Deployment of Stationary and Dynamic Charging Infrastructure for Electric Vehicles along Traffic Corridors (17-01057)

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1. INTRODUCTION

It is well recognized that the deployment of public charging infrastructure plays a critical role in nurturing the electric vehicle (EV) market and promoting the adoption of EVs. Among various types of charging technologies, charging-while-driving (CWD) holds great promise. CWD can electrify roads to be a charging infrastructure via either conductive or inductive charging technology. With charging lanes deployed, EV drivers may not fear any more running out of battery en route. Such a pervasive wireless charging platform can mitigate or even eliminate the "range anxiety" of EV drivers and further boost the adoption of EVs.

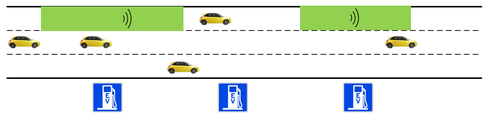
Anticipating that charging lanes can be technically ready for deployment in the foreseeable future, this paper investigates the deployment of two types of charging facilities, namely charging lanes and charging stations, along a long traffic corridor to explore the competitiveness of charging lanes.

2. BASIC CONSIDERATIONS

We adopt a highly simplified setting, where there lies a traffic corridor and fully-charged EVs with identical battery size travel from one end to the other, and the corridor is sufficiently long so that no EV can finish the trip without recharging.

Basic Assumptions

i. Both charging stations and charging lanes are deployed along the corridor;
ii. The number of charging stations is sufficient to support a trip;
iii. Similarly, charging lanes are sufficiently long to support a trip;
iv. Charging stations are uniformly deployed along the corridor;
v. Charging lanes can be intermittent, and the length of each segment may be different;
vi. Travel speed of EVs across the corridor is constant;
vii. EVs do not need to slow down to recharge on charging lanes;
viii. There is no delay for accessing or egressing a charging station nor waiting for a charger at the station;
ix. While preventing their vehicles from running out of energy, drivers of EVs minimize their travel costs, which consist of driving time, a charging fee and the charging time at charging stations or the equipment cost for enabling CWD.



3. CHARGING-FACILITY-CHOICE MODEL

For those using charging stations:

- They have to stop at the stations and thus encounter charging delay.

For those using charging lanes:

- They do not need to stop for charging on the charging lanes, thereby saving their total journey time.
- But, they will have to equip their vehicles with additional devices to enable CWD and pay a potentially higher charging price.

Cost for Using Charging Station

$$\underbrace{\gamma\cdot\frac{\frac{l}{\beta}-\theta E}{\alpha P_s}}_{\text{charging time (in monetary unit)}}+\underbrace{q_s\left(\frac{l}{\beta}-\theta E\right)}_{\text{charging fee at stations}}+\underbrace{\gamma\cdot\frac{l}{v}}_{\text{driving time (in monetary unit)}}$$

Cost for Using Charging Lane

$$\underbrace{q_l\left(\frac{l}{\beta}-\theta E\right)}_{\text{charging fee at charging lanes}}+\underbrace{c_e\left(\frac{l}{\beta}-\theta E\right)}_{\text{equipment cost for enabling CWD}}+\underbrace{\gamma\cdot\frac{l}{v}}_{\text{driving time (in monetary unit)}}$$

Parameter		Value
l	length of the corridor	300 mi
f	EV demand	300 veh/h
β	the distance an EV can run on each unit of battery energy consumed	2.5 mi/kWh
E	battery size	24 kWh
θ	range anxiety factor	0.8
v	travel speed along the corridor	65 mph
ω	converting factor (converting the total cost into hourly cost)	1.19×10^{-5}
α	recharging efficiency of charging stations	0.77
ξ	recharging efficiency of charging lanes	0.67
P_s	electric power of charging stations	100 kW
P_l	electric power of charging lanes	100 kW
q_0	cost to produce and transmit one unit of electricity	\$0.08/kWh
A_s	construction cost for building one charging station	\$208,000
B_s^0	construction cost for installing one charger	\$31,200
B_s^1	installation cost per unit charging power	\$500/kW
A_l	construction cost to convert one mile of regular lane to charging lane	\$800,000/mi
B_l	construction and operation cost per unit charging power	\$550/kW
Variable		
q_s	charging price at charging stations	
q_l	charging price at charging lanes	
f_s	EV demand of using charging stations	
f_l	EV demand of using charging lanes	
c_e	unit equipment cost	
m	total number of charging stations	
n_c	number of chargers at each charging station	
d	total length of charging lanes	

Interior Equilibrium State

Suppose charging stations and charging lanes are both utilized, then for the indifferent driver with VOT γ^*, we have:

$$\gamma^*\cdot\frac{\frac{l}{\beta}-\theta E}{\alpha P_s}+q_s\left(\frac{l}{\beta}-\theta E\right)+\gamma^*\cdot\frac{l}{v}=q_l\left(\frac{l}{\beta}-\theta E\right)+c_e\left(\frac{l}{\beta}-\theta E\right)+\gamma^*\cdot\frac{l}{v}$$

