IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 11 June 2024, accepted 23 June 2024, date of publication 24 June 2024, date of current version 2 July 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3418996

RESEARCH ARTICLE

Competition and Pricing Strategy of Electric Vehicle Charging Services Considering Mobile Charging

YATING DING [1], FENG CHEN [1], JIANGHONG FENG [2], AND HUIBING CHENG [3]

[1] School of Management, Jinan University, Guangzhou 510632, China
[2] School of Economics and Management, South China Agricultural University, Guangzhou 510640, China
[3] School Transportation and Logistics, Guangzhou Railway Polytechnic, Guangzhou, Guangdong 510430, China

Corresponding author: Feng Chen (1007jn@stu2021.jnu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 72071093 and in part by the New Talent Research Project of Guangzhou Railway Polytechnic under Grant GTXYR2208.

ABSTRACT Electric vehicles (EVs) have emerged as the pivotal strategy for mitigating carbon emissions. Nevertheless, the lack and imbalance of charging facilities have greatly reduced consumers' willingness to buy EVs, thereby leading to stagnation in the EV market. Although many studies focus on the imbalance in the EV market, few of them have explored the pricing strategies of charging service providers from the perspective of consumers. Therefore, to assist charging service providers in optimizing pricing decisions, we propose a consumer-perspective utility model. Specially, this utility model analyzes both time and travel costs. Furthermore, considering three charging technologies including fixed charging, mobile charging vehicles, and mobile charging robots, we then apply game theory to characterize charging services providers competition scenarios between charging services providers. After theoretical and numerical analyses, we have the following five conclusions: 1) with the high time cost for consumers, the profits of fixed charging exceed those of mobile charging vehicles; 2) mobile charging robots intensify competition in the charging market and lower the price of conventional charging services; 3) mobile charging robots also reduce the demands for fixed charging services and expedite technological substitution; 4) cost of consumers time has a positive influence on mobile charging vehicles but a negative effect on other charging services; and 5) profits of the three charging providers increase with higher consumer time costs. Finally, we propose an innovative market analyzing tool based on research findings to assist charging service providers in their decision-making process.

INDEX TERMS Game theory, electric vehicles charging, mobile charging vehicles, mobile charging robots, pricing strategy.

I. INTRODUCTION

Carbon emissions contribute to environmental pollution and adversely affect human health [1], [2]. The primary source of carbon emissions is the combustion of fossil fuels [3], such as fuel vehicles [4]. Additionally, survey data indicate that road transport is a significant contributor to global carbon emissions [5]. Therefore, Electric vehicles (EVs) have attracted significant attention from many countries as a sustainable transportation option. Several governments have expressed a strong commitment to reducing carbon emissions during transportation. For example, the European Union (EU) plans to ban the sale of new petrol and diesel cars by 2035 [6]. The US invests 7.5 billion dollars to build a national network of EVs [7]. China strives to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 [8]. Therefore, the development of EVs is necessary to replace fueled vehicles and reduce road carbon emissions [9], [10].

However, the existing charging infrastructure limits the development of EVs [11], [12]. Specifically, charging

The associate editor coordinating the review of this manuscript and approving it for publication was Junho Hong.

technology faces two main problems: high damage rates and long queues at fixed charging stations [13], [14]. Additionally, the number of fixed charging infrastructure is limited by the power grid and land availability [9]. Simultaneously, many researchers found that the stochastic charging/discharging of electric vehicles would result in a large impact on the security and stable of the electric grids [15], [16], [17], [18]. Mobile charging vehicles also have several problems such as long waiting times for service and high pricing [19]. Although a mobile charging robot is a new technology that can address the above problems, it has yet to be widely adopted [20]. Therefore, these factors lead to insufficient resources for the charging infrastructure and hinder the growth of the EV market.

To enhance charging infrastructure and promote the EV industry, new mobile charging robots are expected to compensate for the inadequacy of conventional charging methods [20]. These robots are intelligent and provide automatic charging services within a limited range [21]. They embody a fusion of the maneuverability inherent in mobile charging vehicles and the reliability characteristics of fixed charging stations [22].

Nevertheless, extant scholarly endeavors have predominantly focused on the delineation of location strategies and the infrastructure of fixed charging stations [23], [24], [25]. A paucity of research has delved into the distinctive attributes and operational paradigms underpinning mobile charging methodologies [26], [27], [28]. To fill this gap and provide strategic direction to fee-for-service providers, this study attempts to answer the following question. First, what is the difference between the service methods of mobile charging robots and mobile charging vehicles? Second, what is the equilibrium pricing strategy for mobile charging robots? Finally, what is the impact of the new technology on the market? How should charging service providers adjust their business strategies based on the development of charging technology?

To answer these questions, we first formulate a game-theoretic framework for multiple charging service providers. Second, we present a combination of theoretical and numerical analyses to determine the equilibrium pricing of mobile charging robots. The analysis also examines the impact of mobile robots on other players. In addition, we analyze the impact of consumer time and travel cost on the equilibrium pricing strategy. Finally, we analyze this issue from the perspective of EV drivers(i.e. consumers), particularly the impact of different consumers' time and travel cost on the choice of charging technology. The research outline of this study can be represented by a flow chart as follows figure 1.

We contribute to the EV charging competition literature in the following three aspects. First, We extend the literature on competition in the EV charging service market. Unlike prior studies [23], [24], [25], [29], [30], [31], [32], we incorporate the demand function of EV charging services, accounting for consumers' time and travel costs. Secondly, we analyze and contrast the characteristics of mobile charging vehicles and mobile charging robots. Thirdly, this paper delves into the competitive landscape and pricing strategies of various EV charging services, offering insights into how charging service providers can devise effective strategies to enhance profitability. While existing research primarily focuses on the configuration and pricing of mobile charging vehicles and fixed charging stations, our study extends to encompass the pricing strategy of mobile charging robots and their impact on the charging service market. The contributions of this study can be summarized as follows:

- We discuss the pricing and impact of mobile charging robots. This study is noteworthy for being the first to propose a pricing method for mobile charging robots grounded in game theory, as well as for comparing the distinctions between mobile charging robots and mobile charging vehicles, and exploring their implications on the charging service market from our observation.
- We formulate a game-theoretic framework to portray the competitive equilibrium pricing between different charging technologies. As far as we are aware, no research has ever been conducted on the three charging technologies competition and pricing strategy. This study uses a static complete information game and a two-stage Stackelberg game to distinguish between different charging technology stages.
- We discuss the changes in equilibrium pricing and analyze the impact of mobile charging robots on the original players' pricing and profits. Few studies have discussed the impact of mobile charging robots on the market is demonstrated. Our results provide reliable recommendations for charging service providers to adjust their business strategy.
- We propose an innovative decision-making mechanism aimed at aiding fee-for-service providers. Drawing upon the analysis of consumers' time cost, travel cost, and charging vehicle service costs presented in this study, we have developed both a flowchart and a coordinate diagram, as demonstrated in the conclusion. This diagram illustrates how the research presented in this study provides practical guidance to charging service providers, enabling the formulation of informed and scientifically grounded business strategies.

