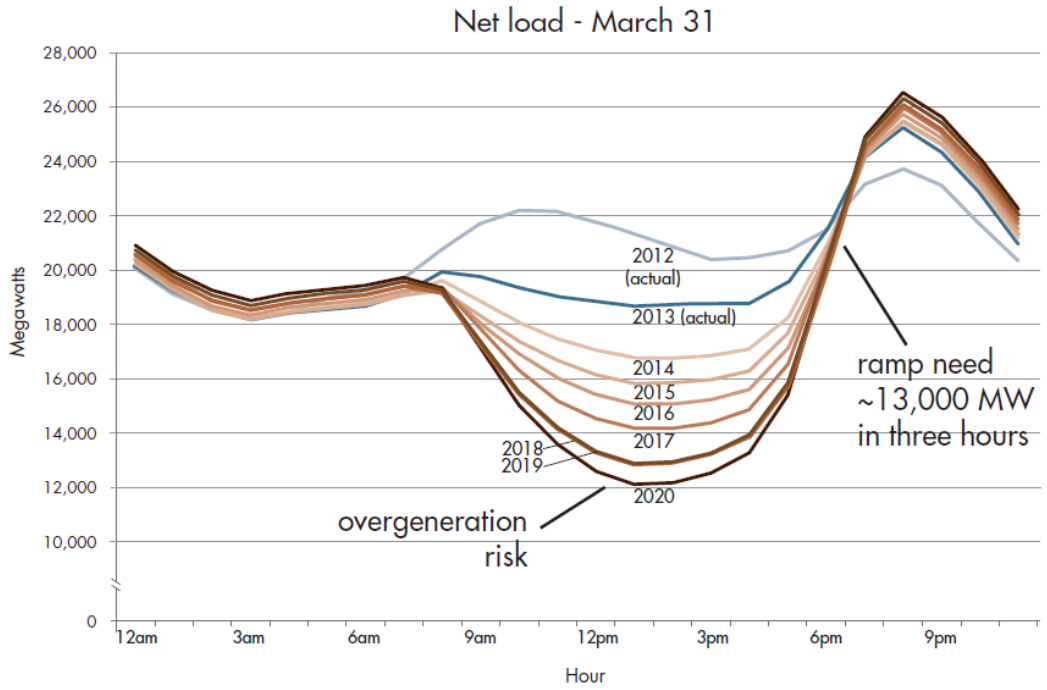
# Barriers: Duck curve

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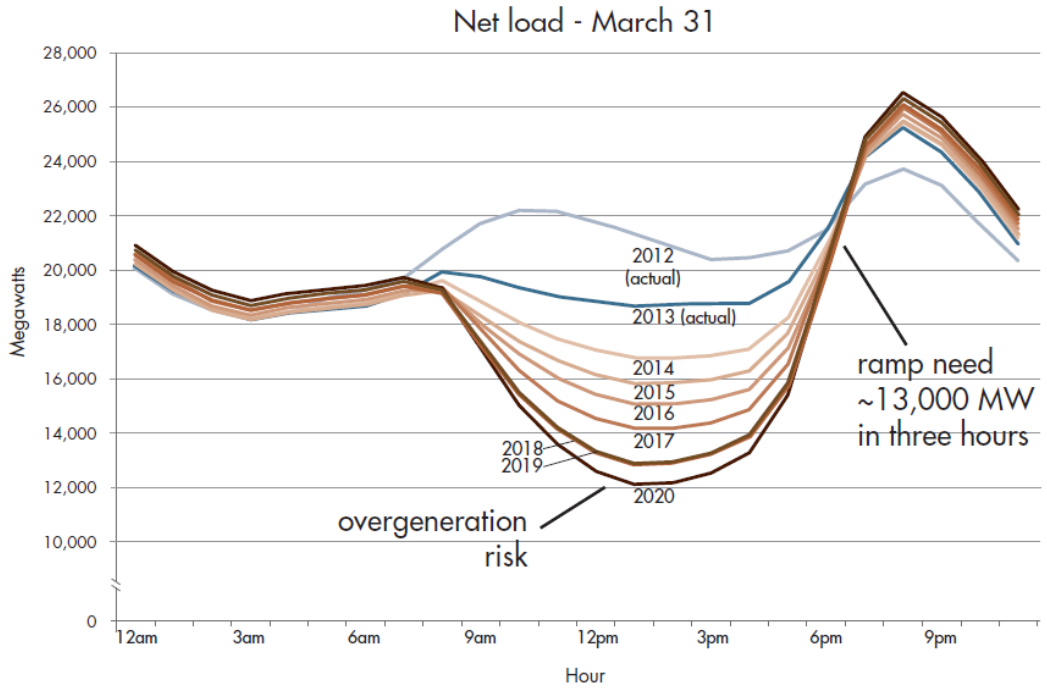


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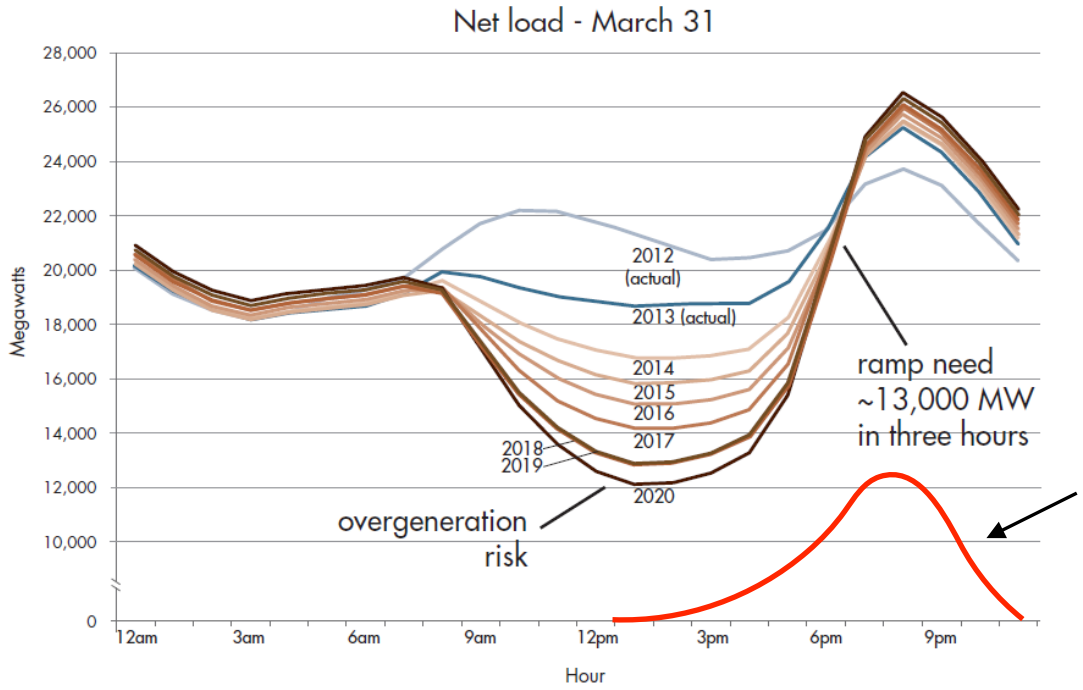


Schematic demand from post-work BEV convenience charging

- Excess PV generation during the day will lead to lower efficiency and higher prices
- BEVs charging in the evening could make this worse

