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?
How does the ANTIQUE way of charging serve you?
How does the ANTIQUE way of charging serve you?
How does the ANTIQUE way of charging serve you?
How does the ANTIQUE way of charging serve you?

Find all charging stations

Range Anxiety

ELECTRIC VEHICLE CHARGING STATION

Waiting...
How does the ANTIQUE way of charging serve you?

Find all charging stations

**Range Anxiety**

Long Queue

Waiting...
How does the ANTICQUE way of charging serve you?

Find all charging stations

Range Anxiety

Long Queue

Waiting...

Time-Consuming
How does the ANTIQUE way of charging serve you?

Find all charging stations

Range Anxiety

Long Queue

Time-Consuming

Fail to maintain State-of-Charge (SoC)
Charge vehicle in motion?
Charge vehicle in motion?

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
Not applicable for dynamic wireless charging
1. Not applicable for dynamic wireless charging

2. Cannot maintain the SoC of vehicles in a metropolitan road network
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
Important Issues

Minimize deployment cost
Important Issues

Minimize deployment cost

1. Vehicle passing velocity at charging lane matters

\[ L_i = \frac{E_{max}}{r} \bar{v}_i \]

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

Minimize deployment cost

1. Vehicle passing velocity at charging lane matters

\[ L_i = \frac{E_{\text{max}}}{r} v_i \]

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
Important Issues

Minimize deployment cost

1. Vehicle passing velocity at charging lane matters

\[ L_i = \frac{E_{max}}{r} \dot{v}_i \]

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
Dataset Analysis

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

- 15,610 taxicabs
- 14,262 buses
- 12,386 dada buses

[Map of Shenzhen city]
Dataset Analysis

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Shenzhen city
Dataset Analysis

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

15,610 taxicabs

14,262 buses

Generally represent the traffic of public transportation vehicles in Shenzhen
Dataset Analysis

Distribution of potential positions for wireless charging
Dataset Analysis

Distribution of potential positions for wireless charging
Dataset Analysis

Distribution of potential positions for wireless charging

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
Dataset Analysis

Multiple sources of vehicle traffic should be considered.
Multiple sources of vehicle traffic should be considered

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
System Design of CatCharger

Vehicle mobility normalization

Original mobility (scattered positions)
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Vehicle mobility normalization

Original mobility (scattered positions)  Normalized mobility (landmarks)
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Charging lane location candidate extraction

FACT

Analysis: consider vehicle passing speed and vehicle visit frequency
System Design of CatCharger

Charging lane location candidate extraction

Analysis: consider vehicle passing speed and vehicle visit frequency

Cluster them by attribute values, and select the groups more suitable for deployment
System Design of CatCharger

Charging lane location candidate extraction

**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?
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Charging lane location candidate extraction

Categorize original continuous numerical values into respective attribute IDs

\[ v : < 0, \ 0 \sim 5 \text{km/h} >, < 1, \ 5 \sim 10 \text{km/h} >, \ldots, \]
\[ f : < 0, \ 0 \sim 1000/\text{day} >, < 1, \ 1000 \sim 2000/\text{day} >, \ldots. \]
System Design of CatCharger
Charging lane location candidate extraction

Categorize original continuous numerical values into respective attribute IDs

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Each position can be described with two labels. For example, \{3 \text{ km/h, 1500 visit/day}\} \rightarrow \{0, 1\}. 
System Design of CatCharger

Charging lane location candidate extraction

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Start from \( k \) starting landmarks \rightarrow 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
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.

Select landmarks in each selected group:

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

\[
R(lm_i) = \frac{\log(f_i)}{L_i}
\]
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

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Select landmarks in each selected group:

Rank the landmarks by their required lane length and visit frequency

\[ R(\text{lm}_i) = \frac{\log(f_i)}{L_i} \]

Select the top ranked landmarks (e.g., 10%) from each group as the candidate positions for deploying charging lanes
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Ensure expected residual energy (i.e., SoC) at any location is higher than a threshold

**FACT**

Analysis: Vehicle trip lengths follow certain distribution

The trip lengths for supporting
System Design of CatCharger

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

FACT

Analysis: Vehicle trip lengths follow certain distribution

GOAL

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

The trip lengths for supporting
System Design of CatCharger

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

The trip lengths for supporting

FACT

Analysis: Vehicle trip lengths follow certain distribution

GOAL

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)

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

Probability of driving a certain distance
System Design of CatCharger

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

Kernel Density Estimator (KDE)

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

Probability of driving a certain distance

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

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

SOC estimated from the distance
System Design of CatCharger

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

Kernel Density Estimator (KDE)

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

Probability of driving a certain distance

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\[ SOC(d) = \begin{cases} \frac{E_{\text{min}} - cd}{E_{\text{min}}}, & \text{if } E_{\text{min}} \geq cd \\ 0, & \text{otherwise} \end{cases} \]

SOC estimated from the distance

Expected SoC of EVs at landmark \( lm_j \)

\[ \overline{SOC}(lm_j) = \sum_{i=0}^{|LM|-1} \hat{f}(d_{i,j}) SOC(d_{i,j})x_i \]
System Design of CatCharger

Formulating optimization problem

- Keep the EVs operable (maintain SoC)
- Minimize total cost
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Formulating optimization problem

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

minimize \[ \sum_{lm_i \in \overline{LM}} \omega_0 x_i L_i \]
subject to \[ \overline{SOC}(lm_j) \geq \alpha, \forall \, lm_j \in LM \]
\[ x_i \in \{0, 1\}, \forall \, lm_i \in \overline{LM} \]
System Design of CatCharger

Formulating optimization problem

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

\[
\text{minimize } \sum_{l m_i \in \tilde{L}M} \omega_0 x_i L_i \\
\text{subject to } \frac{SOC(l m_j)}{\tilde{L}M} \geq \alpha, \forall l m_j \in L M \\
x_i \in \{0, 1\}, \forall l m_i \in \tilde{L}M
\]
Performance Evaluation
Performance Evaluation

Comparison methods

*Random*: randomly deploy the charging lanes

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

Comparison methods

*Random*: randomly deploy the charging lanes

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

Metrics

Keep the EVs operable (Maintaining SoC)
Performance Evaluation

Performance in supporting EV charging demand
Performance Evaluation

Performance in supporting EV charging demand

Operable vehicles over time
Performance Evaluation

Performance in supporting EV charging demand

Operable vehicles over time

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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