To the best of our knowledge, the study is one of the few attempts to investigate the impact of the three types of charging infrastructure on the charging market from the perspective of EV drivers. The implications and significance of our study are as follows:

- **EV Infrastructure Development.** This study analyzes the differences in EV charging methods to assist investors in selecting appropriate charging technology under different conditions.
- **Future Research and Innovation.** The results of this study extend to the impact of new technology on the future, analyzing the characteristics of new technology

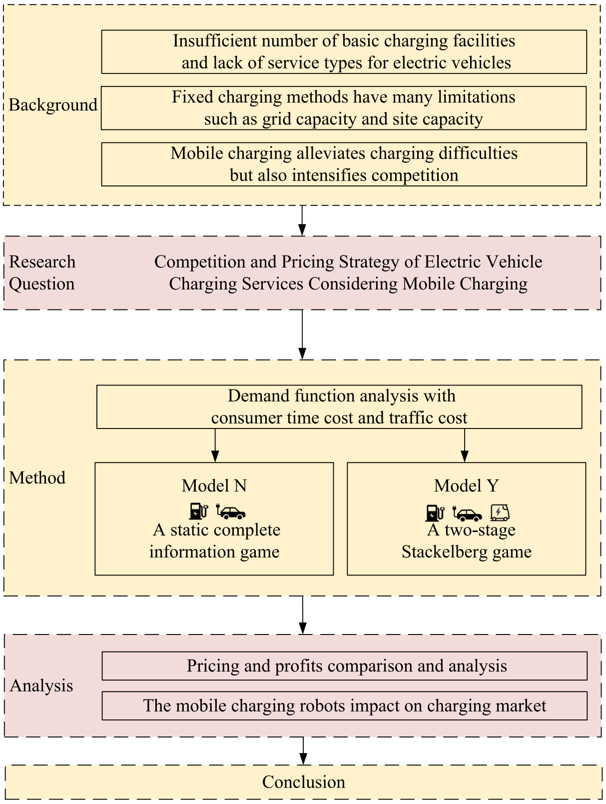

FIGURE 1. Research outline.

and laying the groundwork for innovation in business models for mobile charging technology.

- **Carbon reduction and environmental protection.** This study provides a more precise description of the conditions that facilitate the use of various charging technologies. This is of practical value for the development of charging infrastructure, promotion of EV utilization, and reduction of carbon emissions.

The remainder of this paper is organized as follows. In Section II, we review the relevant literature. Section III presents consumer demand and charging service provider profit models. In Section IV, we analyze the equilibrium pricing strategy for charging services. In Section V, we present our conclusions and potential directions for future work.

II. LITERATURE REVIEW

This section reviews publications relevant to our study in three research fields: (1) Competition and pricing of charging service construction. (2) Charging site selection and path planning. (3) Mobile charging services. This study contributes to EV-charging providers.

A. COMPETITION AND PRICING OF CHARGING SERVICE CONSTRUCTION

Currently, research on EV charging services focuses on charging service construction competition and pricing which considers user preferences. Duan et al. consider the EV charging facility construction strategy affected by consumer queuing [23]. Lee et al. investigate the price competition between heterogeneous EV charging stations [24]. Gupta et al. investigate pricing strategies for charging stations in non-cooperative games with user location awareness [30]. Hu et al. compare EV charging and battery-swapping choices in the context of consumer opportunity cost differences [33]. Some researchers focus on the impact of transportation networks on electric charging competition. Lai et al. [34] considering the competition effect established based on the traffic network, is formulated to facilitate the charging stations to attract the defined competitive charging demand. Yang et al. [35]model the noncooperative pricing game of self-interested fixed charging stations, taking into account the complex interactions between the EV users and the coupled operation of transportation network and power distribution network.

While the above literature considers a fixed charging station construction strategy under consumer preferences, it rarely considers the competition when different charging technologies are available.

B. CHARGING SITE SELECTION AND PATH PLANNING

Furthermore, numerous studies have concentrated on the development of charging stations for EVs, including the challenges related to their placement and the planning of charging routes. Zhao et al. study the site selection optimization problem of new entrants to competitors' fixed charging stations [36]. Feng et al.propose a multi-criteria EV charging station site selection decision from a sustainability perspective [25]. Xu et al. focus on the charging station location problem of consumer range anxiety and path deviation [37]. Schoenberg et al. use centralized charging station data to coordinate EV charging and reduce waiting times [38]. Chung et al.consider the double objective optimization problem of charging cost and user convenience and propose the application of centralized scheduling and low-complexity distributed algorithms to EV charging paths [39].

The literature above examines site selection decisions that consider consumer charging cost but overlooks differences in consumer preferences between various charging technologies.