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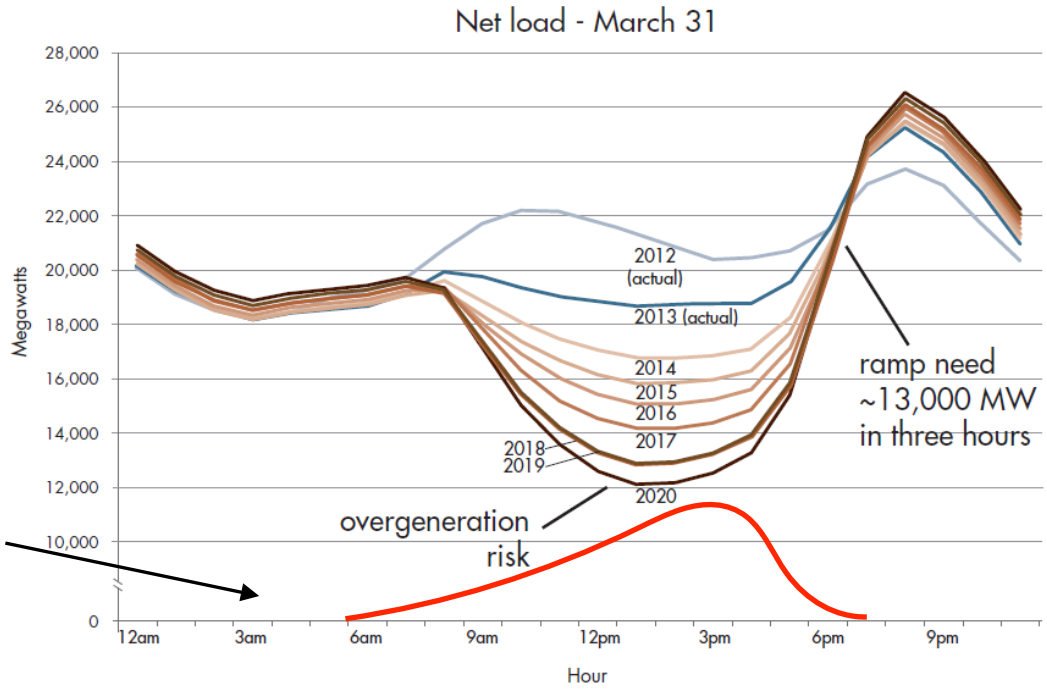


"Valley filling" with BEV charging

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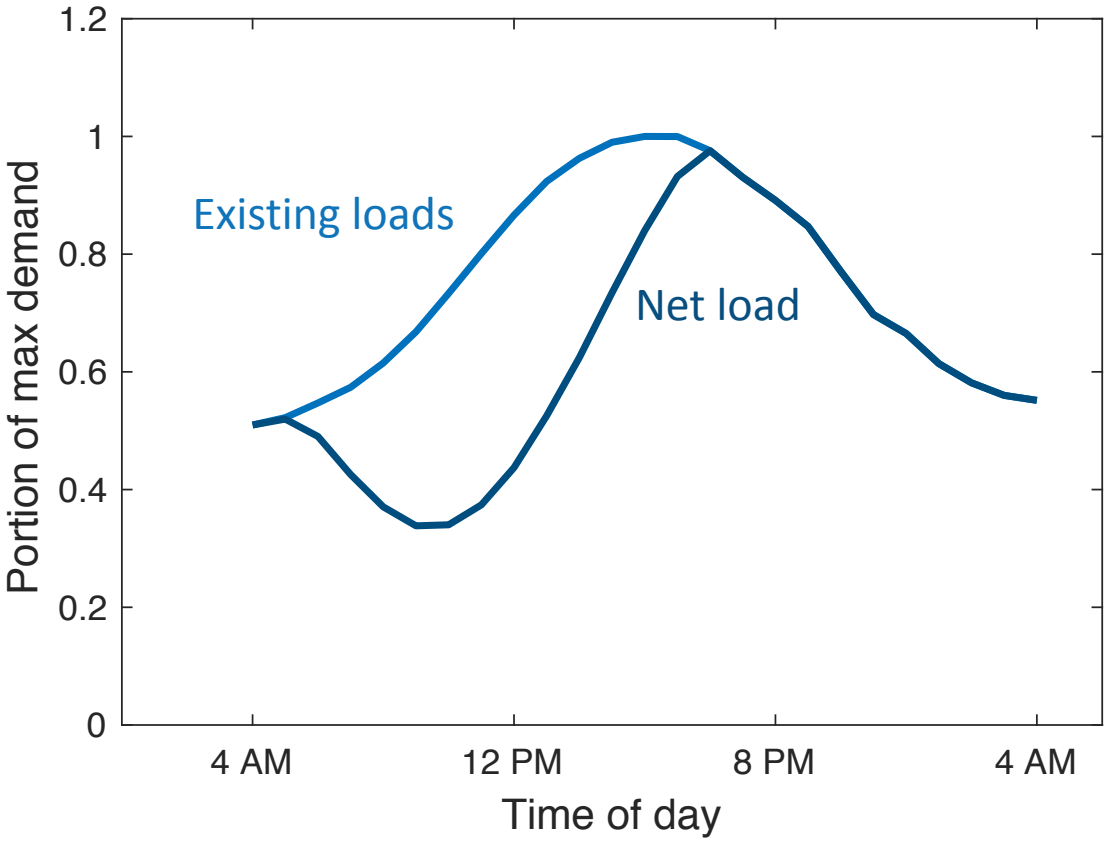

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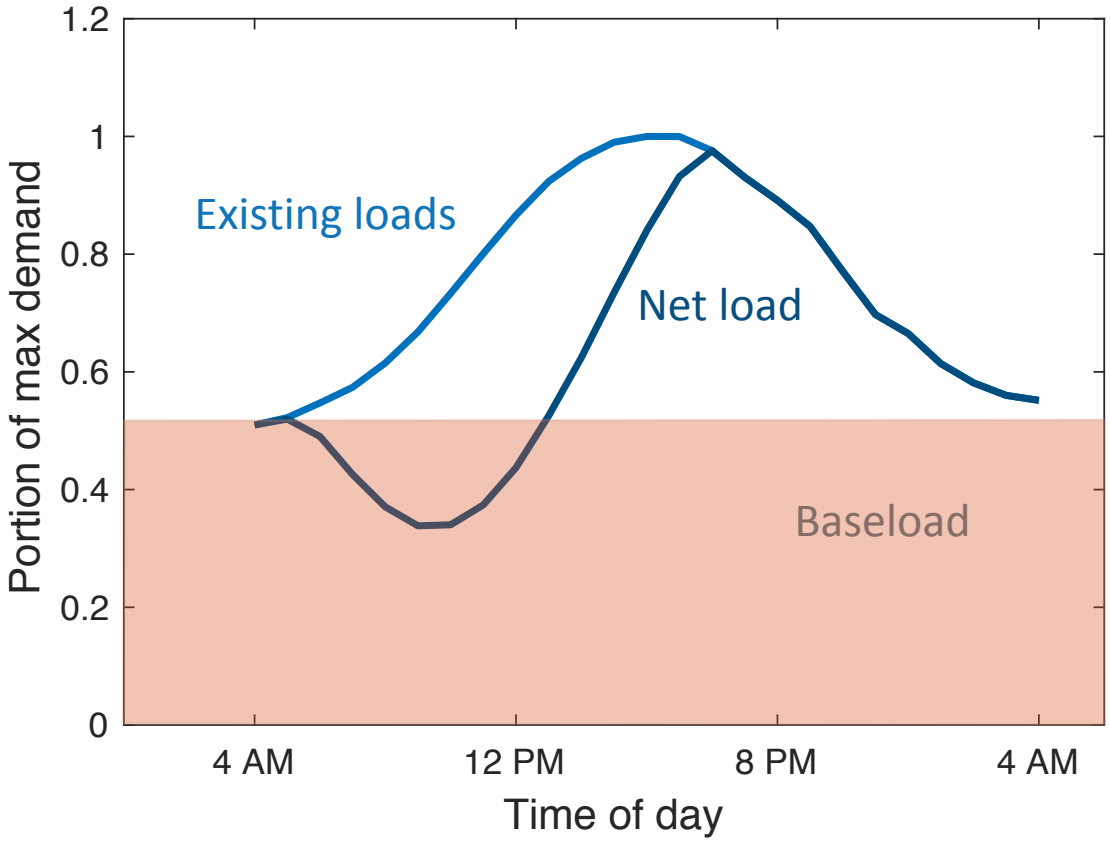

