A Price Determination for Balancing the Charging Demand of Electric Vehicle

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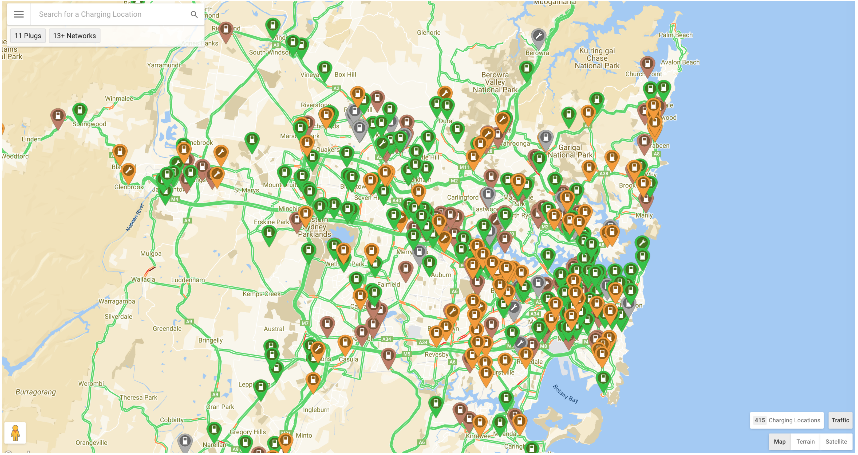
Motivation



Map of charging stations in Sydney

Motivation

Assume each EV chooses charging stations to charge based on:
* Travel cost
* Charging cost
* Waiting time (cost)

If we let each EV made decision, we would have long queues at some charging stations as you will see in our simulation.

Our research is to find how to balance charging queues by varying charging price at different charging stations.

The Model

Stackelberg Game - multi leaders & multi followers

Consider the finite strategic form game

$$\Gamma = \{\boldsymbol{N}, \{\boldsymbol{S_p}\}_{p\in\boldsymbol{N}}, \{u_p(\boldsymbol{s})\}_{p\in\boldsymbol{N}}\}, \tag{1}$$

where

- $\boldsymbol{N} = \{1, 2, ..., n\}$ is a set of players. n is the number of players;
- $\boldsymbol{S_p} = \{1, 2, ..., m_p\}$ is a set of strategies of the player $p \in \boldsymbol{N}$; m_p is a number of strategies of the player p, where $m_p < +\infty, p \in \boldsymbol{N}$; Let $\boldsymbol{S} = \times_{p\in\boldsymbol{N}}\boldsymbol{S_p}$ which is called a profile set;
- For each $\boldsymbol{s} = (s_1, s_2, ..., s_n) \in \boldsymbol{S}$, $u_p(\boldsymbol{s})$ is a utility (payoff, cost) function of the player $p \in \boldsymbol{N}$.
- When the player $p \in N$ moves, the players $1, 2, ..., p-1$ are leaders of the player p and the players $p+1, ..., n$ are followers of the player p.

The Model

Stackelberg Game - multi leaders & multi followers

The correspondent mixed-strategy game of Γ is

$$\hat{\Gamma} = \{\boldsymbol{N}, \{\boldsymbol{X_p}\}_{p\in\boldsymbol{N}}, \{f_p(\boldsymbol{x})\}_{p\in\boldsymbol{N}}\}, \quad (2)$$

where

- $\boldsymbol{X}_p = \{x^p \in \mathbb{R}^{m_p}_{\geq} : x^p_1 + x^p_2 + \cdots + x^p_{m_p} = 1\}$ is a set of mixed strategies of the player $p \in \boldsymbol{N}$. Let $X = \times_{p\in N}\boldsymbol{X}_p$;
- $f_p(\boldsymbol{x}) = \sum_{s_1=1}^{m_1}\sum_{s_2=1}^{m_2}\cdots\sum_{s_n=1}^{m_n} u_p(s_1, s_2, \cdots, s_n)\prod_{p=1}^{n} x^p_{s_p}$

The utility function $f_p(\boldsymbol{x})$ for player p in a mixed strategy game.