C. MOBILE CHARGING SERVICE

In addition to the construction of fixed charging stations, scholars have focused on the characteristics of mobile charging methods [26], mobile charging service models [27], [31], [40] and mobile charging route planning [28], [41]. Wang et al. consider that mobile charging is more flexible than fixed charging when considering the time cost. Mobile charging is also limited by its service cost and charging efficiency of mobile charging [26]. Zhang et al. and Tang et al. propose online booking of mobile charging system planning and operation scheduling and propose that mobile charging can be used as a supplement to fixed charging [27], [40]. Wang et al. investigate a hybrid charging system comprising fixed charging and mobile charging vehicles [31]. By considering demand distribution characteristics, they argue that mobile charging is a relatively high-cost, high-return, and high-risk option. The above literature considers the differences between charging technologies and analyzes the service characteristics of mobile charging. However, they rarely describe service methods for mobile charging robots. Qureshi et al. propose mobile charging vehicle scheduling with random driving time [28]. Liu et al. focus on mobile charging vehicle task allocation and the charging path optimization process [41]. Owing to the high operating cost of mobile charging vehicles, with the development of intelligent technology, automatic charging such as mobile charging robots has gradually emerged [32], [42], [43], [44]. Zhang et al., Fu et al., and Kong et al. design an online scheduling and charging strategy for mobile charging robots to use tracking and positioning to realize automatic charging of EVs and unbind charging facilities from parking spaces [32], [42], [43]. Zhang et al. analyze the mobile charging robot is responsible for the coordination of power distribution networks and operators in charging prices and power, which increases the operators' charging revenue [44].

The above literature discusses the characteristics and applications of mobile charging robots but lacks the pricing of mobile charging robots and their impact on the charging service market.

D. UNIQUENESS AND CONTRIBUTIONS OF THIS STUDY

However, most studies focus on achieving economic benefits while considering preferences for the development of EV charging services. There is a lack of emphasis on analyzing mobile charging service technologies and models. Furthermore, there is also a lack of research on the pricing strategies of mobile charging robots, their impact on the charging services market, and the necessary adjustments that charging service providers should make to address the increasingly competitive environment. Our study examines competition and pricing strategies in the EV charging market, with a particular focus on mobile charging robots and vehicles that consider consumers' time cost. This study explores an optimal strategy for charging service operators with different consumer preferences. In addition, it extends previous work on the impact of new participants and analyzes how to adjust the charging management strategies. We compare the profits of charging service providers using different modes and add new findings to the literature.

III. MODEL DESCRIPTION

A. PROBLEM DESCRIPTION

In this study, we examine the market for EV charging services that includes a fixed charging service provider (e.g. TELD) and two mobile charging service providers (e.g. NIO Company and Sator Technology). Three types of charging service providers are shown in Figure 2. This study considers

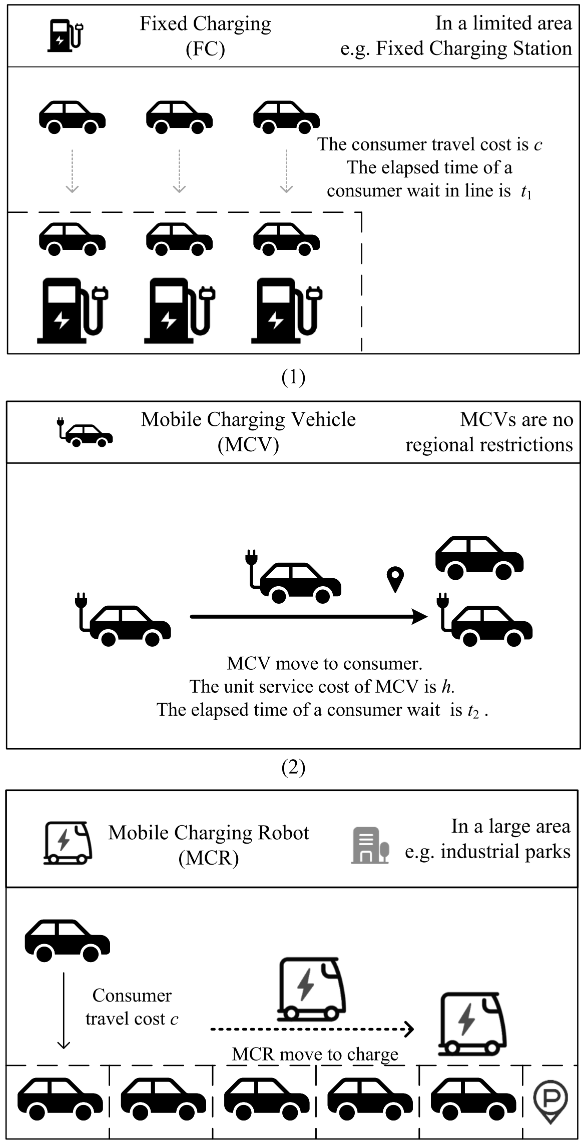

FIGURE 2. Three types of EV charging services.

two competition modes based on the time sequence of mobile charging robots entering the market. The first mode, called Mode N, studies competition and pricing in the charging service market of fixed charging (subscript f) and mobile charging vehicles (subscript m). The second mode, called Mode Y, is a two-stage Stackelberg game in which fixed charging providers and the mobile charging vehicle providers make pricing decisions first, followed by mobile charging robots (subscript b) making pricing decisions. This study examines the variables that influence the pricing of charging services and considers the cost of time and travel cost. Table 1 presents the symbols and definitions of the variables used in the study.

In this section, we introduce two competitive scenarios for the three charging services, Mode N and Mode Y. Subsequently, we analyze the impact of time cost and travel

TABLE 1. Variable and definitions.

Variable	Definitions
$U_{i\in\{m,f,b\}}$	The utility gained by consumers from accepting charging services
$p_{i\in\{m,f,b\}}$	Charging price
$q_{i\in\{m,f,b\}}$	Demand for different charging services
$\pi_{i\in\{m,f,b\}}$	Charging services providers profits
v	Consumers' value of charging services
c	Consumers travel unit cost
θ	Consumer unit time cost, θ Satisfies the uniform distribution of $[0, \Theta]$
k	Entry costs of mobile charging robots
t_1	The elapsed time of a consumer waits in line for fixed charging
t_2	The elapsed time of a consumer wait for the mobile charging vehicle
h	Mobile charging vehicles unit service cost

cost on consumer utility to derive the demand function for charging services. The SectionIII-Cwill demonstrate the profit function of the charging service provider, which will facilitate a more comprehensive analysis of the two competitive scenarios. In Section IV, we show the equilibrium solution and equilibrium analysis of the two modes.

