Deployment of Stationary and Dynamic Charging Infrastructure for Electric Vehicles along Traffic Corridors

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Abstract

As charging-while-driving (CWD) technology advances, charging lanes can be deployed in the near future to charge electric vehicles (EVs) while in motion. Since charging lanes will be costly to deploy, 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. Given the charging infrastructure supply, i.e., the number of charging stations, the number of chargers installed at each station, the length of charging lanes, and the charging prices at charging stations and lanes, we analyze the charging-facility-choice equilibrium of EVs. We then discuss the optimal deployment of charging infrastructure considering either the public or private provision. In the former, a government agency builds and operates both charging lanes and stations to minimize social cost, while in the latter, charging lanes and stations are assumed to be built and operated by two competing private companies to maximize their own profits. Numerical experiments based on currently available empirical data suggest that charging lanes are competitive in both cases for attracting drivers and generating revenue.

Keywords: electric vehicle, charging lane, charging station, deployment plan, choice equilibrium

1. Introduction

The market size of electric vehicles (EVs) has grown steadily in recent years due to the rapid development of battery technology, concern over climate change, and the growing deployment of public charging infrastructure (e.g., Statista, 2016 a, b). Generally, charging infrastructure can be classified into two types: stationary and dynamic. The former, i.e., charging stations and battery swapping stations, have been deployed in many places, where vehicles need to stop for services. The latter, i.e., charging lanes that can charge vehicles while they are in motion, is an emerging application of charging-while-driving (CWD) technology being developed and tested around the world. Charging lanes function by either conductive or inductive charging. The former charges EVs via lines overhead or metal bars in the pavement, while the latter transmits electric power via inductive coupling, magnetic resonance coupling or microwaves (Vilathgamuwa and Sampath, 2015). Recent conductive charging experiments include Scania's field test at a 2-kilometre Siemens eHighway in Gross Dolln, Germany (Herron, 2014; Scania Newsroom, 2014) and the construction of a 400-meter track by Volvo near Gothenburg, Sweden (Schiller, 2013). On the other hand, a 15-mile inductive charging lane has been constructed in Gumi, South Korea to serve a dozen buses (Bansal, 2015). Other companies and universities, such as Qualcomm and Utah State University, are also testing their own CWD technology.

Anticipating that charging lanes can be technically ready for deployment in the foreseeable future, this paper investigates the deployment of charging stations and lanes along a long traffic corridor, in which charging infrastructure is more critical for EVs to finish their trips than in dense residential areas (Nie and Ghamami, 2013). We are particularly interested in determining how charging lanes compare with charging stations. To do so, we model EV drivers' choice of charging facility and then optimize a deployment plan of charging stations and lanes along the corridor to serve the charging need of EVs. The deployment plan specifies the number of charging stations, the number of chargers installed at each station, the length of charging lanes, and charging prices at charging stations and lanes. Based on the deployment plan, we explore the competitiveness of charging lanes for attracting drivers and generating revenue.

We consider two scenarios of charging infrastructure provision: a government agency builds and operates both types of charging facilities or private companies are franchised to do so. For the former, the government agency is considered to minimize the social cost (we refer to this situation as the "public provision"). For the latter, different operators may compete with each other to maximize their own profits (we refer to this as the "private provision"). For simplicity, it is assumed in this paper that there are two private operators each specialized in providing either charging lanes or charging stations. Based on both the public and private provision scenarios, we investigate the optimal deployment of the charging infrastructure and examine the competitiveness of charging lanes.

In contrast to a large body of literature on charging station deployment (see, e.g., He et al., 2013, 2015, 2016; Ghamami et al., 2016, for recent reviews), there are a limited number of studies on the deployment of charging lanes. Riemann et al. (2015) formulated a flow-capturing model to optimize the location plan of charging lanes, and a linearized approach is proposed to solve the model. Fuller (2016) proposed an optimization approach to minimize the total capital cost of deploying charging lanes on the California freeway network. Chen et al. (2016) developed a novel user equilibrium model to describe EV drivers' travel and charging choices when charging lanes are deployed. Further, an optimal deployment of charging lanes is obtained by solving a mathematical program with complementarity constraints. In a series of efforts, Jang and his colleagues optimized the locations of charging lanes and the battery size to minimize the total social cost for an electrified bus line (e.g., Jang et al., 2015, 2016a,b; Jeong et al., 2015; Ko and Jang, 2013; Ko et al., 2015). In particular, Jang et al. (2016a) qualitatively compared stationary, quasi-dynamic, and dynamic wireless charging and suggested that dynamic wireless charging may not be as competitive as the other two due to the high infrastructure cost.

This study contributes to the literature by offering, to our best knowledge, the first study that investigates the deployment of different types of charging infrastructure while taking into account drivers' choice of charging facilities; it explores the competition between charging facilities and examines the competitiveness of charging lanes in both public and private provision scenarios.

The remainder of the paper is organized as follows. In the next section, basic assumptions for the proposed models are presented. In Section 3, the charging-facility-choice equilibrium is formulated to delineate EV drivers' choice of facility for charging their vehicles. Section 4 then models the optimal deployment of charging stations and lanes under both the public and private provision, followed by a discussion and analysis of their solutions in Section 5. Section 6 provides empirical analysis to examine the competitiveness of charging lanes, and Section 7 concludes the paper.

2. Basic Considerations

Since the intent of this paper is to answer a "big picture" question regarding the competitiveness of charging lanes against charging stations, we adopt a highly simplified setting, first used by Nie and Ghamami (2013), where there lies a traffic corridor and fully-charged EVs with identical battery size travel from one end to the other; the corridor is sufficiently long so that no EV can finish the trip without recharging. We will discuss the deployment of charging stations and lanes along the corridor. The models to be developed are macroscopic, and do not attempt to optimize specific locations of charging stations and lanes. Instead, they aim to provide a mathematically tractable means to characterize the deployment and operations of charging lanes and stations. Considerations and assumptions of the modeling framework are summarized as follows:

i. Both charging stations and charging lanes are deployed along the corridor;
ii. The number of charging stations is sufficient to support a trip, i.e., an EV can finish its trip by charging only at charging stations;
iii. Similarly, charging lanes are sufficiently long to support a trip, i.e., an EV can traverse the corridor by using charging lanes only;
iv. Charging stations are uniformly deployed along the corridor (see Fig. 1);

v. Charging lanes can be intermittent, and the length of each segment may be different (see Fig. 1);
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.

We note that most of the above assumptions can be relaxed. Doing so may complicate the models, but it does not alter the major findings of this paper.

Please place Fig. 1 about here

3. Charging-Facility-Choice Model

Both charging stations and lanes are deployed so that EV drivers can choose either option to recharge their vehicles. Those who choose charging stations have to stop at the stations and thus encounter a charging delay. Those using charging lanes will have to equip their vehicles with additional devices to enable CWD and pay a potentially higher charging price. However, they will enjoy a faster travel time because they will not need to stop for charging. Consequently, drivers with a higher value of time (VOT) will likely favor charging lanes. This partly explains why charging lanes are expected to be initially deployed for commercial fleet vehicles such as buses and trucks whose VOT is much higher than those of passenger vehicles (e.g., Bansal, 2015; Herron, 2014; Scania Newsroom, 2014). The charging-facility-choice model possesses a similar structure as the two-mode or two-link tolling problem in the literature (see, e.g., Palma and Lindsey, 2000; Nie and Liu, 2010; Zhang et al., 2014), in which one mode or link costs less but takes more travel time, while the other mode or link takes less travel time but costs more.

To model charging-facility-choice behavior, let l denote the length of the traffic corridor and β denote the distance an EV can run on each unit of battery energy consumed; thus, the energy consumption for finishing the corridor is $\frac{l}{\beta}$. Let E be the battery size for EVs and θ be a given parameter ($0 \leq \theta < 1$) so that $(1-\theta)E$ represents the minimum state of charge that a driver will feel comfortable with. We thus identify θ as a range anxiety factor. The minimum charging needed in order to finish the trip is $\frac{l}{\beta} - \theta E$. As per assumption vi, let v define the travel speed along the corridor. For a charging-station user whose VOT is γ, his or her travel cost consists of charging time (in monetary units) and the charging fee at stations, as well as driving time (in monetary units) along the corridor. Mathematically, it can be written as

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

where $\alpha \in (0,1)$ represents the recharging efficiency; P_s is the electric power of charging stations; q_s is the charging price at charging stations.

Similarly, the travel cost of a charging-lane user with VOT γ consists of a charging fee for using charging lanes, equipment cost for enabling CWD, and driving time (in monetary units) along the corridor, i.e.,

$$q_l\left(\frac{l}{\beta}-\theta E\right)+c_e\left(\frac{l}{\beta}-\theta E\right)+\gamma\cdot\frac{l}{v}$$

where q_l is the charging price at charging lanes and c_e is the equipment cost for unit electricity recharged on charging lanes (for convenience, we refer to c_e as "unit equipment cost"). For example, suppose CWD equipment costs $\$20,000$ for one EV, and can be recharged for 10 years with total usage of $52,000$ kWh (i.e., $130,000$ mi for a passenger car with $\beta = 2.5\text{mi/kWh}$). According to the Office of Management and Budget (OMB), the 10-year discount rate for 2016 is 1.0% (OMB, 2016); thus, we calculate that $c_e = \$0.4/\text{kWh}$.

It should be noted that the above travel cost is irrelevant to the recharging efficiency (denoted as ξ) and charging power (denoted as P_l) of the charging lanes. Drivers using charging lanes can always recharge their vehicles while driving, so the recharging efficiency and charging power have no impact on their travel time as long as the charging lanes are long enough to support their trips.

Consider an interior equilibrium in which both charging stations and charging lanes are utilized. There exists a driver who has no preference for either charging stations or lanes. Let γ^* denote the VOT for this indifferent driver (hereinafter referred to as "indifferent VOT"). Because the cost of using each facility is the same, we have:

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

The above equality leads to:

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

It can be readily verified that travelers with $\gamma < \gamma^*$ will prefer charging stations, while those with $\gamma > \gamma^*$ will favor charging lanes. Suppose the VOTs of EV drivers follow a density function $h(\gamma)$, where $\gamma \in \left[\underline{\gamma}, \bar{\gamma}\right]$. If $\gamma^* > \bar{\gamma}$, the charging lanes will not be competitive at all, and all drivers will choose charging stations. On the other hand, if $\gamma^* < \underline{\gamma}$, all drivers will be attracted to the charging lanes. Neither situation is of interest here, and we thus consider the scenario that $\underline{\gamma} < \gamma^* < \bar{\gamma}$ in our study. It follows that the demands of EVs using charging stations and charging lanes are:

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

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

where f is the total EV demand.

Sensitivity analysis of γ^* with respect to different variables or parameters is summarized in Table 1. As we can easily see, a higher charging price at charging stations (i.e., larger q_s) will lead to a lower indifferent VOT (i.e., lower γ^*); while a higher recharging efficiency (i.e., larger α), charging power at charging stations (i.e., larger P_s), charging price at charging lanes (i.e., larger q_l), and unit equipment cost (i.e., larger c_e) all result in a higher indifferent VOT (i.e., larger γ^*).

Please place Table 1 about here

4. Deployment Model

In this section, we turn to the model development for optimizing the deployment of charging infrastructure under the two provision scenarios.

4.1 Basic consideration for deployment

Let m and n_c denote the number of charging stations and the number of chargers at each charging station. According to assumptions ii and iv, the distance between any two sequential charging stations is equal to $\frac{l}{m+1}$, and it should be within the anxiety-free range of the EV, which yields

$$\beta\theta E \geq \frac{l}{m+1}$$

It can be rewritten as:

$$m \geq \frac{l}{\beta\theta E} - 1 \tag{4}$$

As one charger can provide only αP_s energy per hour, to accommodate the flow using charging stations f_s, the minimum number of chargers at each charging station can be calculated as $\frac{\left(\frac{l}{\beta}-\theta E\right)f_s}{m\alpha P_s}$. Therefore, $n_c \geq \frac{\left(\frac{l}{\beta}-\theta E\right)f_s}{m\alpha P_s}$, which yields

$$mn_c \geq \frac{\left(\frac{l}{\beta}-\theta E\right)f_s}{\alpha P_s} \tag{5}$$

According to assumption iii, the total length of charging lanes (denoted as d) must be long enough to support EVs in completing their trips, i.e.,

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

and it cannot exceed the length of the corridor, i.e.,

$$d \leq l \tag{7}$$

To guarantee the existence of d that satisfies both (6) and (7), the parameters given in this paper will ensure $\left(\frac{l}{\beta} - \theta E\right) \cdot \frac{v}{\xi P_l} \leq l$.

The costs of constructing and operating one charging station with n_c chargers and a one mile charging lane used by f_l EVs are given as follows:

$$C_s(n_c) = A_s + B_s^0 n_c + B_s^1 P_s n_c \tag{8}$$

$$C_l(f_l) = A_l + B_l P_l \cdot \frac{f_l}{v} \tag{9}$$

where $A_s, B_s^0, B_s^1, A_l, B_l$ are all given parameters to our model. Specifically, A_s is the construction cost for building one charging station; B_s^0 is the construction cost for installing one charger; and B_s^1 is the installation cost per unit charging power (Nie and Ghamami, 2013). For charging lanes,

A_l is the construction cost to convert or upgrade one mile of regular lane to a charging lane, and B_l is the construction and operation cost per unit of charging power. Note that $\frac{f_l}{v}$ is the flow density of EVs on charging lanes, and hence $P_l \cdot \frac{f_l}{v}$ represents the total charging need on one mile of charging lane.