The Model

Stackelberg Game - multi leaders & multi followers

In a hierarchical Stackelberg game it is supposed the players make their moves sequentially:

- **Step 1** the first player chooses his strategy $\boldsymbol{x}^1 \in X_1$ and informs the second player about his choice;
- **Step 2** the second player chooses his strategy $\boldsymbol{x}^2 \in X_2$ and informs the third player about the choices $\boldsymbol{x}^1, \boldsymbol{x}^2$, and so on;

  ...
- **Step n** at last, the nth player selects his strategy $\boldsymbol{x}^n \in X_n$ after knowing the choices $\boldsymbol{x}^1, \cdots, \boldsymbol{x}^{n-1}$, of the preceding players.

On the resulting profile $\boldsymbol{x} = (\boldsymbol{x}^1, \cdots, \boldsymbol{x}^n) \in X$, every player computes his payoff as the value of his utility function $f_p(\boldsymbol{x}), p = 1, \cdots, n$.

The Model
Stackelberg Game

At Step n, the best response of player n is:

$$Br_n(\boldsymbol{x}^1, \cdots, \boldsymbol{x}^{n-1}) = \underset{\boldsymbol{y}^n \in \boldsymbol{X}_n}{\arg\max}\, f_n(\boldsymbol{x}^1, \cdots, \boldsymbol{x}^{n-1}, \boldsymbol{y}^n) \tag{3}$$

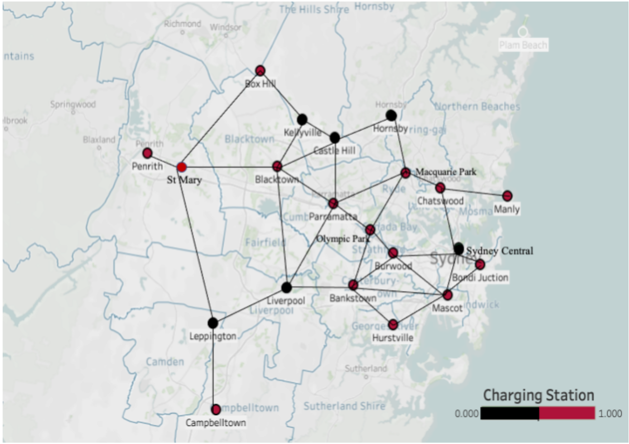
By backward induction, the best response of player p ($p = n-1, n-2, \cdots, 2$) is:

$$Br_p(\boldsymbol{x}^1, \cdots, \boldsymbol{x}^{p-1}) = \underset{\substack{\boldsymbol{y}^p, \cdots, \boldsymbol{y}^n \\ (\boldsymbol{x}^1, \cdots, \boldsymbol{x}^{p-1}, \boldsymbol{y}^p, \cdots, \boldsymbol{y}^n) \in Gr_{p+1}}}{\arg\max} f_p(\boldsymbol{x}^1, \cdots, \boldsymbol{x}^{p-1}, \boldsymbol{y}^p, \cdots, \boldsymbol{y}^n) \tag{4}$$

Finally, we can get the best strategies of the first player are:

$$\hat{\boldsymbol{S}} = \underset{(\boldsymbol{y}^1, \cdots, \boldsymbol{y}^n) \in Gr_2}{\arg\max} f_1(\boldsymbol{y}^1, \cdots, \boldsymbol{y}^n), \tag{5}$$

Numerical Experiments



Road network of Sydney metropolita

Numerical Experiments

Data Setting

- EVs: (Capacity Range: 150-300km; Remaining Range: 10-30km)

Vehicle Id	Origin	Destination	Capacity Range(km)	Remaining Range(km)
0	Liverpool	Manly	275	11
1	Burwood	Bondi Juction	285	29
2	Castle Hill	Mascot	233	26
⋮	⋮	⋮	⋮	
498	Kellyville	Central	187	28
499	Parramatta	St Marys	207	19

