Online Charge Scheduling for Electric Vehicles in Autonomous Mobility on Demand Fleets

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Personal Urban Mobility

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- Specifically, let us consider a fleet of autonomous mobility-on-demand electric vehicles (AMoD EVs)
  - Transport customers from origin to destination
  - Must recharge periodically to remain in operation

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Managing such a system is possible...but it is a challenging problem

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- Information is revealed in an online fashion
  - Do not know next customer's trip length
  - Do not know traffic conditions
- Need to manage the fleet without knowledge of future
  - Mobility-on-Demand arrival distributions highly nonstationary
  - Tool of choice: Online Optimization (instead of MPC)
  - Accounts for adversarial input sequences

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  - Fleet vehicles need sufficient energy levels to serve customers
  - Which vehicle is granted charger usage?
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Require online scheduling systems for routing decisions and shared resource allocation to enable smart charging for fleet EVs in the between-ride state

System Description

- D regions within a service area $\mathcal{D}$

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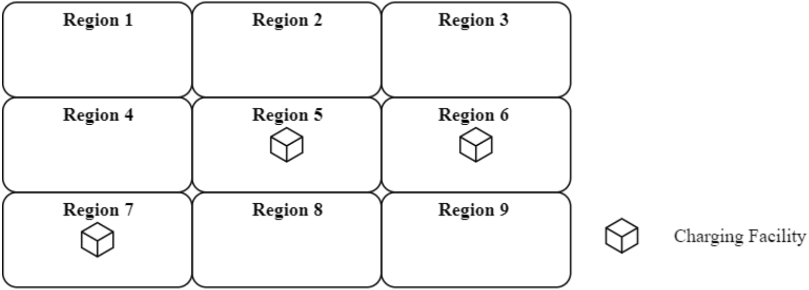
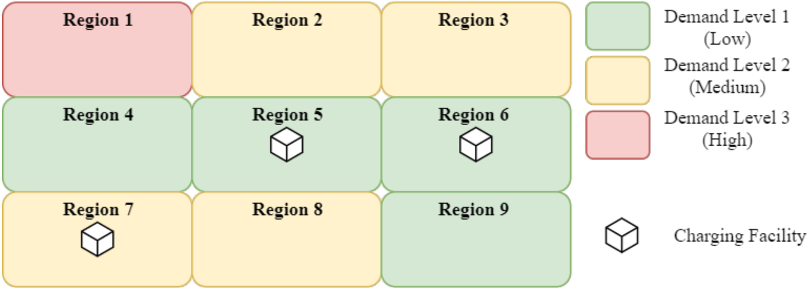


