Opportunistic Energy Sharing Between Power Grid and Electric Vehicles: A Game Theory-based Nonlinear Pricing Policy

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Introduction
Wireless Power Transfer System

Wireless power transfer (WPT) system:

1. Provides drive-through energy for online electric vehicles (OLEVs)
2. A dedicated charging lane, called charging section is installed on top of the road
3. It can mitigate EVs' battery related issues

Related work

WPT Architecture

- ❑ Power transfer architecture [IEEE APEC 2013]
- ❑ Analytical study of WPT infrastructure [JESTPE 2015]
- ❑ Battery size and charger placement of WPT [IEEE TITS 2013]

Related work

WPT Architecture

- Power transfer architecture [IEEE APEC 2013]
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WPT and Power Gird

- Bidirectional static power transfer system [IEEE TITS 2011]
- Integration of EVs into power grid [IEEE ITEC 2015]
- Profit maximization of EVs [IJAT 2015]

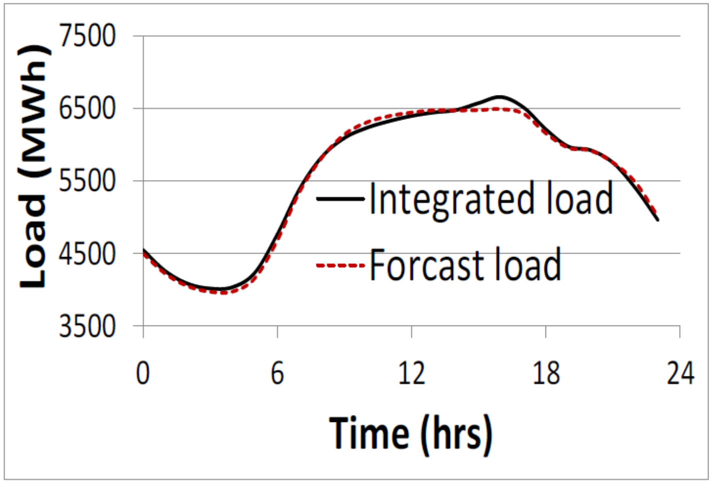
Introduction
Motivation

Study the impact of OLEV on smart grid:

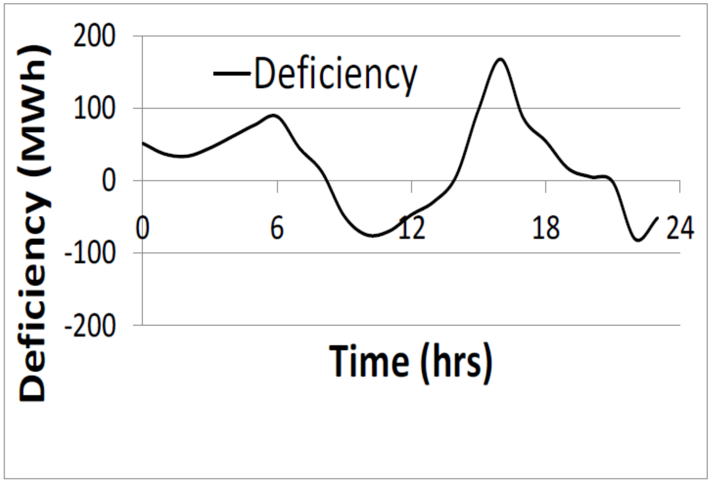
1. A road map of New York city (NYC)
2. Power usages data of New York independent system operator (NYISO)
3. Traffic data of NYC
4. Simulation of Urban MObiltiy (SUMO) traffic simulator

Introduction

Motivation



Actual and forecasted load



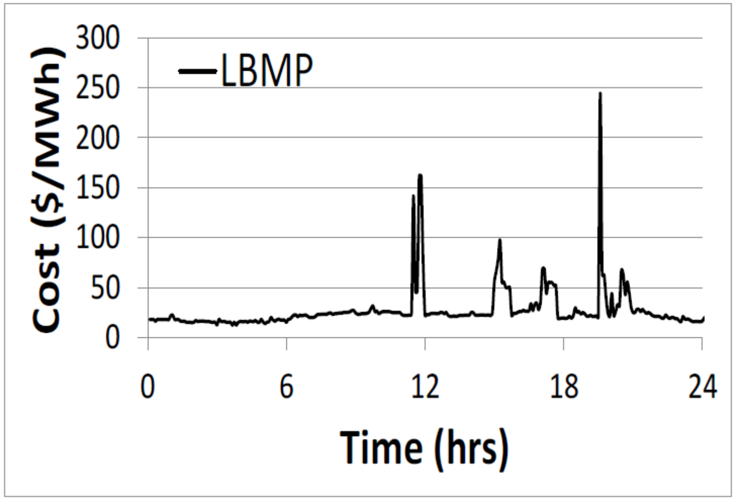
Power deficiency

Power deficiency of NYISO

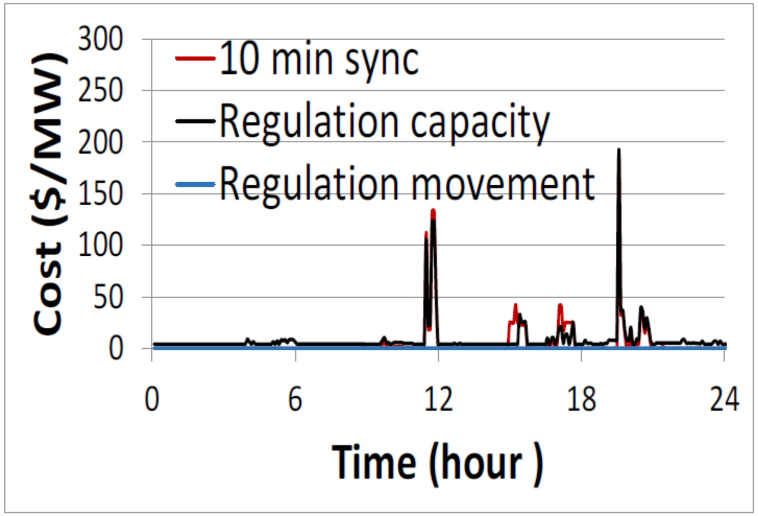
*Integrated load is the actual load of power grid
*Forcast load is the predicted load of power grid