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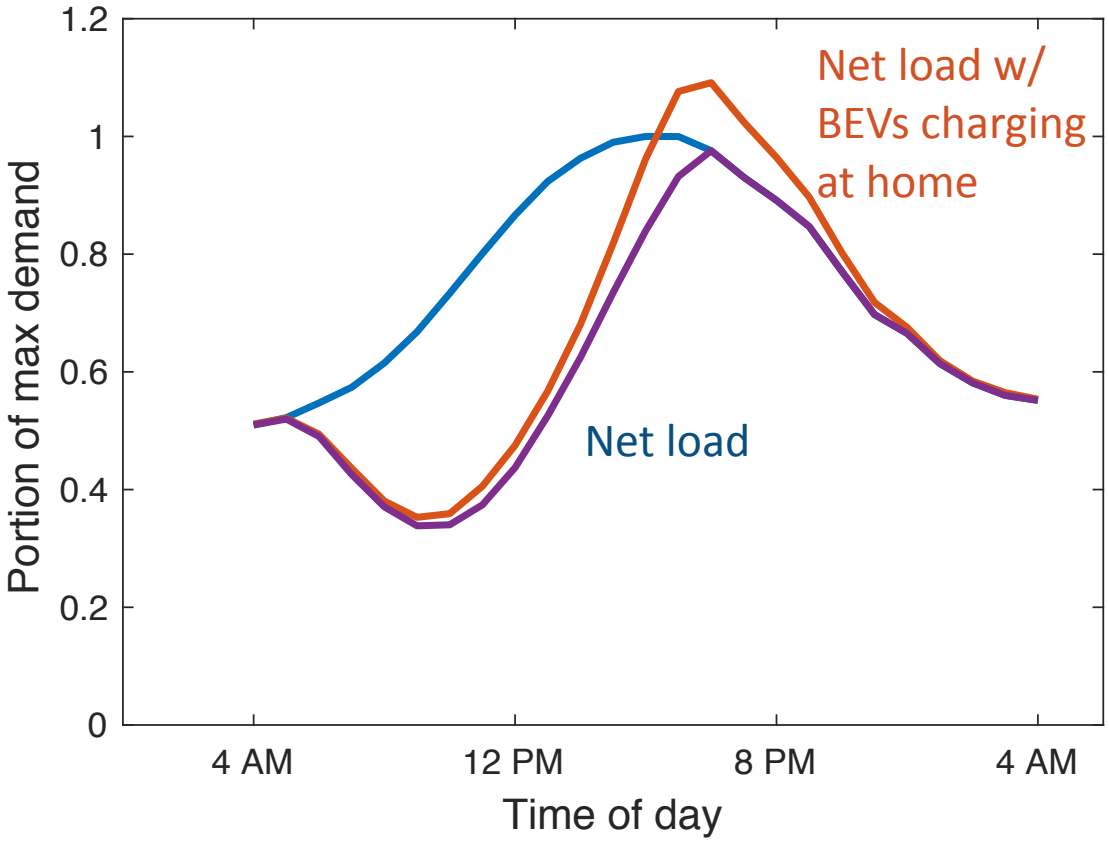

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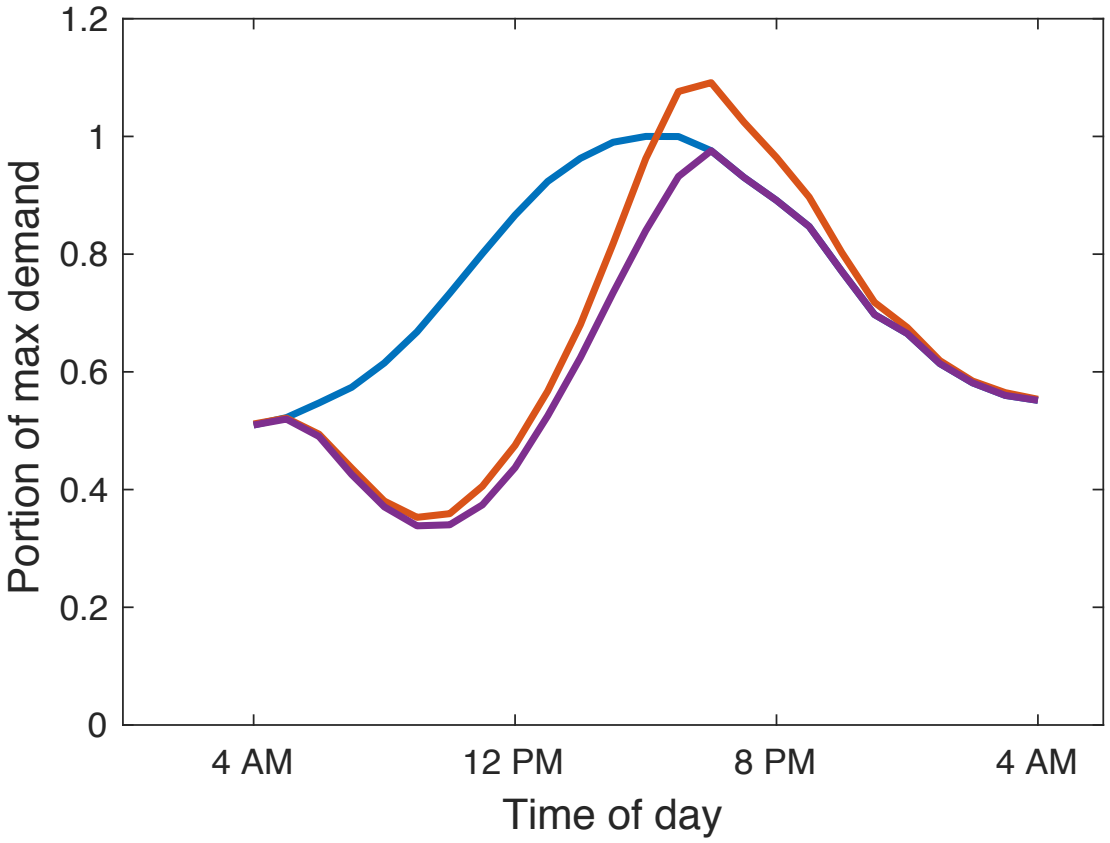

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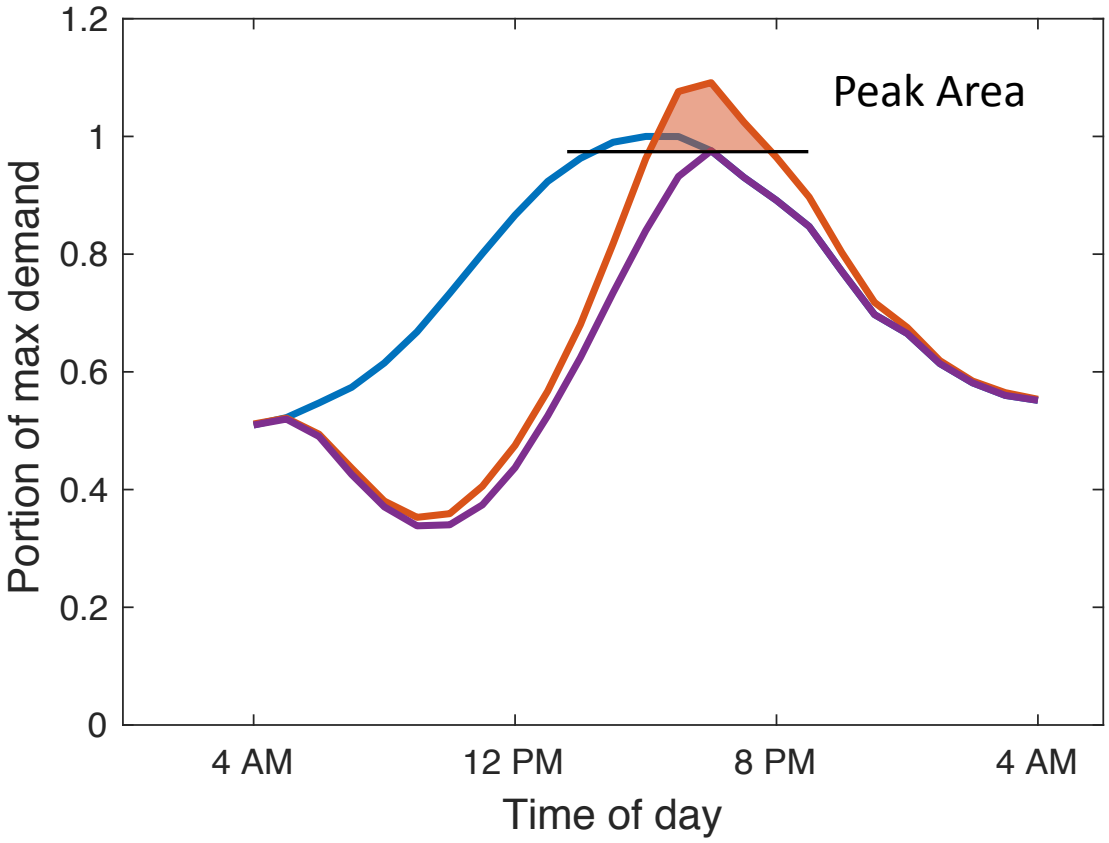