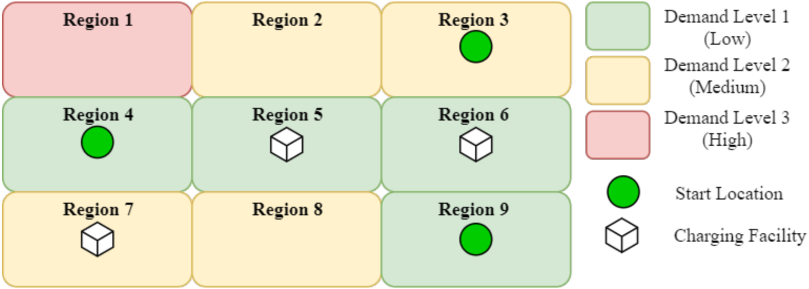
System Description

- Varying customer demand across regions



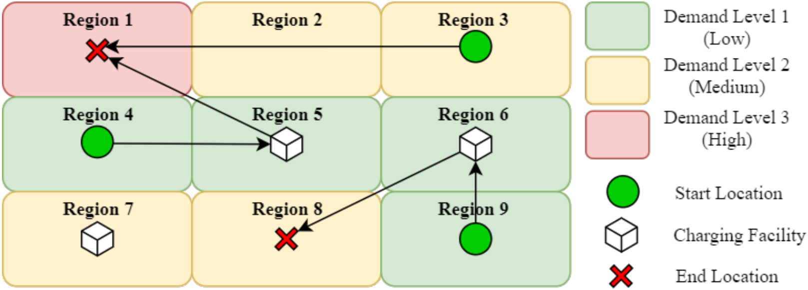
System Description

- AMoD EVs enter the between-ride state



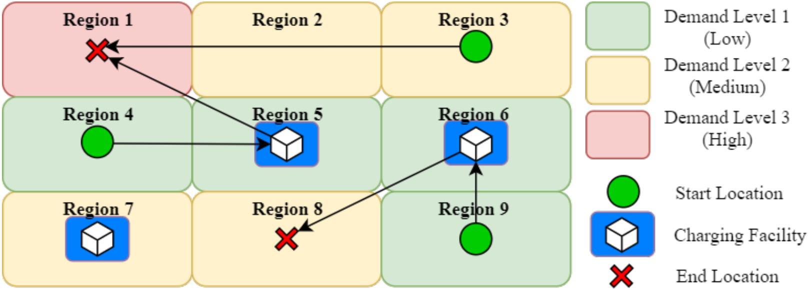
System Description

- EVs select between-ride charging schedules and next stops

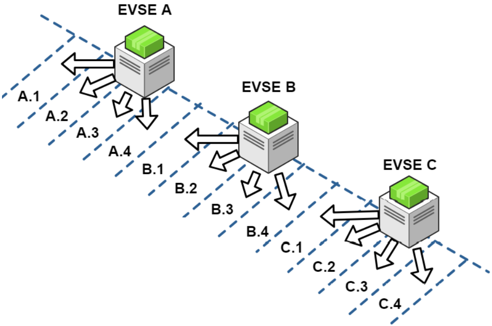


System Description

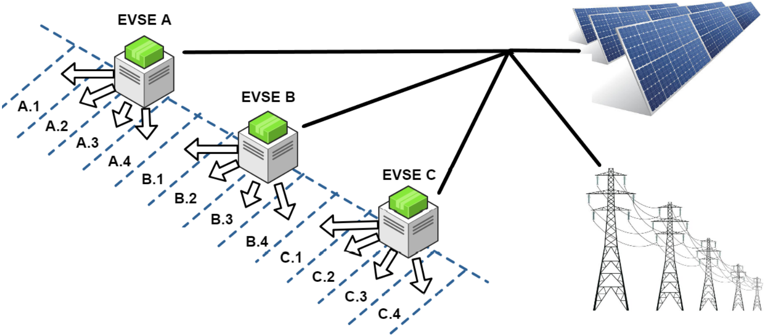
- Now let's examine the charging facilities



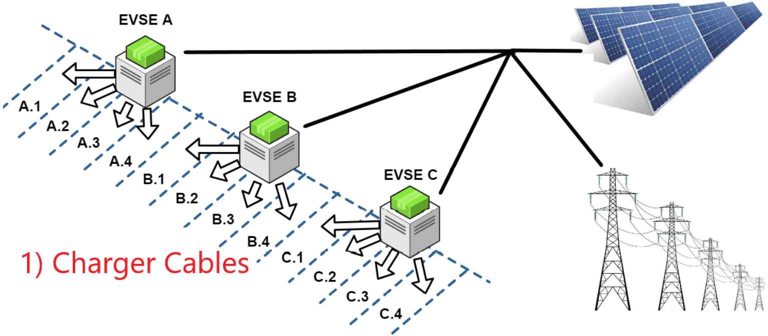
- Charging facilities equipped with multiple-cable chargers



