Demand Response Control for PHEV Charging Stations by Dynamic Price Adjustment

ISGT 2012, Demand Response and Real-Time Pricing

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Motivation

- PHEV use & Power Grid
  - In market,
    - Increase by 80% each year since 2000 [1]
    - 10% vehicle sales will be PHEVs in 2015[2]
  - In power grids,
    - Expected to add an additional 18% load to existing power grids [3][4]
  - Current PHEVs,
    - Relatively *short driving range* and *long charging time*
    - *Charging stations* are essential for their proliferation [6]-[9]

Propose a *cooperative PHEV charging station framework* which addresses above issues

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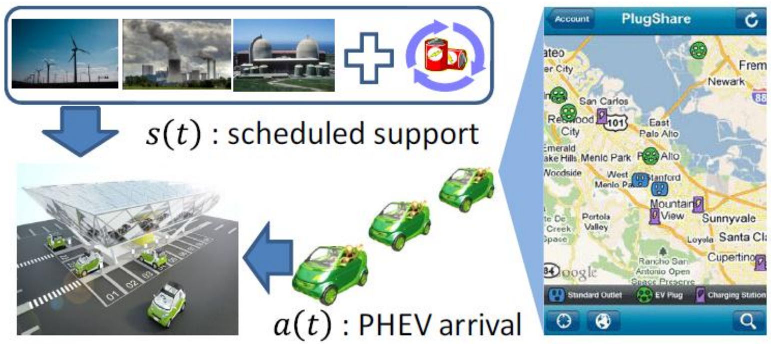
PHEV Charging Station Model

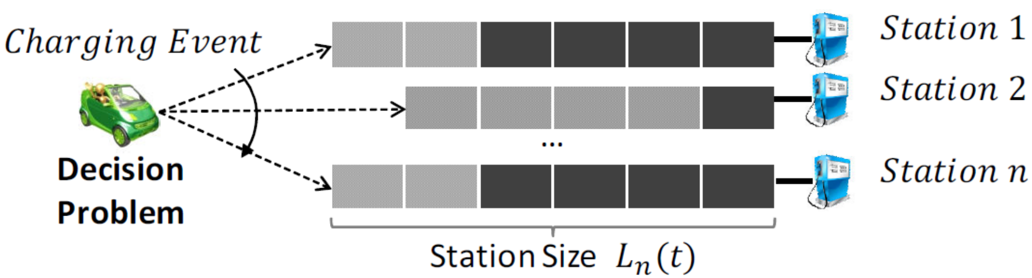
- Linkage between stations and location service



➢ Station Vehicle Backlog Dynamics

$$Q_i(t+1) = \max\left[Q_{i(t)} - s_i(t), 0\right] + a_i(t)$$

- Framework performance under *multiple-stations*



➢ Station Throughput
➢ Customer QoS (e.g., sojourn time at stations)

1. The degree of stations' charging capability
2. Station waiting-room size

} Given Parameter

3. PHEV's station selection behavior ⟵ *Control* Parameter

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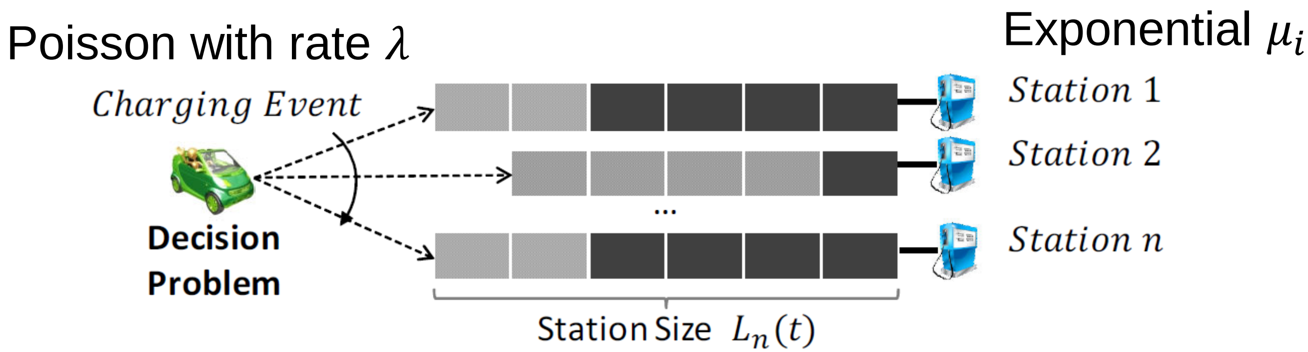
Optimal PHEV Allocation Policy