B. CONSUMER CHARGING DECISION

When consumers choose charging services, they compare the utility of the different services. Assume that the consumer's perceived value of the charging service is v, and the unit waiting time cost is Θ. If consumers choose fixed charging, they may encounter an insufficient number of charging stations. The elapsed time for a consumer waiting in line is t_1, and the transportation cost of driving to a fixed charging station is c. The fixed charging price is p_f. Therefore, the consumer utility gained from choosing a fixed charging mode is:

$$U_f = v - p_f - c - \theta t_1 \tag{1}$$

If consumers choose the mobile charging vehicle, the elapsed time of a consumer wait for the charging vehicle to arrive is t_2, the unit charging cost of the mobile charging vehicle is p_m, and the utility obtained by the consumer is:

$$U_m = v - p_m - \theta t_2 \tag{2}$$

Mobile charging robots are typically installed in locations such as shopping malls, commercial complexes, and industrial parks [20]. These robots are useful in areas with low underground navigation accuracy, high passenger traffic, and high-speed service stations during holidays [26] as shown in Figure 2. If the consumer chooses the mobile charging robot service, the mobile charging robot will go to any parking space, where the consumer only needs to wait for a short time to charge. Compared with mobile charging vehicle services, mobile charging robots have a limited movement range and self-service. Therefore it is assumed that they do not need to wait. And the service costs are 0. The unit charging cost is p_b, the consumer's travel cost is c, and the utility gained by

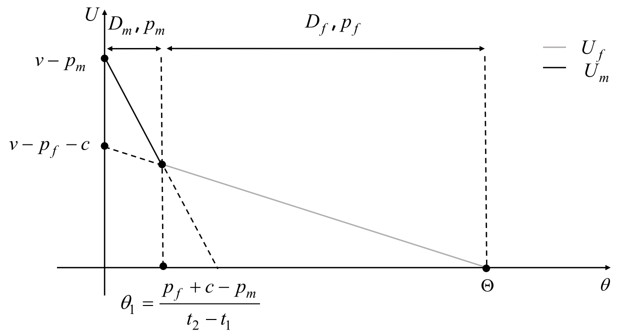

FIGURE 3. The relationship between consumer utility *U* and time cost θ in Mode N.

consumers choosing the mobile charging robot is:

$$U_b = v - p_b - c \tag{3}$$

This study assumes that consumers have no preference for the two charging services and derives the relationship between the charging demand function and time cost. The relationship between the charging demand function and time cost is derived from the consumer utility function by assuming that consumers have equal utility.

By comparing the two charging services in Mode N, two scenarios can be obtained as follows:
The consumers will choose

1) The fixed charging if

$$U_f > max\left\{U_m, 0\right\}, i.e., \theta > \frac{p_f + c - p_m}{t_2 - t_1}.$$

2) The mobile charging vehicles if

$$U_f < max\left\{U_m, 0\right\}, i.e., \theta < \frac{p_f + c - p_m}{t_2 - t_1}.$$

Assuming that the consumer's unit time cost θ satisfies the uniform distribution of $[0, \Theta]$, consumer demand and time cost are presented as a linear uniform distribution based on the relationship between consumer utility and time cost as shown in Figure 3. The charging demand of Mode N is obtained as follows:

$$q_m^N = \frac{p_f + c - p_m}{(t_2 - t_1)\,\Theta} \tag{4}$$

$$q_f^N = 1 - \frac{p_f + c - p_m}{(t_2 - t_1)\,\Theta} \tag{5}$$

By comparing the three charging services in Mode Y, Three scenarios can be obtained as follows: The consumers will choose

1) The fixed charging if

$$U_f > max\left\{U_m, U_f, 0\right\},$$
$$i.e., \frac{p_f + c - p_m}{t_2 - t_1} < \theta < \frac{p_b - p_f}{t_1 \Theta}.$$

2) The mobile charging vehicles if

$$U_m > max\left\{U_b, U_f, 0\right\},$$
$$i.e., \theta < min\left\{\frac{p_f + c - p_m}{t_2 - t_1}, \frac{p_b + c - p_m}{t_2}, \frac{v - p_b}{t_2}\right\}.$$

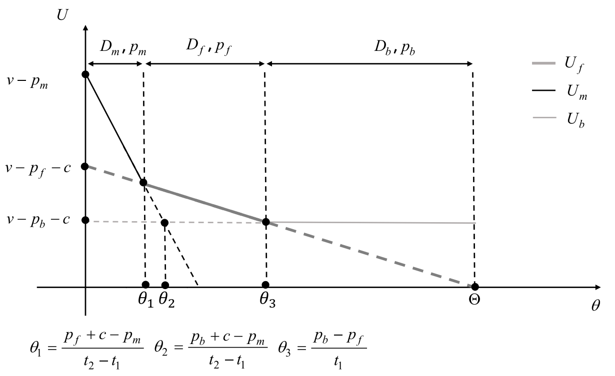

FIGURE 4. The relationship between consumer utility U and time cost θ in Mode Y.

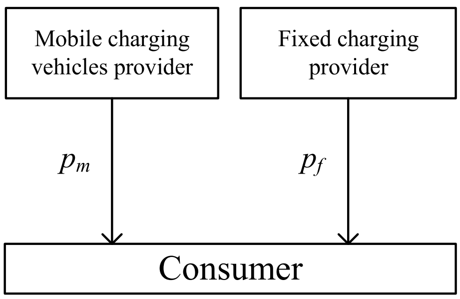

FIGURE 5. Mode N: Two charging services for consumers.

3) The mobile charging robots if

$$U_b > max\left\{U_m, U_f, 0\right\},$$
$$i.e., \theta > max\left\{\frac{p_b - p_f}{t_1\Theta}, \frac{p_b + c - p_m}{t_2}\right\}.$$

As charging technology develops, mobile charging robots join the charging service market, and the relationship between consumer utility and unit time cost is shown in Figure 4. If Mode Y is established, it satisfies $p_m < p_f + c < p_b + c$. The utility of different charging services for EV drivers can be compared using the following three scenarios:

Similarly, the charging demand in Mode Y is:

$$q_m^Y = \frac{p_f + c - p_m}{(t_2 - t_1)\,\Theta} \tag{6}$$
$$q_f^Y = \frac{p_b - p_f}{t_1\Theta} - \frac{p_f + c - p_m}{(t_2 - t_1)\,\Theta} \tag{7}$$
$$q_b^Y = 1 - \frac{p_b - p_f}{t_1\Theta} \tag{8}$$

According to the different participants in the development stage of the EV charging technology, this study constructs two market competition modes N and Y as shown in Figure5-Figure6.