- Energy procured from solar and distribution grid



- Limited shared charging resources



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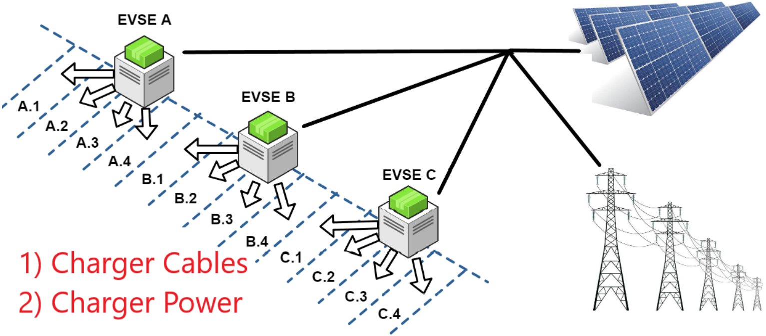
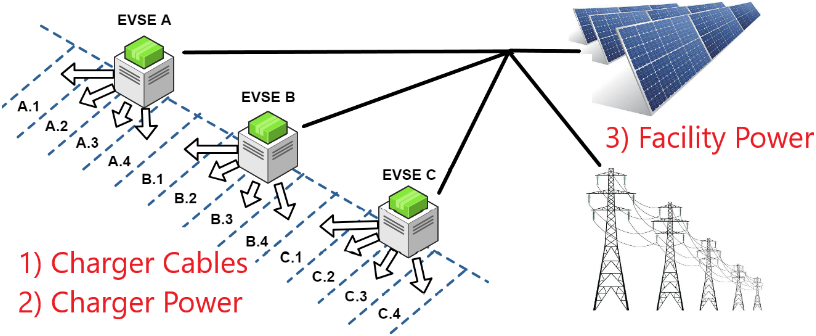


1) Charger Cables
2) Charger Power

- Limited shared charging resources



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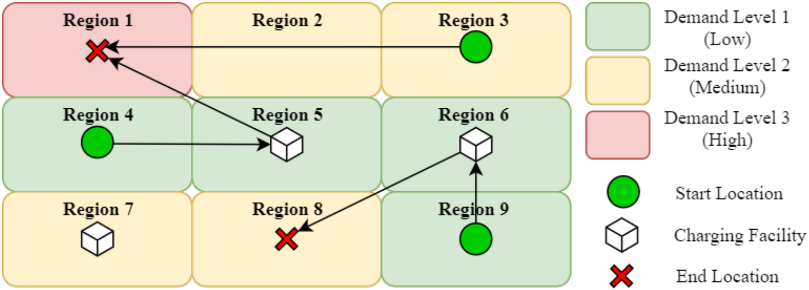
- A set of feasible between-ride schedules is generated based on the vehicle's current battery level and location
- Schedules include:
  - Start/end time of the between-ride session
  - Start/end destination
  - Potential stop at a charging facility with charging schedule
  - Utility of the schedule to the fleet dispatcher

Example

- Recall the previous example:



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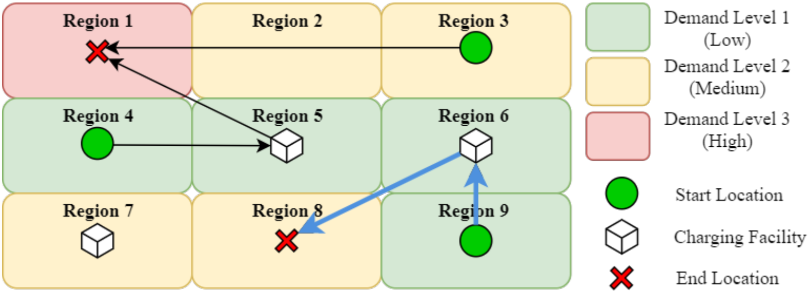

- Highlighted between-ride schedule was selected

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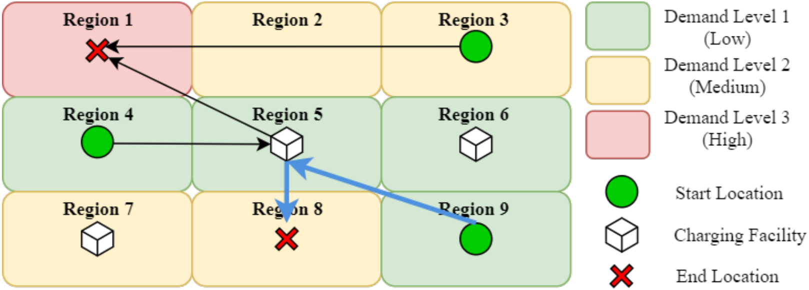

- Why not this schedule?