Introduction

Motivation



Marginal price



Ancillary service cost

Economical impacts of power deficiency

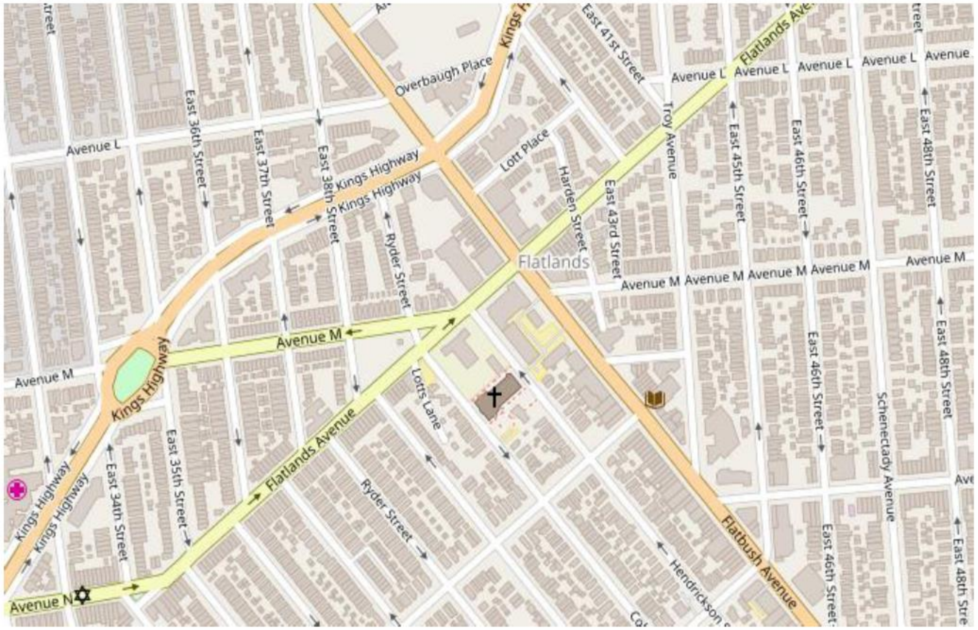
*LBMP stands for location-based marginal price
*Ancillary service accounts for the service to maintain stability of power supply

Introduction

Motivation

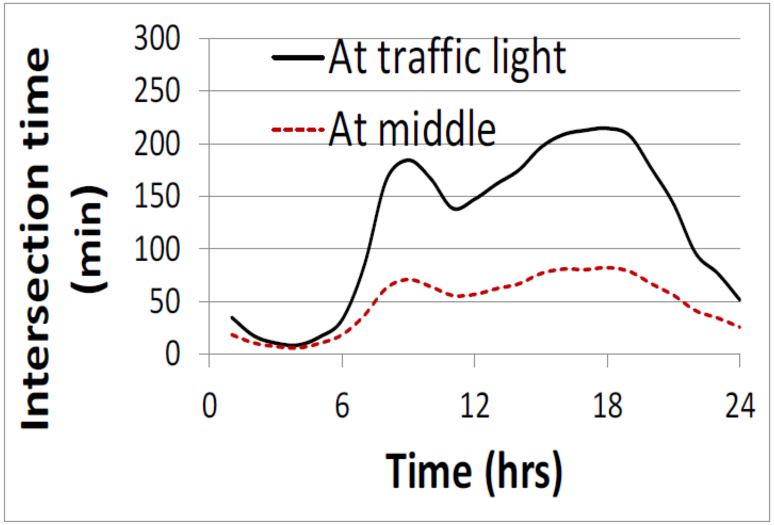
Energy consumption analysis of vehicles using SUMO:

1. Download the OpenStreetMap and convert to SUMO net file
2. Load net file, EVs, charging sections in SUMO
3. Calculate power consumption of OLEVs

