CatCharger: Deploying Wireless Charging Lanes in a Metropolitan Road Network through Categorization and Clustering of Vehicle Traffic

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How does the ANTIQUE way of charging serve you?

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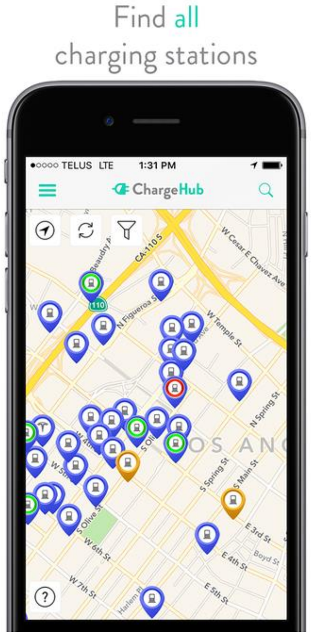

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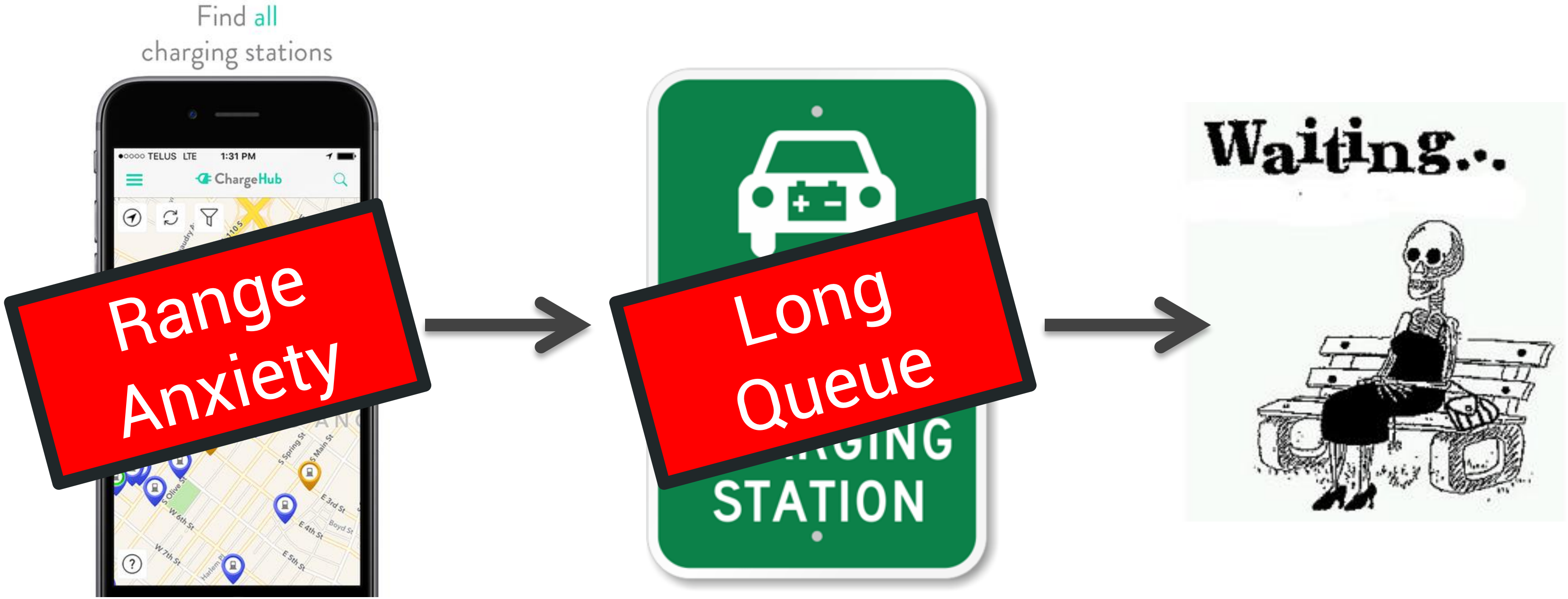

How does the ANTIQUE way of charging serve you?

Range Anxiety

Long Queue

Time-Consuming

How does the ANTIQUE way of charging serve you?

Fail to maintain State-of-Charge (SoC)

Charge vehicle in motion?

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Long Queue ✓

Charge vehicle in motion?

Long Queue

Time-Consuming

Charge vehicle in motion?

Long Queue ✓

Time-Consuming ✓

Range Anxiety ✗

Charge vehicle in motion?

- Long Queue ✓
- Time-Consuming ✓
- Range Anxiety ✗
- Maintain SoC ✗

Charge vehicle in motion?