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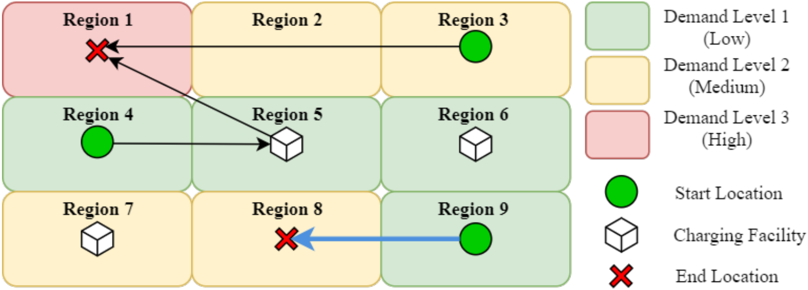

- Or this one?

Offline Welfare Maximization Problem

$$\max_{x} \sum_{\mathcal{J},\mathcal{S}_j} v_{js} x_{js} - \sum_{\mathcal{T},\mathcal{F}} G_f(y_g^f(t)) - \sum_{\mathcal{T}} O(y_o(t))$$

subject to:

$$\sum_{\mathcal{S}_j} x_{js} \leq 1, \qquad \forall\, j$$

$$x_{js} \in \{0,1\}, \qquad \forall\, j, s$$

$$y_c^{mf}(t) \leq C_f, \quad \forall\, f, m, t$$

$$y_e^{mf}(t) \leq E_f, \quad \forall\, f, m, t$$

$$y_d(t) \leq \Omega_d(t), \quad \forall\, d, t$$

Facilities' Electricity Costs

The energy procurement, $y_g^f(t)$, determines the operational cost of facility f (i.e., purchasing electricity from the distribution grid):

$$G_f(y_g^f(t)) =$$
$$\begin{cases} 0 & y_g^f(t) \in [0, \delta_f(t)] \\ \pi_f(t)(y_g^f(t) - \delta_f(t)) & y_g^f(t) \in \big(\delta_f(t), \delta_f(t) + \mu_f(t)\big] \\ +\infty & y_g^f(t) > \delta_f(t) + \mu_f(t). \end{cases}$$

Fleet Out-Of-Service Penalty

The number of AMoD EVs in the between-ride state, $y_o(t)$, determines the out-of-service penalty:

$$O(y_o(t)) = \begin{cases} \phi(t) y_o(t), & y_o(t) \leq I(t) \\ +\infty & y_o(t) > I(t), \end{cases}$$

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Discourages excessively long recharging sessions

Scheduling Decisions

- Can examine the following dual constraint:

$$u_j = \max_{s \in \mathcal{S}_j} \Big\{ v_{js} - p_d(t_{js}^+) d_{js}^+(t_{js}^+) - \sum_{t \in [t_j^-, t_{js}^+]} \Big(o_{js}(t) p_o(t) + c_{js}^{mf}(t) p_c^{mf}(t) + e_{js}^{mf}(t) \big[p_e^{mf}(t) + p_g^f(t) \big] \Big) \Big\}$$

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- Want to estimate the optimal dual variables in an online fashion

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- Make irrevocable scheduling decisions in an online fashion
- Handle adversarial sequences (due to the nonstationary distributions of customer arrivals in Mobility-on-Demand)
- Provide performance guarantees

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- We are able to provide performance guarantees for pricing functions of the following form:

$$p_g^f(y_g^f(t)) = \begin{cases} \left(\frac{L_g}{2\Psi}\right)\left(\frac{2\Psi\pi_f(t)}{L_g}\right)^{\frac{y_g^f(t)}{\delta_f(t)}}, & y_g^f(t) < \delta_f(t), \\ \left(\frac{L_g-\pi_f(t)}{2\Psi}\right)\left(\frac{2\Psi(U_g-\pi_f(t))}{L_g-\pi_f(t)}\right)^{\frac{y_g^f(t)}{\delta_f(t)+\mu_f(t)}} + \pi_f(t), & y_g^f(t) \geq \delta_f(t). \end{cases}$$