4.2 Public provision

In the public provision scenario, the government aims to minimize the social cost, including the construction and operation cost of charging facilities, charging time (in monetary units) at charging stations, equipment cost for using charging lanes, total cost for producing and transmitting electricity for charging facilities, and total driving time (in monetary units). As γ^* is the VOT of the indifferent user at equilibrium, the social cost minimization (SCM) problem can be formulated as follows:

SCM:

$$\min Z(f_s, f_l, \gamma^*, m, n_c, d) = \omega m \cdot C_s(n_c) + \omega d \cdot C_l(f_l) + \frac{\frac{l}{\beta}-\theta E}{\alpha P_s} \cdot f \cdot \int_{\underline{\gamma}}^{\gamma^*} xh(x)dx + \frac{\frac{l}{\beta}-\theta E}{\alpha} \cdot q_0 f_s + \frac{\frac{l}{\beta}-\theta E}{\xi} \cdot q_0 f_l + c_e\left(\frac{l}{\beta} - \theta E\right) \cdot f_l + \frac{l}{v} \cdot f \cdot \int_{\underline{\gamma}}^{\overline{\gamma}} xh(x)dx \tag{10}$$

s.t. (2)-(7)

where ω is a conversion parameter, which converts the total cost into hourly cost, and q_0 is the cost to produce and transmit one unit of electricity. Specifically, the first two terms represent the total cost to construct and operate charging stations and charging lanes, respectively; the third term specifies the charging-time cost at charging stations; the fourth and fifth terms represent the total cost to produce and transmit electricity for charging facilities to serve the charging need of EVs; the sixth term represents the total equipment cost for enabling CWD; and the last term specifies the total driving-time cost.

Proposition 1. There exists at least one optimal solution to SCM.

Proof: By substituting (8) into the objective function and defining $N = mn_c$, SCM can be rewritten as

$$\min Z(f_s, f_l, \gamma^*, m, N, d) = \omega \cdot (mA_s + NB_s^0 + NB_s^1 P_s) + \omega d \cdot C_l(f_l) + \frac{\frac{l}{\beta}-\theta E}{\alpha P_s} \cdot f \cdot \int_{\underline{\gamma}}^{\gamma^*} xh(x)dx + \frac{\frac{l}{\beta}-\theta E}{\alpha} \cdot q_0 f_s + \frac{\frac{l}{\beta}-\theta E}{\xi} \cdot q_0 f_l + c_e\left(\frac{l}{\beta} - \theta E\right) \cdot f_l + \frac{l}{v} \cdot f \cdot \int_{\underline{\gamma}}^{\overline{\gamma}} xh(x)dx \tag{11}$$

s.t. (2)-(4), (6), (7), and

$$N \geq \frac{\left(\frac{l}{\beta}-\theta E\right) f_s}{\alpha P_s}$$

Apparently, adding some upper bounds (e.g., a sufficiently large number) for m and N will not affect the optimal solution of the above problem. With those upper-bound constraints, the set of constraints turns out to be compact. In addition, since each term in the objective function (11) is continuous, the objective function is thus also continuous. Therefore, the problem has at least one optimal solution. □

Proposition 2. Constraints (4)-(6) must be binding under an optimal solution to SCM.

Proof: Let $(\tilde{f}_s, \tilde{f}_l, \tilde{\gamma}^*, \tilde{m}, \tilde{n}_c, \tilde{d})$ denote an optimal solution to SCM. By contradiction, suppose one or more of constraints (4)-(6) are not binding. Take constraint (4) as an example. It follows $\tilde{m} > \frac{l}{\beta\theta E} - 1$. We construct another solution $(\tilde{f}_s, \tilde{f}_l, \tilde{\gamma}^*, \hat{m}, \hat{n}_c, \tilde{d})$ where $\hat{m} \cdot \hat{n}_c = \tilde{m} \cdot \tilde{n}_c$, and $\hat{m} = \frac{l}{\beta\theta E} - 1$, i.e., constraint (4) is binding under this solution. It is easy to verify that $(\tilde{f}_s, \tilde{f}_l, \tilde{\gamma}^*, \hat{m}, \hat{n}_c, \tilde{d})$ is a feasible solution. Further, $Z(\tilde{f}_s, \tilde{f}_l, \tilde{\gamma}^*, \hat{m}, \hat{n}_c, \tilde{d}) - Z(\tilde{f}_s, \tilde{f}_l, \tilde{\gamma}^*, \tilde{m}, \tilde{n}_c, \tilde{d}) = \omega A_s(\hat{m} - \tilde{m}) < 0$, which contradicts that $(\tilde{f}_s, \tilde{f}_l, \tilde{\gamma}^*, \tilde{m}, \tilde{n}_c, \tilde{d})$ is an optimal solution. Similarly, we can prove that constraints (5) and (6) are also binding under an optimal solution to SCM. □

According to Proposition 2 and, as previously mentioned, $\left(\frac{l}{\beta} - \theta E\right) \cdot \frac{v}{\xi P_l} \leq l$, solving SCM is equivalent to solving the following problem:

$$\min Z(f_s, f_l, \gamma^*, m, n_c, d) = \omega m \cdot C_s(n_c) + \omega d \cdot C_l(f_l) + \frac{\frac{l}{\beta}-\theta E}{\alpha P_s} \cdot f \cdot \int_{\underline{\gamma}}^{\gamma^*} x h(x) dx + \frac{\frac{l}{\beta}-\theta E}{\alpha} \cdot q_0 f_s + \frac{\frac{l}{\beta}-\theta E}{\xi} \cdot q_0 f_l + c_e \left(\frac{l}{\beta} - \theta E\right) \cdot f_l + \frac{l}{v} \cdot f \cdot \int_{\underline{\gamma}}^{\overline{\gamma}} x h(x) dx$$

s.t. (2), (3), and

$$m = \frac{l}{\beta\theta E} - 1 \tag{4a}$$

$$n_c = \frac{\theta E f_s}{\alpha P_s} \tag{5a}$$

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

Note that in practice, the number of charging stations and chargers per charging station should be integer, but we ignore this requirement for simplicity. We further note that the optimization of battery size can be easily incorporated into SCM if the government is interested in determining a socially optimum one (e.g., Nie and Ghamami, 2013; Kontou et al., 2015; Jang et al, 2016a).

4.3 Private provision

In the private provision scenario, both operators aim at maximizing their profits in building and operating their charging facilities. The competition leads to the Nash equilibrium where each operator will make the best response to the deployment plan of its competitor. In other words, at the Nash equilibrium, neither operator can improve its current profit by unilaterally changing its deployment plan.

Specifically, given the deployment plan of the charging-lane operator (i.e., d and q_l), the charging-station operator attempts to maximize his or her profit:

$$Z_s(q_s, f_s, f_l, \gamma^*, m, n_c) = q_s f_s \left(\frac{l}{\beta} - \theta E\right) - q_0 f_s \cdot \frac{\frac{l}{\beta}-\theta E}{\alpha} - \omega m \cdot C_s(n_c)$$

s.t. (1)-(5)

Similar to Propositions 1 and 2, it can be readily shown that there must exist at least one optimal solution to the above problem, and constraints (4) and (5) must be binding in an optimal solution. Therefore, the problem (dubbed as PS) can be represented below:

$$\max Z_s(q_s, m, n_c, f_s, f_l, \gamma^*) = q_s f_s\left(\frac{l}{\beta} - \theta E\right) - q_0 f_s \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} - \omega m \cdot C_s(n_c)$$

s.t. (1)-(3), (4a), (5a)

Similarly, given the deployment plan of the charging-station operator (i.e., m, n_c and q_s), the profit-maximizing problem of the charging-lane operator (dubbed as PL) is as follows:

$$\max Z_l(q_l, d, f_s, f_l, \gamma^*) = q_l f_l\left(\frac{l}{\beta} - \theta E\right) - q_0 f_l \cdot \frac{\frac{l}{\beta} - \theta E}{\xi} - \omega d \cdot C_l(f_l)$$

s.t. (1)-(3), (6a)

5. Solution and Analysis

This section provides and analyzes the solutions to the deployment models formulated in Section 4.

5.1 Public provision

By substituting (2), (3), and (4a)-(6a) into $Z(f_s, f_l, \gamma^*, m, n_c, d)$, and replacing f_l with $f - f_s$, we can obtain the social cost as a function of f_s. The first and second derivatives of the social cost with respect to f_s can then be derived as:

$$\frac{dZ}{df_s} = \omega \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot \left(\frac{B_s^0}{P_s} + B_s^1\right) + \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} \cdot \gamma^* + \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot q_0 - \omega \cdot \frac{\frac{l}{\beta} - \theta E}{\xi} \cdot B_l - \left(\frac{q_0}{\xi} + c_e\right) \cdot \left(\frac{l}{\beta} - \theta E\right)$$

$$\frac{d^2 Z}{df_s^2} = \frac{\frac{l}{\beta} - \theta E}{\alpha P_s f} \cdot \frac{1}{h(\gamma^*)}$$

Obviously, $\frac{d^2 Z}{df_s^2} > 0$, $\forall \gamma^* \in \left(\underline{\gamma}, \overline{\gamma}\right)$. That is, given the interior equilibrium assumption, the above social cost minimization problem is a convex problem. At optimality, $\frac{dZ}{df_s} = 0$, implying that the increased cost at charging stations due to one driver switching from charging lanes to stations, i.e., $\omega \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot \left(\frac{B_s^0}{P_s} + B_s^1\right) + \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} \cdot \gamma^* + \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot q_0$, is equal to the decreased cost at charging lanes, i.e., $\omega \cdot \frac{\frac{l}{\beta} - \theta E}{\xi} \cdot B_l + \left(\frac{q_0}{\xi} + c_e\right) \cdot \left(\frac{l}{\beta} - \theta E\right)$. The condition yields

$$\gamma^* = \omega\left(\frac{\alpha B_l P_s}{\xi} - B_s^0 - B_s^1 P_s\right) + \left(\frac{q_0}{\xi} + c_e - \frac{q_0}{\alpha}\right) \cdot \alpha P_s \tag{12}$$

Equality (12) gives the indifferent VOT with the optimal share of two charging modes. Via (2), (3), and (4a)-(6a), the optimal number of charging stations, number of chargers per station, and the total length of charging lanes can be easily calculated.

Given (1) and (12), the optimal charging prices need to satisfy the following condition:

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

Specifically, $\frac{\omega B_l}{\xi}+\frac{q_0}{\xi}$ and $\frac{\omega}{\alpha}\cdot\left(\frac{B_s^0}{P_s}+B_s^1\right)+\frac{q_0}{\alpha}$ are the marginal costs of constructing and operating charging lanes and stations to provide one more unit of electricity, respectively:

$$\frac{\partial\left(\omega d\cdot C_l(f_l)+\frac{\frac{l}{\beta}-\theta E}{\xi}\cdot q_0 f_l\right)}{\partial f_l\left(\frac{l}{\beta}-\theta E\right)}=\frac{\omega B_l}{\xi}+\frac{q_0}{\xi}$$

$$\frac{\partial\left(\omega m\cdot C_s(n_c)+\frac{\frac{l}{\beta}-\theta E}{\alpha}\cdot q_0 f_s\right)}{\partial f_s\left(\frac{l}{\beta}-\theta E\right)}=\frac{\omega}{\alpha}\cdot\left(\frac{B_s^0}{P_s}+B_s^1\right)+\frac{q_0}{\alpha}$$

In other words, in order to minimize social cost, the difference of charging prices at charging lanes and charging stations must be equal to the difference of the marginal costs of constructing and operating charging lanes and stations. Maintaining the same difference, we can find an infinite number of optimal charging price patterns due to the fixed demand setting. Note that the marginal-cost pricing pattern is one of them. If the demand is elastic, the optimal charging prices are unique and equal to the marginal costs (see Appendix A). It should be noted that just as the marginal costs are irrelative to the travel demand f, the battery size E, the distribution of VOT $h(\gamma)$, and cost parameters A_s and A_l, so is the indifferent VOT at optimality also irrelevant to them.

Please place Table 2 about here

According to equality (12), Table 2 shows how each variable or parameter in the model could affect the indifferent VOT (i.e., γ^*). Specifically, a change that leads to a higher cost for charging stations (i.e., larger B_s^0 and B_s^1) and a lower recharging efficiency at charging stations (i.e., smaller α) will lead to a lower γ^*. Also, a higher recharging efficiency at charging lanes (i.e., larger ξ) will result in a lower γ^*, but higher unit equipment cost (i.e., larger c_e) and larger B_l will lead to a higher γ^*. In addition, increasing q_0 can increase γ^*, as the recharging efficiency of charging lanes (i.e., ξ) is assumed to be lower than the one of charging stations (i.e., α). It is worth pointing out that, as $\frac{\partial\gamma^*}{\partial P_s}$ can be either positive or negative, the impact of the charging power of charging stations (i.e., P_s) on γ^* is ambiguous. On one hand, as P_s increases, the charging time in charging stations will be reduced, which in turn will attract more drivers and likely increase γ^*. On the other hand, the cost for constructing and operating charging stations will increase, which will lead to a higher charging price at charging stations and will likely decrease γ^*. The overall effect of the change of P_s will depend on the dominating effect.