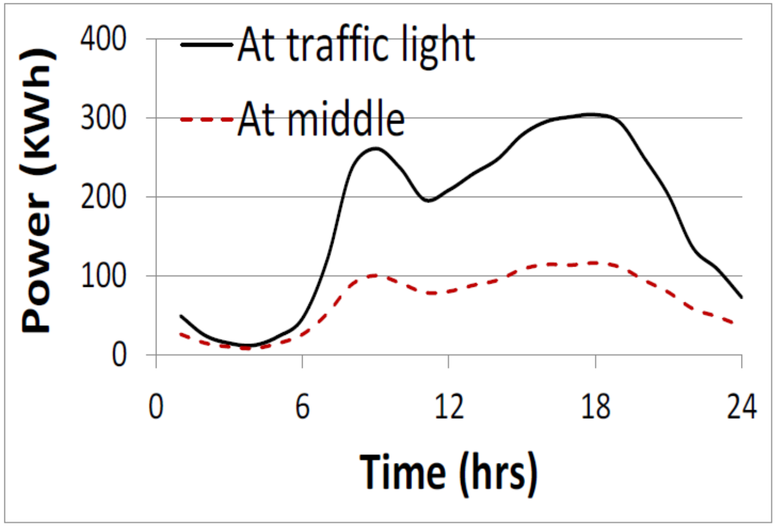


OpenStreetMap

Introduction
Motivation



Intersection time



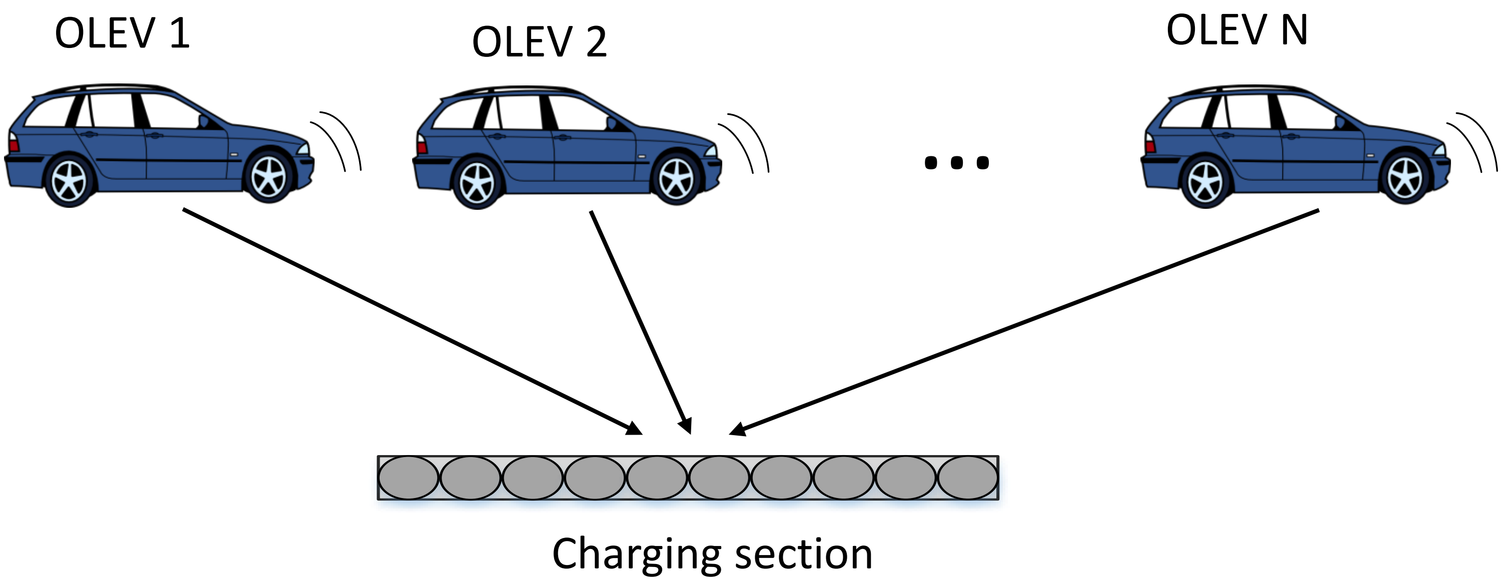
Amount of Power

Data-driven energy usage analysis of OLEVs

*Intersection time represents the time EVs are on top of charging section
*Amount of power represents total hourly energy received by OLEVs

Introduction

Motivation



How to decide the price?

Introduction

Pricing Policy

1. Traffic congestion is spatio-temporal, highly varied
2. Smart grid should adopt some pricing policy
3. Linear pricing policy would hurt smart grid

Introduction

Pricing Policy

1. Traffic congestion is spatio-temporal, highly varied
2. Smart grid should adopt some pricing policy
3. Linear pricing policy would hurt smart grid

Our Approach: Non linear Pricing Policy

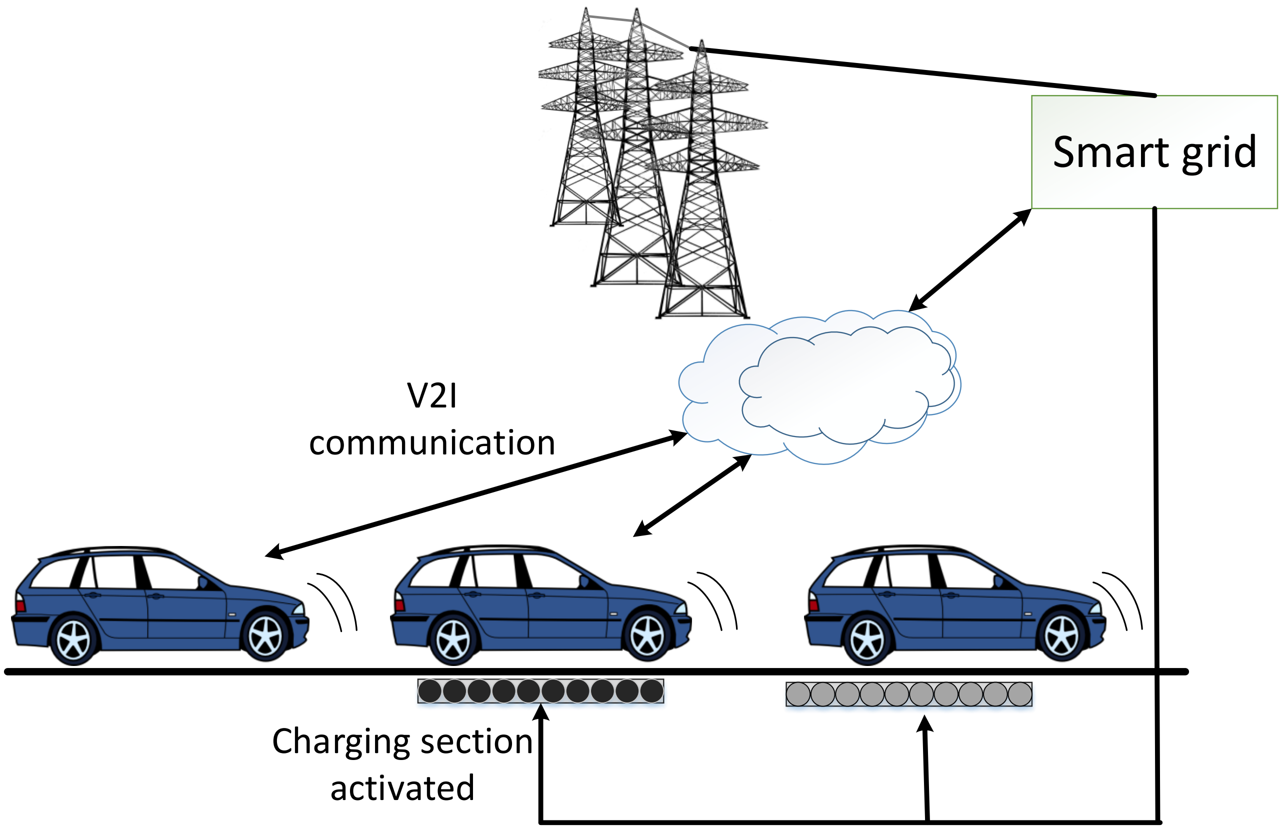
1. Non linear pricing policy for smart grid
   - Based on the current energy demands from OLEVs
2. Non cooperative game
   - Between different OLEVs to fix a price of energy
3. Reduce congestion at charging sections
   - Balance the load at different charging sections so that power distributions at different charging sections are even

Outline

- Introduction
- System Design
- Performance Evaluation
- Conclusion

System Design

Overview



Overall architecture

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System Design
Price of Power Schedule

Social welfare of OLEVs

$$\mathcal{W}(\mathbf{p}) = \sum_{n=1}^{N} \mathcal{U}_n(\sum_{c\in C} p_{n,c}) - \sum_{c\in C} \mathcal{V}(P_c) - \sum A(P_c - \eta P_{line})$$