Performance Guarantee: Competitive Ratio

- Competitive ratio:

$$\frac{\text{Optimal Offline Solution's Welfare}}{\text{Worst Case[Online Mechanism's Welfare]}} \geq 1$$

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- An online mechanism is "α-competitive" when:

$$\alpha \geq \frac{\text{Optimal Offline Solution's Welfare}}{\text{Worst Case[Online Mechanism's Welfare]}} \geq 1$$

Online Scheduling System Competitive Ratio

The proposed online fleet scheduling heuristic is α-competitive in welfare across all fleet resources for the fleet dispatcher over J between-ride sessions where $\alpha = \max\{\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5\}$.

Performance Guarantee: Competitive Ratio

$$\alpha_1 = \ln\left(\frac{2\Psi U_c}{L_c}\right)$$

$$\alpha_2 = \ln\left(\frac{2\Psi U_e}{L_e}\right)$$

$$\alpha_3 = \max_{\mathcal{F},\mathcal{T}}\left\{ \ln\left(\frac{2\Psi(U_g - \pi_f(t))}{L_g - \pi_f(t)}\right)\right\}$$

$$\alpha_4 = \ln\left(\frac{2\Psi U_d}{L_d}\right)$$

$$\alpha_5 = \max_{\mathcal{T}}\left\{ \ln\left(\frac{2\Psi(U_o - \phi(t))}{L_o - \phi(t)}\right)\right\}$$

Performance Guarantee: Competitive Ratio

$$\alpha_1 = \ln\left(\frac{2\Psi U_c}{L_c}\right)$$ (Charger Cables)

$$\alpha_2 = \ln\left(\frac{2\Psi U_e}{L_e}\right)$$ (Charger Energy)

$$\alpha_3 = \max_{\mathcal{F},\mathcal{T}}\left\{\ln\left(\frac{2\Psi(U_g - \pi_f(t))}{L_g - \pi_f(t)}\right)\right\}$$ (Facility Energy)

$$\alpha_4 = \ln\left(\frac{2\Psi U_d}{L_d}\right)$$ (Regional AMoD EV Limit)

$$\alpha_5 = \max_{\mathcal{T}}\left\{\ln\left(\frac{2\Psi(U_o - \phi(t))}{L_o - \phi(t)}\right)\right\}$$ (Out-of-Service Penalty)

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$$\big(p(t) - f'(y(t))\big)\mathrm{d}y(t) \geq \frac{1}{\alpha(t)} f^{*'}(p(t))\mathrm{d}p(t)$$

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- Resulting α is the maximum $\alpha(t)$ over all regions, facilities, resources, and time.

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San Jose Case Study

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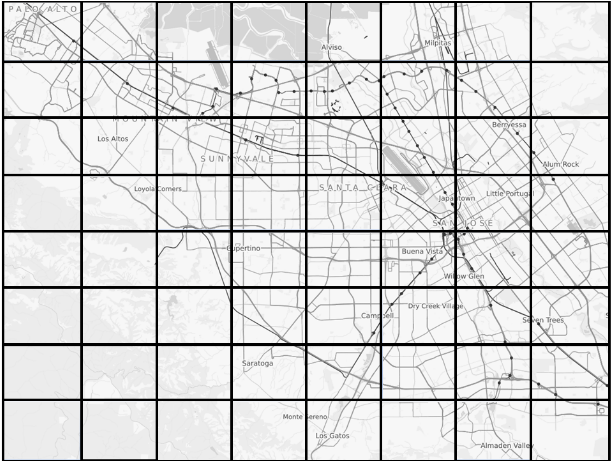