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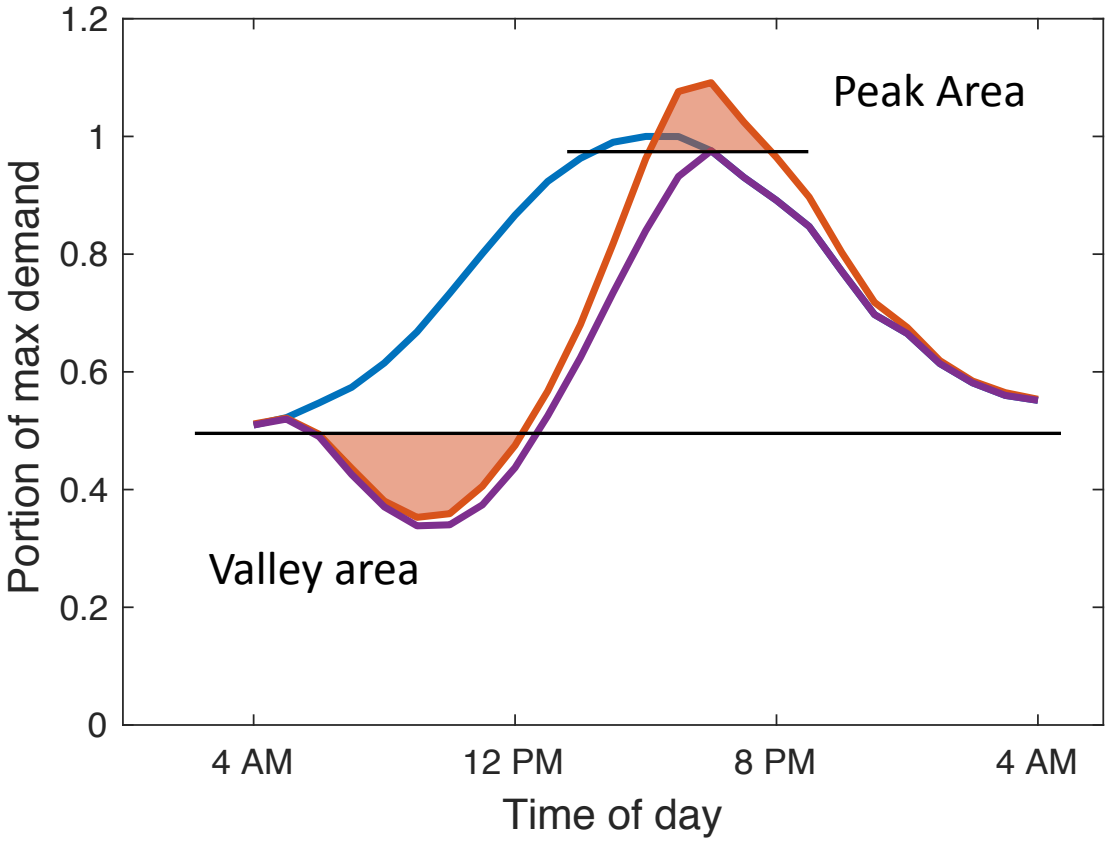

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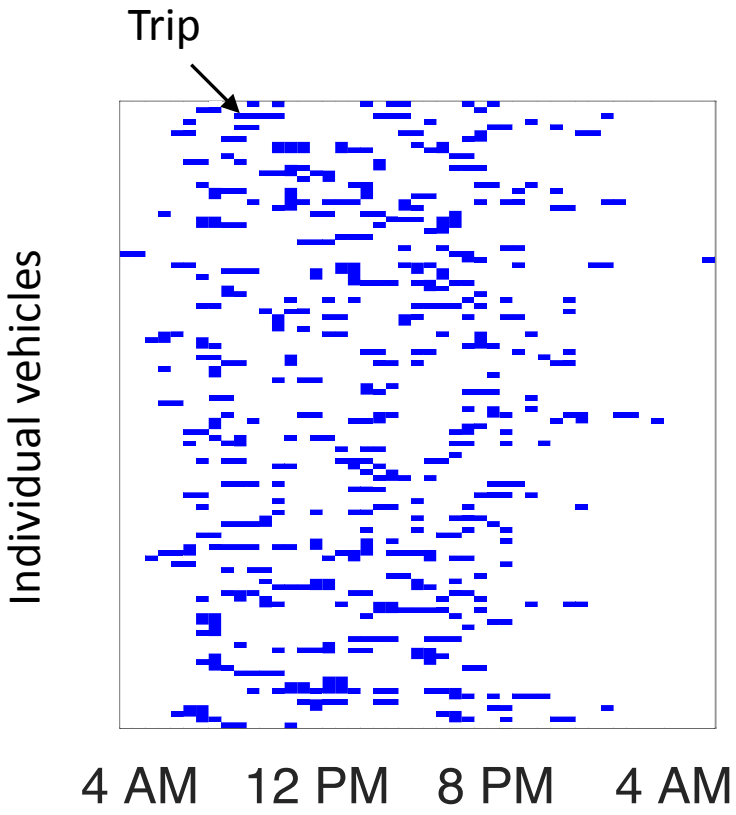

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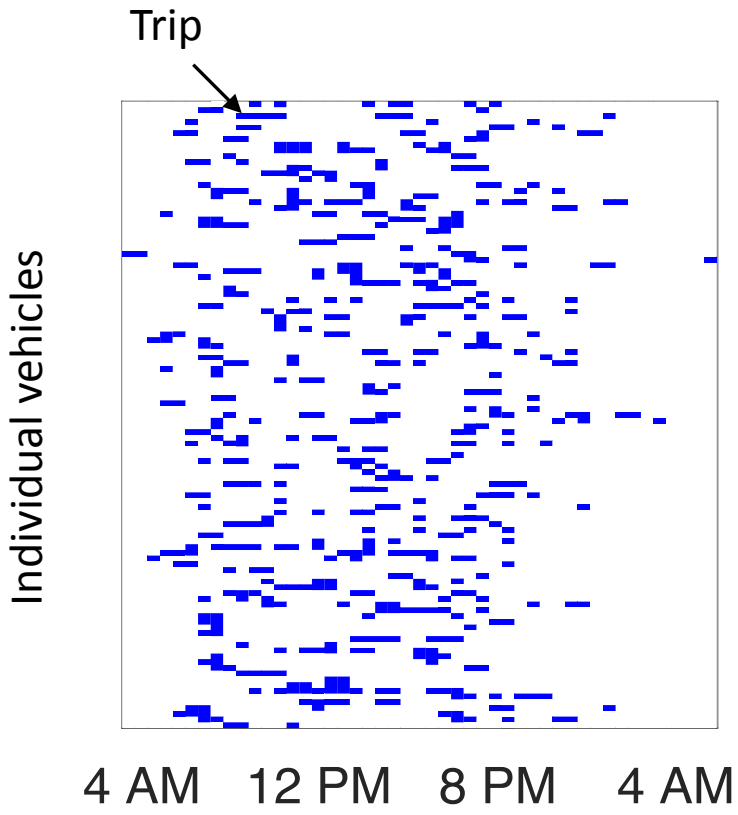
Optimization formulation of charging decisions