We need a method to schedule the deployment of wireless charging lanes that

1. Supports electric vehicles' continuous operability (maintain SoC at any location)

2. Minimizes the total deployment cost

Plug-in charging station

IEEE TSG'12

IEEE TPS'14

IEVC'14

IEEE TSG'14

IEEE TPD'13

IEEE TPS'12

IEEE TPS'14

Plug-in charging station

IEEE TSG'12

IEEE TPS'14

IEVC'14

IEEE TSG'14

IEEE TPD'13

IEEE TPS'12

IEEE TPS'14

Wireless power transfer

Annals of Physics'08

IEEE Systems Journal'16

ICPP'16

1

Not applicable for dynamic wireless charging

Wireless power transfer

Annals of Physics'08

IEEE Systems Journal'16

ICPP'16

1

Not applicable for dynamic wireless charging

2

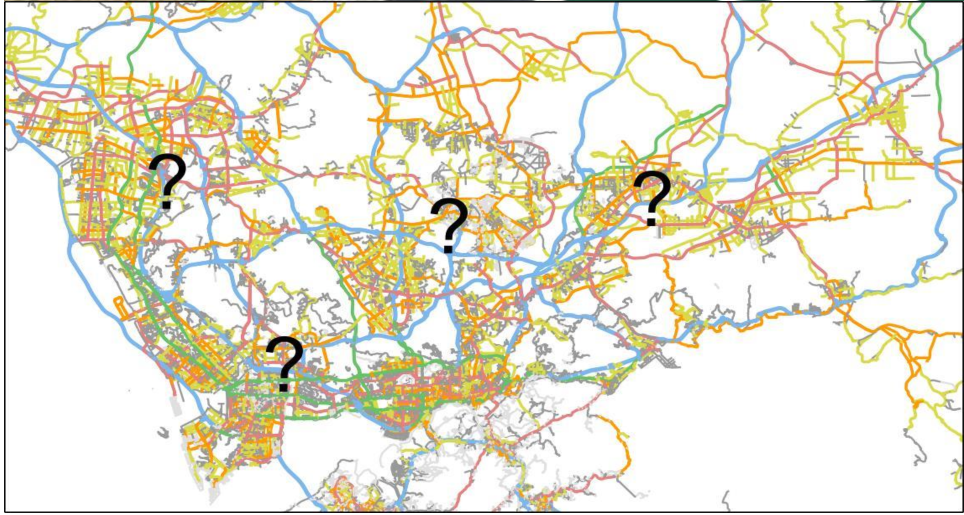
Cannot maintain the SoC of vehicles in a metropolitan road network

UNIVERSITY of VIRGINIA

Our Approach:

CatCharger

Categorization and clustering of multiple sources of vehicle traffic for the deployment of dynamic wireless Chargers in a metropolitan road network



Outline

Dataset analysis

Design of CatCharger

Performance evaluation

Conclusions

Important Issues

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Minimize deployment cost

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1. Vehicle passing velocity at charging lane matters

$$L_i = \frac{E_{max}}{r}\overline{v}_i$$

The slower the passing velocity, the shorter the charging lane needed

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2. Vehicle visit frequency and multi-source vehicle traffic matter

Charge as many EVs as possible

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The slower the passing velocity, the shorter the charging lane needed

2. Vehicle visit frequency and multi-source vehicle traffic matter

Charge as many EVs as possible

Keep the EVs operable (maintain SoC) on any position

Dataset Analysis

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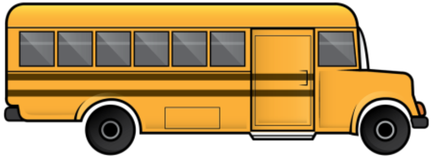
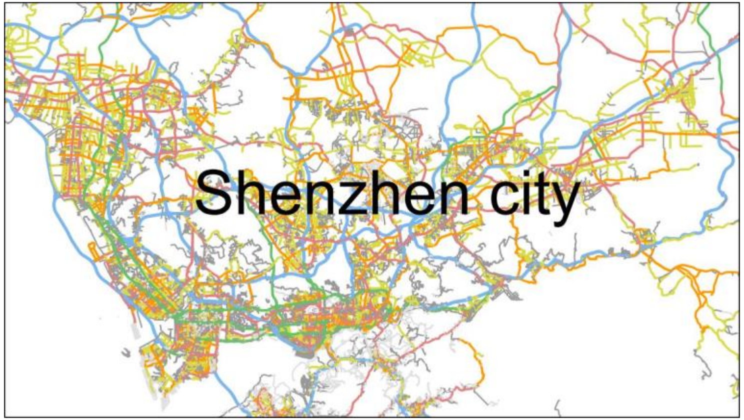
Our datasets (Jul 1~31, 2015) consist of:

15,610 taxicabs

14,262 buses



12,386 dada buses



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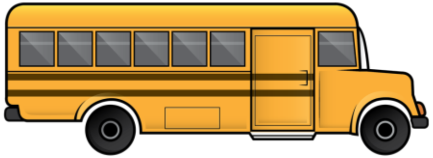