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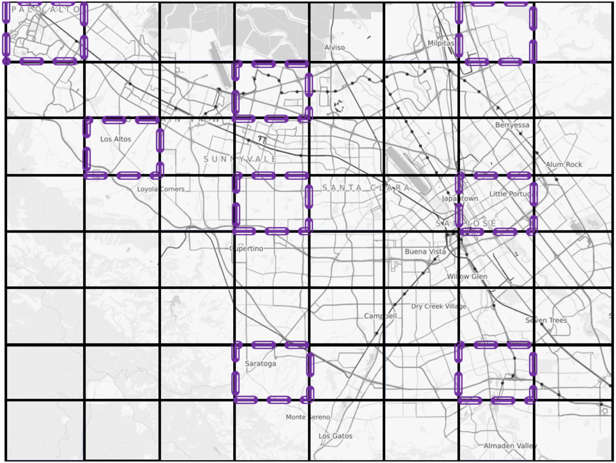

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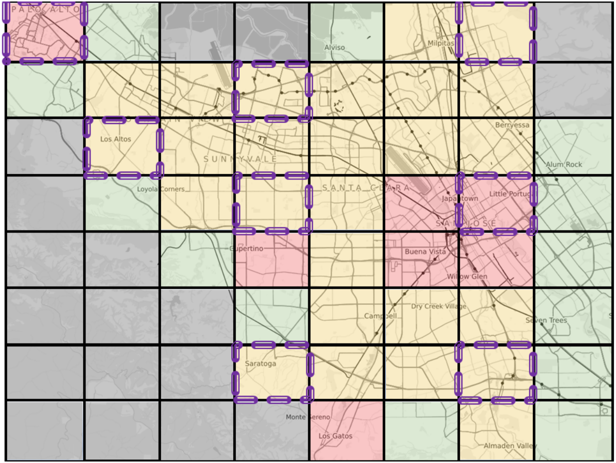

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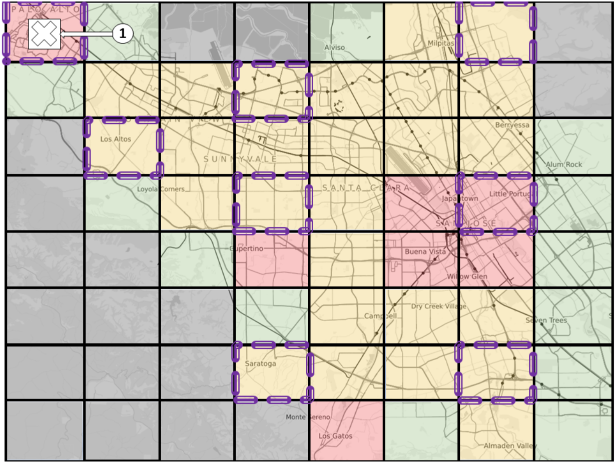

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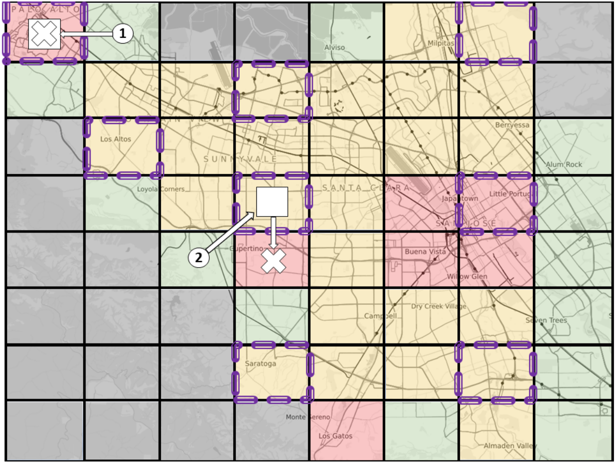