Although the marginal-cost pricing pattern can achieve the minimum social cost, it will lead to a deficit due to the large capital cost of constructing charging lanes and stations. Specifically, the deficit can be calculated as $\omega\left(\frac{A_s}{\theta E}+\frac{v A_l}{\xi P_l}\right)\cdot\left(\frac{l}{\beta}-\theta E\right)$. In practice, in addition to minimizing the social cost, the government may be interested in helping charging infrastructure break-even or be self-financed. To do so, we can require the revenue to be equal to the cost, i.e.,

$$(q_l f_l + q_s f_s) \cdot \left(\frac{l}{\beta} - \theta E\right) = \omega m \cdot C_s(n_c) + \omega d \cdot C_l(f_l) + \frac{\frac{l}{\beta} - \theta E}{\xi} \cdot q_0 f_l + \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot q_0 f_s \quad (13)$$

By solving (1), (12), and (13) simultaneously, we can obtain the revenue-neutral charging prices q_s^* and q_l^* as follows:

$$\begin{cases} q_l^* = \frac{\omega}{f} \cdot \left(\frac{A_s}{\theta E} + \frac{v A_l}{\xi P_l}\right) + \frac{\omega B_l}{\xi} + \frac{q_0}{\xi} \\ q_s^* = \frac{\omega}{f} \cdot \left(\frac{A_s}{\theta E} + \frac{v A_l}{\xi P_l}\right) + \frac{\omega B_s^0}{\alpha P_s} + \frac{\omega B_s^1}{\alpha} + \frac{q_0}{\alpha} \end{cases} \quad (14)$$

Compared with the marginal-cost pricing, there is an additional item: $\frac{\omega}{f} \cdot \left(\frac{A_s}{\theta E} + \frac{v A_l}{\xi P_l}\right)$, which represents the additional charging price to cover the sunk cost of constructing the charging infrastructure.

As per (14), a change that leads to a higher cost for charging stations or lanes (e.g., larger $A_s, A_l, B_l, B_s^0, B_s^1$) and larger $q_0$will increase the revenue-neutral charging prices. In particular, a larger A_s, A_l, or q_0 increases charging prices at both charging lanes and stations while a larger B_l or B_s^0, B_s^1 can only result in a higher price at charging lanes or stations. That is because A_s and A_l are fixed costs and q_0 is a common variable cost for both charging facilities, while B_l, B_s^0, and B_s^1 are variable costs for each charging facility (see equalities (8) and (9)). Additionally, higher travel demand (i.e., a larger f) and higher charging power of charging lanes (i.e., a larger P_l) can lower revenue-neutral charging prices. Larger battery size (i.e., a larger E) can as well, because a larger battery size can reduce the number of charging stations and the total length of charging lanes, as per equalities (4a) and (6a).

5.2 Private provision

We now turn to the private provision scenario. To achieve the Nash equilibrium, both operators will maximize their profits simultaneously. That is, we must solve problems PS and PL simultaneously.

First, we consider problem PS. Taking the first-order derivative of Z_s, we obtain:

$$\frac{dZ_s}{dq_s} = f_s\left(\frac{l}{\beta} - \theta E\right) + q_s\left(\frac{l}{\beta} - \theta E\right) \cdot \frac{\partial f_s}{\partial q_s} - q_0 \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot \frac{\partial f_s}{\partial q_s} - \omega \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot \left(\frac{B_s^0}{P_s} + B_s^1\right) \cdot \frac{\partial f_s}{\partial q_s} \quad (15)$$

Specifically, the term $f_s\left(\frac{l}{\beta} - \theta E\right) + q_s\left(\frac{l}{\beta} - \theta E\right) \cdot \frac{\partial f_s}{\partial q_s}$ represents the change in revenue due to changing the charging price; $q_0 \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot \frac{\partial f_s}{\partial q_s} + \omega \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot \left(\frac{B_s^0}{P_s} + B_s^1\right) \cdot \frac{\partial f_s}{\partial q_s}$ specifies the change in cost. Consequently, $\frac{dZ_s}{dq_s} = 0$ implies that the former is offset by the latter, a necessary condition for an interior optimum.

As $\gamma^* = (q_l + c_e - q_s) \cdot \alpha P_s$, $f_s = f \cdot \int_{\underline{\gamma}}^{\gamma^*} h(x) dx$, we then have:

$$\frac{\partial f_s}{\partial q_s} = f \cdot h(\gamma^*) \cdot (-\alpha P_s) \quad (16)$$

Substituting (16) into (15), and letting $\frac{dZ_s}{dq_s} = 0$, we obtain:

$$q_s - \frac{q_0}{\alpha} - \frac{\omega}{\alpha} \cdot \left(\frac{B_s^0}{P_s} + B_s^1\right) = \int_{\underline{\gamma}}^{\gamma^*} h(x)dx \cdot (h(\gamma^*) \cdot \alpha P_s)^{-1} \tag{17}$$

The second-order derivative of Z_s yields

$$\frac{d^2 Z_s}{dq_s^2} = \left(\frac{l}{\beta} - \theta E\right) f \cdot \left[2h(\gamma^*) \cdot (-\alpha P_s) + \left[q_s - \frac{q_0}{\alpha} - \frac{\omega}{\alpha} \cdot \left(\frac{B_s^0}{P_s} + B_s^1\right)\right] \cdot \frac{dh(\gamma^*)}{d\gamma^*} \cdot (\alpha P_s)^2\right]$$

Substituting (17) into the above, we have:

$$\frac{d^2 Z_s}{dq_s^2} = \left(\frac{l}{\beta} - \theta E\right) f \cdot (-\alpha P_s) \cdot \left(2h(\gamma^*) - \int_{\underline{\gamma}}^{\gamma^*} h(x)dx \cdot h(\gamma^*)^{-1} \cdot \frac{dh(\gamma^*)}{d\gamma^*}\right)$$

If $\frac{d^2 Z_s}{dq_s^2} \leq 0$, which yields

$$\frac{dh(\gamma^*)}{d\gamma^*} \leq \frac{2h(\gamma^*)^2}{\int_{\underline{\gamma}}^{\gamma^*} h(x)dx}, \tag{18}$$

then $\frac{dZ_s}{dq_s} = 0$ is also a sufficient condition for local optimum.

Similarly, for the charging-lane operator, $\frac{dZ_l}{dq_l} = 0$ yields

$$q_l - \frac{q_0}{\xi} - \frac{\omega B_l}{\xi} = \int_{\gamma^*}^{\overline{\gamma}} h(x)dx \cdot (h(\gamma^*) \cdot \alpha P_s)^{-1} \tag{19}$$

Taking the second-order derivative of Z_l, we have:

$$\frac{d^2 Z_l}{dq_l^2} = \left(\frac{l}{\beta} - \theta E\right) f \cdot (-\alpha P_s) \cdot \left(2h(\gamma^*) - \int_{\gamma^*}^{\overline{\gamma}} h(x)dx \cdot h(\gamma^*)^{-1} \cdot \frac{dh(\gamma^*)}{d\gamma^*}\right)$$

If $\frac{d^2 Z_l}{dq_l^2} \leq 0$, which yields

$$\frac{dh(\gamma^*)}{d\gamma^*} \leq \frac{2h(\gamma^*)^2}{\int_{\gamma^*}^{\overline{\gamma}} h(x)dx}, \tag{20}$$

then $\frac{dZ_l}{dq_l} = 0$ is also a sufficient condition for local optimum.

Given $h(\gamma)$, which satisfies (18) and (20), we can obtain the Nash equilibrium by solving (17) and (19) simultaneously.

To further our analysis, we present an analytical example assuming that VOT is uniformly distributed, i.e., $\gamma \sim U\left(\underline{\gamma}, \overline{\gamma}\right)$ and $h(\gamma) = \frac{1}{\overline{\gamma} - \underline{\gamma}}$. Note that a uniform VOT distribution satisfies (18) and (20) simultaneously. Solving (17) and (19) simultaneously, we can obtain the Nash equilibrium solution for the two profit-maximizing operators:

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

$$q_s^* = \frac{1}{3}\left(\frac{2q_0}{\alpha} + \frac{q_0}{\xi} + c_e + \frac{\omega}{\alpha} \cdot \left(\frac{\alpha B_l}{\xi} + \frac{2B_s^0}{P_s} + 2B_s^1\right) + \frac{\overline{\gamma} - 2\underline{\gamma}}{\alpha P_s}\right) \tag{21}$$

$$q_l^* = \frac{1}{3}\left(\frac{2q_0}{\xi} + \frac{q_0}{\alpha} - c_e + \frac{\omega}{\alpha} \cdot \left(\frac{2\alpha B_l}{\xi} + \frac{B_s^0}{P_s} + B_s^1\right) + \frac{2\overline{\gamma} - \underline{\gamma}}{\alpha P_s}\right) \tag{22}$$

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

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

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

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

According to (4a)-(6a), the optimal number of charging stations, number of chargers per station, and the total length of charging lanes can be easily calculated.

Table 3 shows how each variable in the model could affect γ^* at the Nash equilibrium. Compared with Table 2, coincidently, the only difference in Table 3 is that all the partial derivatives of γ^* are divided by 3. Therefore, the sensitivity analysis is similar to the one in Section 5.1.

Please place Table 3 about here

6. Empirical Analysis

This section presents an empirical analysis to investigate the optimal deployment of charging lanes and stations and examine the competitiveness of charging lanes. Table 4 presents the data obtained from previous studies. We try to represent the reality as closely as possible by utilizing available empirical data.

Please place Table 4 about here

We explain the chosen values in Table *4* in the following. Conservatively, suppose that charging facilities can be used for 10 years. As the 10-year discount rate for 2016 is 1.0% (OMB, 2016), we can calculate that $\omega = 1.19\times10^{-5}$. Furthermore, based on the discount rate, if we assume that the cost of the CWD equipment is very high, say, \$20,000 for one EV, and the equipment can be used for 10 years with a total usage of 52,000 kWh, then the unit equipment cost can be calculated as $c_e = \$0.4/\text{kWh}$. Since there is no available empirical data about c_e, sensitivity analysis will be conducted in this section.

According to Nie and Ghamami (2013), $\alpha = 0.77$; $\beta = 2.5\text{mi/kWh}$; $B_s^1 = \$500/\text{kW}$; the unit construction cost for new stations is $\$104/\text{ft}^2$, and the minimum construction area for a charging station is 2,000 ft^2, hence $A_s = \$2{,}000\times104 = \$208{,}000$; and the construction area for one charger is taken as 300 ft^2, thus $B_s^0 = \$300\times104 = \$31{,}200$.

In addition, based on the OLEV system used in Korea (Jang et al, 2016a), the average cost of a power transmitter (including construction cost) is about \$500/m; thus, the construction cost for converting one mile of regular lane to a charging lane is estimated at $A_l = \$800{,}000/\text{mi}$. Additionally, the average cost of one inverter unit, which can provide 100 kW power, is \$55,000. Therefore, the construction cost per unit of charging power can be estimated as $B_l = \$55{,}000/100\text{ kW} = \$550/\text{kW}$.

The length of the corridor (i.e., l) is set to be 300 miles long. Note that changing it will not affect the main findings of this study, as charging prices, the indifferent VOT, and the relation between the profits of charging-lane and charging-station operators at the Nash equilibrium are all irrelevant to the length of the corridor. The demand of EVs on the corridor is set to be $300\ \mathrm{veh/h}$, consistent with the currently low market penetration of EVs. Nevertheless, as travel demand can affect the profits of charging-lane and charging-station operators, sensitivity analysis will be provided in this section.

6.1 Public provision

According to equality (12), we can obtain the indifferent VOT such that the government can maximize social welfare, which is

$$\gamma^* = \$31.79/\mathrm{h}$$

Furthermore, based on equality (14), the revenue-neutral prices at charging stations and charging lanes can be calculated below.

$$q_s^* = \$0.148/\mathrm{kWh}, q_l^* = \$0.161/\mathrm{kWh}$$

For ease of calculation, suppose $\gamma \in U(10,70)$. Fig. 2 and Fig. 3 plot the changes of social cost and profit in a two-dimension space of charging prices at charging stations and lanes. As observed in Fig. 2, every social-cost contour has an angle of 45 degrees. This is consistent with the fact that the social cost is solely relative to the indifferent VOT, which, as per equality (1), only depends on the price difference between charging lanes and stations rather than their absolute values. It is worth highlighting that the red dashed line in Fig. 2 represents the minimum social-cost contour that is equal to \$70,803, and its expression is $q_l = q_s + 0.013$, which follows $\gamma^* = \$31.79/\mathrm{h}$ based on equality (1). Also, note that there is no contour in the lower right corner in Fig. 2 since the social cost remains the same if the price difference between charging lanes and stations is sufficiently small. Actually, this phenomenon, which stems from the boundary condition of the VOT, is also true when the price difference is sufficiently large. More specifically, when the price difference is so small that $\gamma^* = (q_l + c_e - q_s) \cdot \alpha P_s < \underline{\gamma}$ (so large that $\gamma^* > \bar{\gamma}$), all drivers are attracted to charging lanes (stations), and the social cost will thus remain the same no matter how much q_s (q_l) increases (decreases).

We can observe from Fig. 3 that the profit increases along any 45-degree slanting line. That is, an increase of charging prices at charging stations and lanes while maintaining their difference (i.e., not changing the indifferent VOT) will lead to increasing profit, because in the setting of this case, the total demand is fixed. Also, it can be observed that all the contours under the red dashed line (see Fig. 3) are horizontal. For example, when the charging price at charging lanes is set at $\$0.22/\mathrm{kWh}$, the profit remains at \$2,000 no matter how much the charging price at charging stations increases from $\$0.5/\mathrm{kWh}$. The reason is that the associated indifferent VOT has reached the lower bound of the VOT distribution, and drivers will no longer use charging stations. Consequently, both the revenue and operation cost are fixed no matter how much the charging price at charging stations increases. Fig. 4 combines Fig. 2 and Fig. 3, and we find that the revenue-neutral charging prices are achieved at the red point, the point of intersection of the minimum social-cost and the zero-profit contours.