EVs specifications

Numerical Experiments

Data Setting

- Locations:

Location Index	Location name	Chargers	Charging price
0	Penrith	3	$0.1/kWh
1	St Marys	0	N/A
2	Box Hill	5	free of charge
⋮	⋮	⋮	
19	Leppington	0	N/A
20	Campbelltown	7	$0.55/kWh

Locations specifications

Numerical Experiments

Results for EVs

Vehicle Id	Origin	Destination	Charging station
0	Liverpool	Manly	Liverpool
1	Burwood	Bondi Juction	———
2	Castle Hill	Mascot	Box Hill (Blacktown)
⋮	⋮	⋮	⋮
498	Kellyville	Central	Box Hill (Olympic Park)
499	Parramatta	St Marys	Blacktown

Numerical Experiments

Results for Locations

The overall average waiting time:
Before balancing is 4 hours VS after balancing is 2.1 hours.

Index	Location name	Charging station	Charging price	Waiting Time	Queuing Length
0	Penrith	3	$0.1/kWh	3.2	19
1	St Marys	0	N/A	0	0
2	Box Hill	5	free of charge	7.5	75
3	Kellyville	0	N/A	0	0
4	Castle Hill	0	N/A	0	0
5	Blacktown	7	$0.25/kWh	1.8	25
6	Parramatta	11	$0.25/kWh	3	67
7	Olympic Park	3	$0.4/kWh	1.2	7
8	Burwood	2	$0.46/kWh	1.2	5
9	Mascot	9	$0.45/kWh	1.1	20
10	Bondi Juction	13	$0.75/kWh	0.23	6
11	Manly	12	free of charge	1.3	31
12	Chatswood	2	$0.55/kWh	0	0
13	Macquarie Pk	2	$0.33/kWh	7.8	31
14	Hornsby	0	N/A	0	0
15	Central	0	N/A	0	0
16	Hurstville	3	$0.3/kWh	7.3	44
17	Bankstown	10	$0.55/kWh	0.05	1
18	Liverpool	10	$0.3/kWh	1.4	27
19	Leppington	0	N/A	0	0
20	Campbelltown	7	$0.55/kWh	1.8	25

Before balancing

2.4Waiting Time

Index	Location name	Charging station	Charging price	Waiting Time	Queuing Length
0	Penrith	3	$0.22/kWh	3.2	19
1	St Marys	0	N/A	0	0
2	Box Hill	5	$0.12/kWh	4.2	42
3	Kellyville	0	N/A	0	0
4	Castle Hill	0	N/A	0	0
5	Blacktown	7	$0.29/kWh	2.4	34
6	Parramatta	11	$0.31/kWh	2.4	52
7	Olympic Park	3	$0.3/kWh	2.7	16
8	Burwood	2	$0.34/kWh	2.2	9
9	Mascot	9	$0.33/kWh	2.1	38
10	Bondi Juction	13	$0.63/kWh	0.23	6
11	Manly	12	free of charge	1.3	31
12	Chatswood	2	$0.51/kWh	2.5	10
13	Macquarie Pk	2	$0.45/kWh	4	16
14	Hornsby	0	N/A	0	0
15	Central	0	N/A	0	0
16	Hurstville	3	$0.32/kWh	2.3	14
17	Bankstown	10	$0.43/kWh	1.2	24
18	Liverpool	10	$0.28/kWh	2.4	47
19	Leppington	0	N/A	0	0
20	Campbelltown	7	$0.44/kWh	1.8	25

After balancing

Conclusion and Future Work

- A dynamic pricing strategy based on Stackelberg game for EV charging station is proposed.
- A number of real-life factors are considered, such as the remaining power of the electric vehicle, battery capacity, etc.
- Further improvement in the algorithm and the model

Thanks