Satisfaction of OLEV Price of power Congestion degree

$$\doteq \sum_{n=1}^{N} \mathcal{U}_n(p_n) - \sum_{c\in C} \mathcal{Z}(P_c)$$

where
W(p)social welfare of OLEV
$P_{n,c}$ is the power of OLEV n from charging section c
P_c is the total power from a charging section c
P_{line} maximum capacity of a charging section

System Design

Price of Power Schedule

Price function of OLEVs

$$\mathcal{Y}_{n,c}(\mathbf{p}_{-n}, p_{n,c}) = \mathcal{Z}\left(\sum_{j \in \mathcal{N}/\{n\}} p_{j,c} + p_{n,c}\right)$$

Price w.r.t. other EVs

System Design
Price of Power Schedule

Price function of OLEVs

$$\mathcal{Y}_{n,c}(\mathbf{p}_{-n}, p_{n,c}) = \mathcal{Z}\left(\sum_{j \in \mathcal{N}/\{n\}} p_{j,c} + p_{n,c}\right)$$

Price w.r.t. other EVs

Power payment of OLEVs

$$\xi_n(\mathbf{p}_{-n}, \mathbf{p}_n) = \sum_{c \in C}[\mathcal{Y}_{n,c}(\mathbf{p}_{-n}, \mathbf{p}_n) - \mathcal{Y}_{n,c}(\mathbf{p}_{-n}, \mathbf{0})]$$

Price w.r.t. other EVs　　Price of other EVs

System Design
Price of Power Schedule

Utility function of OLEVs

$$\mathcal{F}_n(\mathbf{p}_{-n}, \mathbf{p}_n) = \mathcal{U}_n\left(\sum_{c \in \mathcal{C}} p_{n,c}\right) - \xi_n(\mathbf{p}_{-n}, \mathbf{p}_n)$$

Satisfaction of OLEV   Cost of schedule p_n

System Design

Price of Power Schedule

Utility function of OLEV n

$$\mathcal{F}_n(\mathbf{p}_{-n}, \mathbf{p}_n) = \mathcal{U}_n\left(\sum_{c \in \mathcal{C}} p_{n,c}\right) - \xi_n(\mathbf{p}_{-n}, \mathbf{p}_n)$$

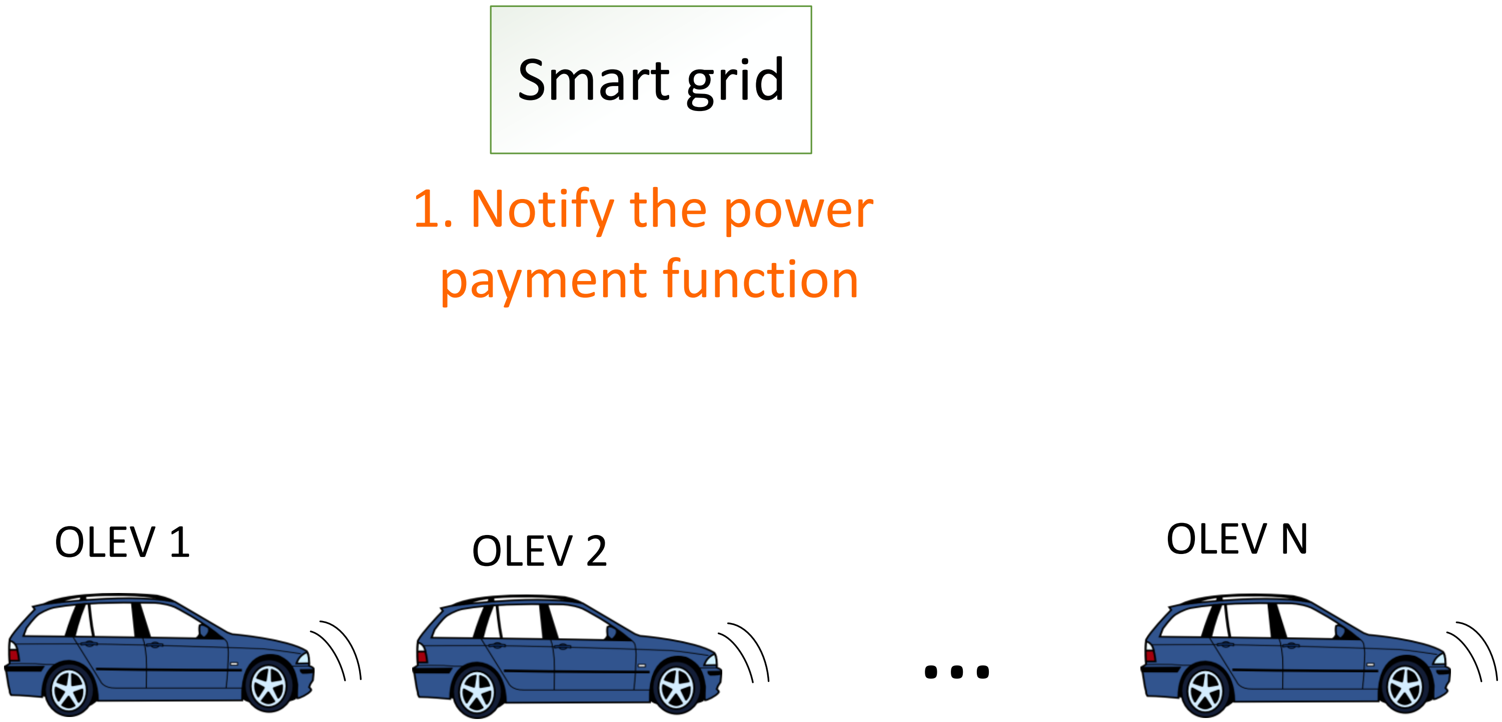
Satisfaction of OLEV — Cost of schedule p_n

Power schedule to minimize payment

$$\hat{\mathbf{p}}_n(p_n) = \arg\min_{\mathbf{p}_n \in \mathcal{P}_n(p_n)} \sum_{c \in C} \mathcal{Y}_{n,c}(\mathbf{p}_{-n}, p_{n,c})$$
$$= \arg\min_{\mathbf{p}_n \in \mathcal{P}_n(p_n)} \xi_n(\mathbf{p}_{-n}, \mathbf{p}_n)$$