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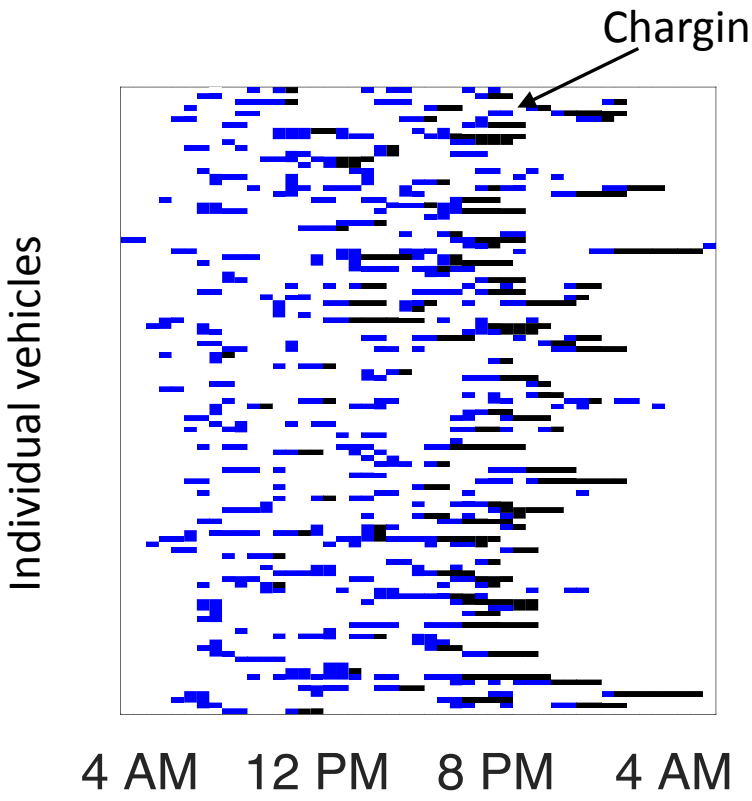

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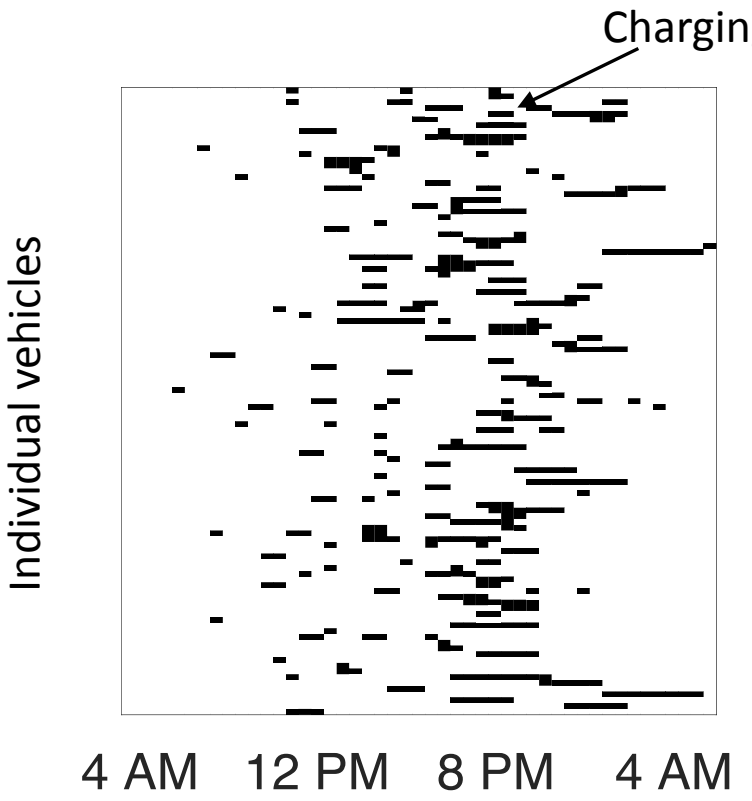

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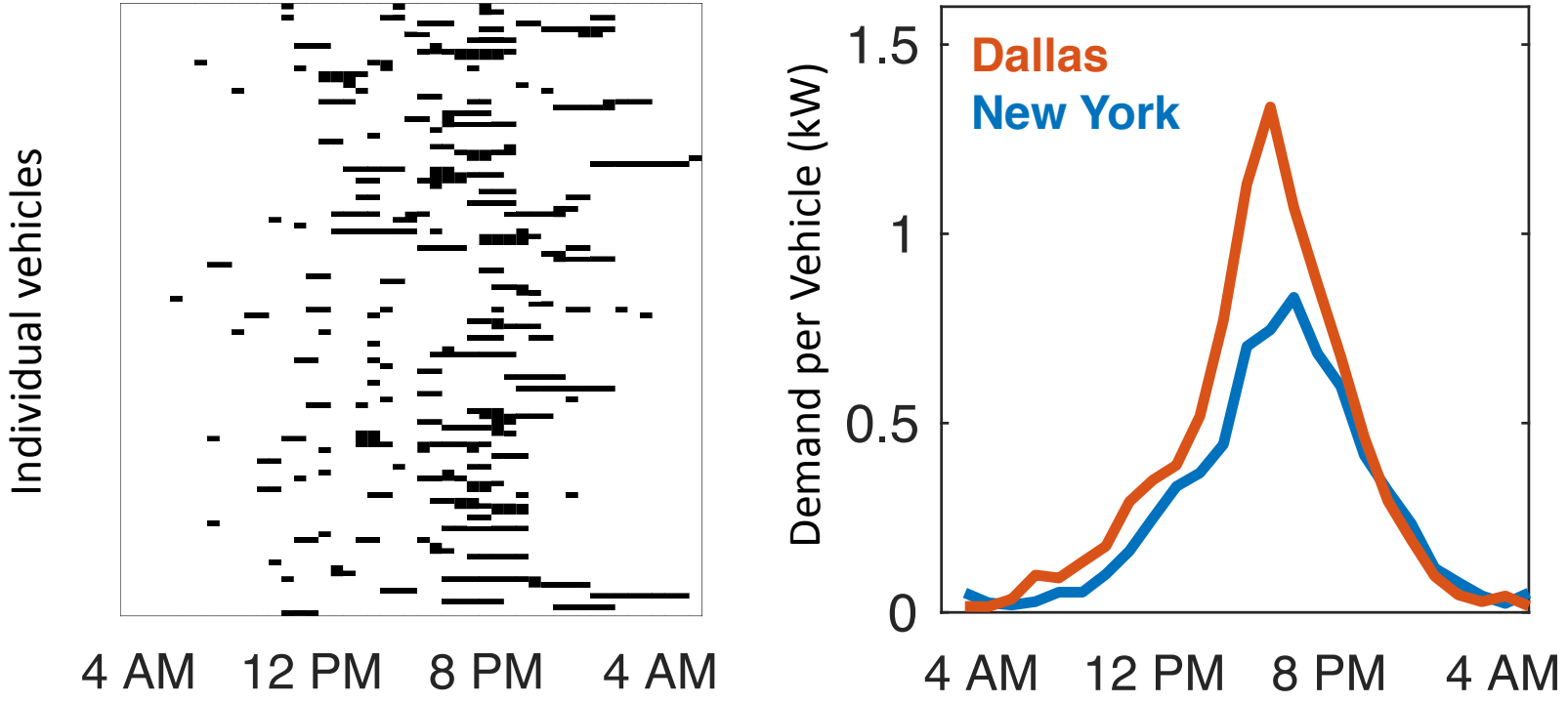

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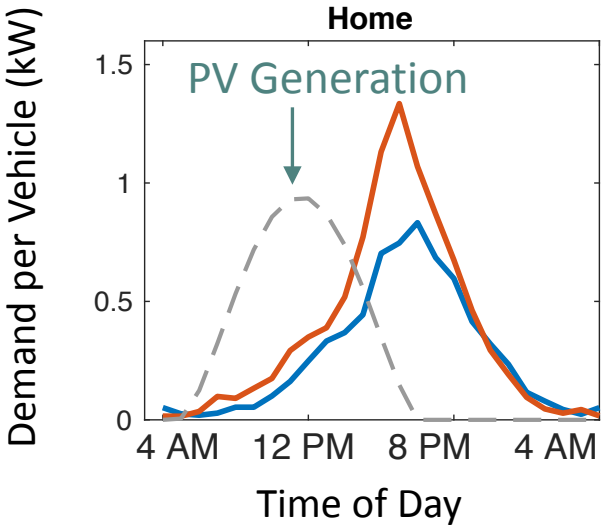
**Objectives for changes to charging patterns:**