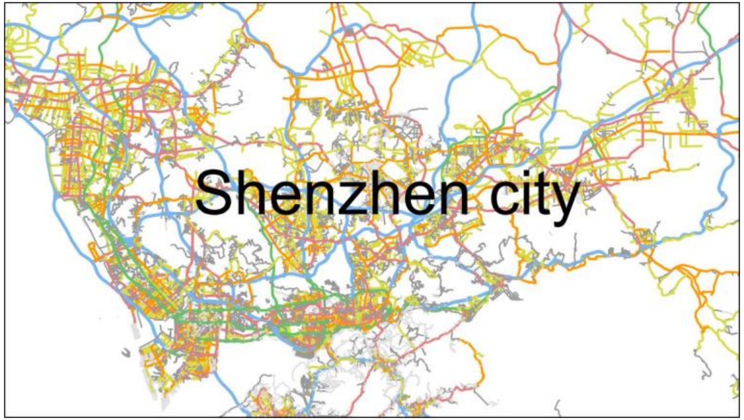

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Road map

OpenStreetMap
FOUNDATION

Dataset Analysis

Our datasets (Jul 1~31, 2015) consist of:

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Generally represent the traffic of public transportation vehicles in Shenzhen

OpenStreetMap FOUNDATION

Dataset Analysis

Distribution of potential positions for wireless charging

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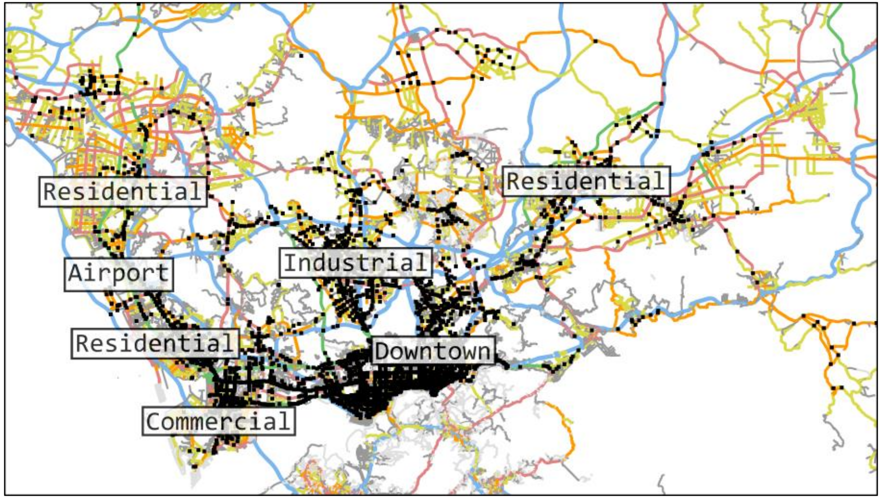

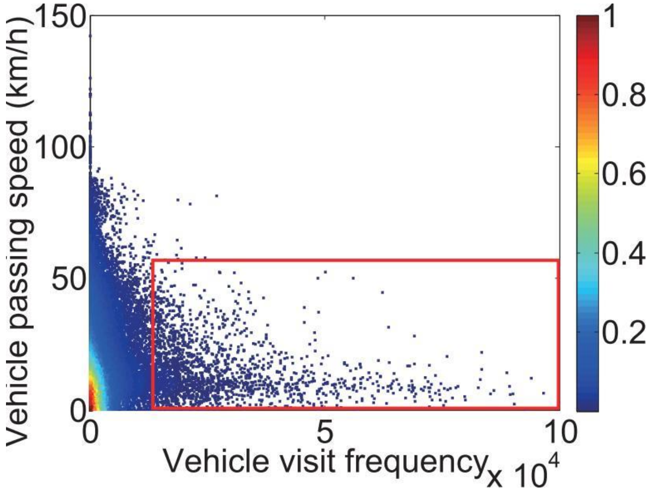

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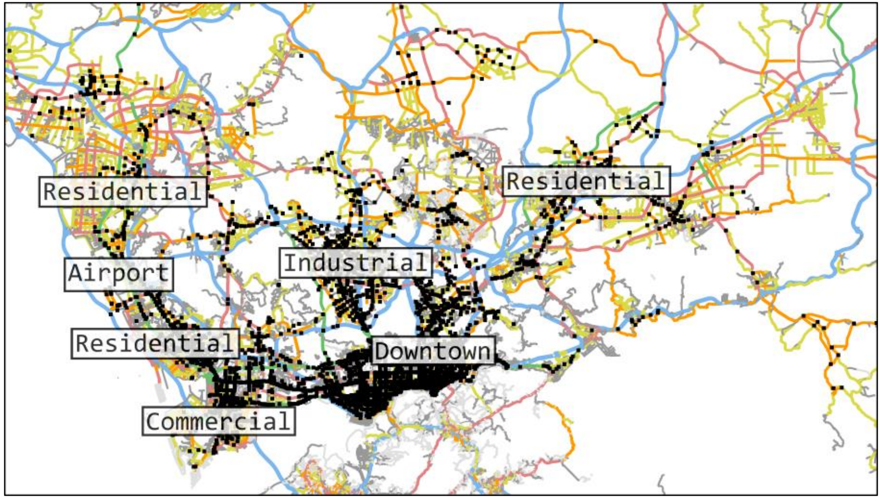