It follows:

$$\gamma^*=(q_l+c_e-q_s)\cdot\alpha P_s \qquad (1)$$

Demand Split

Suppose the VOTs of EV drivers follow a density function $h(\gamma)$, where $\gamma\in[\underline{\gamma},\overline{\gamma}]$, it follows that the demands of EVs using charging stations and charging lanes are:

$$f_s=f\cdot\int_{\underline{\gamma}}^{\gamma^*}h(x)dx \qquad (2)$$

$$f_l=f\cdot\int_{\gamma^*}^{\overline{\gamma}}h(x)dx \qquad (3)$$

4. DEPLOYMENT MODEL

Basic Consideration for Deployment

$$m\ge\frac{l}{\beta\theta E}-1 \qquad (4)$$

$$n_c\ge\frac{\left(\frac{l}{\beta}-\theta E\right)f_s}{m\alpha P_s} \qquad (5)$$

$$d\ge\left(\frac{l}{\beta}-\theta E\right)\cdot\frac{v}{\xi P_l} \qquad (6)$$

$$d\le l \qquad (7)$$

Cost function of one charging stations with n_c chargers:

$$C_s(n_c)=A_s+B_s^0n_c+B_s^1P_sn_c \qquad (8)$$

Cost function of one-mile charging lane used by f_l EVs:

$$C_l(f_l)=A_l+B_lP_l\cdot\frac{f_l}{v} \qquad (9)$$

Public Provision

The government acts as a system planner, aiming to minimize the social cost (SCM):

$$\min Z(f_s,f_l,\gamma^*,m,n_c,d)=\omega m\cdot C_s(n_c)+\omega d\cdot C_l(f_l)+\frac{\frac{l}{\beta}-\theta E}{\alpha P_s}\cdot f\cdot\int_{\underline{\gamma}}^{\gamma^*}xh(x)dx$$
$$+\frac{\frac{l}{\beta}-\theta E}{\alpha}\cdot q_0f_s+\frac{\frac{l}{\beta}-\theta E}{\xi}\cdot q_0f_l+c_e\left(\frac{l}{\beta}-\theta E\right)\cdot f_l+\frac{l}{v}\cdot f\cdot\int_{\underline{\gamma}}^{\overline{\gamma}}xh(x)dx$$

s.t. (2)-(7)

It yields:

$$\gamma^*=\omega\left(\frac{\alpha B_lP_s}{\xi}-B_s^0-B_s^1P_s\right)+\left(\frac{q_0}{\xi}+c_e-\frac{q_0}{\alpha}\right)\cdot\alpha P_s$$

Considering equality (1), the optimal charging fees should satisfy the following condition:

$$q_l^*-q_s^*=\frac{\omega B_l}{\xi}+\frac{q_0}{\xi}-\frac{\omega}{\alpha}\cdot\left(\frac{B_s^0}{P_s}+B_s^1\right)-\frac{q_0}{\alpha}$$

Revenue-neutral charging prices:

$$\begin{cases}q_l^*=\frac{\omega}{f}\cdot\left(\frac{A_s}{\theta E}+\frac{vA_l}{\xi P_l}\right)+\frac{\omega B_l}{\xi}+\frac{q_0}{\xi}\\ q_s^*=\frac{\omega}{f}\cdot\left(\frac{A_s}{\theta E}+\frac{vA_l}{\xi P_l}\right)+\frac{\omega B_s^0}{\alpha P_s}+\frac{\omega B_s^1}{\alpha}+\frac{q_0}{\alpha}\end{cases}$$

Private Provision

There are two private operators each specialized in providing either charging lanes or charging stations, and they compete with each other to maximize their own profits.

- Charging-station operator:

$$\max Z_s(q_s,m,n_c,f_s,f_l,\gamma^*)=q_sf_s\left(\frac{l}{\beta}-\theta E\right)-q_0f_s\cdot\frac{\frac{l}{\beta}-\theta E}{\alpha}-\omega m\cdot C_s(n_c)$$

s.t. (1)-(5)

- Charging-lane operator:

$$\max Z_l(q_l,d,f_s,f_l,\gamma^*)=q_lf_l\left(\frac{l}{\beta}-\theta E\right)-q_0f_l\cdot\frac{\frac{l}{\beta}-\theta E}{\xi}-\omega d\cdot C_l(f_l)$$

s.t. (1)-(3), (6), and (7)

Suppose $\gamma\sim U\left(\underline{\gamma},\overline{\gamma}\right)$, i.e., $h(x)=\frac{1}{\overline{\gamma}-\underline{\gamma}}$,

$$\gamma^*=\frac{1}{3}\left(\left(\frac{q_0}{\xi}+c_e-\frac{q_0}{\alpha}\right)\alpha P_s+\omega\left(\frac{\alpha B_lP_s}{\xi}-B_s^0-B_s^1P_s\right)+\overline{\gamma}+\underline{\gamma}\right)$$

$$q_s^*=\frac{1}{3}\left(\frac{2q_0}{\alpha}+\frac{q_0}{\xi}+c_e+\frac{\omega}{\alpha}\cdot\left(\frac{\alpha B_l}{\xi}+\frac{2B_s^0}{P_s}+2B_s^1\right)+\frac{\overline{\gamma}-2\underline{\gamma}}{\alpha P_s}\right)$$