- Multi M/M/1 system conversion with work conserving queues
- Reduce PHEV waiting-time at stations
  - Mean Queue size ($\frac{\mu_i}{\mu_i-\lambda_i}$) is proportional to waiting time by Little's Law.
  - Global queue size minimization problem

$$\begin{aligned} \underset{\vec{\lambda}}{\text{minimize}} \quad & \sum_{i=1}^{n} \frac{\mu_i}{\mu_i - \lambda_i} \\ \text{subject to} \quad & \sum_{i=1}^{n} \lambda_i = \lambda \\ & \mu_i - \lambda_i > 0 \\ & \mu_i > 0, \ \lambda_i > 0 \end{aligned}$$

Allocation vector $\overrightarrow{\lambda^{opt}}$

$$\lambda_i^{opt} = \frac{\lambda + \sum_{j=1}^{n} (\sqrt{\mu_i \mu_j} - \mu_j)}{\sum_{j=1}^{n} \sqrt{\frac{\mu_j}{\mu_i}}}, \ \text{where } i = \{1, \dots, n\}$$

(shown in Appendix A)

Optimal Allocation with Station-Size

- Charging stations can suffer congestions
  - Congestion indicator $C_i(t)$:

    $$C_i(t) = \mathbf{1}_{\{Q_i(t) > L_i\}}, \text{ where } i == \{1, \ldots, n\}$$

  - [IDEA] Temporarily *exclude* congestion suffering stations from optimal allocation computations

Algorithm 1 PHEV Allocation with Overflow Relaxation

Require: Station reports $\lambda_i[k], \mu_i[k]$ and $C_i[k]$, where $i \in \mathcal{N}$ and k is a measurement time-slot.

$\lambda[k] = \sum_{i \in \mathcal{N}} \lambda_i[k]$

for $i = 1 \to |\mathcal{N}|$ **do**

  if $C_i[k] = 1$ **then**

    $\mu_i[k] \leftarrow 0$ (Exclude Station i)

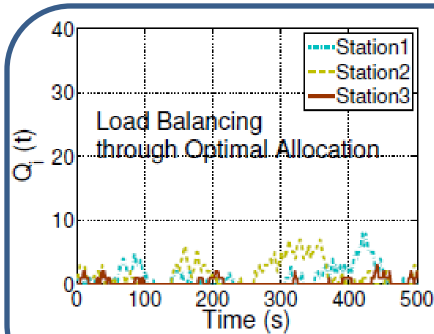
  end if

end for

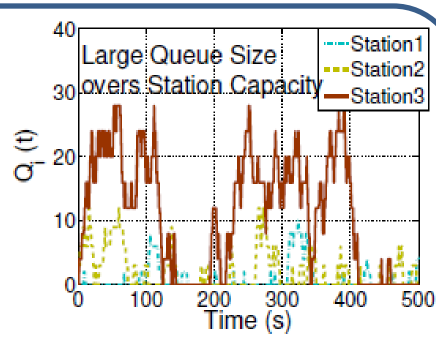
$$\overrightarrow{\lambda^{opt}}[k+1] \leftarrow \frac{\lambda[k] + \sum_{j=1}^{|\mathcal{N}|}\left(\sqrt{\mu_i[k]\mu_j[k]} - \mu_j[k]\right)}{\sum_{j=1}^{|\mathcal{N}|}\sqrt{\frac{\mu_j[k]}{\mu_i[k]}}}$$