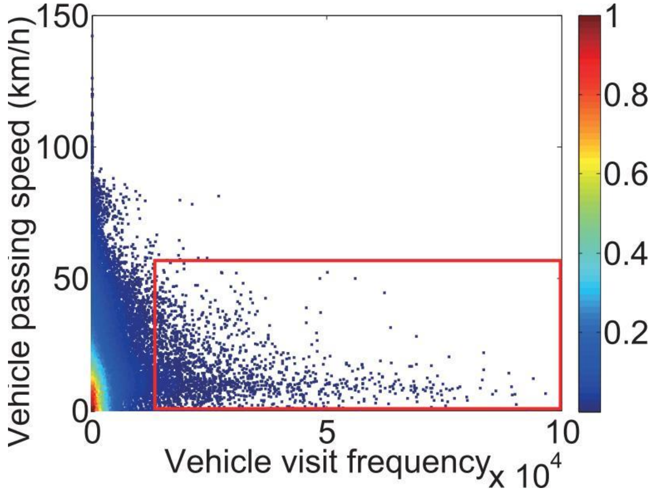

Consider vehicle passing speed and vehicle visit frequency → Minimize the cost of a charging lane and the serving capability

Dataset Analysis

Multiple sources of vehicle traffic should be considered

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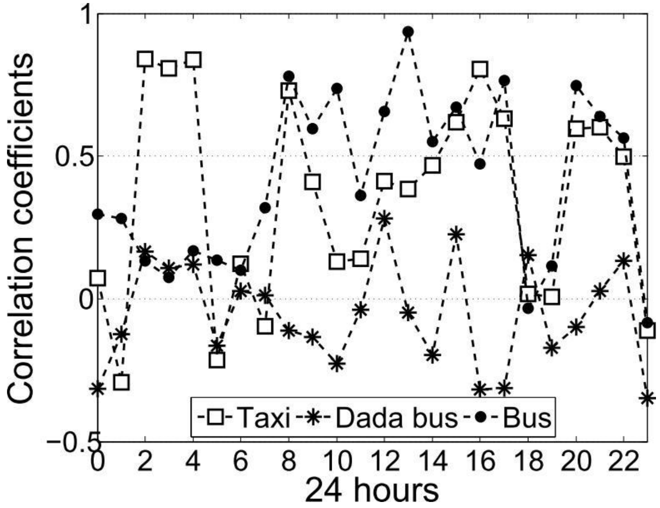

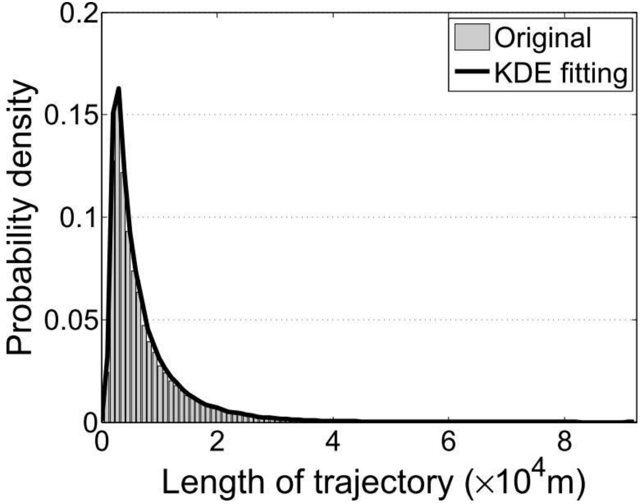

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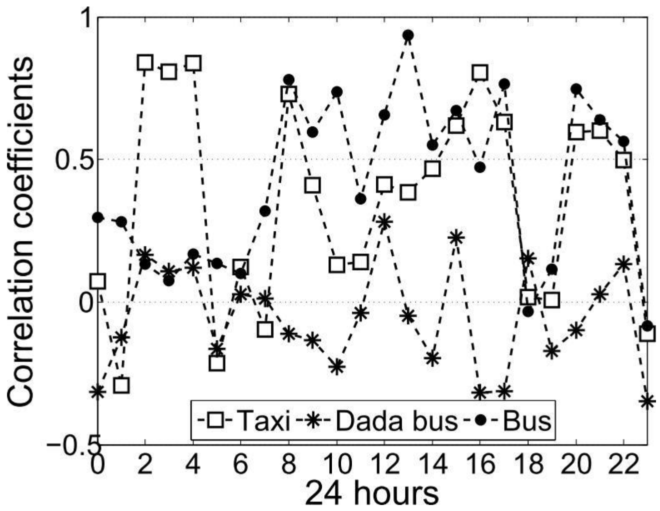

