Infrastructure Planning for Public Fast Charging Stations in a Competitive Market

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Abstract

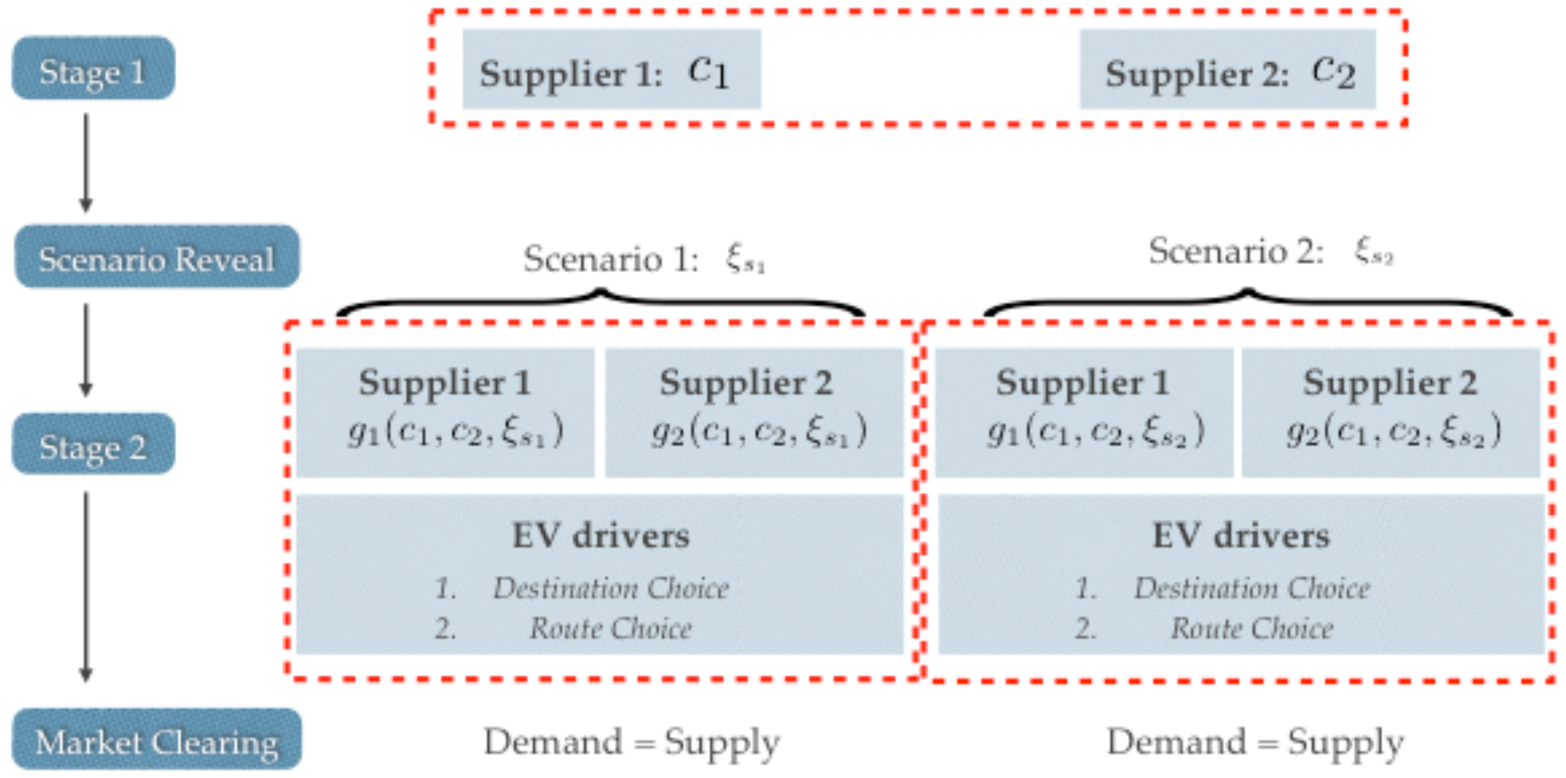
This study presents a mathematical model that supports fast charging infrastructure planning under uncertainty and competition. Uncertainty about future electric vehicles adoption rate is modeled explicitly. Based on preliminary numerical results, we find that the investment pattern could be affected by consumers' weights on charging price and charging availability: if consumers care more about charging availability, the investment may cluster to a few locations; on the contrary, the investment may diffuse through out the network.

Key Research Questions

1. Are there going to be enough public fast charging stations provided by market?
2. How is a profitable and self-sustainable fast charging network going to look like?
3. How to capture the interactions among investors, travelers, and transportation network?
4. What is the impact of uncertainty on fast charging investment?