C. EV CHARGING SERVICE COMPETITION MODEL

In Mode N, fixed charging and mobile charging vehicles make simultaneous decisions. In Mode Y, fixed charging and mobile charging vehicles make simultaneous decisions

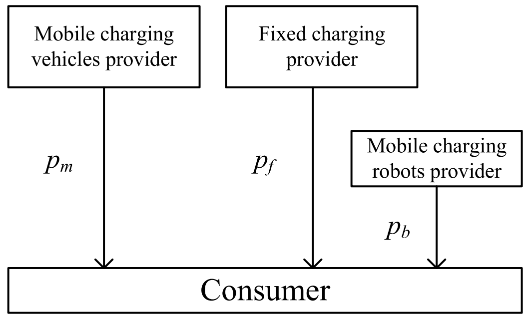

FIGURE 6. Mode Y: Three charging services for consumers.

first, and then mobile charging robots make pricing decisions. The profits of fixed charging, mobile charging vehicles, and mobile charging robots are:

$$\pi_f = p_f q_f \tag{9}$$
$$\pi_m = (p_m - h)\, q_m \tag{10}$$
$$\pi_b = p_b q_b - k \tag{11}$$

h is the labor cost of charging delivery service in mobile charging vehicles, and k is the entry cost of choosing a mobile charging robot to join the charging service market. The demands of fixed charging, mobile charging vehicles, and mobile charging robots are independent of each other. The charging service providers usually charge unit charging service fees of p_f, p_m, p_b to obtain differential income. To show the impact of consumer time cost on different charging services, we assume that production and construction costs are 0.

IV. EQUILIBRIUM SOLUTION AND ANALYSIS

A. EQUILIBRIUM SOLUTION STRATEGY

In Mode N, consumers can choose between two charging services: fixed charging or mobile charging vehicles. The demand for fixed charging and mobile charging vehicles is independent of each other, and the two charging service providers simultaneously make pricing decisions. Through the Nash equilibrium solution, when $t_2 > t_1$ is satisfied, the optimal pricing is:

$$p_m^N = \frac{1}{3}\left(c + 2h - \Theta t_1 + \Theta t_2\right) \tag{12}$$
$$p_f^N = \frac{1}{3}\left(-c + h - 2\Theta t_1 + 2\Theta t_2\right) \tag{13}$$

Substituting Equatiosn (12)-(13) into the participants' profit functions (9)-(10), we obtain:

$$\pi_m^N = \frac{\left(c - h - \Theta t_1 + \Theta t_2\right)^2}{9\Theta\left(t_2 - t_1\right)} \tag{14}$$
$$\pi_f^N = \frac{\left(c - h + 2\Theta t_1 - 2\Theta t_2\right)^2}{9\Theta\left(t_2 - t_1\right)} \tag{15}$$

The detailed process can be seen in Appendix A-A

Lemma 1: The equilibrium outputs in Mode N are as follows. Assume that the following conditions hold.

$$t_2 > t_1, \Theta > \max\{\frac{c - h}{2t_2 - 2t_1}, \frac{c - h}{t_1 - t_2}\}.$$

Based on the deduce of IV-A, in addition to Equation (12)-(15), the following equations for demands of charging services are formulated as follows.

$$q_m^N = \frac{c-h+2\Theta t_1 - 2\Theta t_2}{3\Theta t_1 - 3\Theta t_2}. \tag{16}$$

$$q_f^N = \frac{(c-h-\Theta t_1 + \Theta t_2)^2}{9\Theta (t_2 - t_1)}. \tag{17}$$

Lemma 1 shows the consumers' time cost and travel cost have an effect on equilibrium profits.

Next, we analyze the equilibrium prices and profits after the introduction of mobile charging robot providers in Mode Y.

In Mode Y, we consider the charging service market consisting of fixed charging, mobile charging vehicles, and mobile charging robots. Fixed charging and mobile charging vehicle providers first make pricing decisions simultaneously. Then, the mobile charging robots determine the price. To solve the two-stage Stackelberg model, according to the backward induction method, we can derive the optimal pricing decision for mobile charging robot service providers:

$$p_b^{Y'} = \frac{1}{2}\left(p_f + \Theta t_1\right) \tag{18}$$

Substituting Equations (18) into (9)-(10), we obtain the optimal pricing of the charging service as follows:

$$p_m^Y = \frac{-\Theta t_1^2 + 2(c+h)t_2 + t_1(2h + \Theta t_2)}{2(t_1 + 2t_2)} \tag{19}$$

$$p_f^Y = \frac{t_1(-c+h-\Theta t_1 + \Theta t_2)}{t_1 + 2t_2} \tag{20}$$

$$p_b^Y = \frac{t_1(-c+h+3\Theta t_2)}{2(t_1+2t_2)} \tag{21}$$

The expression analysis of optimal pricing shows that, the optimal pricing of fixed charging, mobile charging vehicles, and mobile charging robots is positively proportional to the consumer time cost. The pricing of mobile charging robots is affected by the waiting times of the other charging services.

When we have

$$k < \frac{t_1(-c+h+3\Theta t_2)^2}{4\Theta(t_1+2t_2)^2},$$

We obtain the following Equations (22)-(24) by substituting Equations (19)-(21) into Equation (9)-(11).

$$\pi_m^Y = \frac{\left(\Theta t_1^2 - (2c - 2h + \Theta t_1)t_2\right)^2}{4\Theta(t_2 - t_1)(t_1+2t_2)^2} \tag{22}$$

$$\pi_f^Y = \frac{t_1(t_1+t_2)(c-h+\Theta t_1 - \Theta t_2)^2}{2\Theta(t_2-t_1)(t_1+2t_2)^2} \tag{23}$$

$$\pi_b^Y = \frac{-4k\Theta t_1^2 - 16k\Theta_2^2 + t_1((c-h)^2 + \Theta t_2\sigma)}{4\Theta(t_1+2t_2)^2}$$

$$s.t.\ \sigma = -6c + 6h - 16k + 9\Theta t_2 \tag{24}$$

The detailed process can be seen in Appendix A-B

Lemma 2: The equilibrium outputs in Mode Y are as follows. Assume that the following conditions hold.