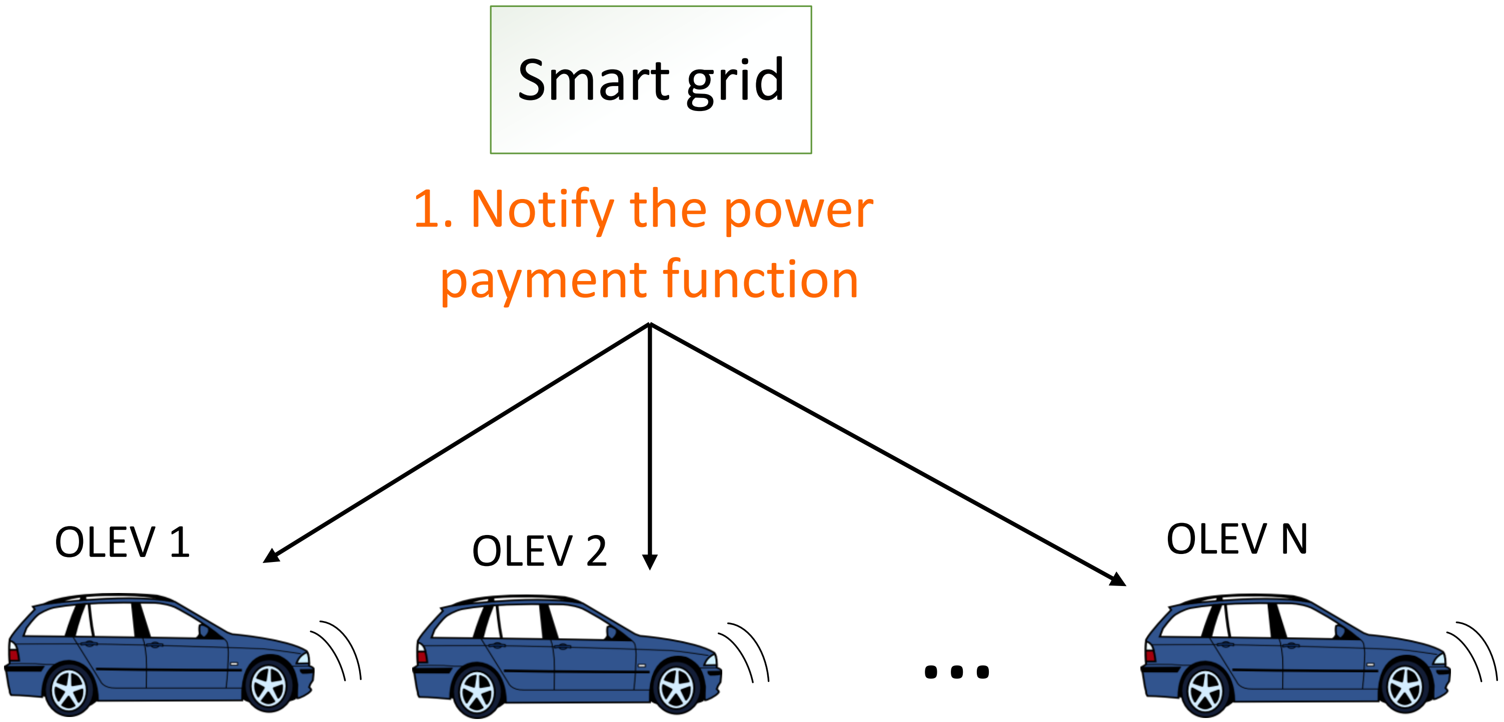
Find a schedule to minimize the cost

System Design
Asynchronous Response Strategy



Non cooperative game between OLEVs

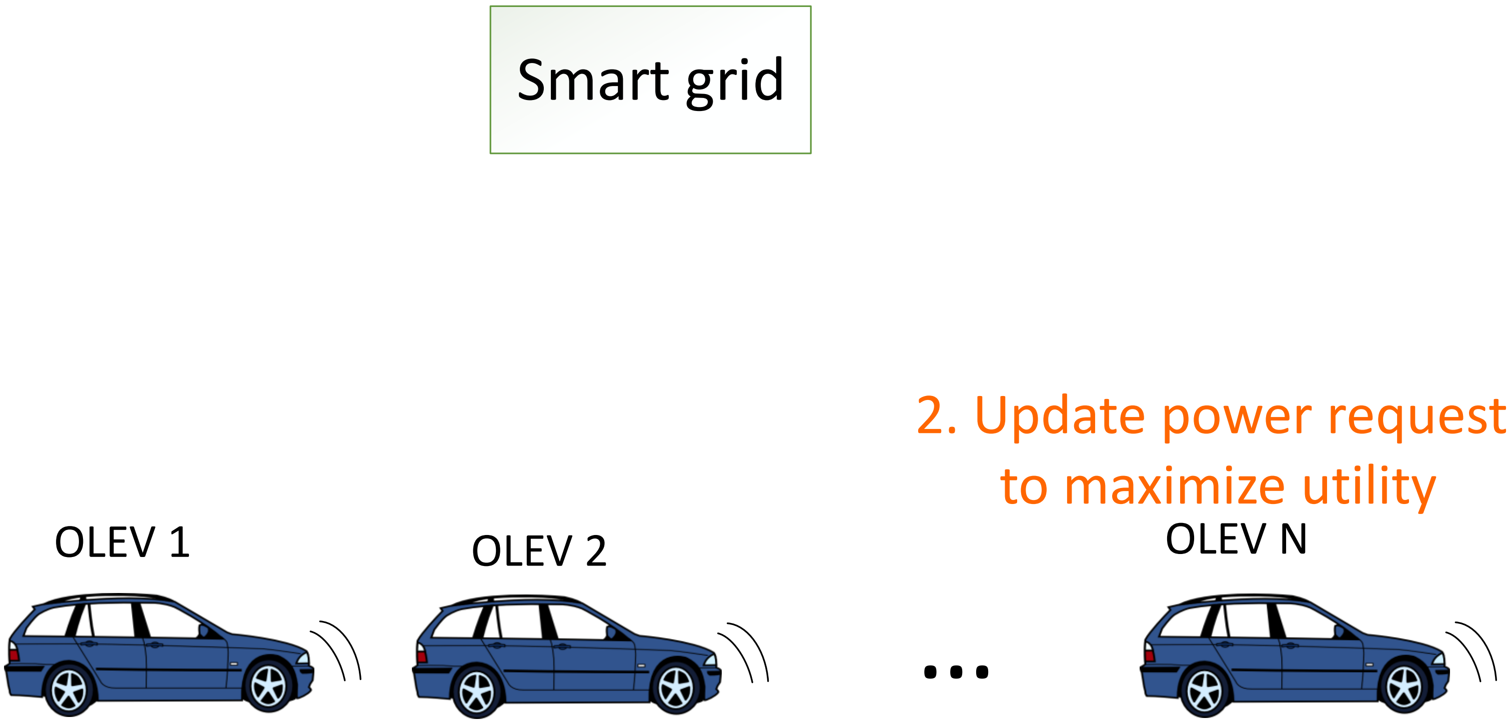
System Design
Asynchronous Response Strategy