	Optimal Allocation	Uniform Random
Mean Queue size	3.307	15.124
Throughput	6337	6343

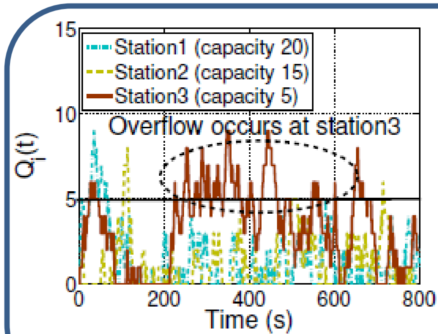
<Measurement for 10,000 s>



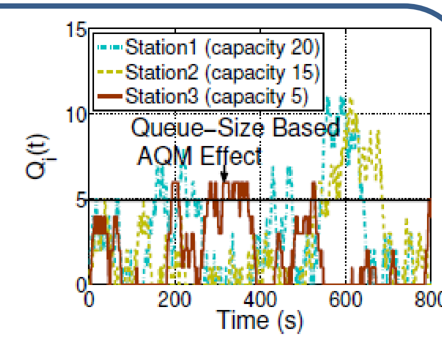
(a) Optimal Vehicle Allocation $\overrightarrow{\lambda^{opt}}$



(b) Uniform Random Allocation $\overrightarrow{\lambda^{uni}}$

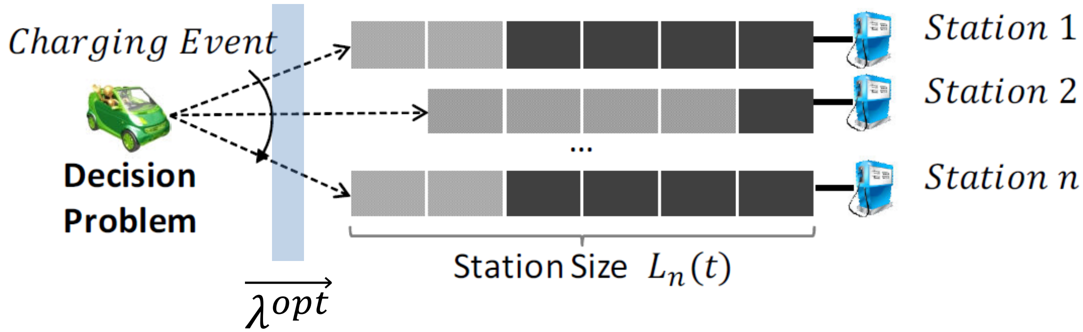


(a) Optimal Allocation $\overrightarrow{\lambda^{opt}}$ Only

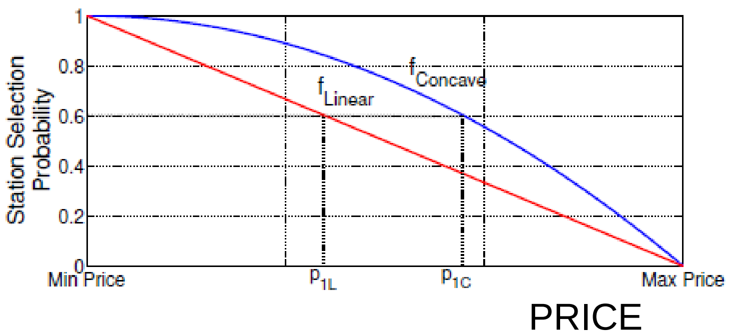


(b) Optimal+Size-Based AQM

Price Control and PHEV Behaviors



- PHEV behaviors are controllable?
  - We have the optimal condition $\overrightarrow{\lambda^{opt}}$ to maximize performance both for *station throughput* and *customer service quality*
  - But, no guarantee that PHEVs' charging station selection will follow the condition
- Price differentiation at stations
  - Give *incentives* or *penalties* for PHEVs
  - Modify their station selection behavior