$$t_2 > t_1, k < \frac{t_1(-c+h+3\Theta t_2)^2}{4\Theta(t_1+2t_2)^2},$$

$$\Theta > \max\left\{\frac{2(c-h)t_2}{t_1(t_1-t_2)} \frac{-c+h}{t_1-t_2}\right\}.$$

Besides the optimal prices and profits in Equation (18)-(24), the following equations of demands for charging services are formulated.

$$q_f^Y = \frac{(t_1+t_2)(c-h+\Theta t_1 - \Theta t_2)}{2\Theta(t_1-t_2)(t_1+2t_2)}. \tag{25}$$

$$q_m^Y = \frac{\Theta t_1^2 + 2(-c+h)t_2 - \Theta t_1 t_2}{2\Theta(t_1^2 + t_1 t_2 - 2t_2^2)}. \tag{26}$$

$$q_b^Y = \frac{h + 3\Theta t_2 - c}{2\Theta t_1 + 4\Theta t_2}. \tag{27}$$

In Equation (24), the equilibrium profit of mobile charging robots is comprehensively affected by the waiting time of other charging services, travel cost, and service costs.

B. EQUILIBRIUM ANALYSIS

Theorem 1: Through the assumptions of Lemma 1, we have the following relations in Mode N:

1) The relation between p_f^N and p_m^N:
   a) $p_f^N > p_m^N$ holds when
   $$\Theta > \frac{2c+h}{-t_1+t_2}.$$
   b) $p_f^N < p_m^N$ holds when
   $$\frac{c-h}{t_1-t_2} < \Theta < \frac{2c+h}{-t_1+t_2}.$$
2) The relation between π_f^N and π_m^N:
   a) If $h > c$, $\pi_f^N > \pi_m^N$ holds.
   b) If $c > h$, $\pi_f^N < \pi_m^N$ holds when
   $$\frac{c-h}{2(t_2-t_1)} < \Theta < \frac{2(c-h)}{t_2-t_1}.$$
   c) If $c > h$, $\pi_f^N > \pi_m^N$ holds when
   $$\Theta > \frac{2(c-h)}{t_2-t_1}.$$

Proof: We prove Theorem 1 by the following difference between p_f^N and p_m^N:

$$p_f^N - p_m^N = \frac{1}{3}(-2c - h - \Theta t_1 + \Theta t_2).$$

■

Assume $p_f^N - p_m^N > 0$ (i.e., $p_f^N > p_m^N$), we obtain

$$\Theta > \frac{2c+h}{-t_1+t_2};$$

Otherwise $p_f^N - p_m^N < 0$ (i.e., $p_f^N < p_m^N$), we obtain

$$\frac{c-h}{t_1-t_2} < \Theta < \frac{2c+h}{-t_1+t_2}.$$

Similarly, It is easy to prove the difference with π_f^N and π_m^N:

$$\pi_f^N - \pi_m^N = \frac{2c-2h+\Theta t_1-\Theta t_2}{3\Theta t_1-3\Theta t_2}.$$

Thus, Theorem 1 is proved.

Theorem 1 shows that the profits of charging service providers are affected by the service costs, travel cost, and consumer time cost. Theorem 1 (a) shows that when consumers are time-sensitive, they prefer to go to the charging station by themselves rather than wait for a mobile charging vehicle. Consumers opting for fixed charging are relieved of the time-related uncertainties typically associated with waiting for charging delivery service. In addition, fixed-charging providers do not have to bear the cost of charging delivery services. Furthermore, we find that mobile charging vehicles are more business-advantageous only when the cost of their service is less than the cost of consumers' time and the cost per unit of consumers' time is lower. Therefore, charging service providers should devise business strategies that are more acdptable. Mobile charging vehicle providers need to curtail labor and operational expenses associated with visiting services. The implementation of efficient charging routes for mobile units and the introduction of online booking services can logically minimize consumer wait times and increase revenue.

To present the previous conclusions more intuitively, we adopted a numerical analysis method. Based on market research data for different charging service waiting times, we set the parameter values as follows: $t_2 = 30, t_1 = 15$, $h = 5$. The results are shown in Figure 7.

We find that travel cost and time cost affect the profit levels of fixed charging and mobile charging vehicles, as shown in Figure 7. When $h > c$, fixed charging has more advantages than mobile charging vehicles, and the profit of fixed charging providers is greater than that of mobile charging

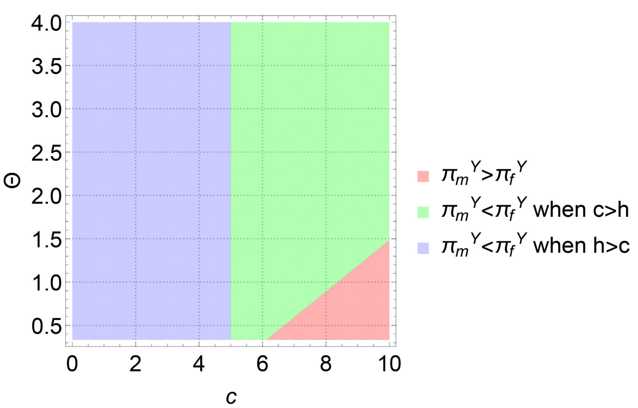

FIGURE 7. Charging Service Providers Profit Comparison in Mode N.

vehicle providers. As consumers' travel cost increases, the revenue of mobile charging vehicles improves.

Theorem 2: Through the assumptions of Lemma 2, we have the following relations in Mode N:

1) $p_f^Y < p_m^Y$ holds when

$$\Theta < \frac{2\left(ct_1+(c+h)\,t_2\right)}{t_1\left(t_2-t_1\right)};$$

otherwise, $p_f^Y > p_m^Y$.

2) $p_m^Y > p_b^Y$ holds when

$$\Theta < \frac{c+h}{t_1};$$

otherwise, $p_m^Y > p_b^Y$.

3) $p_b^Y > p_f^Y$ holds when

$$\Theta > \max\left\{\frac{(c-h)\left(t_1+3t_2\right)}{\left(t_1-t_2\right)t_2}, \frac{2\left(c-h\right)t_2}{t_1\left(t_1-t_2\right)}\right\};$$

otherwise, $p_f^Y > p_b^Y$.