Non-cooperative game between OLEVs

System Design

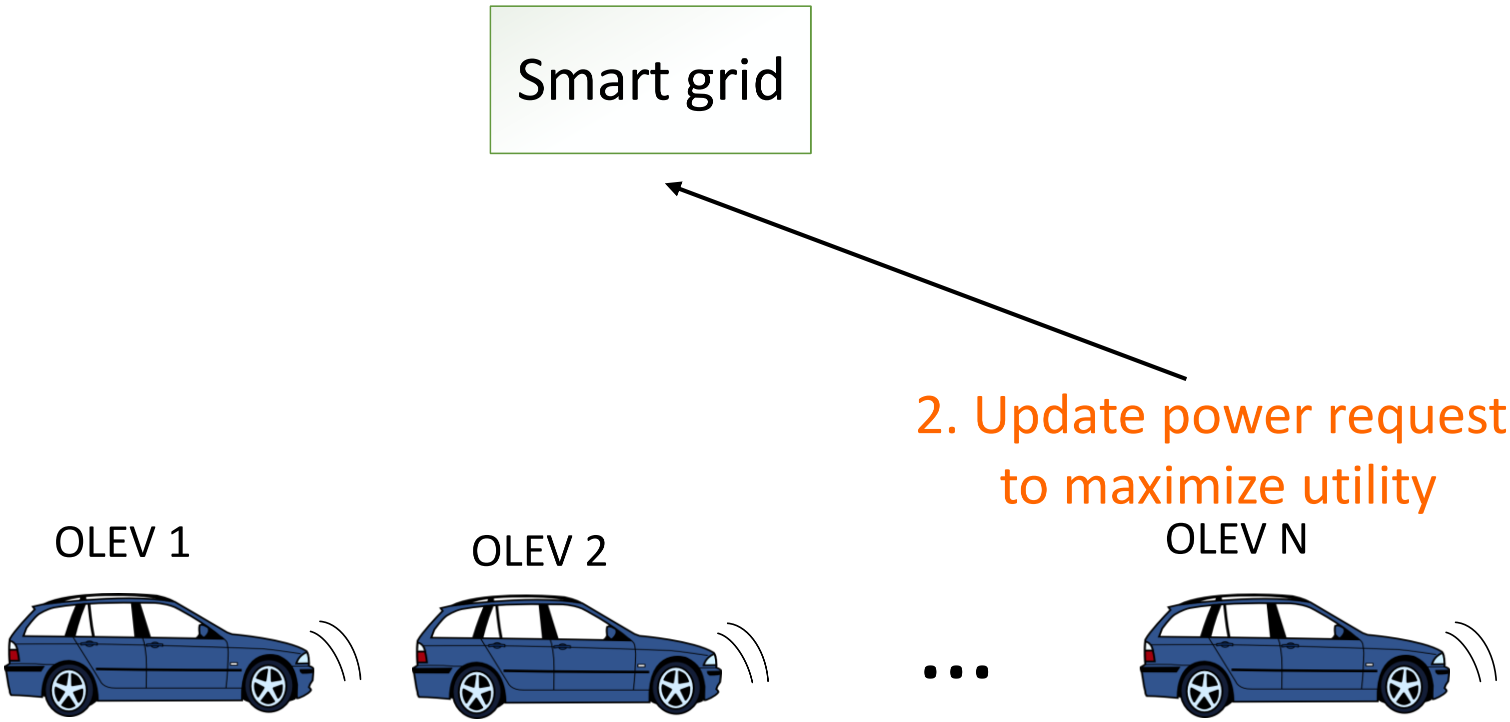
Asynchronous Response Strategy



Non cooperative game between OLEVs

System Design

Asynchronous Response Strategy

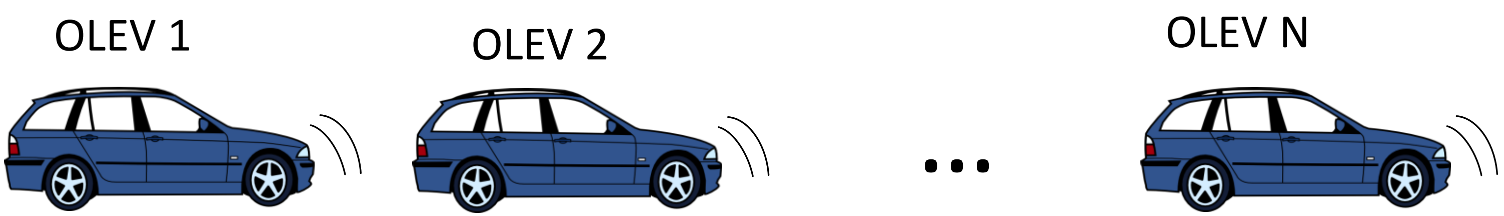


Non cooperative game between OLEVs

System Design
Asynchronous Response Strategy

Smart grid

3. Find power schedule to minimize charging cost

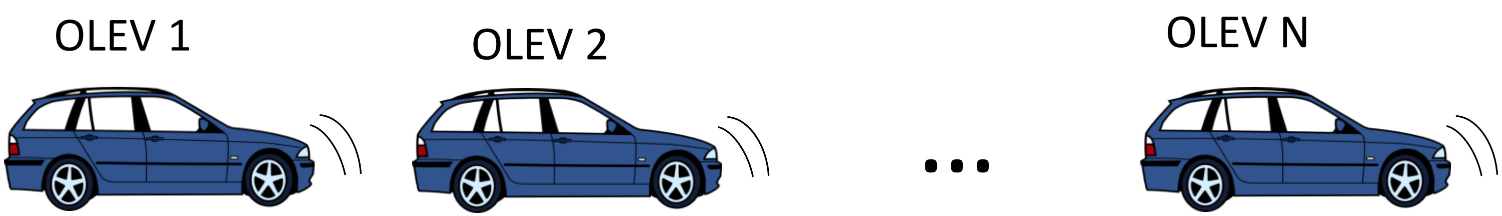


Non cooperative game between OLEVs

System Design
Asynchronous Response Strategy

Smart grid

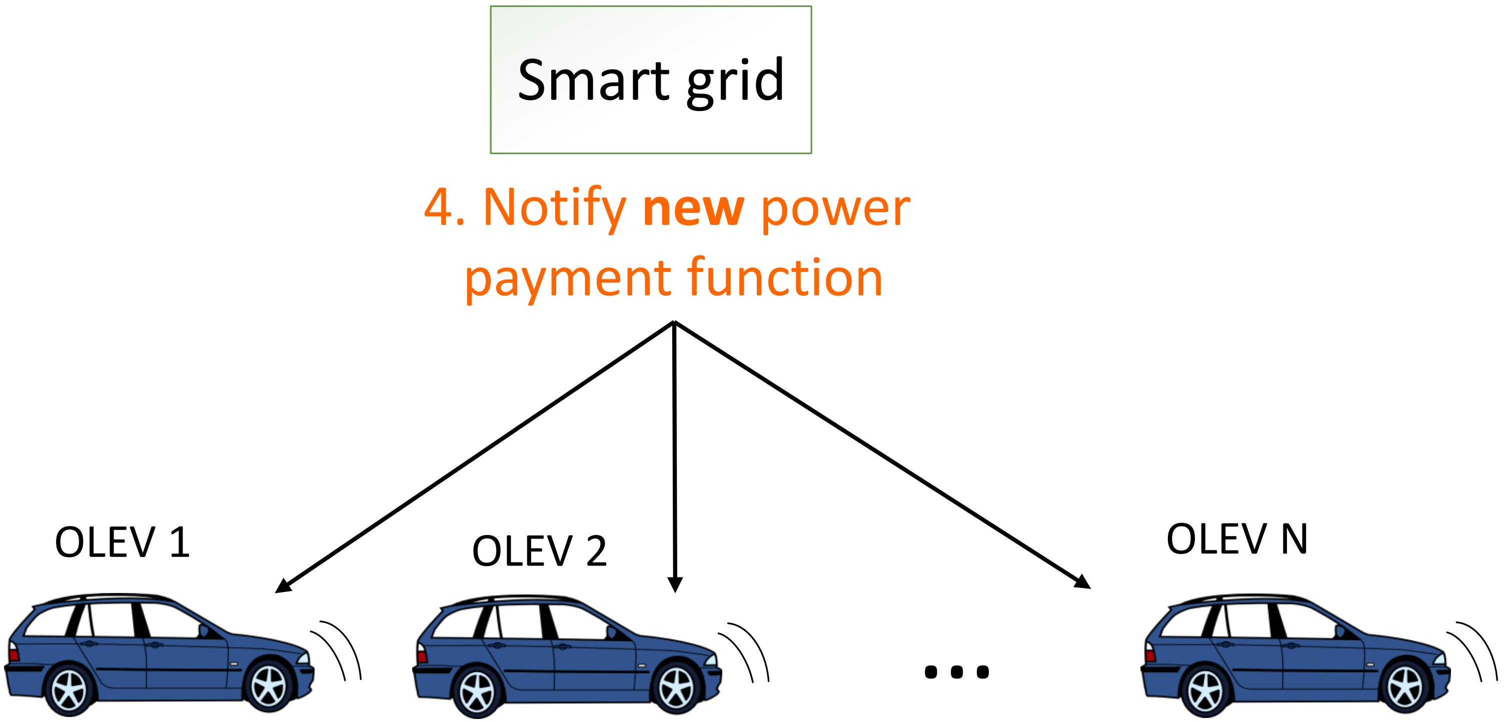
4. Notify **new** power payment function



Non cooperative game between OLEVs

System Design

Asynchronous Response Strategy



Non-cooperative game between OLEVs

System Design

Asynchronous Response Strategy

OLEV n tries to maximize its individual utility (step 2)

$$p_n^{k+1} = \arg\max_{p_n \in \mathcal{P}_n} \mathcal{F}_n(p_n, \Psi_n^{k+1}(\cdot))$$