$$q_l^*=\frac{1}{3}\left(\frac{2q_0}{\xi}+\frac{q_0}{\alpha}-c_e+\frac{\omega}{\alpha}\cdot\left(\frac{2\alpha B_l}{\xi}+\frac{B_s^0}{P_s}+B_s^1\right)+\frac{2\overline{\gamma}-\underline{\gamma}}{\alpha P_s}\right)$$

$$Z_s^*=\left(\frac{l}{\beta}-\theta E\right)\cdot\left[\frac{f\alpha P_s}{9\left(\overline{\gamma}-\underline{\gamma}\right)}\cdot\left(\frac{q_0}{\xi}+c_e-\frac{q_0}{\alpha}+\frac{\omega}{\alpha}\cdot\left(\frac{\alpha B_l}{\xi}-\frac{B_s^0}{P_s}-B_s^1\right)+\frac{\overline{\gamma}-2\underline{\gamma}}{\alpha P_s}\right)^2-\frac{\omega A_s}{\theta E}\right]$$

$$Z_l^*=\left(\frac{l}{\beta}-\theta E\right)\cdot\left[\frac{f\alpha P_s}{9\left(\overline{\gamma}-\underline{\gamma}\right)}\cdot\left(\frac{q_0}{\alpha}-\frac{q_0}{\xi}-c_e+\frac{\omega}{\alpha}\cdot\left(\frac{B_s^0}{P_s}+B_s^1-\frac{\alpha B_l}{\xi}\right)+\frac{2\overline{\gamma}-\underline{\gamma}}{\alpha P_s}\right)^2-\frac{\omega vA_l}{\xi P_l}\right]$$

5. EMPIRICAL ANALYSIS

Public Provision

- Indifferent VOT: $\gamma^*=\$33.37/h$
- Revenue-neutral prices: $q_s^*=\$0.148/\text{kWh}, q_l^*=\$0.161/\text{kWh}$

TABLE 1 VOT distribution of passenger cars on Interstate 95 express corridor

VOT (\$/h)	PDF (%)	CDF (%)
2-7	2.7	2.7
7-12	6.7	9.4
12-16	5.3	14.7
16-20	12.0	26.7
20-25	2.7	29.4
25-30	16.0	45.4
30-35	13.3	58.7
35-40	16.0	74.7
40-45	4.0	78.7
45-60	18.7	97.4

49.8% of EV drivers will use charging lanes

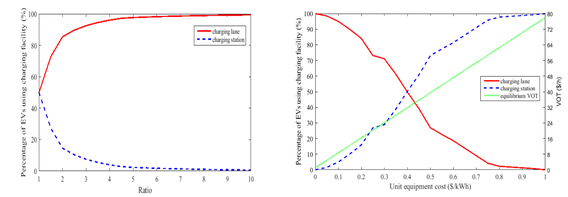


FIGURE 1 Sensitivity of VOT distribution and c_e

Private Provision

- $\gamma\sim U(10,70)$
- Indifferent VOT: $\gamma^*=\$37.26/h$
- Revenue-neutral prices: $q_s^*=\$0.471/\text{kWh}, q_l^*=\$0.555/\text{kWh}$
- Profits: $Z_s^*=\$4{,}857, Z_l^*=\$6{,}083$

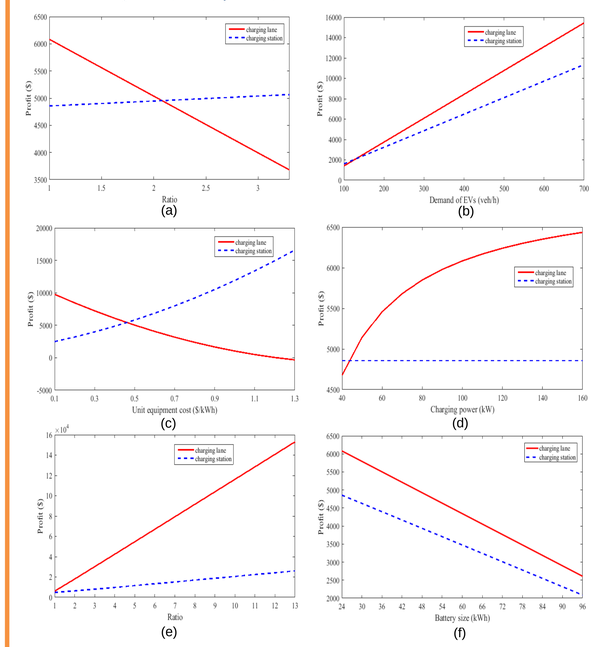


FIGURE 2 Sensitivity of (a) A_l and B_l; (b) f; (c) c_e; (d) P_l; (e) VOT distribution; and (f) E

6. FINDING

- The charging lanes are competitive as compared with charging stations for attracting drivers.
- In the private provision scenario, operating charging lanes is more profitable than operating charging stations.
- The Nash equilibrium charging prices in the private provision scenario is much higher than the revenue-neutral charging prices in the public provision scenario.