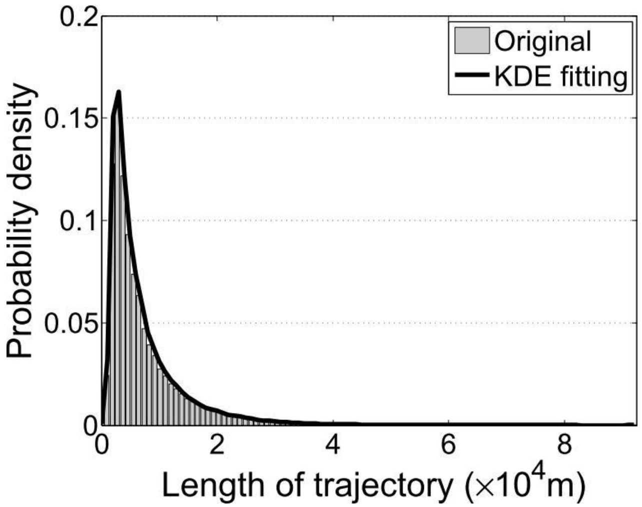

Consider multi-source vehicle traffic

Vehicle trip lengths follow certain distribution

→ Supports metropolitan-scale charging demand (maintain SoC)

System Design

System Design of CatCharger

Vehicle mobility normalization

Charging lane location candidate extraction

-- High visit frequency and low passing speed

Charging lane location determination

--Ensure expected residual energy (i.e., SoC) at any location is higher than a threshold

System Design of CatCharger

Vehicle mobility normalization

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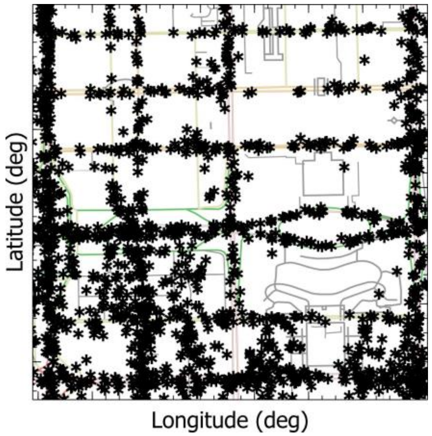

Original mobility
(scattered positions)

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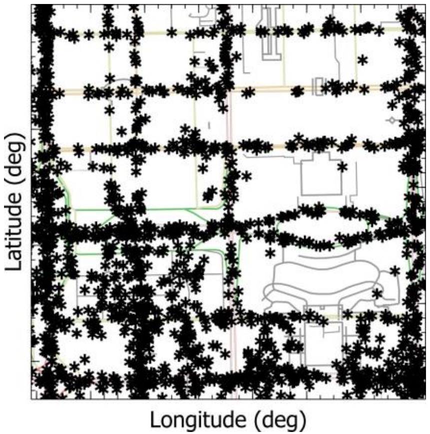
Vehicle mobility normalization



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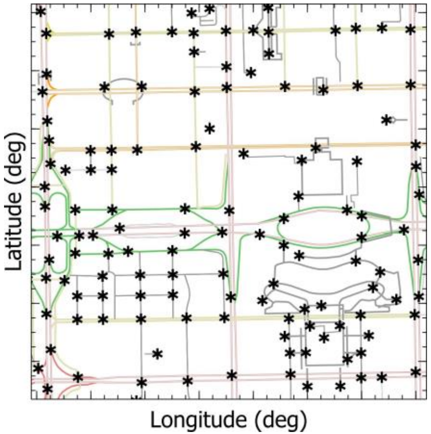

Normalized mobility
(landmarks)

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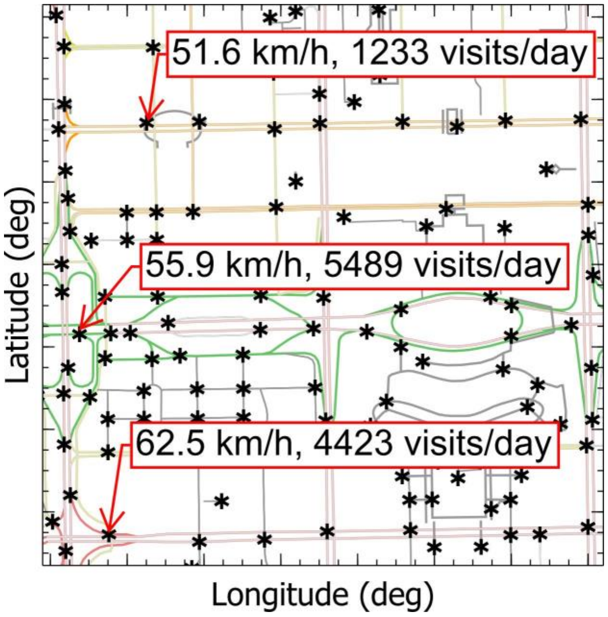
Charging lane location candidate extraction