$$= \arg\max_{p_n \in \mathcal{P}_n} \mathcal{U}_n(p_n) - \Psi_n^{k+1}(p_n)$$

Find a power amount w.r.t. satisfaction and cost

System Design

Asynchronous Response Strategy

OLEV n tries to maximize its individual utility (step 2)

$$p_n^{k+1} = \arg\max_{p_n \in \mathcal{P}_n} \mathcal{F}_n(p_n, \Psi_n^{k+1}(\cdot))$$
$$= \arg\max_{p_n \in \mathcal{P}_n} \mathcal{U}_n(p_n) - \Psi_n^{k+1}(p_n)$$

Find a power amount w.r.t. satisfaction and cost

Power payment function of OLEV n at step k+1 (step 4)

$$\Psi_n^{k+1}(p_n) = \xi_n(\mathbf{p}_n^k, \hat{\mathbf{p}}_n(p_n)), \forall n$$

Updated power payment function based on requested amount $\mathrm{p}_\mathrm{n}^\mathrm{k}$

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Experiment
Simulation Settings

1. NYC Traffic data
2. 10-50 EVs
   a. Each OLEV has 46.2Ah capacity, 399V regular voltage, 325V cutoff voltage, and 240A current
   b. SOC_{min} to 0.2 and SOC_{max} to 0.9.
3. 10-100 charging sections
4. Compare with linear pricing policy