Proof: We prove the relationship between p_f^Y and p_m^Y, we follow the assumptions of Lemma 2, then we obtain the following expression of $p_f^Y - p_m^Y$.

$$p_f^Y - p_m^Y = \frac{-\Theta t_1^2 - 2\left(c+h\right)t_2 + t_1\left(-2c+\Theta t_2\right)}{2\left(t_1+2t_2\right)}.$$

Assume $p_f^Y - p_m^Y > 0$ (i.e., $p_f^Y > p_m^Y$), we obtain

$$\Theta > \frac{2\left(ct_1+(c+h)\,t_2\right)}{t_1\left(t_2-t_1\right)}.$$

Otherwise $p_f^Y - p_m^Y < 0$ (i.e., $p_f^Y < p_m^Y$), we obtain

$$\max\left\{\frac{2\left(c-h\right)t_2}{t_1\left(t_1-t_2\right)}, \frac{-c+h}{t_1-t_2}\right\} < \Theta < \frac{2\left(ct_1+(c+h)\,t_2\right)}{t_1\left(t_2-t_1\right)}.$$

Thus, we prove the statement (1) of Theorem 2 according to the above reduction.

Similarly, the relations of p_m^Y, p_b^Y, and p_b^Y, p_f^Y can also be proved through reduction.

$$p_m^Y - p_b^Y = \frac{1}{2}\left(c+h-\Theta t_1\right).$$

$$p_b^Y - p_f^Y = \frac{t_1\left(c-h+2\Theta t_1+\Theta t_2\right)}{2\left(t_1+2t_2\right)}.$$

Theorem 2 is proved based on the similar reduction of the proof of statement (1). ■

Theorem 2 demonstrates that when the time cost of a consumer is higher, the price of mobile charging robots exceeds that of fixed charging. The results show that as the pace of consumer life accelerates, consumers may prefer self-service charging provided by mobile charging robots. Conversely, mobile charging vehicles exhibit better pricing performance when the time cost of a consumer is lower. This is because the consumers with lower time cost can accept the longer time of waiting for mobile charging delivery services. Next, we will analyze the profit performance of three charging service providers in terms of consumer time cost and travel cost.

Theorem 3: The profits of charging service providers are shown as follows:

1) If $h>c$, $\pi_f^Y > \pi_m^Y$ holds; but if $c>h$,

a) $\pi_f^Y > \pi_m^Y$ when

$$\Theta > \frac{(c-h)\left(2+\sqrt{2+\frac{2t_2}{t_1}}\right)}{t_2-t_1},$$

b) $\pi_f^Y < \pi_m^Y$ when

$$\frac{c-h}{t_2-t_1} < \Theta < \frac{(c-h)\left(2+\sqrt{2+\frac{2t_2}{t_1}}\right)}{t_2-t_1}.$$

2) $\pi_b^Y > \pi_m^Y$ when $k < k_1$; $\pi_b^Y < \pi_m^Y$ when

$$k_1 < k < \frac{t_1(\beta+2\Theta t_2)^2}{4\Theta(t_1+2t_2)^2}.$$

3) $\pi_b^Y > \pi_f^Y$ when $k < k_1 + k_2$; $\pi_b^Y < \pi_f^Y$ when

$$k_1 + k_2 < k < \frac{t_1(\beta+2\Theta t_2)^2}{4\Theta(t_1+2t_2)^2}.$$

In the aforementioned inequalities, k_1 and k_2 are denoted as follows.

$$\begin{aligned} k_1 &= \frac{1}{4\Theta\,(t_1-t_2)\,(t_1+2t_2)^2}[\Theta^2 t_1^3\,(t_1-2t_2) \\ &\quad + \left(4t_2^2 - t_1^2\right)(c-h)^2 - t_1 t_2 \beta\,(\beta+8\Theta t_2) \\ &\quad + 10\Theta t_2 t_1^2 \beta] \\ k_2 &= \frac{2(c-h)^2 + \Theta t_1\,(4c-4h+\Theta t_1 - \Theta t_2)}{4\Theta\,(t_1+2t_2)} \end{aligned}$$

Proof: Following the assumption of Lemma 2, we prove Theorem 3 by the following difference between π_f^Y and π_m^Y, π_b^Y and π_f^Y, π_b^Y and π_m^Y.

$$\pi_f^Y - \pi_m^Y = \frac{-2(c-h)^2 - \Theta^2 t_1^2 + \Theta t_1\,(-4c+4h+\Theta t_2)}{4\Theta\,(t_1+2t_2)}.$$

Then, we can derive a conclusion: If $-2(c-h)^2 - \Theta^2 t_1^2 + \Theta t_1\,(-4c+4h+\Theta t_2) > 0$, $\pi_f^Y > \pi_m^Y$ holds; otherwise, $\pi_f^Y < \pi_m^Y$ holds.

Similarly, in order to proof the relations between π_b^Y and π_f^Y, we obtain the following statements.

$$\begin{aligned} \pi_b^Y - \pi_m^Y &= \frac{1}{4\Theta\,(t_1-t_2)\,(t_1+2t_2)^2}[D + 16k\Theta t_2^3 \\ &\quad + 2\Theta t_2 t_1^2 E + F - t_1 t_2 \beta\,(\beta+8\Theta t_2)] \\ s.t.\ \beta &= -c+h+\Theta t_2 \\ D &= \Theta^2 t_1^4 - 2\Theta t_1^3\,(2k+\Theta t_2) \\ E &= -5c+5h-6k+5\Theta t_2 \\ F &= (c-h)^2\left(t_1^2+4t_2^2\right) \end{aligned}$$

$$\begin{aligned} \pi_b^Y - \pi_f^Y &= \frac{1}{4\Theta\,(t_1-t_2)\,(t_1+2t_2)^2}[\Theta t_1 t_2^2 B + 7\Theta^2 t_1^2 \\ &\quad - 6\,(A+k) - 2\Theta t_1^3\,(2A+\Theta t_2) + C] \\ s.t.\ A &= -c+h+k \\ B &= 2c-2h-7\Theta t_2 \\ C &= 2\Theta^2 t_1^4 + 16k\Theta t_2^3 + 3(c-h)^2 t_1^2 + t_1 t_2 (c-h)^2 \end{aligned}$$

Similarly, we can compare the profits between different charging services.