Price Matching Methods

- Method1:Utilizing pre-measured sensitivity
  - The price sensitivity of PHEVs is known by surveys or long-period measurements
  - Inverse Matching Problem

$$p_i = f(c_i) \longleftrightarrow c_i = f^{-1}(p_i)$$

Charging Price at station i

PHEV Sensitivity function

Station Selection Probability

  - Station Price Vector

$$\overrightarrow{P}_{(t_k, t_k+T]} = [f^{-1}(\frac{\overline{\lambda_1}}{\overline{\lambda}}), \ldots, f^{-1}(\frac{\overline{\lambda_{|\mathcal{N}|}}}{\overline{\lambda}})]$$

- Method2:Regression-Based price matching
  - The PHEV price sensitivity (i.e., distribution) is *unknown*.
  - Consider $d_i[l]$:

$$d_i[l] = \overline{\lambda_i}[l] - \lambda_i^{opt}[l]$$

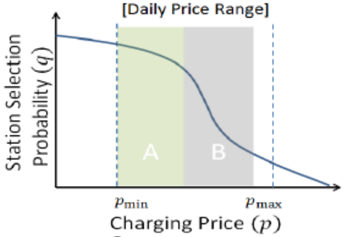
Rate Gap in slot l

Desired allocation for optimal performance

  - Price p_i Set up

$$p_i[l+1] = p_i[l] + \gamma \cdot d_i[l]$$

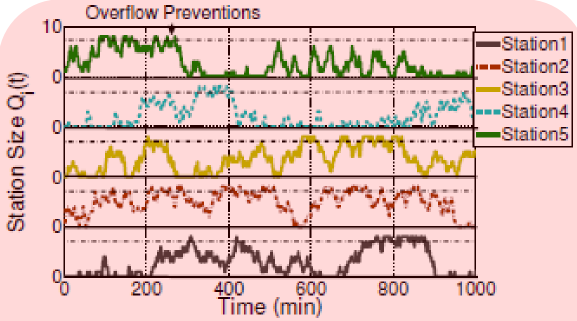
  - Reduce the gap $d[l]$ all the time under general PHEV behaviors



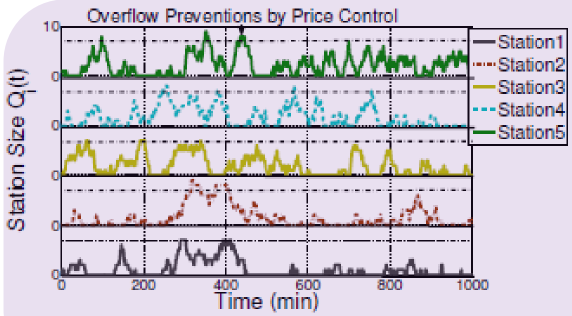
Price Control Tests (Method 1)

- 5 PHEV charging station framework ($\vec{\mu} = [0.2,0.2,0.25,0.25,0.3], L_i = 10$)

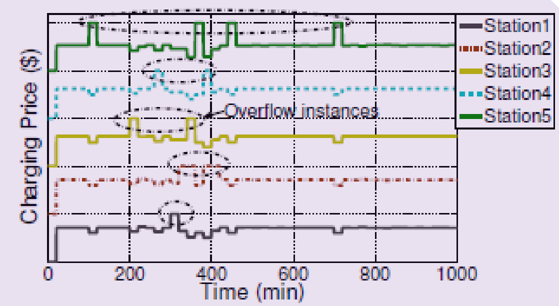
1. Normal charging event occurrence with $\lambda = 1$ and *linear* PHEV price sensitivity