Methodology

Two-staged Stochastic Multi-agent Optimization Problem with Equilibrium Constraints (SMOPEC)



- First stage: all the suppliers (investors) make long term (e.g. 10years) charging capacity investment decisions.
- Scenario Reveal: uncertainties reveal gradually over time. For example, electric vehicle adoption rate in the next 10 years is quite uncertain now, but may become much more certain 5 years later.
- Second stage: on one hand, based on what actually happens (how many EVs in the market) and how much capacities they built in first stage, each investors then decides the short term production decisions; on the other hand, the consumers making their destination and route choice, which determines the charging demand at each location.
- Market clearing: decide locational charging prices which make supplies equal to demand at all the locations

Key assumptions:

1. Perfect competition among investors
2. Travel destination choice depends on charging service (price and availability)
3. Only consider EV drivers

Formulations - Investors

$\forall i \in I$ — Profits from Charging Services; Profits from Traffic Flow; Capital Cost

$$\underset{c_i^s, g_i^s(\boldsymbol{\xi})}{\text{maximize}} \quad \mathrm{E}_{\boldsymbol{\xi}} \left\{ \boxed{\sum_{s \in S_i} [\rho^s(\boldsymbol{\xi}) g_i^s(\boldsymbol{\xi}) - \phi_g(g_i^s(\boldsymbol{\xi}), \boldsymbol{\xi})]} + \boxed{\sum_{s \in S_i} \sum_{r \in R} \alpha_i q^{rs}(\boldsymbol{\xi}) \frac{g_i^s(\boldsymbol{\xi})}{\sum_{i' \in I} g_{i'}^s(\boldsymbol{\xi})}} \right\} - \boxed{\sum_{s \in S_i} \phi_c(c_i^s)} \quad (1a)$$

$$\text{subject to} \quad (\gamma_i^s) \quad g_i^s(\boldsymbol{\xi}) - c_i^s \le 0, \ \forall s \in S_i, \boldsymbol{\xi} \in \Xi; \quad (1b)$$

$$g_i^s(\boldsymbol{\xi}) \ge 0, \ \forall s \in S_i, \boldsymbol{\xi} \in \Xi; \quad (1c)$$

$$c_i^s \ge 0, \ \forall s \in S_i. \quad (1d)$$

- c_i^s : charging capacity allocated at location s by firm i;
- g_i^s : total charging supply at location s by firm i;
- q^{rs} : traffic flow from r to s;
- ρ_i^s : unit charging price set by firm i at location s;
- α_i : value of traffic flow for firm i^1;
- $\phi_c(\cdot)$: total capital cost function with respect to charging capacity;
- $\phi_g(\cdot)$: total operational cost function with respect to supply quantity and scenario.

Formulations - Travelers

- Distribution (Destination Choice, Multinomial Logit Model)

Location Attractiveness; Travel Time; Charging Availability; Charging Price

$$U^{rs} = \boxed{\beta_0^s} - \boxed{\beta_1 t^{rs}} + \boxed{\beta_2 \sum_{i \in I_s} c_i^s} - \boxed{\beta_3 \frac{\rho^s e^{rs}}{inc^r}}$$

- U^{rs} : deterministic component of destination s from r;
- β : utility function parameter;
- t^{rs} : equilibrium travel time from r to s;
- e^{rs} : average charging demand from r to s.

- Traffic Assignment (Wardrop User Equilibrium)
- Combined Distribution and Assignment

User Equilibrium; Destination Choice

$$\underset{\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{q}}{\text{minimize}} \quad \boxed{\sum_{a \in \mathcal{A}} \int_0^{v_a} t_a(u) \mathrm{d}u} + \boxed{\frac{1}{\beta_1} \sum_{r \in R} \sum_{s \in S} q^{rs} \left(\ln q^{rs} - 1 + \beta_3 \frac{\rho^s e^{rs}}{inc^r} - \beta_2 \sum_{i \in I_s} c_i^s - \beta_0^s \right)} \quad (1a)$$

$$\text{subject to} \quad v_a = \sum_{r \in R} \sum_{s \in S} x_a^{rs}, \forall a \in \mathcal{A} \quad (1b)$$

$$(\zeta^{rs}) \quad A\boldsymbol{x}^{rs} = q^{rs} E^{rs}, \ \forall r \in R, s \in S, \quad (1c)$$

$$(\eta^r) \quad \sum_{s \in S} q^{rs} = d^r(\boldsymbol{\xi}), \forall r \in R \quad (1d)$$