FACT

Analysis: consider vehicle passing speed and vehicle visit frequency

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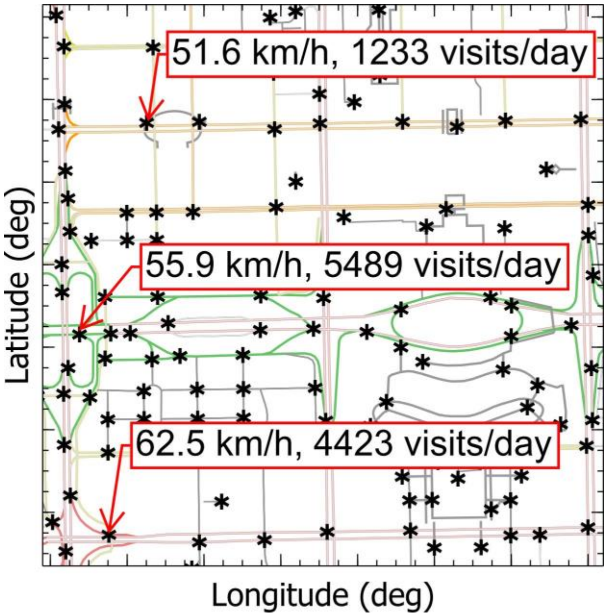

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GOAL

Cluster them by attribute values, and select the groups more suitable for deployment

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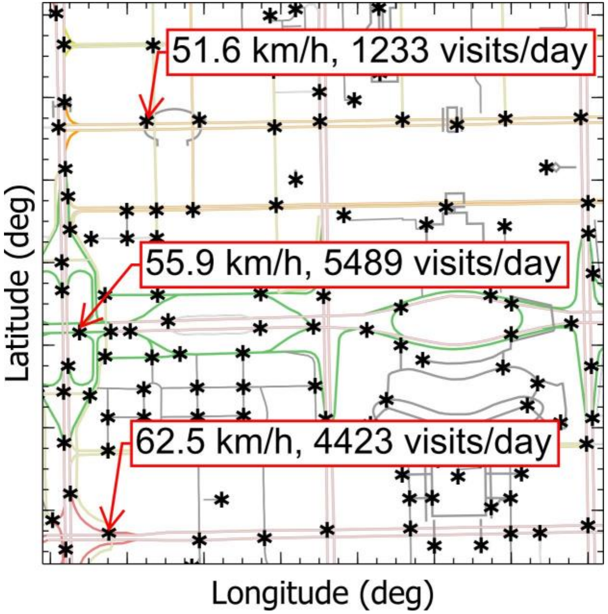

FACT

Analysis: consider vehicle passing speed and vehicle visit frequency

GOAL

Cluster them by attribute values, and select the groups more suitable for deployment

PROBLEM

How to cluster landmarks with similar attributes?

System Design of CatCharger

Charging lane location candidate extraction

Categorize original continuous numerical values into respective attribute IDs

$$v : < 0,\ 0 \sim 5km/h >, < 1,\ 5 \sim 10km/h >, \ldots,$$
$$f : < 0,\ 0 \sim 1000/day >, < 1,\ 1000 \sim 2000/day >, \ldots.$$

System Design of CatCharger

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Start from *k* starting landmarks → Landmarks clustered into *k* groups

In landmark clustering, for each landmark, we measure its “similarity” (entropy) with each group

System Design of CatCharger

Charging lane location candidate extraction

Select landmark groups:

- We filter out the groups with passing speed higher than 60 km/h, and vehicle visit frequency lower than 10,000 visits/day
- We choose landmarks with slow passing speed and high visit frequency

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Select landmarks in each selected group:

- Rank the landmarks by their required lane length and visit frequency

$$R(\boldsymbol{lm_i}) = \frac{\log(f_i)}{L_i}$$

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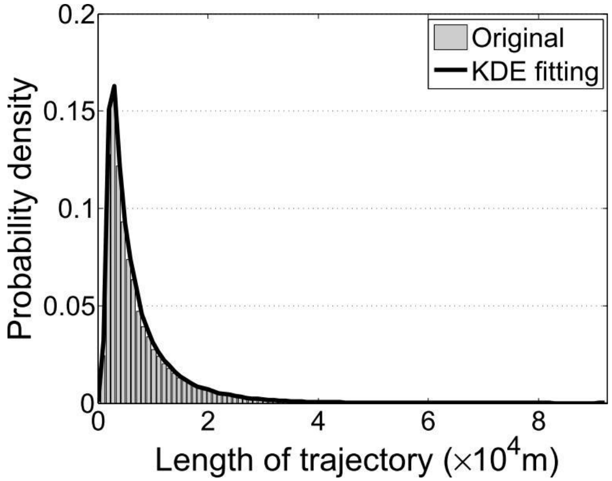
- Select the top ranked landmarks (e.g., 10%) from each group as the candidate positions for deploying charging lanes

System Design of CatCharger

Ensure expected residual energy (i.e., SoC) at any location is higher than a threshold