Please place Fig. 2 about here
Please place Fig. 3 about here
Please place Fig. 4 about here

Now we turn to calculating what percentage of EV drivers will use charging lanes based on an empirical VOT distribution. Table 5 shows the VOT distribution of passenger cars traveling on the managed lanes on Interstate 95 in Miami, Florida, which was estimated from a survey conducted by Perk et al. (2011). Based on the distribution and the default values of parameters in Table 4, 49.8% of EV drivers are expected to choose charging lanes. However, as CWD technologies advance, the unit equipment cost (i.e., c_e) is likely to decrease significantly, which may have a critical impact on the facility choice. Fig. 5 plots how the indifferent VOT (i.e., γ^*) and the percentage of EV drivers using charging lanes and stations change with respect to c_e. As c_e increases, γ^* increases linearly from \$1.0/h to \$78.0/h. Accordingly, the percentage of using charging stations, like an S-shape curve, initially increases mildly from 0%, then rises drastically, and finally reaches 100%; while the percentage of using charging lanes first decreases mildly from 100%, then descends drastically, and eventually converges to 0%. Apparently, if c_e can be reduced to a low level (e.g., \$0.3/kWh), most EV drivers will prefer to use charging lanes instead of charging stations. As mentioned in Section 1, charging lanes can be achieved by either conductive or inductive charging. Because conductive charging is more mature, the CWD equipment cost for enabling conductive charging is expected to be lower. For example, if c_e decreases to \$0.3/kWh by using conductive charging technology, then the percentage of using charging lanes will increase to 71.1% (see Fig. 5).

Since the VOTs of commercial vehicles are much higher than those of passenger cars, we can envision that commercial vehicles are likely to be early users of charging lanes. Accordingly, we are interested in investigating how the VOT distribution will affect the charging-facility choice of drivers (see Fig. 6). Specifically, the horizontal axis "Ratio" in Fig. 6 represents how many times the VOT distribution is uniformly increased (take the one in Table 5 as the initial distribution). For example, "2" means that the VOTs in the first column of Table 5 are doubled. Obviously, the increasing "Ratio" leads to increasing percentages of drivers using charging lanes. In particular, when the "Ratio" equals 3, more than 90% of drivers will choose to use charging lanes. This result is in agreement with the fact that charging-lane experiments are currently designed for EVs with high VOT, e.g., electric buses or trucks.

Please place Table 5 about here
Please place Fig. 5 about here
Please place Fig. 6 about here

6.2 Private provision

In this subsection, we firstly analyze some basic results, including the optimal profits and charging prices of two operators and the corresponding indifferent VOT, and then conduct sensitivity analysis for various parameters, such as the cost function, recharging efficiency, and charging power of charging lanes.

6.2.1 Basic results

Using the default values in Table 4, and assuming $\gamma \sim U(10,70)$, the profits of the two operators in the private provision scenario can be calculated as:

$$Z_s^* = \$4{,}857;\ Z_l^* = \$6{,}083$$

The corresponding charging prices and indifferent VOT are calculated as follows:

$$q_s^* = \$0.471/\text{kWh}; q_l^* = \$0.555/\text{kWh};\ \gamma^* = \$37.26/\text{h}$$

We can see that both operators are profitable, and the charging-lane operator makes more profit than its competitor. Furthermore, as per the VOT distribution and the indifferent VOT, we find that 54.6% of EVs prefer charging lanes. The above findings imply that, based on the settings in our paper, charging lanes are competitive in terms of attracting drivers and generating revenue.

Fig. 7 and Fig. 8 display how the profits of charging-lane and charging-station operators vary in the domain of these two charging prices, respectively. It can be readily seen that, while keeping a charging price within the profitable region (the contours with values greater than zero), one operator will not suffer loss if the other operator increases his or her charging price. Take Fig. 7 as an example. By setting the price at $\$0.3/\text{kWh}$, the charging-lane operator can make a greater profit when the charging price at charging stations increases from $\$0.1/\text{kWh}$ to $\$0.56/\text{kWh}$; over $\$0.56/\text{kWh}$, the profit remains the same. The reason is rather straightforward, as an increasing charging price at charging stations will force more drivers to use charging lanes. As a result, the profit of a charging-lane operator will keep growing until all drivers switch to charging lanes.

Fig. 9 combines Fig. 7 and Fig. 8. In the figure, the Nash equilibrium charging prices are achieved at the red point, at which neither operator can benefit by changing their own prices. By comparing Fig. 9 and Fig. 4, one may also notice that the Nash equilibrium prices in the private provision scenario are quite different from the revenue-neutral optimal prices in the public provision scenario. The prices of the former are much higher than those of the latter. However, the associated social cost of the former is $\$70{,}900$, which only slightly differs from the latter, $\$70{,}803$. In fact, such a finding also holds when considering elastic demand (see, Appendix B).

Please place Fig. 7 about here

Please place Fig. 8 about here

Please place Fig. 9 about here

6.2.2 Sensitivity analysis

Due to the development of CWD technology and the market penetration of EVs, the cost function, recharging efficiency and charging power of charging lanes, the demand level, the battery size, and the unit equipment cost may change drastically, and such changes are very likely to have a critical impact on the competitiveness of charging lanes. Accordingly, we further investigate how the profits of operators will change with respect to those changes. Furthermore, as discussed in the public provision scenario, the VOT distribution has a profound impact on the charging-facility choice, we thus also explore how it will affect the profits of operators in the private provision scenario.

Fig. 10 specifies how the profits of operators change as the construction and operation cost of charging lanes changes. Similar to Fig. 6, the horizontal axis "Ratio" represents how many times the construction and operation cost of charging lanes (i.e., A_l and B_l) will increase (take the default values in Table 4 as the initial setting). As expected, increasing A_l and B_l will decrease the profit of the charging-lane operator, but increase the profit of the charging-station operator. In other words, a higher A_l and B_l will weaken the competitiveness of charging lanes. However, even if A_l and B_l double, the profit of the charging-lane operator will still be higher than that of the charging-station operator. Moreover, the charging-lane operator will be profitable even if such costs triple or more.

Fig. 11 illustrates the relation between the profits of operators and the EV demand. The charging-lane operator makes more profit than its competitor unless the EV demand is at a low level (e.g., less than $120\ \text{veh/h}$). Both operators benefit from an increase in EV demand, but the charging-lane operator gains more. As a result, the profit difference between the two operators becomes more noticeable as the EV market penetration increases, which suggests a favorable prospect for investing in charging lanes.

Fig. 12 plots the relation between the profits of operators and the unit equipment cost. The charging-lane operator suffers from an increase in the unit equipment cost (i.e., larger c_e), but the charging-station operator benefits. Specifically, when c_e is higher than $\$0.46/\text{kWh}$, operating charging stations is more profitable. On the contrary, when the CWD technology advances to a high level such that $c_e < \$0.46/\text{kWh}$, operating charging lanes will be a better choice.

Fig. 13 describes the relation between the profits of operators and the charging power of charging lanes. The profit of operating charging lanes increases from $\$4{,}676$ to $\$6{,}436$ when the level of charging power of the charging lanes (i.e., P_l) changes from 40 kW to 160 kW, but the profit of charging stations remains the same, $\$4{,}857$. This result is rooted in the fact that the indifferent VOT and the optimal charging prices are irrelevant to P_l. More specifically, as P_l has little impact on the charging-facility choice of EV drivers and the Nash equilibrium price at charging stations, it will not affect the profit of operating charging stations. For charging lanes, as P_l increases, although the per-mile construction and operation cost will increase, the total cost will decrease since their length is reduced. As a result, the charging-lane operator can benefit from an increase in P_l.

Fig. 14 presents the relation between the profits of operators and the recharging efficiency of charging lanes. Not surprisingly, a lower recharging efficiency of charging lanes leads to a lower profit for the charging-lane operator, and a higher profit for the charging-station operator. However, even if the recharging efficiency of charging lanes is pretty low, say, 0.5, its profit is still higher than that of charging stations.

Fig. 15 delineates the change of operators' profits due to the change of battery size. It can be observed that the profits of both operators decrease as the battery size increases, because with a larger battery, drivers can reduce the amount of electricity recharged.

Fig. 16 shows the relation between operators' profits and various VOT distributions. Like Fig. 6, the horizontal axis "Ratio" indicates how many times the VOT distribution will increase. As we can see, an increase in "Ratio" leads to a higher profit for both operators, as the Nash equilibrium prices rise according to (18) and (19). In particular, the charging-lane operator gains more. In other words, with increasing VOT distribution, the profitability of operating charging lanes is more considerable than that of operating charging stations.

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7. Conclusion

We have investigated the optimal deployment of charging stations and lanes along a long traffic corridor to serve the charging need of EVs and have examined the competitiveness of charging lanes. When both charging stations and lanes are deployed along the corridor, EV drivers traveling from one end to the other are assumed to choose charging facilities to minimize their travel costs, which include driving time, charging fee, charging time at charging stations, and amortized equipment cost for enabling CWD. Given the charging infrastructure supply, a choice equilibrium model is firstly proposed to capture the charging facility choices of EV drivers for charging their vehicles. With the proposed charging-facility-choice model, we then formulate mathematical programs to optimally deploy charging stations and lanes with regard to different operating regimes, i.e., the public and private provision. Based on the optimal deployment plans, empirical analysis is conducted to explore the competitiveness of charging lanes. Below are the main observations from our analysis:

- Charging lanes are competitive as compared with charging stations for attracting drivers. Specifically, in the public provision scenario, EV drivers with a VOT higher than $31.79/h would favor charging lanes; in the private provision scenario, EV drivers with a VOT higher than $37.26/h may prefer charging lanes to charging stations, when drivers' VOTs follow a uniform distribution between $10.00/h and $70.00/h.

- 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 are much higher than the revenue-neutral charging prices in the public provision scenario. Nevertheless, their resulting social costs do not differ substantially, which can be partly attributed to the competition between the private operators.

It is worth pointing out that the continuing advance of CWD technology can significantly affect the empirical data in Table *4*, and thus the above observations should not be treated conclusive. Our analysis primarily shows that charging lanes are economically viable and competitive for attracting drivers even with the current CWD technology. Further development of the technology will likely make them even more economically viable. The proposed modeling framework in this paper is generally applicable to investigate the competition between charging lanes and charging stations with further development of CWD technology.

Future study may extend the proposed models to a general network where besides selecting charging facilities, EV drivers will make route choices. In addition, as it is impossible to sufficiently deploy each type of charging facility along each route in the network, drivers may choose to alternate between charging stations and lanes during their trips to meet their charging needs. Considering the above issues in the proposed deployment models, however, would be rather challenging.

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Appendix A

This appendix considers the elastic demand for the public provision scenario, i.e., the total demand of EVs is sensitive to travel cost. Suppose travelers always have another alternative (e.g., transit), with constant travel time $t_c > \left(\frac{l}{\beta} - \theta E\right) \cdot \frac{\alpha}{P_s} + \frac{l}{v}$ (that is, using charging stations without payment is always a better choice). Accordingly, the travel cost of a driver with VOT γ is equal to γt_c.

Consider an interior equilibrium where both the alternative and charging stations are utilized, there exist a driver who is indifferent between using them. Let $\hat{\gamma}$ denote the VOT for this indifferent driver, because the cost of using the alternative and charging stations is the same, we have:

$$\hat{\gamma} t_c = \hat{\gamma} \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} + q_s \left(\frac{l}{\beta} - \theta E\right) + \hat{\gamma} \cdot \frac{l}{v}$$

The above implies that travel cost of using the alternative is identical to that of using charging stations for the indifferent traveler with $\hat{\gamma}$. It follows:

$$\hat{\gamma} = \frac{q_s\left(\frac{l}{\beta} - \theta E\right)}{t_c - \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} - \frac{l}{v}} \tag{A1}$$

It can be readily shown that any traveler with $\gamma < \hat{\gamma}$ will choose to travel on the alternative, while others prefer to use charging stations or lanes. We assume that $\hat{\gamma} < \gamma^*$ (γ^* is the VOT of the driver who is indifferent to use charging stations and charging lanes). Then the travelers with $\hat{\gamma} < \gamma < \gamma^*$ will choose charging stations, and the others with $\gamma > \gamma^*$ will choose charging lanes. We exclude the case with $\hat{\gamma} > \gamma^*$, where no traveler will choose to use charging stations[1].