(a) Station Size Dynamics from Alg. 1

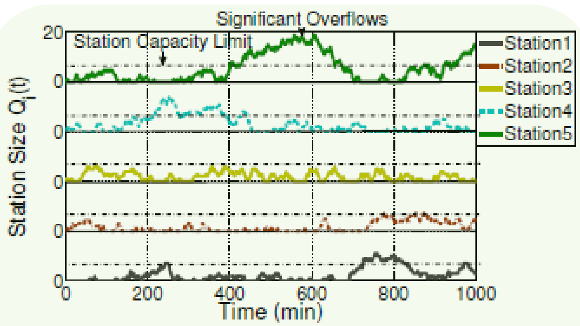


(b) Station Size Dynamics from Price Method 1

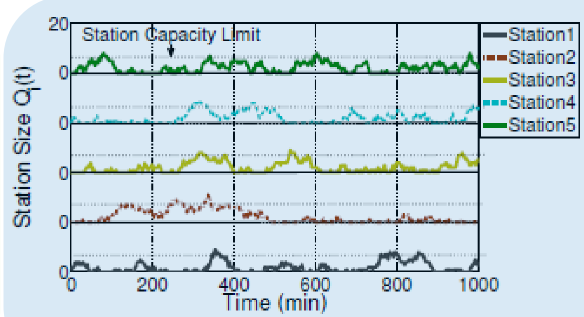


(c) Charging Price Dynamics of (b)

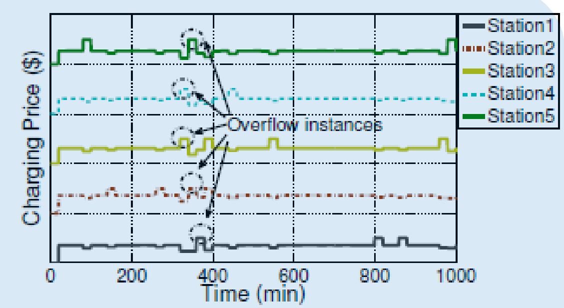
2. Heavy charging event occurrence with $\lambda = 1.5$ and *concave* PHEV sensitivity



(a) Station Size Dynamics without AQM



(b) Station Size Dynamic with AQM



(c) Charging Price Dynamics of (b)

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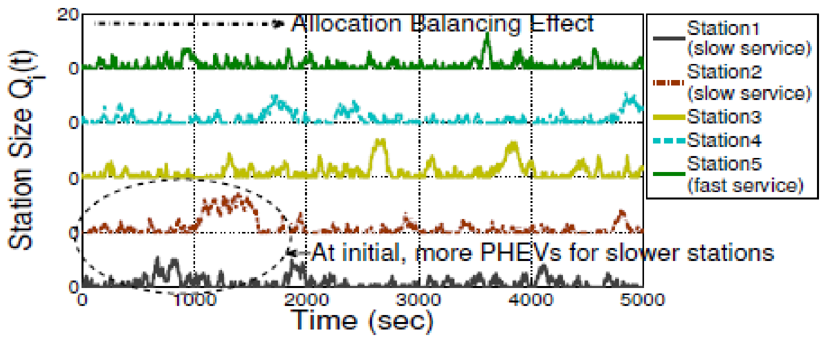
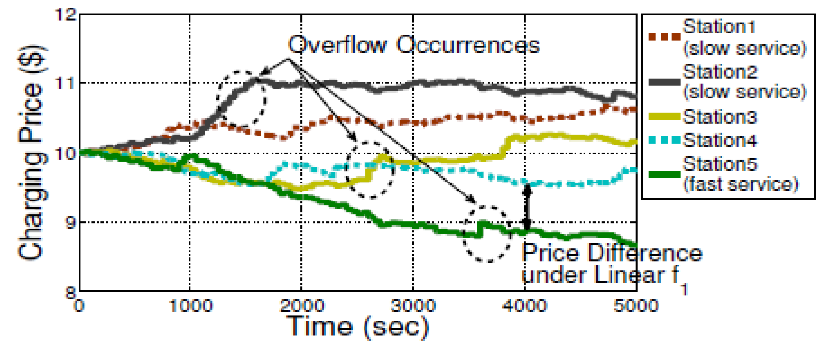
Price Control Tests (Method 2)