$$x_a^{rs} \ge 0, \ \forall a \in \mathcal{A}, r \in R, s \in S \quad (1e)$$

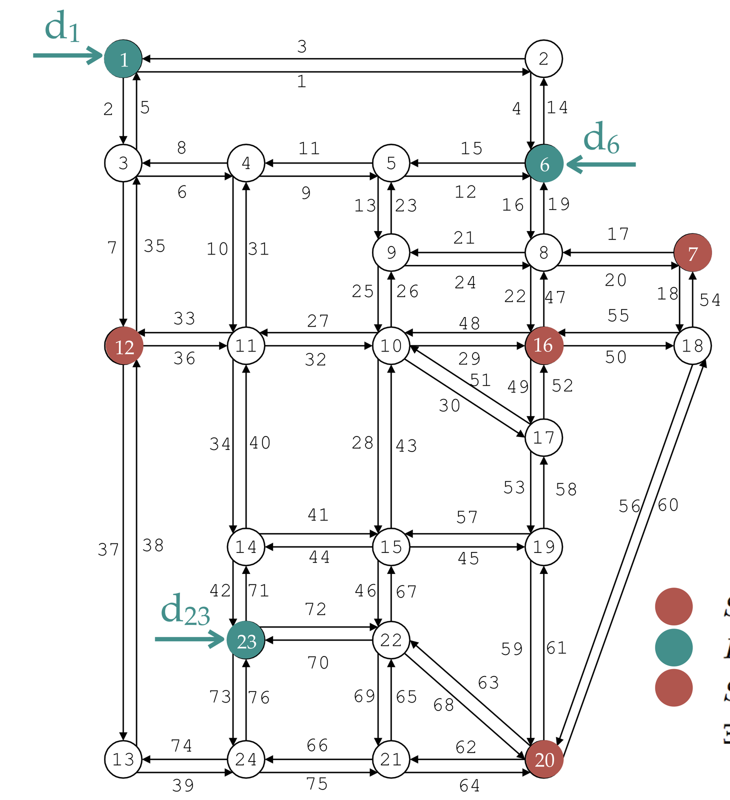
$$q^{rs} \ge 0, \ \forall r \in R, s \in S. \quad (1f)$$

Formulations – Market Clearing

Charging Supply; Charging Demand

$$(\rho_s) \quad \boxed{\sum_{i \in I_s} g_i^s(\boldsymbol{\xi})} - \boxed{\sum_{r \in R} e^{rs}(\boldsymbol{\xi}) q^{rs}(\boldsymbol{\xi})} = 0, \ \forall s \in S_i, \boldsymbol{\xi} \in \Xi;$$

A Transportation Network for Illustration Purpose



What are the decisions for each agents?

Investors:

1. Decide which candidate locations (red locations) to invest?
2. Decide how to operate these charging stations given actual EV penetration rate?

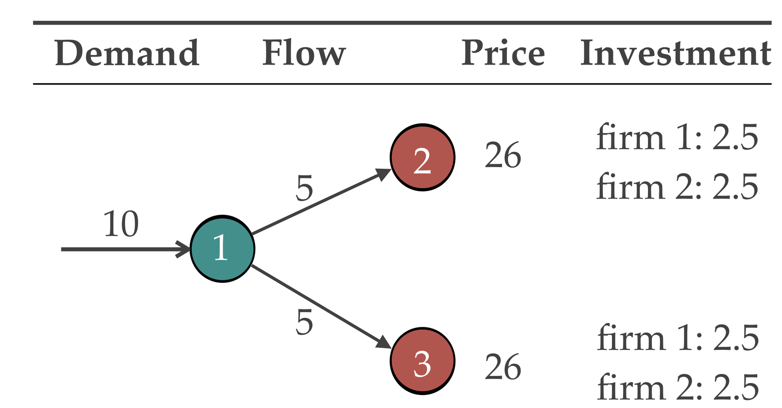
EV Drivers:

1. Decide which destination (red location) to go from their origins (green locations).
2. Decide which route they are going to take.

Preliminary Results

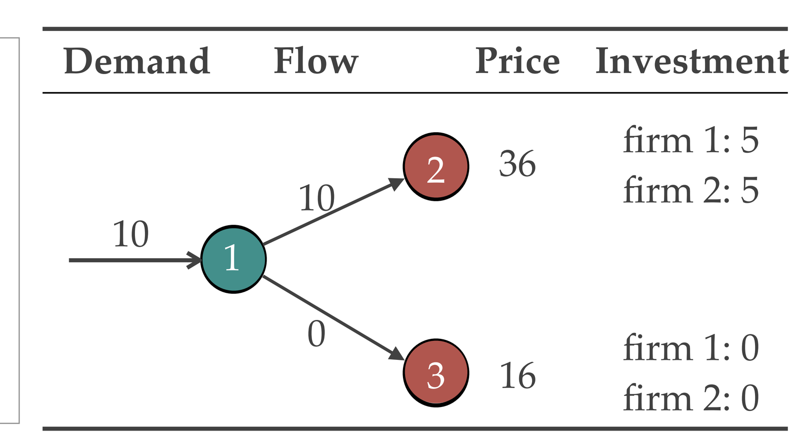
If EV drivers care more about charging price, e.g. $\beta_2 = 0, \beta_3 = 100$

Diffused investment:
Both firms invest the same amount in both locations and all the travelers favor both locations equality in equilibrium.



If EV drivers care more about charging availability, e.g.

Clustered investment:
Both firms concentrate their investment at the same location and all the travelers go to that locations in equilibrium.



Discussion

Observations:
Through preliminary results, we observe that the weights EV drivers put on charging price and charging availability may affect the equilibrium investment pattern:

- Cluster Investment: when EV drivers care more about the charging price
- Diffuse Investment: when EV drivers care more about the charging availability

Future Research:

- Generalized: does this investment pattern can be seen in more realistic network?
- Extensions: if so, how can the decision maker setting up incentives for the investor to guide the competition towards more efficient direction, e.g. charging facilities cover more area.

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