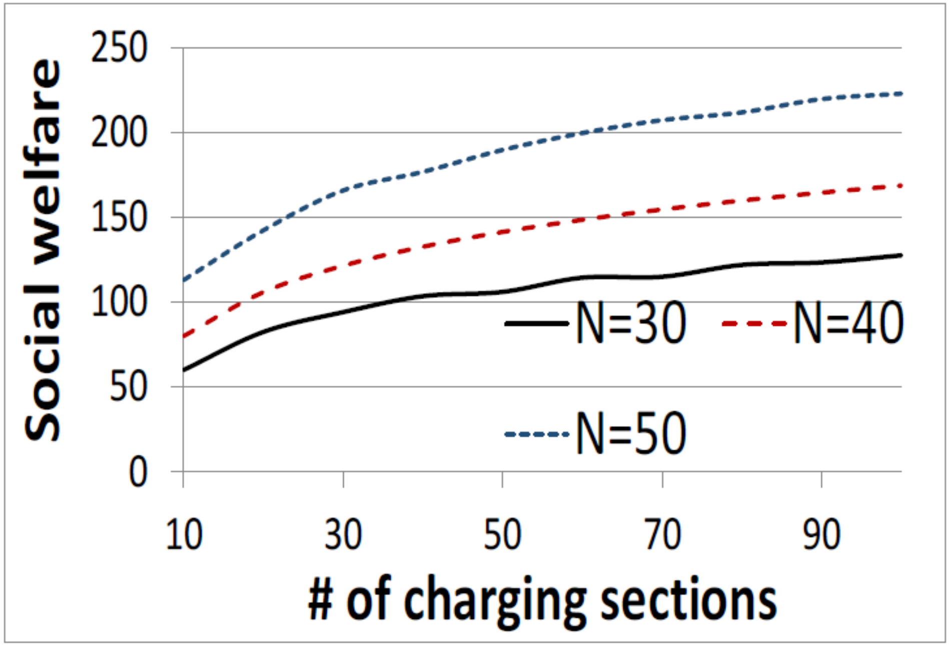
Experiment

Social Welfare

Metric: Social welfare

Observation: Increasing w.r.t. number of charging sections

Reason: More charging section increases social welfare of OLEVs



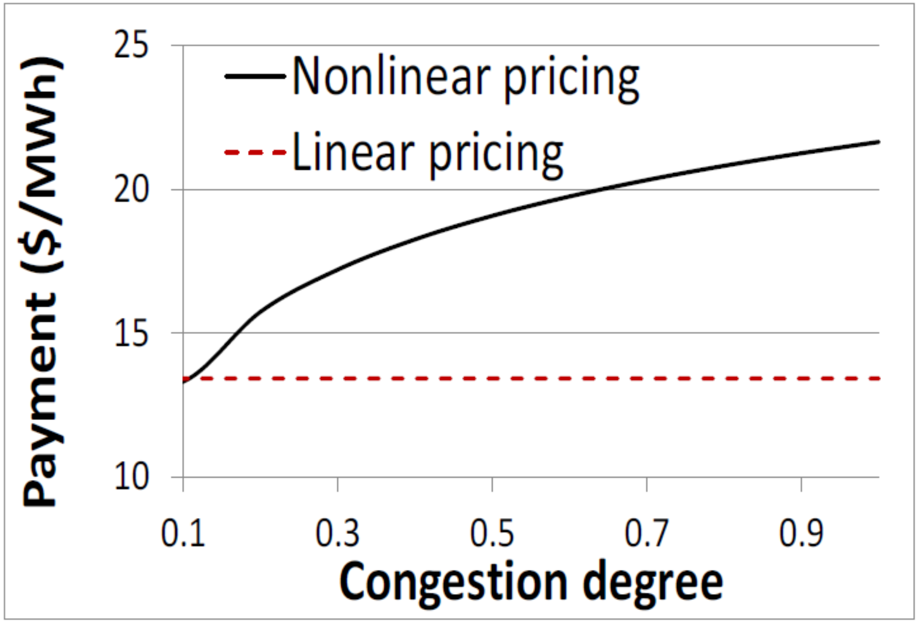
Social welfare

Experiment
Congestion Degree

Metric: Payment

Observation: Non linear pricing consider congestion degree

Reason: Try to adjust schedule at different charging sections



Congestion degree

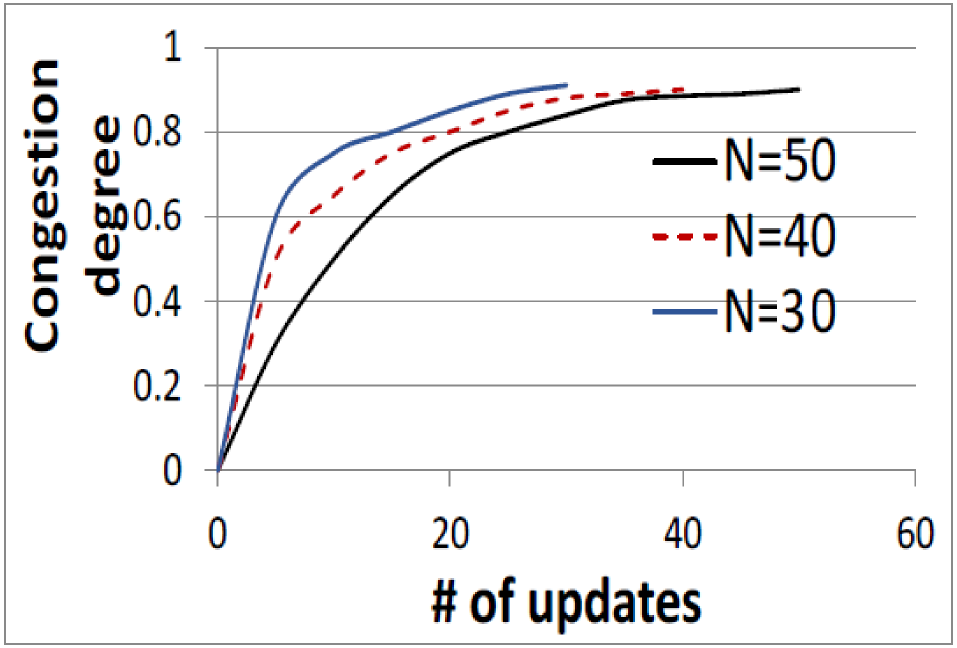
Experiment

Number of Updates

Metric: Number of updates

Observation: Requires less number of updates

Reason: Convergence is fast



Number of updates

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Conclusions

1. We proposed a nonlinear pricing policy for OLEVs consider power taken from smart grid
2. We designed a non cooperative game between charging sections and OLEVs

Future Work

Further take into account:

1. Complex scenarios of OLEVs and roads
2. Consider the interest of smart grid
3. More experimental evaluations

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Thank you!
Questions & Comments?

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