Consequently, if we define the demand of choosing the alternative as f_c, then to minimize the social cost, it is to solve:

$$\min Z(f_s, f_l, f_c, \gamma^*, \hat{\gamma}, m, n_c, d) = \omega m \cdot C_s(n_c) + \omega d \cdot C_l(f_l) + \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} \cdot f \cdot \int_{\hat{\gamma}}^{\gamma^*} x h(x) dx + \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot q_0 f_s + \frac{\frac{l}{\beta} - \theta E}{\xi} \cdot q_0 f_l + c_e \left(\frac{l}{\beta} - \theta E\right) \cdot f_l + \frac{l}{v} \cdot f \cdot \int_{\hat{\gamma}}^{\overline{\gamma}} x h(x) dx + t_c f \cdot \int_{\underline{\gamma}}^{\hat{\gamma}} x h(x) dx$$

s.t. (4a)-(6a)

$$f_c = f \cdot \int_{\underline{\gamma}}^{\hat{\gamma}} h(x) dx \tag{A2}$$

$$f_s = f \cdot \int_{\hat{\gamma}}^{\gamma^*} h(x) dx \tag{A3}$$

$$f_l = f \cdot \int_{\gamma^*}^{\overline{\gamma}} h(x) dx \tag{A4}$$

By substituting all the constraints into $Z(f_s, f_l, f_c, \gamma^*, \hat{\gamma}, m, n_c, d)$, and replacing f_l with $f - f_s - f_c$, we obtain the partial derivatives as below:

$$\frac{\partial Z}{\partial f_s} = \omega \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} \cdot \left(\frac{B_s^0}{P_s} + B_s^1\right) - \omega \cdot \frac{\frac{l}{\beta} - \theta E}{\xi} \cdot B_l + \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} \cdot \gamma^* + \left(\frac{q_0}{\alpha} - \frac{q_0}{\xi} - c_e\right) \cdot \left(\frac{l}{\beta} - \theta E\right)$$

$$\frac{\partial Z}{\partial f_c} = -\omega \cdot \frac{\frac{l}{\beta} - \theta E}{\xi} \cdot B_l + \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} \cdot (\gamma^* - \hat{\gamma}) - \left(\frac{q_0}{\xi} + c_e\right) \cdot \left(\frac{l}{\beta} - \theta E\right) - \frac{l}{v} \cdot \hat{\gamma} + t_c \cdot \hat{\gamma}$$

$$\frac{\partial^2 Z}{\partial f_s^2} = \frac{\frac{l}{\beta} - \theta E}{\alpha P_s f} \cdot \frac{1}{h(\gamma^*)}$$

$$\frac{\partial^2 Z}{\partial f_s \partial f_c} = \frac{\frac{l}{\beta} - \theta E}{\alpha P_s f} \cdot \frac{1}{h(\gamma^*)}$$

$$\frac{\partial^2 Z}{\partial f_c^2} = \frac{\frac{l}{\beta} - \theta E}{\alpha P_s f} \cdot \frac{1}{h(\gamma^*)} + \left(t_c - \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} - \frac{l}{v}\right) \cdot \frac{1}{h(\hat{\gamma})}$$

$$\frac{\partial^2 Z}{\partial f_c \partial f_s} = \frac{\frac{l}{\beta} - \theta E}{\alpha P_s f} \cdot \frac{1}{h(\gamma^*)}$$

It is easy to verify that $\begin{bmatrix} \frac{\partial^2 Z}{\partial f_s^2} & \frac{\partial^2 Z}{\partial f_s \partial f_c} \\ \frac{\partial^2 Z}{\partial f_c \partial f_s} & \frac{\partial^2 Z}{\partial f_c^2} \end{bmatrix}$ is positive definite, hence the above problem is a convex problem. The optimality conditions $\frac{\partial Z}{\partial f_s} = 0$ and $\frac{\partial Z}{\partial f_c} = 0$ yield (assuming interior optimal solution)

[1] While this is not the focus of the paper, it can be similarly formulated as the charging-facility-choice model of charging lanes and charging stations.

$$\gamma^* = \omega\left(\frac{\alpha B_l P_s}{\xi} - B_s^0 - B_s^1 P_s\right) + \left(\frac{q_0}{\xi} - \frac{q_0}{\alpha} + c_e\right) \cdot \alpha P_s \tag{A5}$$

$$\hat{\gamma} = \left(\frac{l}{\beta} - \theta E\right) \cdot \frac{\frac{\omega}{\alpha P_s}(B_s^0 + B_s^1 P_s) + \frac{q_0}{\alpha}}{\left(t_c - \frac{\frac{l}{\beta} - \theta E}{\alpha P_s} - \frac{l}{v}\right)} \tag{A6}$$

Substituting (1) and (A1) into (A5) and (A6), and solving them simultaneously, we can obtain:

$$q_l^* = \frac{q_0}{\xi} + \frac{\omega B_l}{\xi} \tag{A7}$$

$$q_s^* = \frac{q_0}{\alpha} + \frac{\omega}{\alpha P_s} \cdot (B_s^0 + B_s^1 P_s) \tag{A8}$$

As a result, the revenue is shown as below:

$$(q_l^* f_l^* + q_s^* f_s^*) \cdot \left(\frac{l}{\beta} - \theta E\right) \tag{A9}$$

Comparing equalities (A5) and (12), we can see that they are exactly the same, which implies that adding an alternative has no impact on travelers using charging lanes based on our setting. Indeed, the travelers using the alternative used to use charging stations (in the fixed demand case). Based on (A6), a higher travel time (i.e., larger t_c) leads to a smaller $\hat{\gamma}$, hence less travelers using the alternative (i.e., smaller f_c). Observed from equalities (A7) and (A8), the optimal charging prices at charging stations and lanes are exactly equal to their marginal costs, and are not relevant to the constant travel time t_c.

Given the specific values of the parameters, we can evaluate the gap between charging revenue and operating cost.

Appendix B

This appendix considers the elastic demand for the private provision scenario, and we adopt the same setting in Appendix A. Accordingly, (A1)-(A4) will also hold in this scenario. Given the deployment plan of the charging-lane operator (i.e., d and q_l), the charging-station operator attempts to maximize his or her profit:

$$Z_s(q_s, f_s, f_l, f_c, \gamma^*, \hat{\gamma}, m, n_c) = q_s f_s\left(\frac{l}{\beta} - \theta E\right) - q_0 f_s \cdot \frac{\frac{l}{\beta} - \theta E}{\alpha} - \omega m \cdot C_s(n_c)$$

s.t. (1), (4a), (5a), (A1)-(A4)

Similarly, given the deployment plan of the charging-station operator (i.e., m, n_c and q_s), the profit-maximizing problem of the charging-lane operator is as follows:

$$\max Z_l(q_l, d, f_s, f_l, f_c, \gamma^*, \hat{\gamma}) = q_l f_l\left(\frac{l}{\beta} - \theta E\right) - q_0 f_l \cdot \frac{\frac{l}{\beta} - \theta E}{\xi} - \omega d \cdot C_l(f_l)$$

s.t. (1), (6a), (A1)-(A4)

Following the solution procedure in Section 5.2, we can obtain the Nash equilibrium by solving the following equations simultaneously:

$$\begin{cases} q_s - q_0\alpha - \omega\alpha\left(\frac{B_s^0}{P_s} + B_s^1\right) = -[H(\gamma^*) - H(\hat{\gamma})]\cdot\left(h(\gamma^*)\cdot\left(-\frac{P_s}{\alpha}\right) - h(\hat{\gamma})\cdot\frac{\left(\frac{l}{\beta}-\theta E\right)}{t_c-\left(\frac{l}{\beta}-\theta E\right)\cdot\frac{\alpha}{P_s}-\frac{l}{v}}\right)^{-1} \\ q_l - q_0\xi - \omega\xi B_l = -\left(1-H(\gamma^*)\right)\cdot\left(h(\gamma^*)\cdot\left(-\frac{P_s}{\alpha}\right)\right)^{-1} \end{cases}$$

To further our analysis, we present an analytical example in the following assuming that VOT is uniformly distributed, i.e., $\gamma\sim U\left(\underline{\gamma},\overline{\gamma}\right)$ and $h(\gamma) = \frac{1}{\overline{\gamma}-\underline{\gamma}}$. Then, we can obtain:

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

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

$$\gamma^* = \frac{\left(\frac{q_0}{\xi}+\frac{\omega B_l}{\xi}+\frac{\overline{\gamma}}{\alpha P_s}+c_e\right)\cdot\left(\alpha P_s+\frac{\frac{l}{\beta}-\theta E}{t_c-\frac{l}{v}}\right)-q_0P_s-\omega\left(B_s^0+B_s^1P_s\right)}{3+\frac{\frac{l}{\beta}-\theta E}{\alpha P_s\left(t_c-\frac{l}{v}\right)}}$$

$$\hat{\gamma} = \left(\frac{l}{\beta}-\theta E\right)\frac{2\left(\frac{q_0}{\alpha}+\frac{\omega}{\alpha}\cdot\left(\frac{B_s^0}{P_s}+B_s^1\right)\right)+\left(\frac{q_0}{\xi}+\frac{\omega B_l}{\xi}+\frac{\overline{\gamma}}{\alpha P_s}+c_e\right)\cdot\left(1-\frac{\frac{l}{\beta}-\theta E}{\alpha P_s\left(t_c-\frac{l}{v}\right)}\right)}{\left(3+\frac{\frac{l}{\beta}-\theta E}{\alpha P_s\left(t_c-\frac{l}{v}\right)}\right)\left(t_c-\frac{\frac{l}{\beta}-\theta E}{\alpha P_s}-\frac{l}{v}\right)}$$

Accordingly, the travelers using charging stations, lanes, and the alternative (i.e., f_s, f_l, and f_c), the profits of different operators (i.e., Z_s and Z_l), the optimal number of charging stations, number of chargers per station, and the total length of charging lanes can be easily calculated.

Using the default values in Table 4, and assuming $\gamma\sim U(10,70)$, Fig. 17 and Fig. 18 delineate the change of charging prices and social costs due to the change of travel time on the alternative. From Fig. 17, it is easy to observe that charging prices at both charging stations and lanes in the private provision scenario are always higher than the ones in the public provision scenario. Particularly, as per (A7) and (A8), the latter ones are equal to the marginal costs of constructing and operating charging lanes and stations to provide one more unit of electricity, both of which are irrelative with the travel time on the alternative, they are thus invariant. For the private provision scenario, as the travel time on the alternative increases, both charging-station and -lane operators increase their charging prices so as to maximize their profits. Fig. 18 reveals that with the increasing travel time on the alternative, the social costs in both private and provision scenarios increase, and more important, their discrepancy is always less than 2%.

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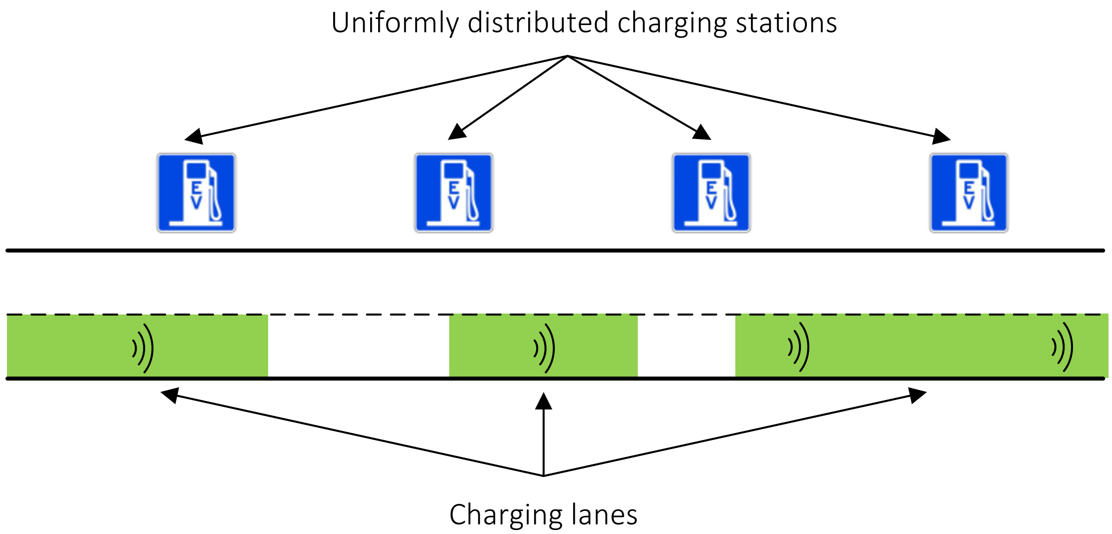

Fig. 1 Charging infrastructure deployment

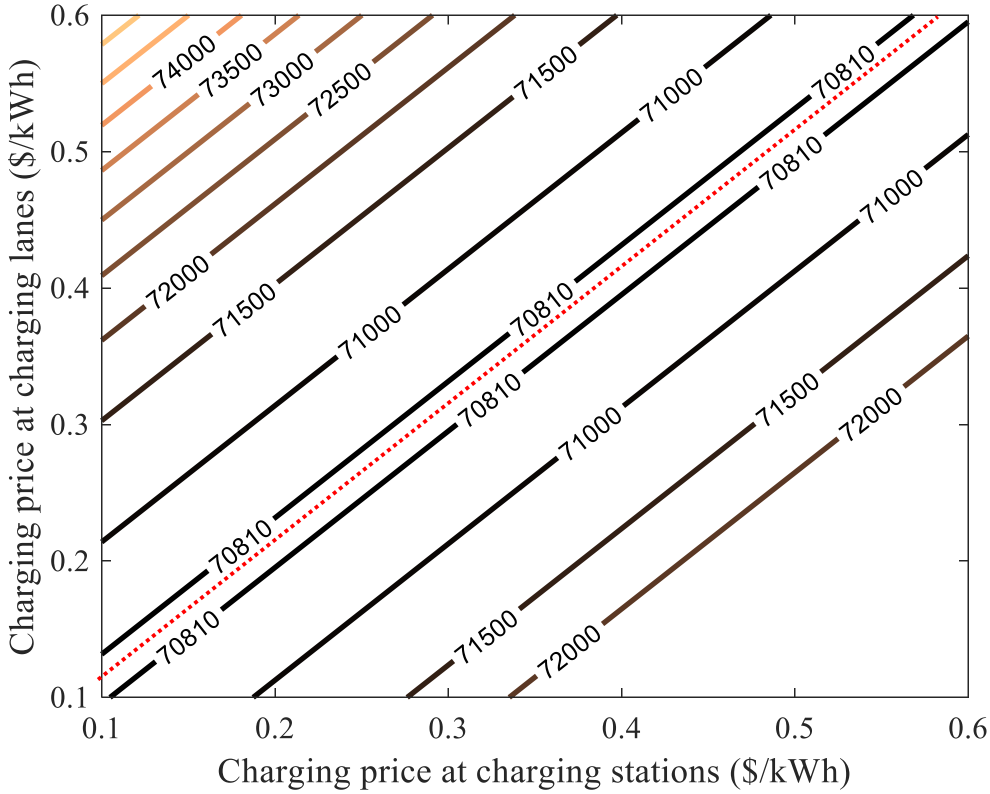

Fig. 2 Change of social cost ($) in the two-dimension space of charging prices at charging stations and lanes