- Reduce early evening peak
- Better align charging with PV generation

# Different charging profiles

**Dallas**
**New York**



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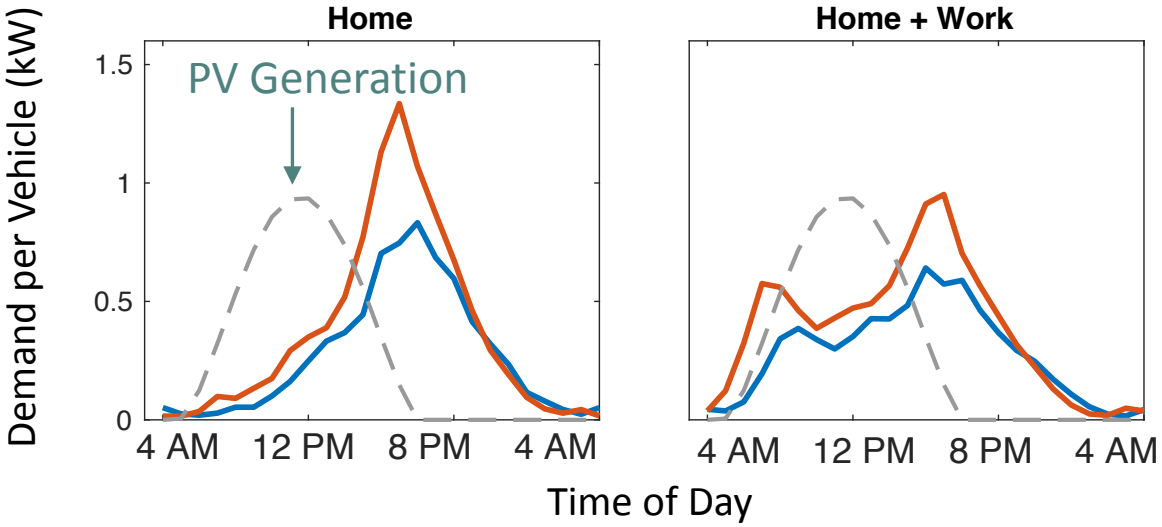

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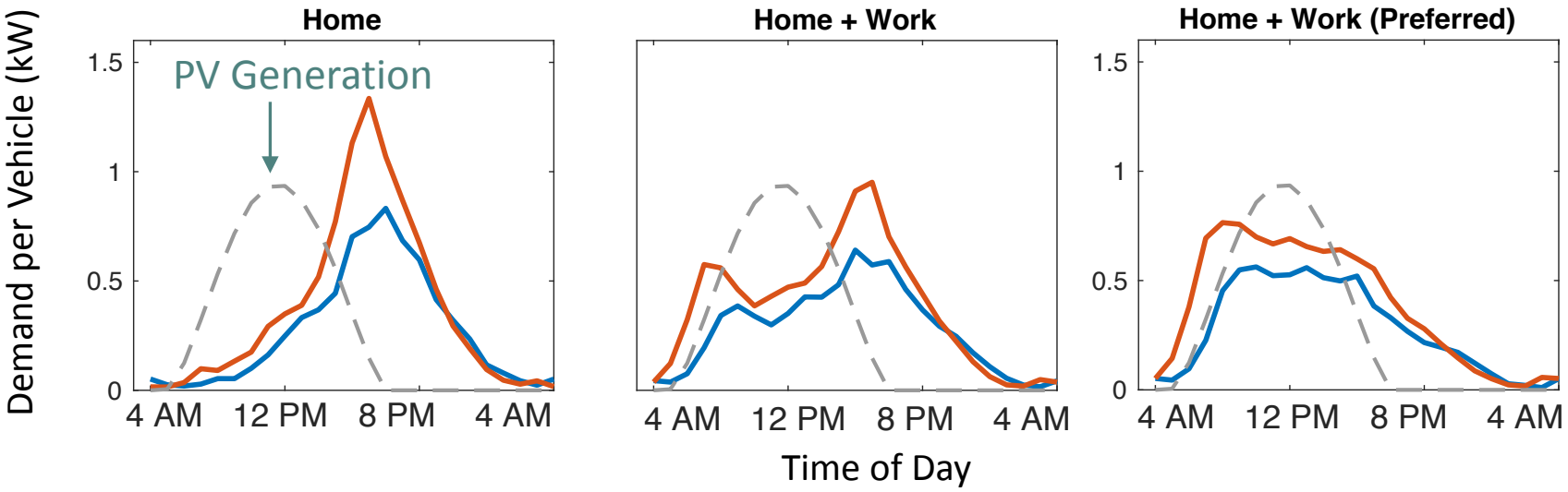

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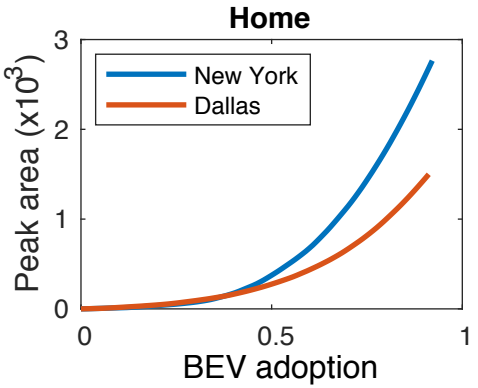

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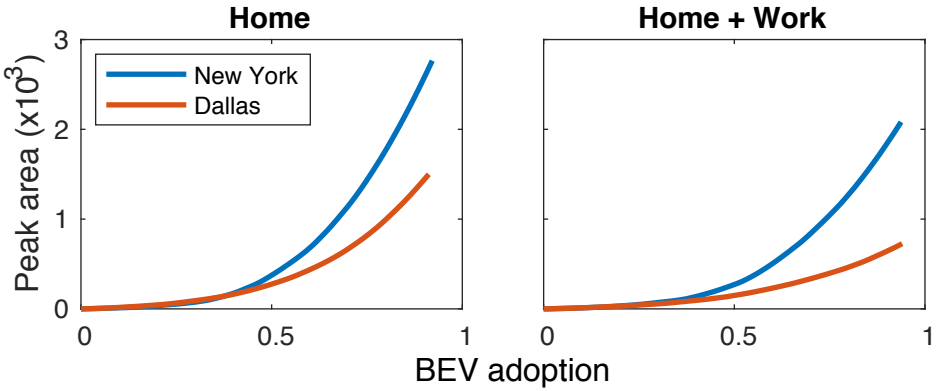

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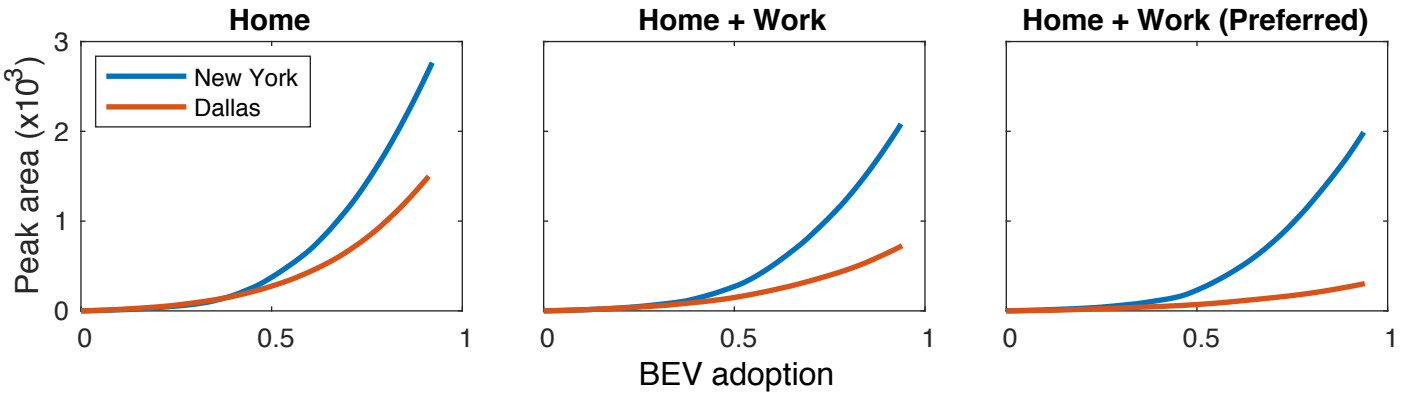

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(25% of electricity supplied by PV)