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Analysis: Vehicle trip lengths follow certain distribution

The trip lengths for supporting

System Design of CatCharger

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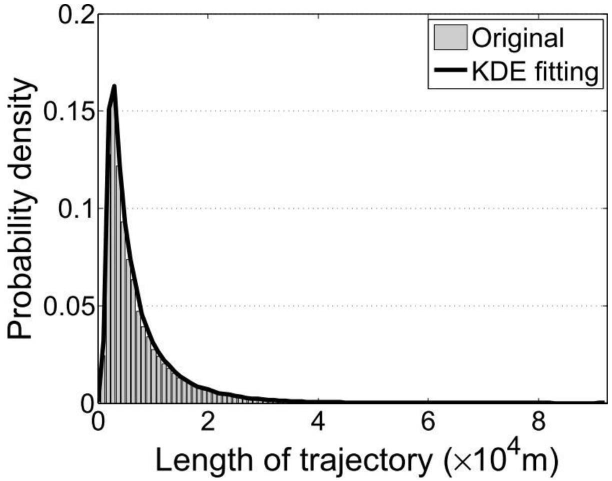

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Infer the expected SoC of EVs given the deployed charging lanes in certain landmarks

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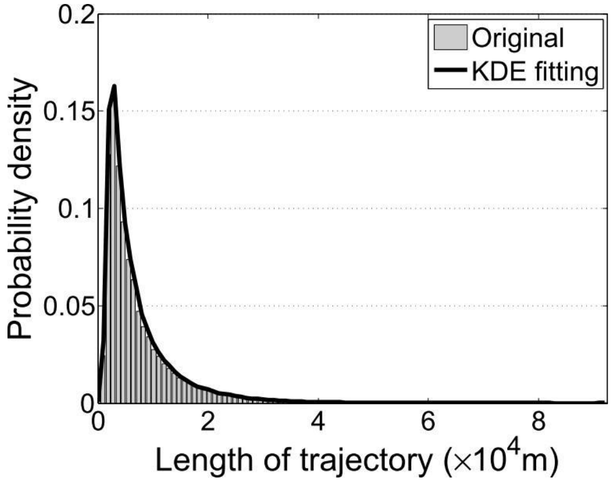

The trip lengths for supporting

FACT

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Infer the expected SoC of EVs given the deployed charging lanes in certain landmarks

PROBLEM

Cannot be described with parametric distribution

System Design of CatCharger

Ensure expected residual energy (i.e., SoC) at any location is higher than a threshold

Kernel Density Estimator (KDE)

$$\hat{f}_h(d) = \frac{1}{mh}\sum_{i=0}^{m-1} K\left(\frac{d-d_i}{h}\right); \; -\infty < d < \infty$$

Probability of driving a certain distance

System Design of CatCharger

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Probability of driving a certain distance

Vehicles energy consumption rate per meter c, minimum battery capacity E_{min}

$$SOC(d) = \begin{cases} \dfrac{E_{min} - cd}{E_{min}}, & \text{if } E_{min} \geqslant cd \\ 0, & \text{otherwise} \end{cases}$$

SOC estimated from the distance

System Design of CatCharger

Ensure expected residual energy (i.e., SoC) at any location is higher than a threshold

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SOC estimated from the distance

Expected SoC of EVs at landmark lm_j

$$\overline{SOC}(\boldsymbol{lm_j}) = \sum_{i=0}^{|\widetilde{LM}|-1} \hat{f}(d_{i,j}) SOC(d_{i,j}) x_i$$

System Design of CatCharger

Formulating optimization problem

Keep the EVs operable (maintain SoC) + Minimize total cost

System Design of CatCharger

Formulating optimization problem

Keep the EVs operable (maintain SoC) + Minimize total cost

$$
\begin{aligned}
\text{minimize} \quad & \sum_{\boldsymbol{lm_i} \in \widetilde{LM}} \omega_0 x_i L_i \\
\text{subject to} \quad & \overline{SOC}(\boldsymbol{lm_j}) \geqslant \alpha, \forall\, \boldsymbol{lm_j} \in LM \\
& x_i \in \{0, 1\}, \forall\, \boldsymbol{lm_i} \in \widetilde{LM}
\end{aligned}
$$

System Design of CatCharger

Formulating optimization problem

Keep the EVs operable (maintain SoC)

+

Minimize total cost

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$$x_i \in \{0, 1\}, \forall\, \boldsymbol{lm_i} \in \widetilde{LM}$$

Binary Integer Programming problem

Performance Evaluation

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Comparison methods

Random: randomly deploy the charging lanes

MaxFlow: deploy chargers to maximally cover traffic flows (IEEE TPS'14)

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Metrics

Keep the EVs operable (Maintaining SoC)