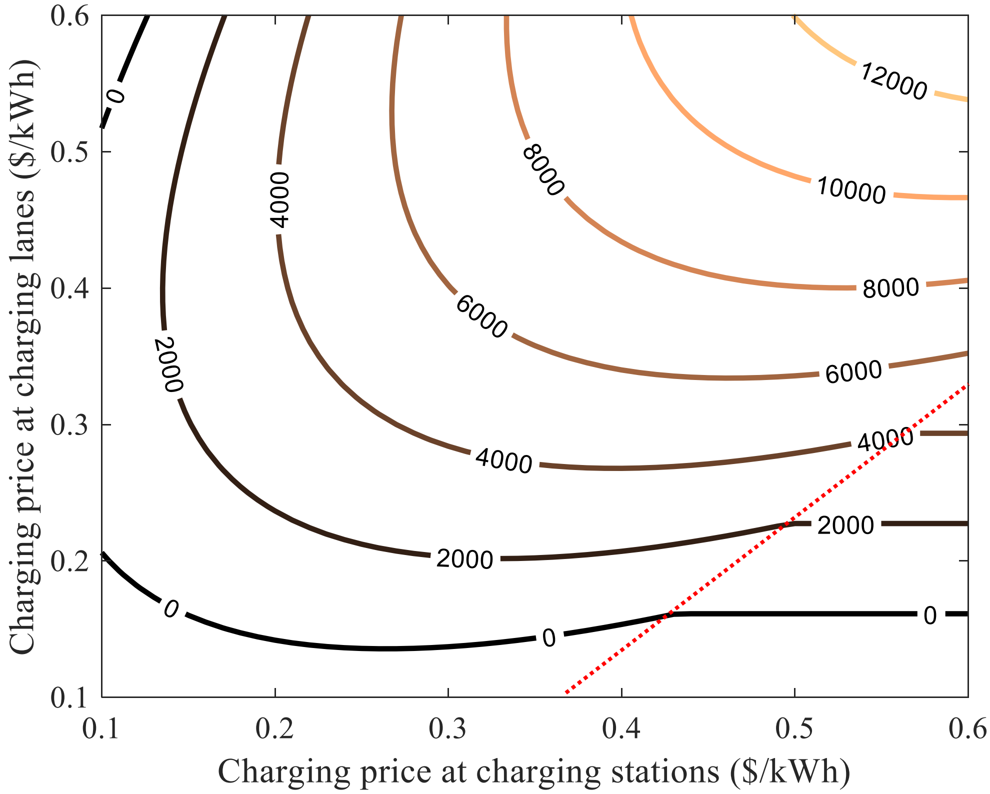

Fig. 3 Change of profit ($) in the two-dimension space of charging prices at charging stations and lanes

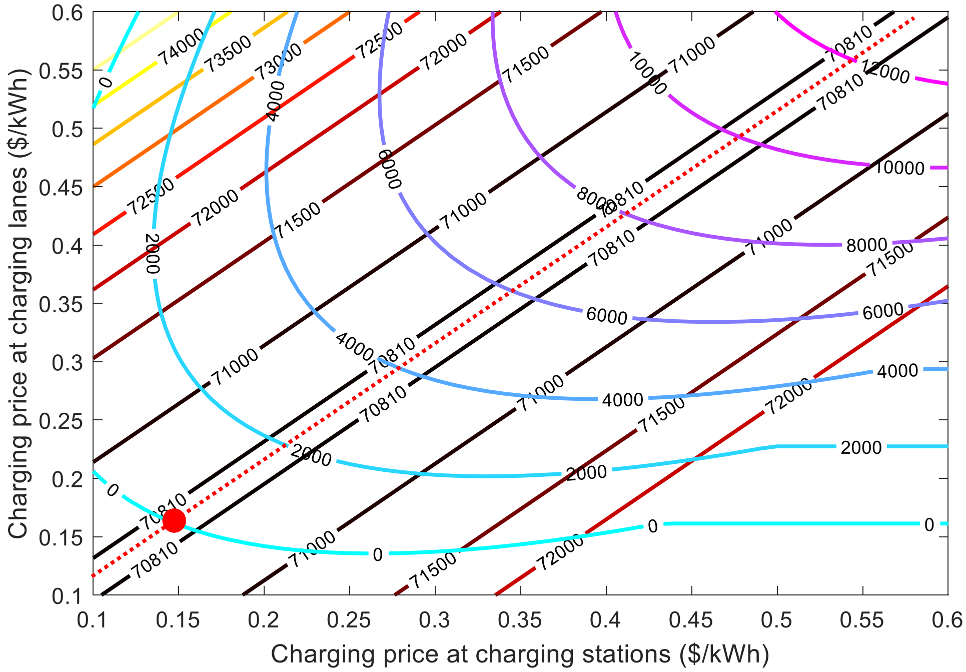

Fig. 4 Change of social cost and profit ($) in the two-dimension space of charging prices at charging stations and lanes

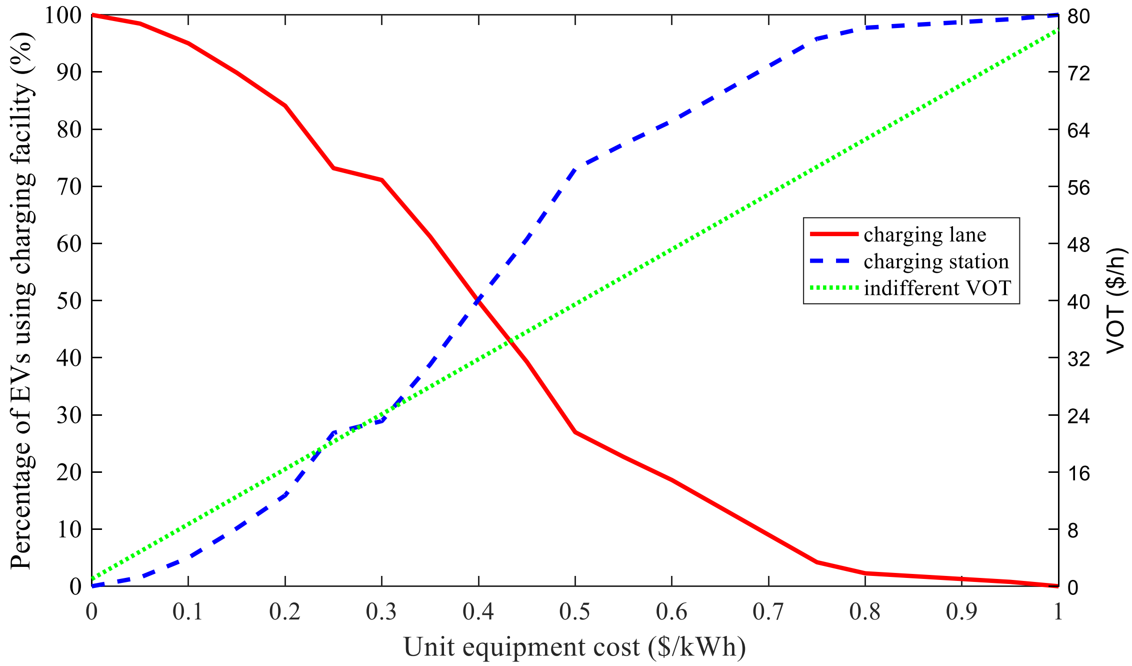

Fig. 5 Relation among the indifferent VOT, the charging facility choice, and the unit equipment cost

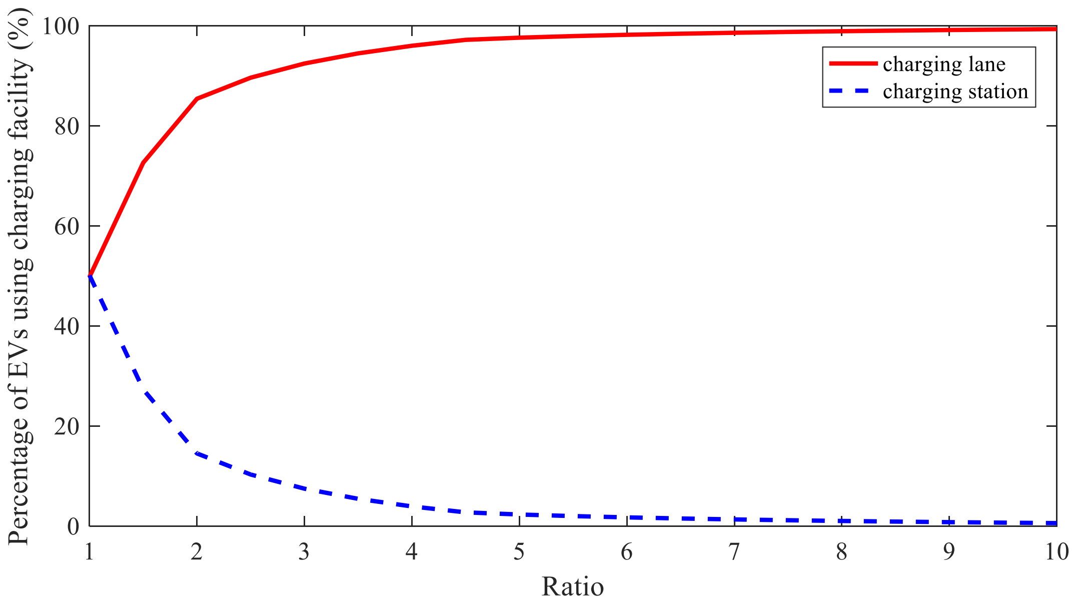

Fig. 6 Relation between the charging facility choice and various VOT distributions

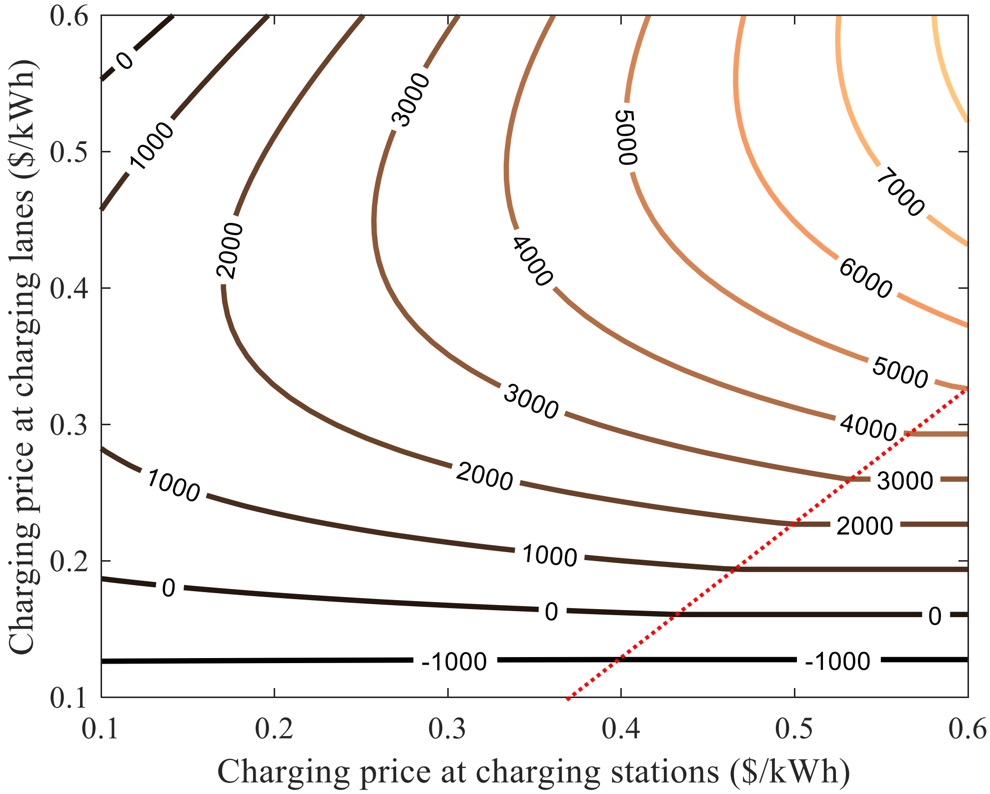

Fig. 7 Change of profit ($) of the charging-lane operator in the two-dimension space of charging prices at charging stations and lanes

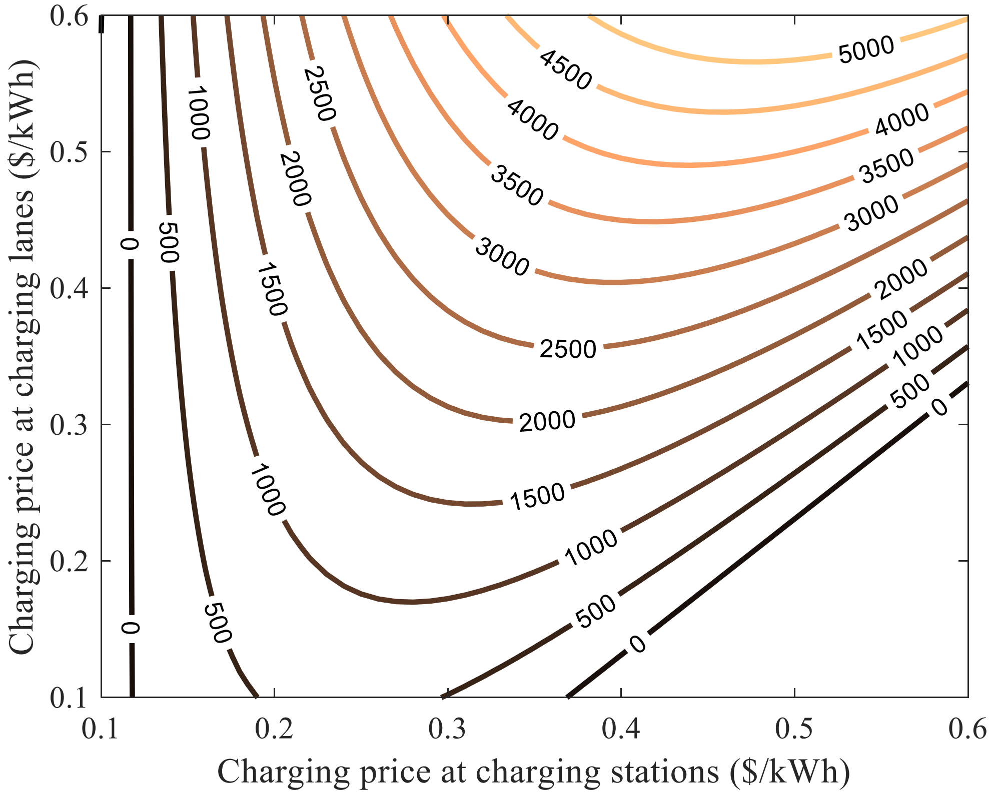

Fig. 8 Change of profit ($) of the charging-station operator in the two-dimension space of charging prices at charging stations and lanes