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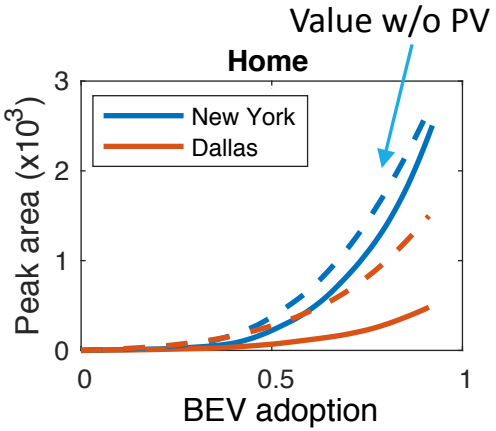

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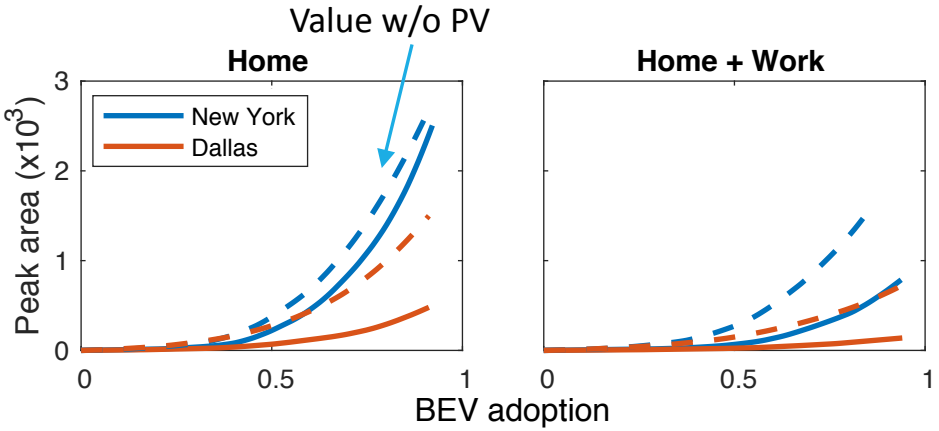

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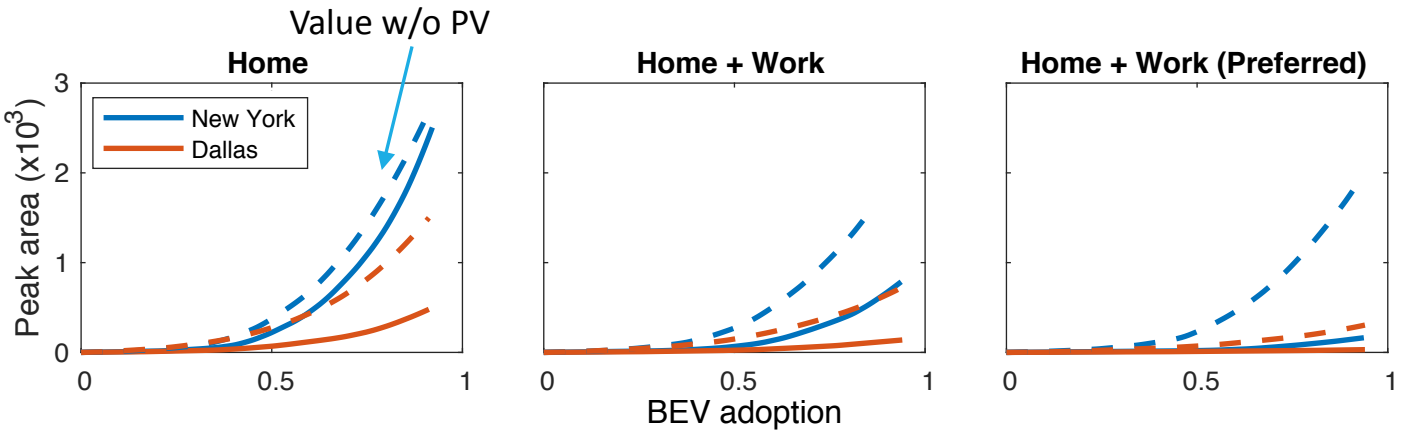

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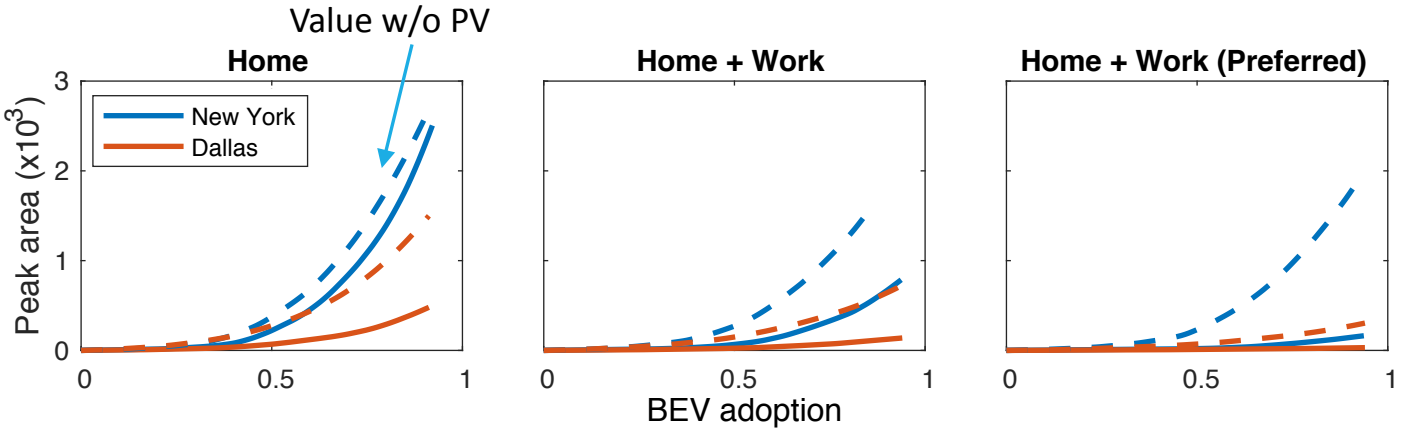


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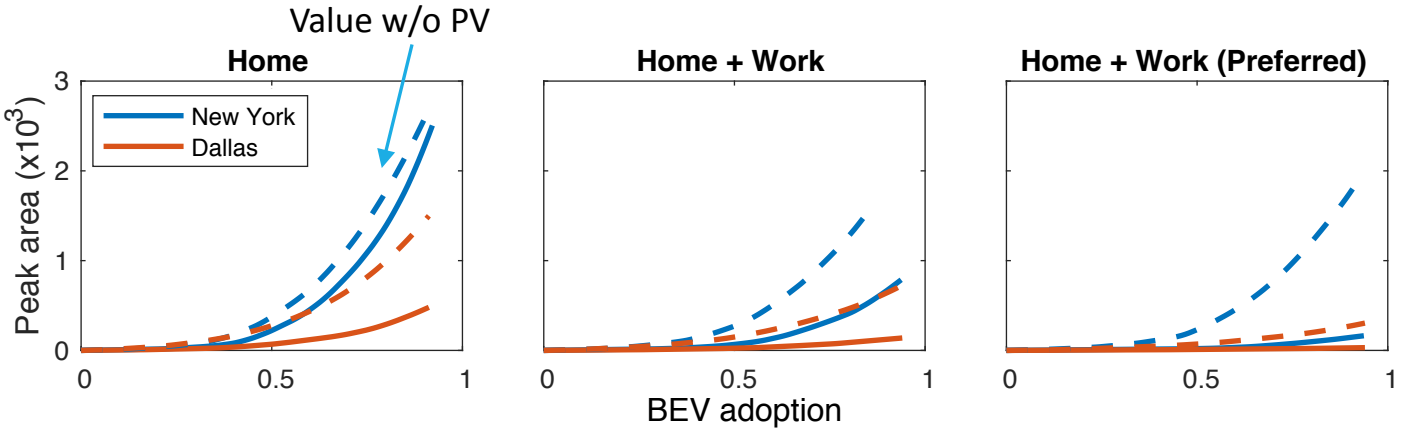