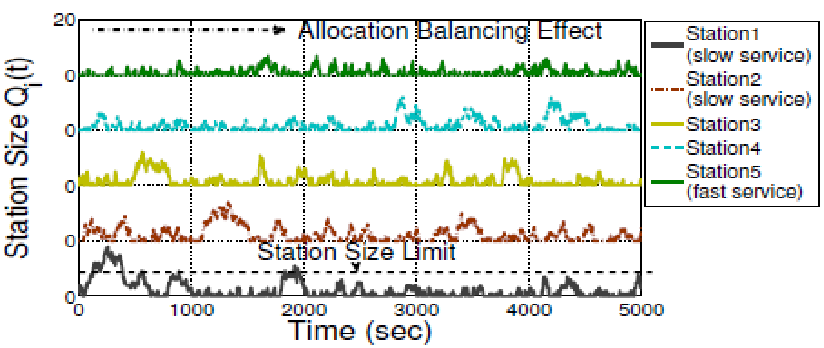
- 5 PHEV charging station framework ($\vec{\mu} = [0.2, 0.2, 0.25, 0.25, 0.3], L_i = 10, \gamma = 0.5$)

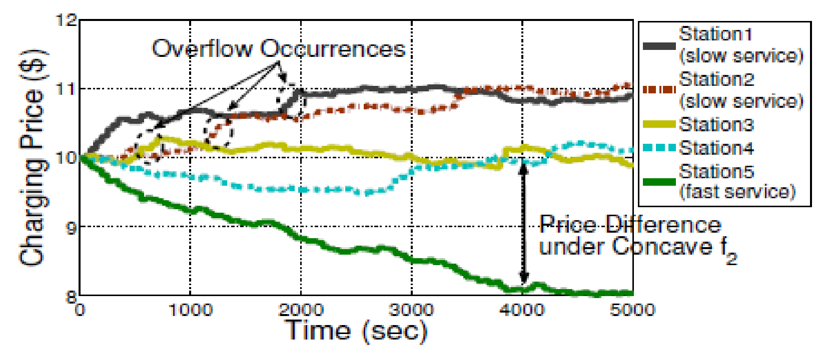
Under *linear PHEV price sensitivity*





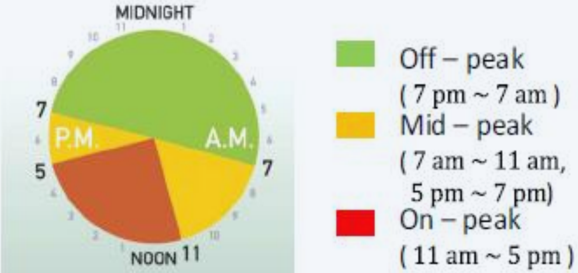
Under *concave PHEV price sensitivity*





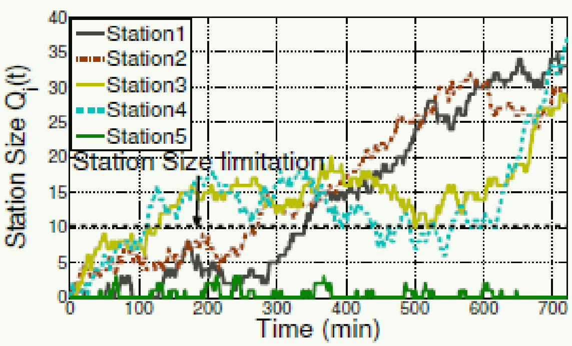
Tests under Electric Regulation

Time-varying electric support



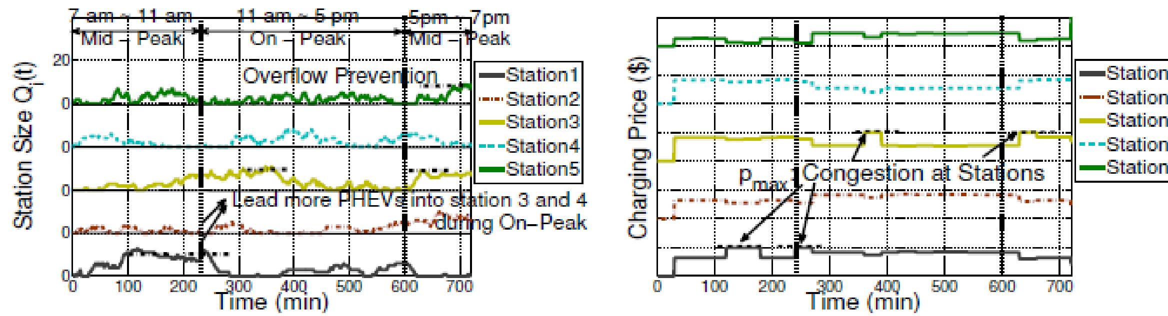
$$\vec{\mu}_{\text{Mid-Peak}} = [0.2, 0.2, 0.1, 0.1, 0.4]$$

$$\vec{\mu}_{\text{On-Peak}} = [0.1, 0.1, 0.25, 0.25, 0.3]$$

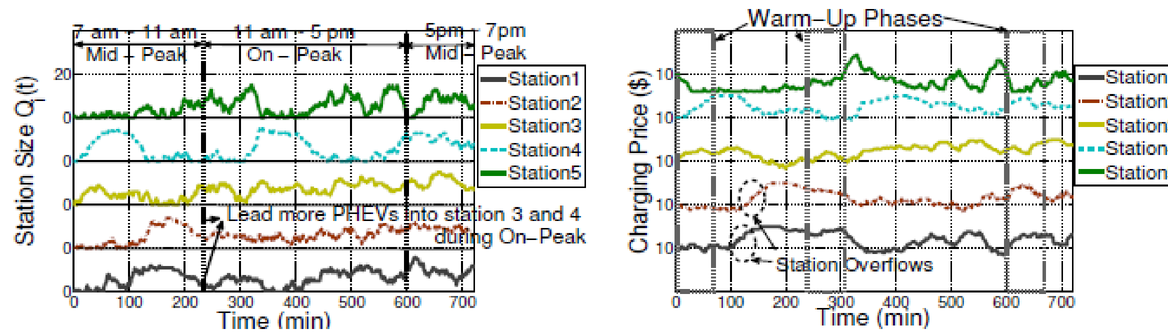


<Station backlogs without Framework>

- *Concave* PHEV price sensitivity



<Method 1: with a *pre-measured price sensitivity function*>