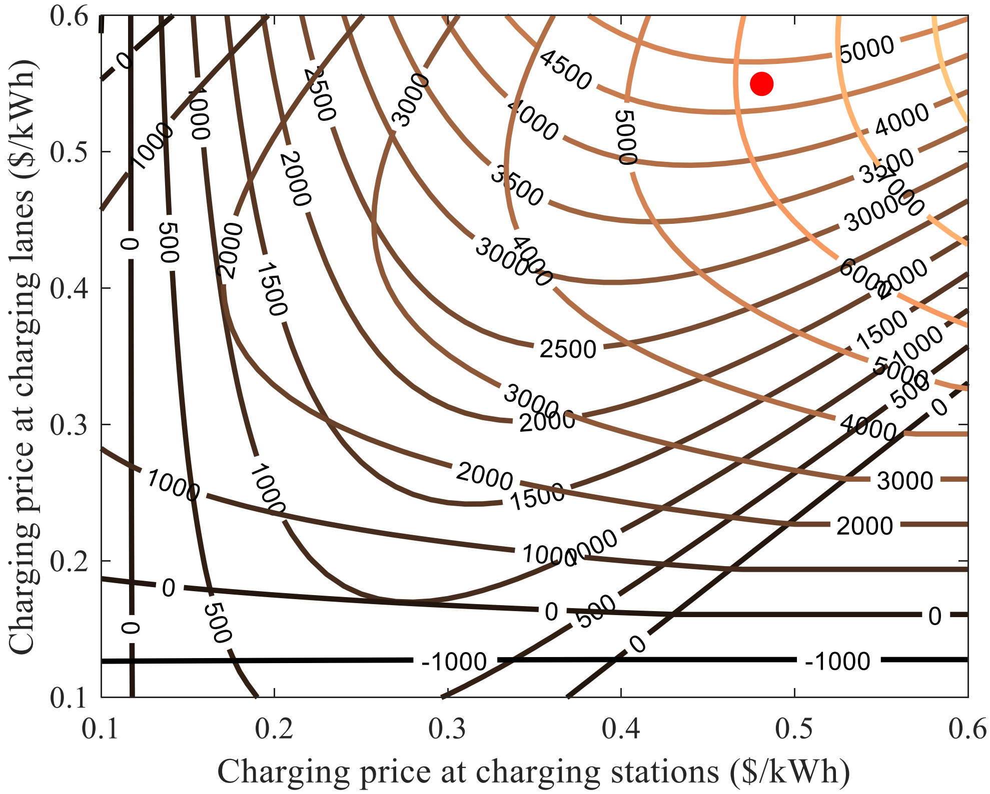

Fig. 9 Change of profit ($) of the two operators in the two-dimension space of charging prices at charging stations and lanes

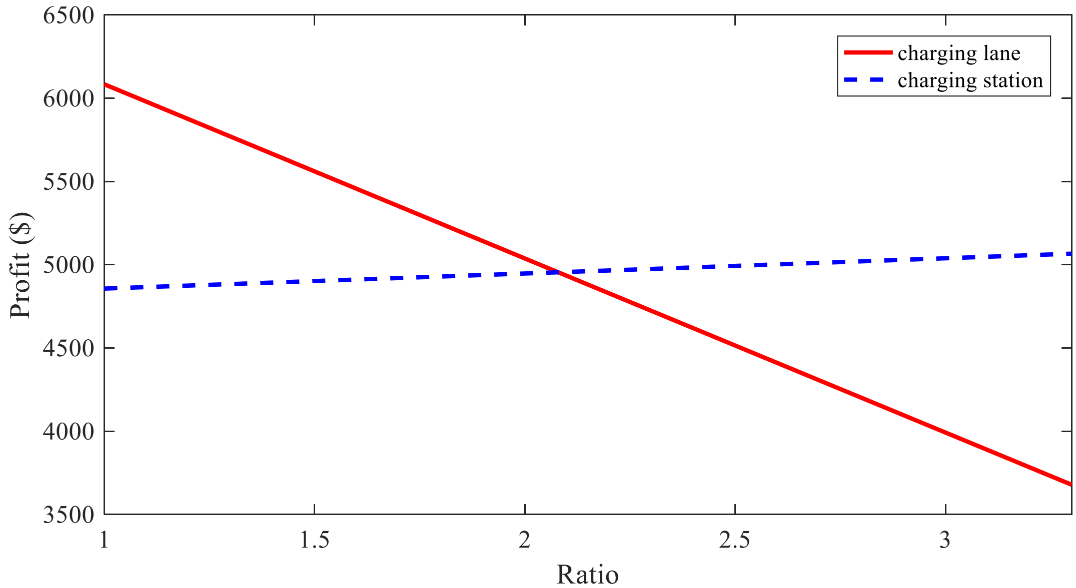

Fig. 10 Relation between profits of operators and the increasing construction cost of charging lanes

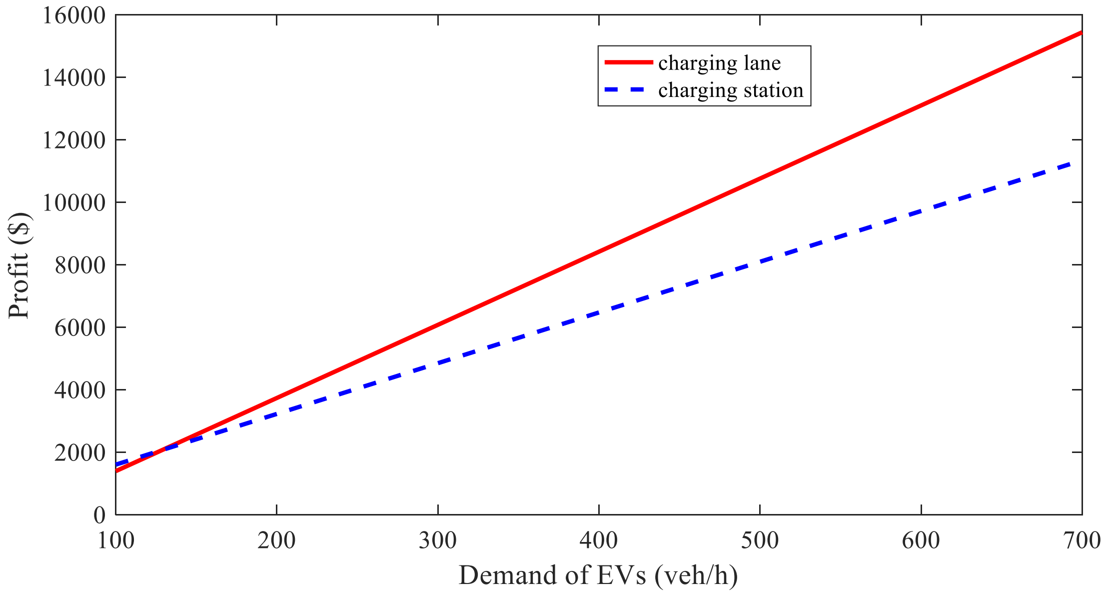

Fig. 11 Relation between profits of operators and EV demand

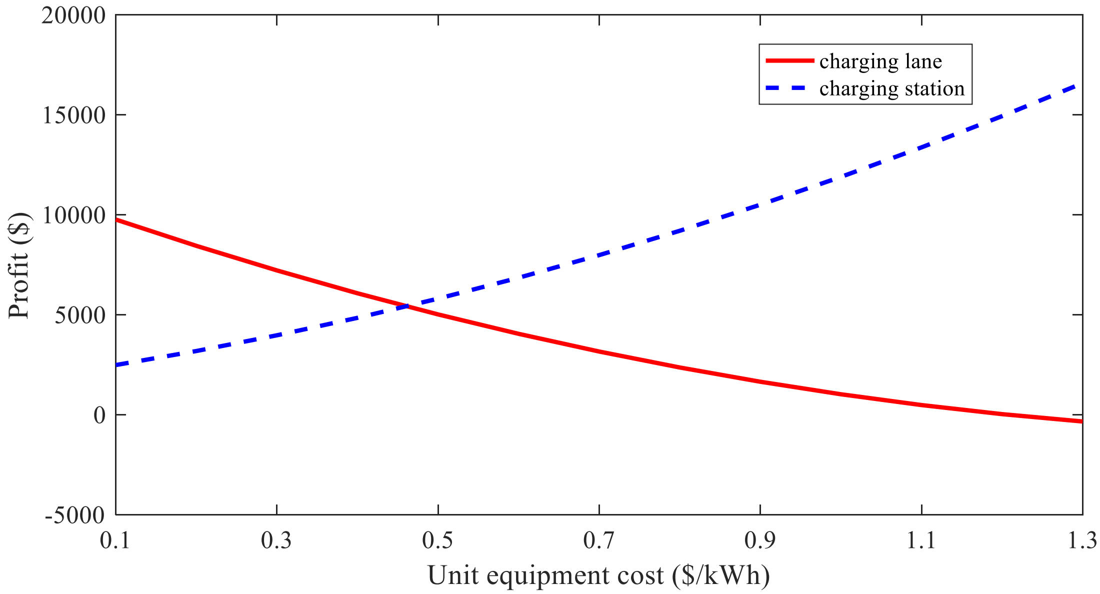

Fig. 12 Relation between profits of operators and the unit cost of CWD equipment

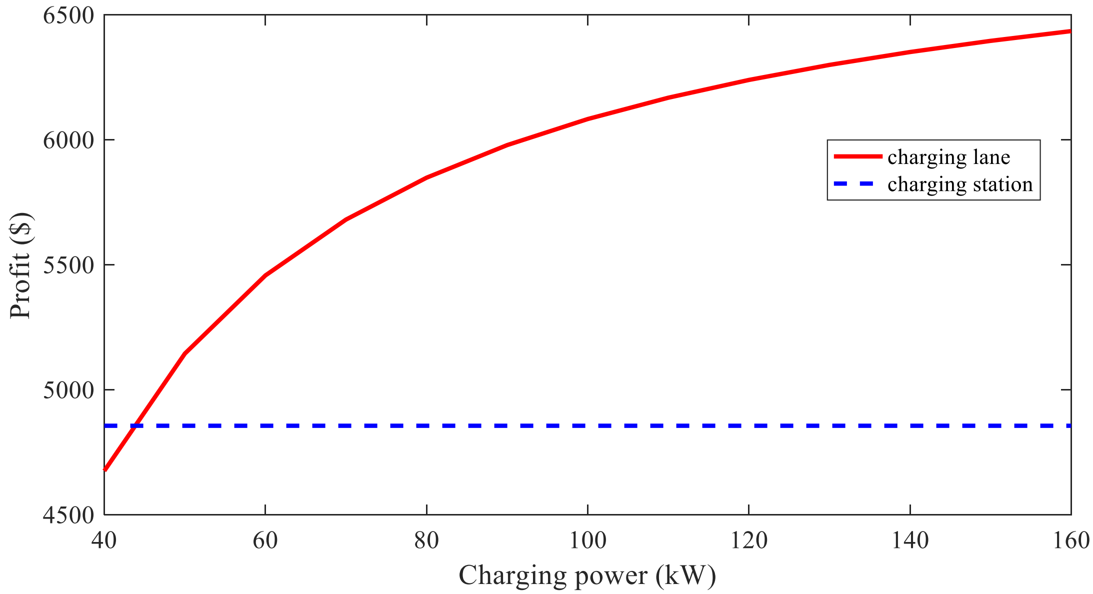

Fig. 13 Relation between profits of operators and the charging power of charging lanes

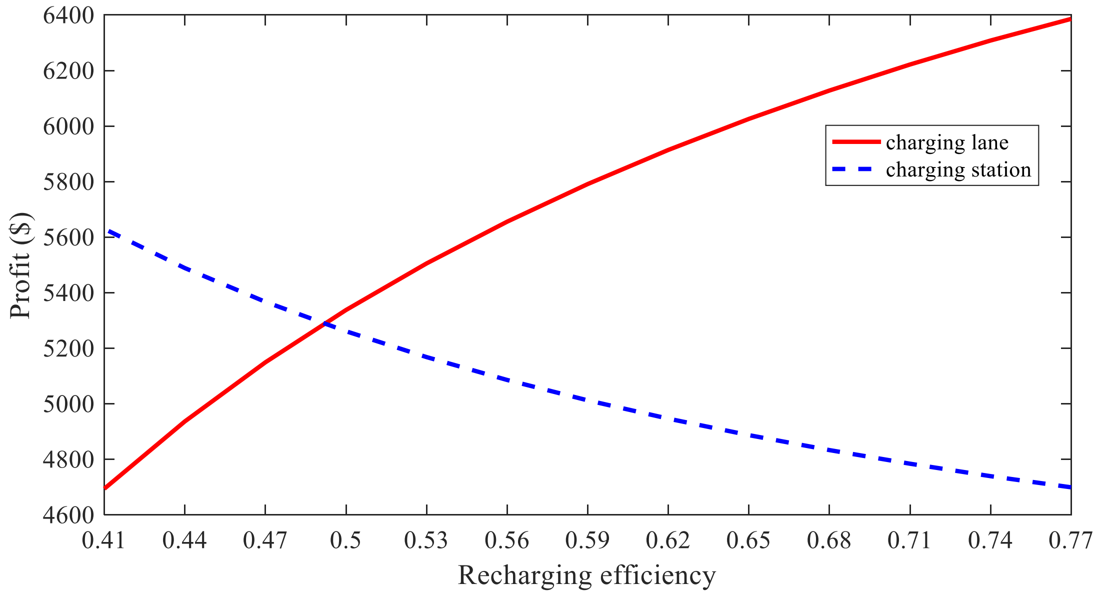

Fig. 14 Relation between profits of operators and the recharging efficiency of charging lanes