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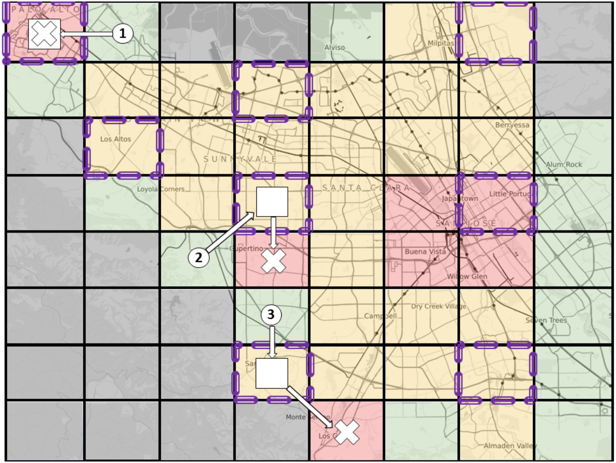

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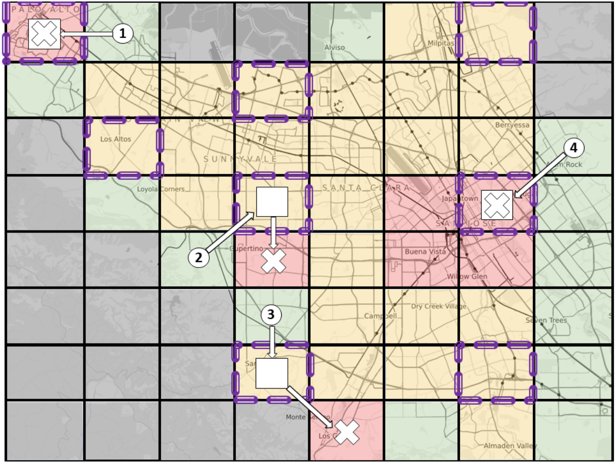

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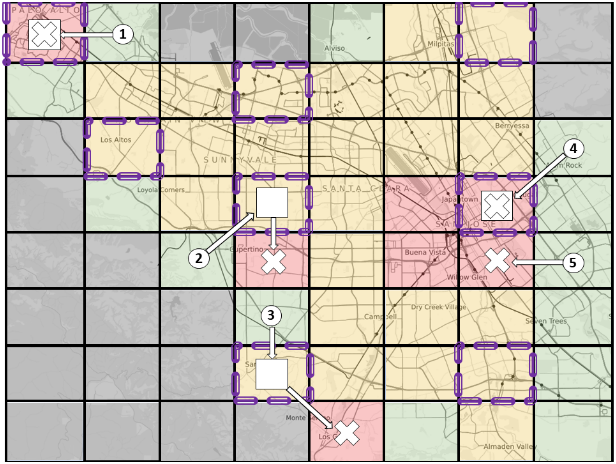
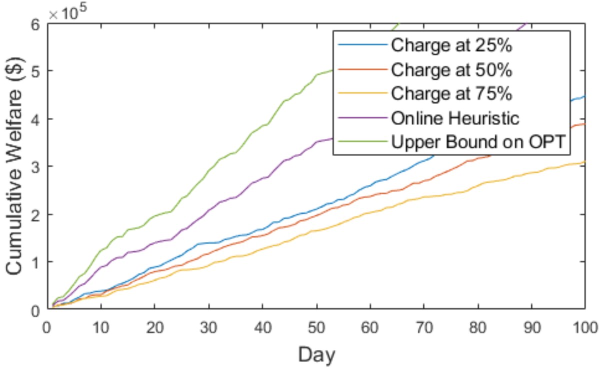


Comparison with Threshold Strategies



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Online scheduling system for fleet routing and smart charging via heuristic dual variable update functions:

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2. Shared resource manager that optimizes smart charging strategies for AMoD EVs within the charging facilities
3. Does not rely on statistics and is robust to adversarially chosen arrival sequences
4. Solution is α-competitive in welfare compared to the optimal offline solution

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Online scheduling system for fleet routing and smart charging via heuristic dual variable update functions:

1. Dispatcher for the AMoD EVs next customer pickup destination
2. Shared resource manager that optimizes smart charging strategies for AMoD EVs within the charging facilities
3. Does not rely on statistics and is robust to adversarially chosen arrival sequences
4. Solution is α-competitive in welfare compared to the optimal offline solution

Thank You!