<Method 2: With an *uncertain price sensitivity function*>

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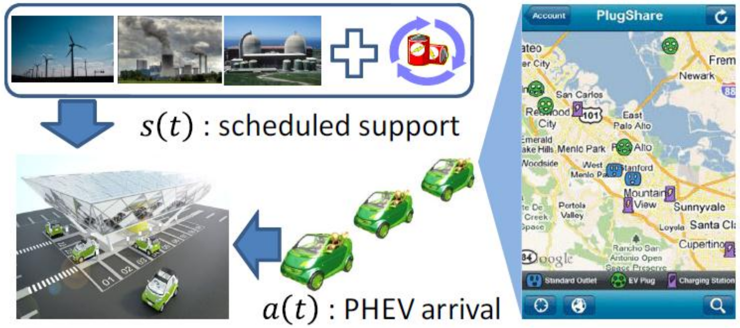
Conclusion

- The necessity of PHEV allocation policy:
  - Station backlog comparisons between $\overrightarrow{\lambda^{opt}}$ and *uniform policy*
- Determine an optimal allocation policy:
  - At station side: *Maximize Throughput*
  - At PHEV user side: *minimize sojourn time*
- PHEV behavior controllability
  - Achieve the optimal solution by *price differentiation*
- Framework test and effectiveness
  - *Autonomous Price Adjustment*
  - *Load Balancing*
  - *Relax Station Overflows*



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Thank you