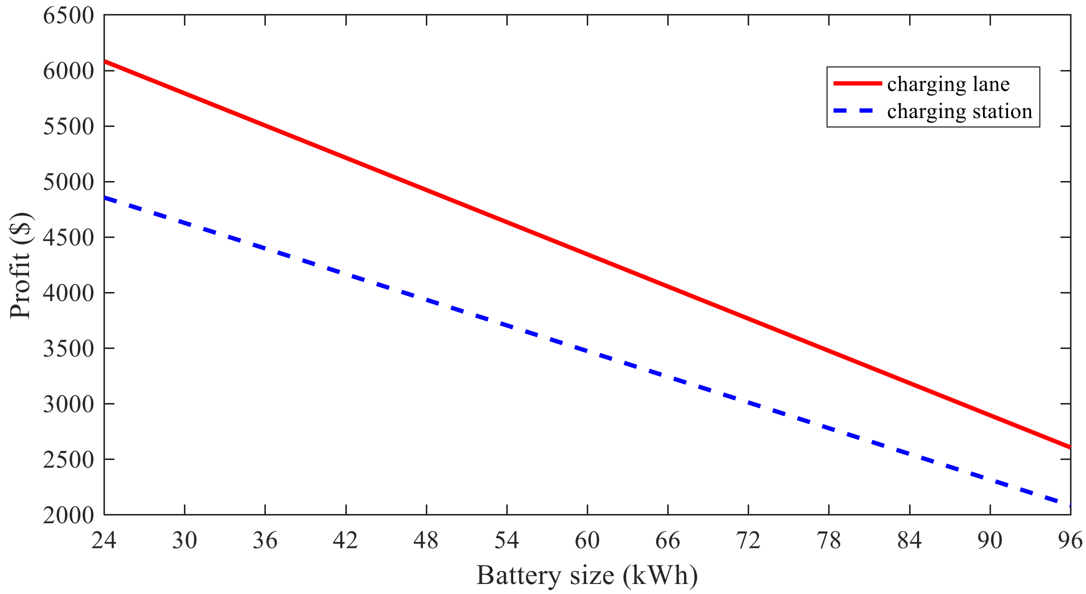

Fig. 15 Relation between profits of operators and battery size

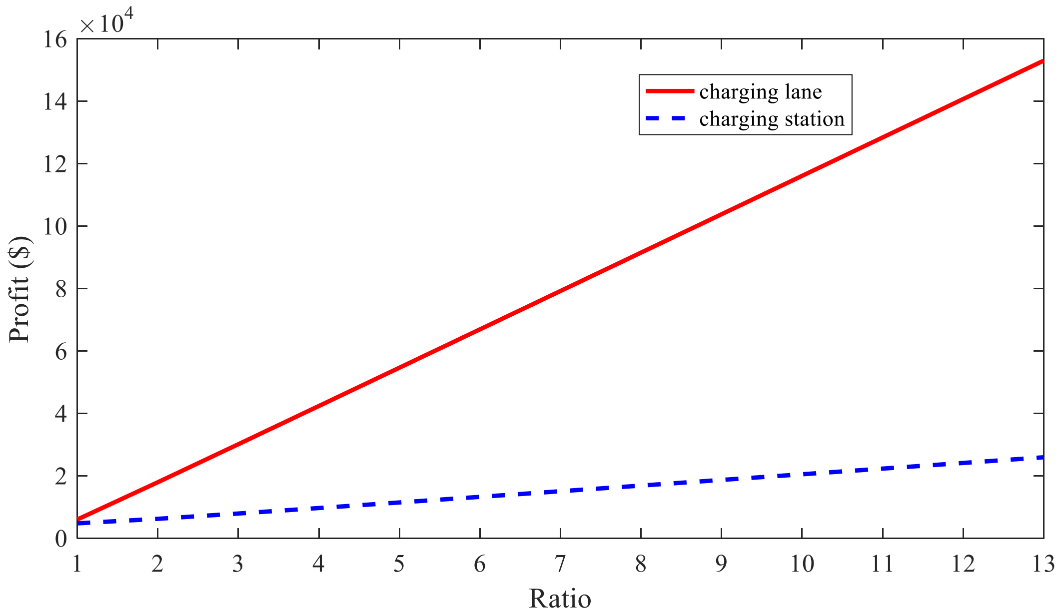

Fig. 16 Relation between profits of operators and various VOT distributions

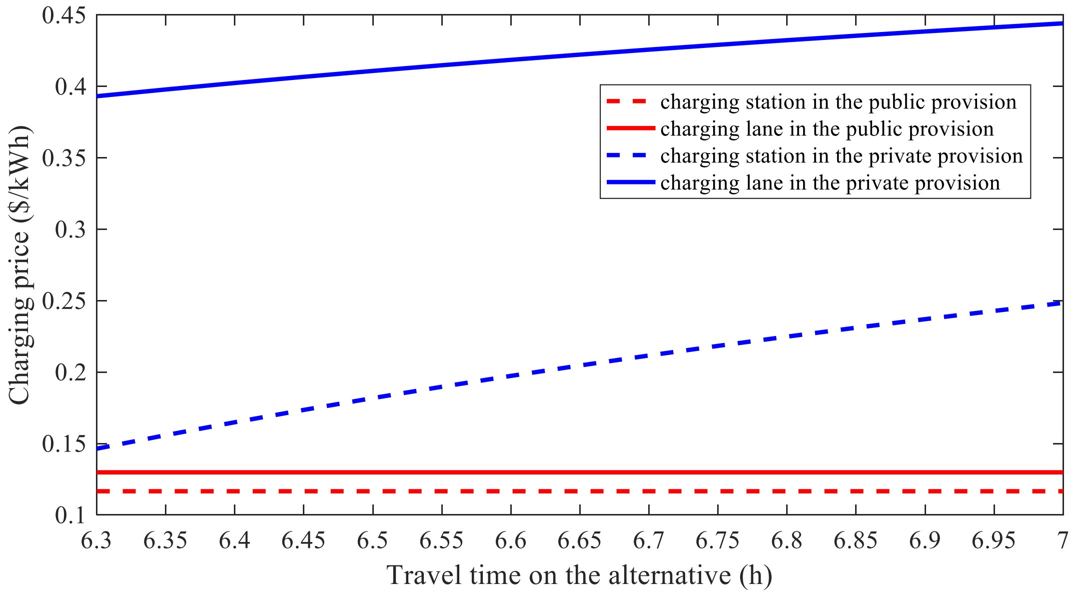

Fig. 17 Relation between charging prices and travel time on the alternative

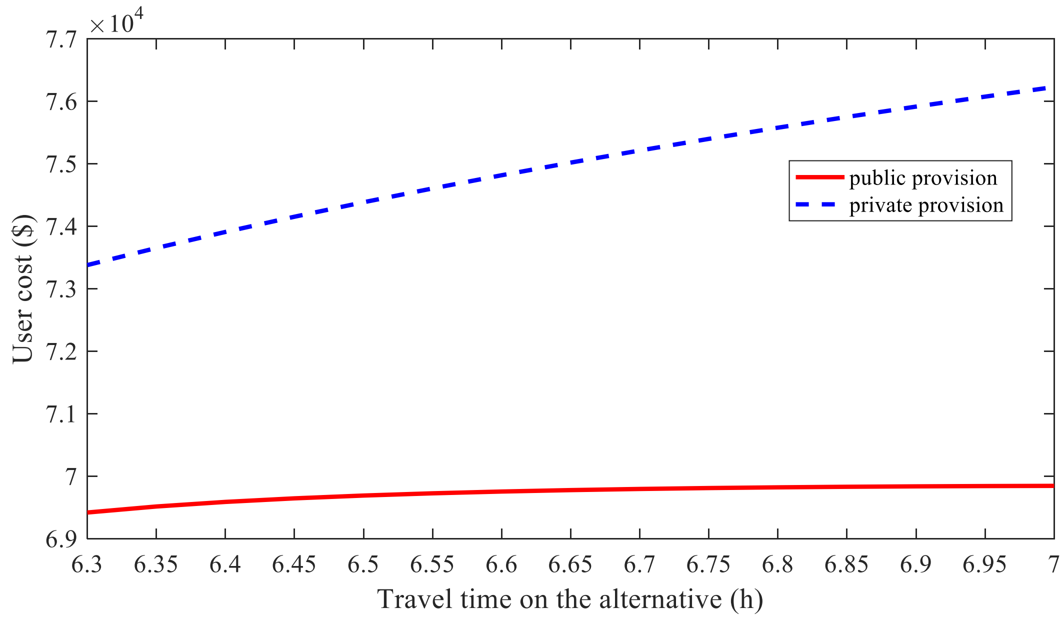

Fig. 18 Relation between social costs and travel time on the alternative

Table 1 Indifferent VOT

Variable	Partial derivative of γ^*
α	$\frac{\partial \gamma^*}{\partial \alpha} = (q_l + c_e - q_s) \cdot P_s > 0$
P_s	$\frac{\partial \gamma^*}{\partial P_s} = (q_l + c_e - q_s) \cdot \alpha > 0$
q_s	$\frac{\partial \gamma^*}{\partial q_s} = -\alpha P_s < 0$
q_l	$\frac{\partial \gamma^*}{\partial q_l} = \alpha P_s > 0$
c_e	$\frac{\partial \gamma^*}{\partial c_e} = \alpha P_s > 0$

Table 2 Indifferent VOT at the optimum for the public provision

Variable	Partial derivative of γ^*
α	$\frac{\partial\gamma^*}{\partial\alpha} = \frac{\alpha B_l P_s}{\xi} + \left(\frac{q_0}{\xi} + c_e\right) P_s > 0$
ξ	$\frac{\partial\gamma^*}{\partial\xi} = -\frac{\omega\alpha B_l P_s + q_0 \alpha P_s}{\xi^2} < 0$
P_s	$\frac{\partial\gamma^*}{\partial P_s} = \frac{\omega\alpha B_l + q_0\alpha}{\xi} + \alpha c_e - \omega B_s^1 - q_0$
q_0	$\frac{\partial\gamma^*}{\partial q_0} = \frac{(\alpha - \xi)P_s}{\xi} > 0$
c_e	$\frac{\partial\gamma^*}{\partial c_e} = \alpha P_s > 0$
B_s^0	$\frac{\partial\gamma^*}{\partial B_s^0} = -\omega < 0$
B_s^1	$\frac{\partial\gamma^*}{\partial B_s^1} = -\omega P_s < 0$
B_l	$\frac{\partial\gamma^*}{\partial B_l} = \frac{\omega\alpha P_s}{\xi} > 0$

Table 3 Indifferent VOT at the Nash equilibrium for the private provision

Variable	Partial derivative of γ^*
α	$\frac{\partial \gamma^*}{\partial \alpha} = \frac{1}{3}\left[\frac{\alpha B_l P_s}{\xi} + \left(\frac{q_0}{\xi} + c_e\right) P_s\right] > 0$
ξ	$\frac{\partial \gamma^*}{\partial \xi} = -\frac{\omega \alpha B_l P_s + q_0 \alpha P_s}{3\xi^2} < 0$
P_s	$\frac{\partial \gamma^*}{\partial P_s} = \frac{1}{3}\left[\frac{\omega \alpha B_l + q_0 \alpha}{\xi} + \alpha c_e - \omega B_s^1 - q_0\right]$
q_0	$\frac{\partial \gamma^*}{\partial q_0} = \frac{(\alpha - \xi) P_s}{3\xi} > 0$
c_e	$\frac{\partial \gamma^*}{\partial c_e} = \frac{\alpha P_s}{3} > 0$
B_s^0	$\frac{\partial \gamma^*}{\partial B_s^0} = -\frac{\omega}{3} < 0$
B_s^1	$\frac{\partial \gamma^*}{\partial B_s^1} = -\frac{\omega P_s}{3} < 0$
B_l	$\frac{\partial \gamma^*}{\partial B_l^1} = \frac{\omega \alpha P_s}{3\xi} > 0$

Table 4 Parameter definitions and default values

Parameter	Description	Value
f	Demand of EVs in the corridor	300 veh/h
l	Corridor length	300 mi
v	Average speed along the corridor	65 mph
α	Recharging efficiency for charging stations	0.77
ξ	Recharging efficiency for charging lanes	0.67
β	Battery performance	2.5 mi/kWh
θ	Range anxiety factor	0.8
ω	Converting factor (converting the total cost into hourly cost)	1.19×10^{-5}
E	Battery size	24 kWh
c_e	Unit cost of CWD equipment	\$0.4/kWh
q_0	Cost to produce and transmit one unit of electricity for charging facilities	\$0.08/kWh
P_s	Electric power of charging station	100 kW
P_l	Electric power of charging lane	100 kW
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	Operation and maintenance cost per unit of charging power	\$500/kW
A_l	Construction cost for building one mile of charging lane	\$800,000/mi
B_l	Construction cost per unit of charging power	\$550/kW

Table 5 VOT distribution of passenger cars for survey respondents traveling on Interstate 95 express corridor (reproduced by authors based on Perk et al. (2011))

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
>60	2.6	100