## PV attenuation due to over-supply

Valley area

**38%**

**23%**

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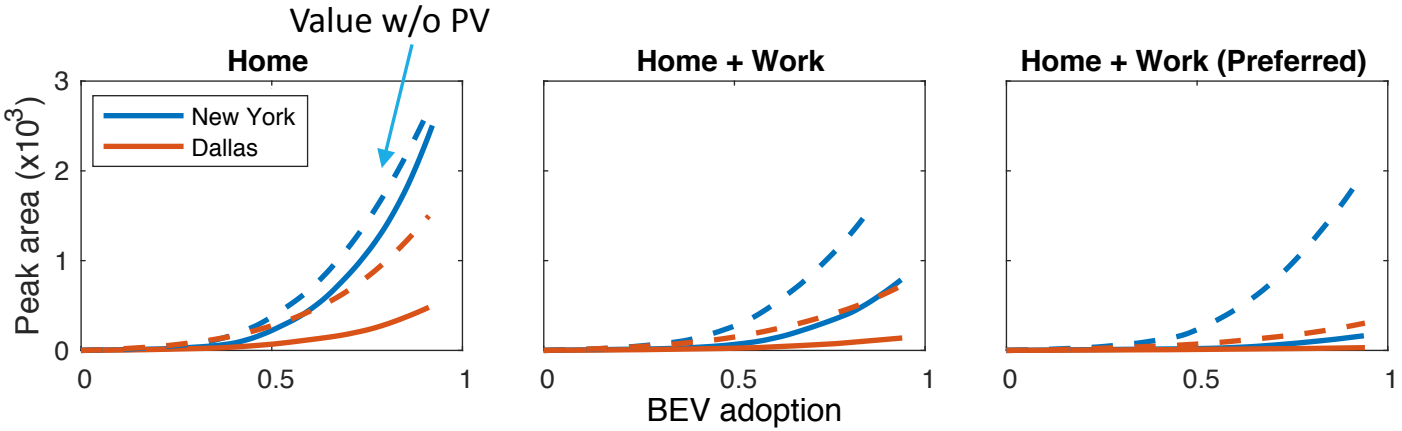


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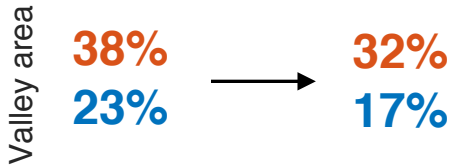

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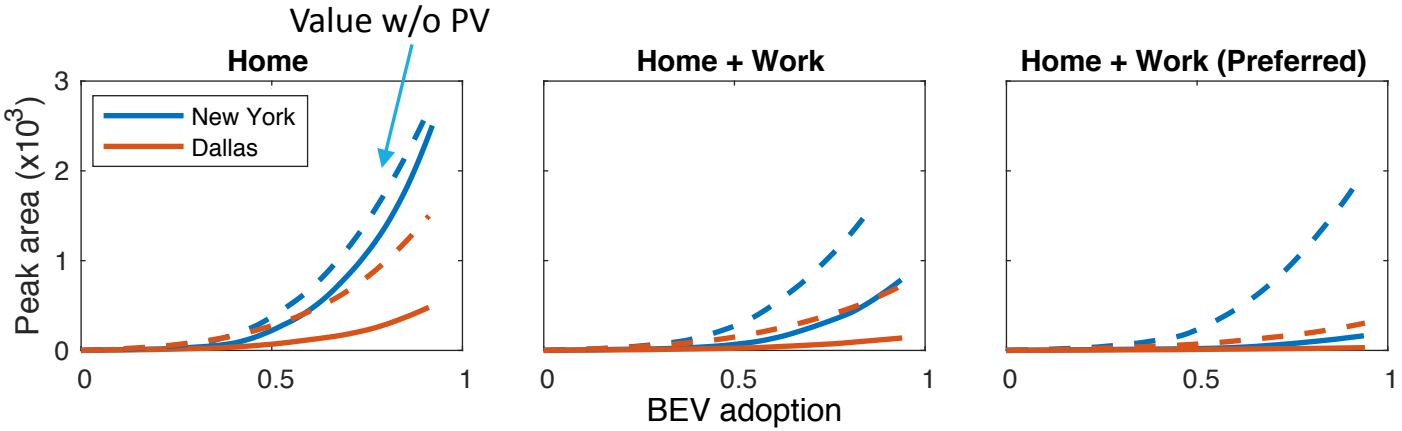


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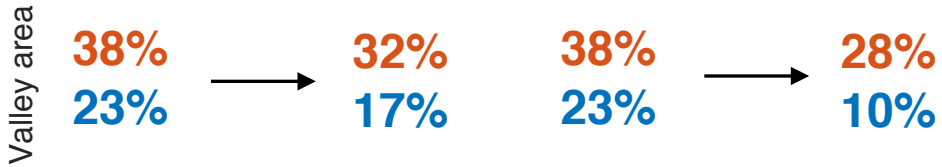

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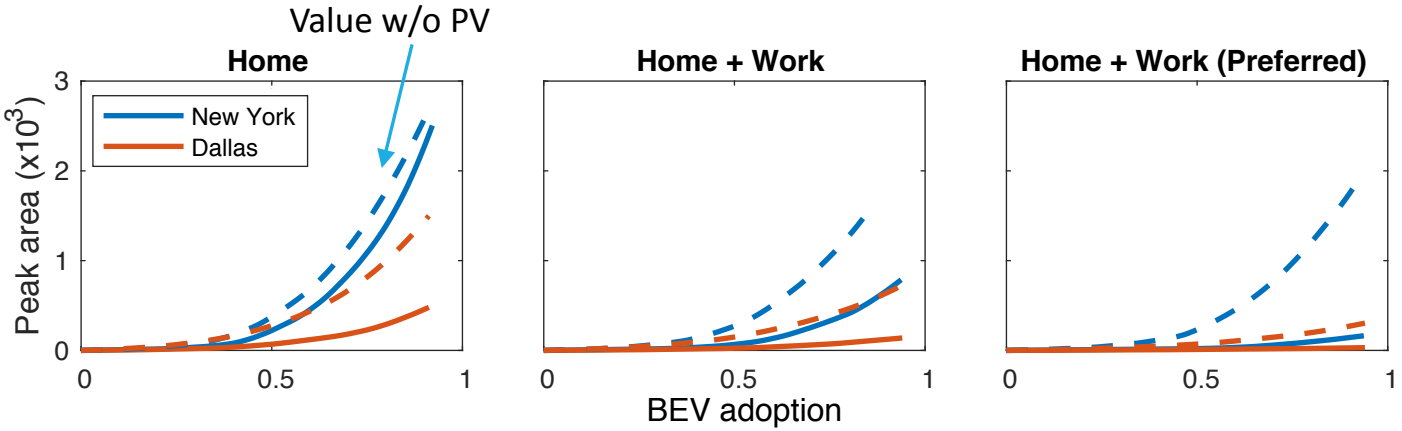


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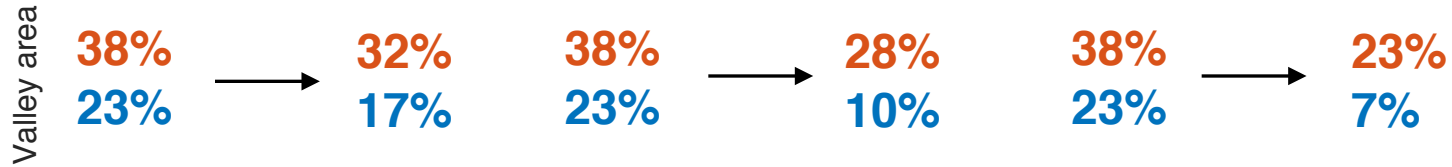

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    - Explore policies to promote workplace charger installation and use (without subsidizing driving over other modes)

# Summary

# New research areas

**Behavior**

**Technology**

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**Technology**

- Geographic variability in travel distances and BEV range, with implications for BEV adoption
- The relationship between travel behavior, charging patterns, and potential to shift charging to ease PV integration

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**Applied contributions**

- High resolution picture of trip-by-trip energy requirements across the United States, for any vehicle
- Efficient energy model integrated with a mesoscopic transport network simulation
- Benchmarks for battery technology improvement related to real travel behavior and technology performance
- Quantified relationship between BEV/PV adoption and grid integration challenges and opportunities

**Fundamental contributions**

- Determinants of transport energy consumption at a vehicle and systemwide level

# Thank you!