Performance Evaluation

Performance in supporting EV charging demand

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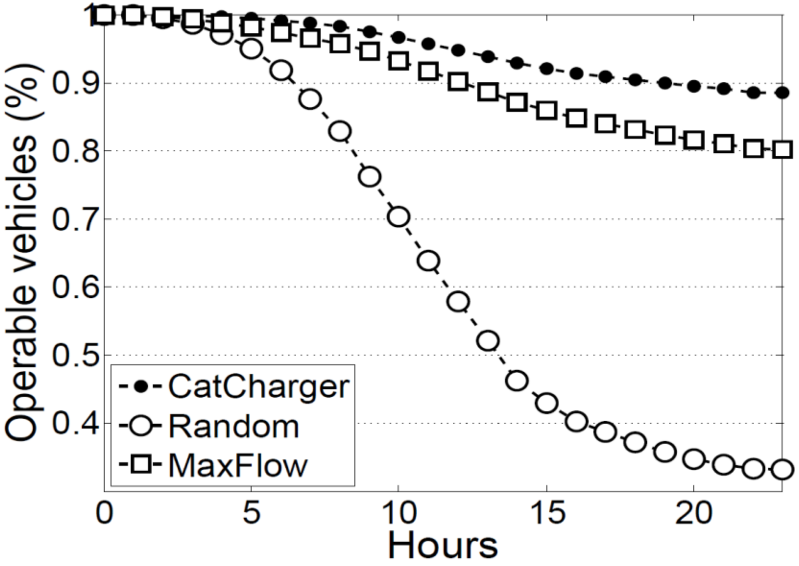
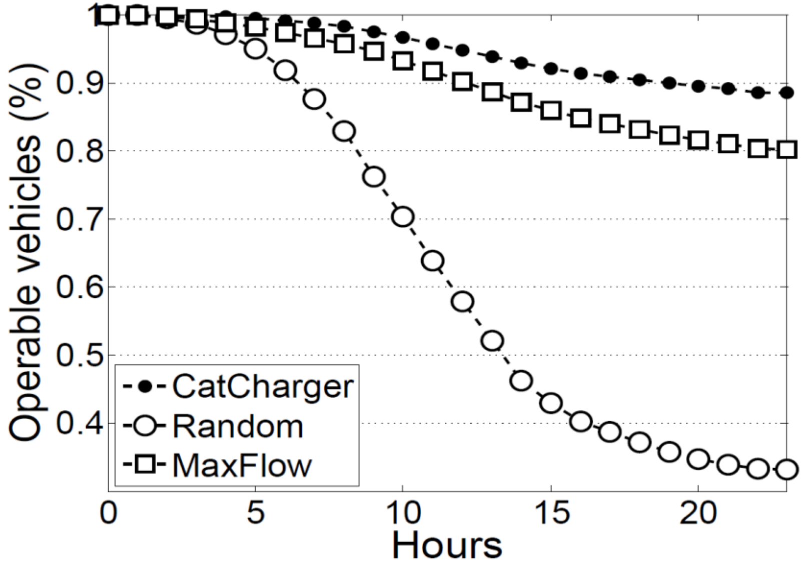


Operable vehicles over time

Performance Evaluation

Performance in supporting EV charging demand



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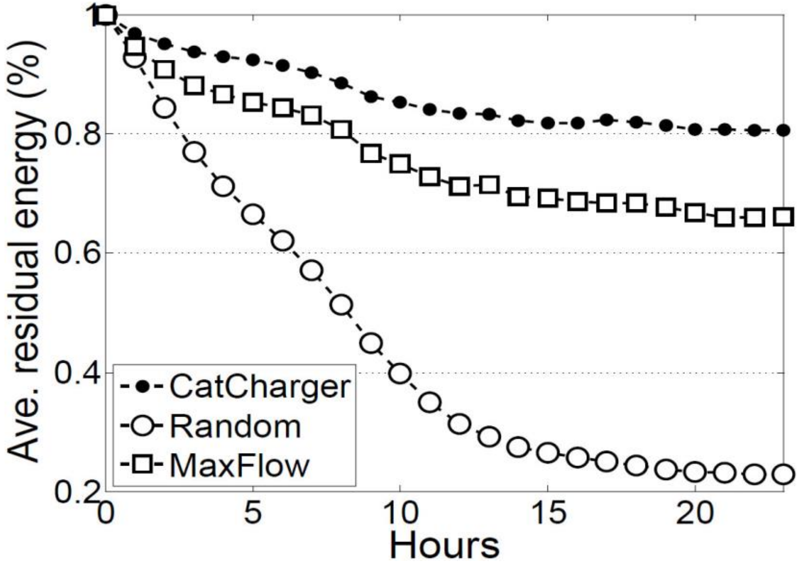

Average residual energy

Conclusions

1. We designed a scheme to deploy wireless charging lanes to support metropolitan-scale EV charging demand

2. We conducted extensive experiments to verify the effectiveness of CatCharger in supporting the SoC of EVs

3. In the future, we plan to consider the influence of human activities and analyze the after-effect brought by the deployment of charging lanes

Thank you!
Questions & Comments?

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Pervasive Communication Laboratory

University of Virginia