Thus, Theorem 3 is proved. ■

The equilibrium strategy in the market is influenced by the combined effects of service costs, consumer travel cost, and consumer time cost. When consumers face high time cost, fixed charging stations, and mobile charging robots become preferable options over mobile charging vehicles. The introduction of mobile charging robots has intensified competition in the market and marginalized fixed charging stations. Only when service costs are low, the introduction of mobile charging robots intensifies the market performance of mobile charging vehicles. Mobile charging robots reduce the inconvenience of searching for charging stations by automating the process and transforming manual search efforts into automated ones. This strategy optimizes the consumer service experience and mitigates the inconvenience associated with searching for charging stations. The parameter values are set as follows: $t_2 = 30$, $t_1 = 15$, $k = 10$, $h = 5$. The results are shown in Figure 8.

As shown in Figure 8, after the introduction of mobile charging robots, consumers are increasingly inclined to mobile charging robots, especially when the time cost are high. This preference arises from the convenience offered by mobile charging robots, which eliminates waiting times by enabling vehicles to be charged while parked. Specifically, the mobile charging robotics strategy combines the reliability of a defined charging range with the flexibility of mobile charging, thereby reducing consumer wait times. Consequently, the introduction of mobile charging robots will increase competition in the charging service market and expedite technological advancement. For consumer segments with heightened sensitivity to time cost, mobile charging robots are poised to emerge as their preferred charging solution, gradually encroaching on the fixed charging market. Notably during the initial phase of mobile charging robot introduction, providers may incur negative profits, thereby enhancing the competitive performance of mobile charging vehicles. With escalating travel cost, the operational landscape of mobile charging vehicles is expected to improve. This trend not only underscores the advantages of mobile charging robots in catering to the demands of a fast-paced lifestyle but also signals the growing significance of their competitive position in the forthcoming charging market.

Theorem 4: After the introduction of mobile charging robots, the equilibrium prices and profits of fixed charging and mobile charging vehicles have the following order:

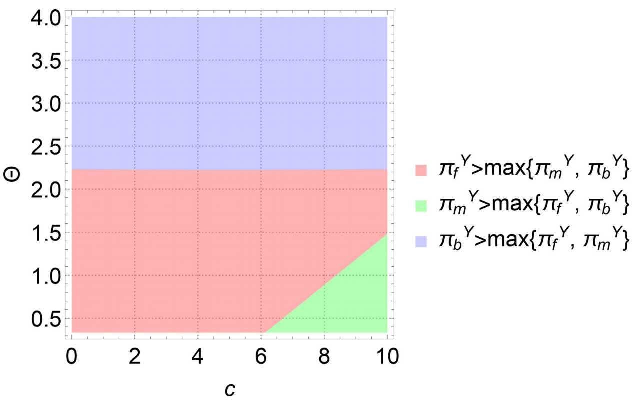

FIGURE 8. **Charging Service Providers Profit Comparison in Mode Y.**

1) $p_m^N \geq p_m^Y, p_f^N \geq p_f^Y, \pi_m^N \geq \pi_m^Y, \pi_f^N \geq \pi_f^Y$.

2) The consumer utility in the charging service market has improved, $U_m^Y \geq U_m^N, U_f^Y \geq U_f^N$.

Proof: We derive the proof with three parts as follows, including the proof of the prices, the profits, and the utility, respectively.

For the proof of the prices $p_m^N \geq p_m^Y$ and $p_f^N \geq p_f^Y$, we follow the assumptions of Lemma 1-2, thus $2c-2h+\Theta t_1-4\Theta t_2 \leq 0$ holds. Then, we can get the following statements.

$$p_m^N - p_m^Y = \frac{(t_1-t_2)(2c-2h+\Theta t_1-4\Theta t_2)}{6(t_1+2t_2)} > 0.$$

$$p_f^N - p_f^Y = \frac{(t_1-t_2)(2c-2h+\Theta t_1-4\Theta t_2)}{3(t_1+2t_2)} > 0.$$

Therefore, $p_m^N > p_m^Y$ and $p_f^N > p_f^Y$ are proved.

Similarly, we can get the result of charging providers profits as the following statement.

$$\pi_m^N - \pi_m^Y = -\frac{1}{36\Theta(t_1+2t_2)^2}(2c-2h+\Theta t_1-4\Theta t_2) \cdot \Big[-5\Theta t_1^2 + t_1(2c-2h+\Theta t_2) + 2t_2(5c-5h+2\Theta t_2)\Big] > 0.$$

$$\pi_f^N - \pi_f^Y = \frac{t_1(t_1+t_2)(c-h+\Theta t_1-\Theta t_2)^2}{2\Theta(t_1-t_2)(t_1+2t_2)^2} - \frac{(c-h+2\Theta t_1-2\Theta t_2)^2}{9\Theta(t_1-t_2)} > 0.$$

Therefore, $\pi_m^N > \pi_m^Y$ and $\pi_f^N \geq \pi_f^Y$ are proved.

For the proof of the utility, we have $2c-2h+\Theta t_1-4\Theta t_2 \leq 0$, then we can get the following statements.

$$U_f^Y - U_f^N = \frac{(t_1-t_2)(2c-2h+\Theta t_1-4\Theta t_2)}{3(t_1+2t_2)} > 0.$$

$$U_m^Y - U_m^N = \frac{(t_1-t_2)(2c-2h+\Theta t_1-4\Theta t_2)}{6(t_1+2t_2)} > 0.$$

Therefore, $U_m^Y \geq U_m^N$ and $U_f^Y \geq U_f^N$ are proved. ■

After the introduction of mobile charging robots, the equilibrium prices of both mobile charging vehicles and fixed charging stations have decreased. This phenomenon arises from intensified service competition driven by mobile charging robots. It will prompt other charging service providers to set a lower price to retain a larger market. Additionally, the introduction of mobile charging robots can improve consumer utility, potentially eroding the competitive advantages of incumbent market players. Moreover, mobile charging robot providers can enhance consumer utility across by intensifying market competition, thereby reducing the prices of other charging services and increasing consumers' surplus value.

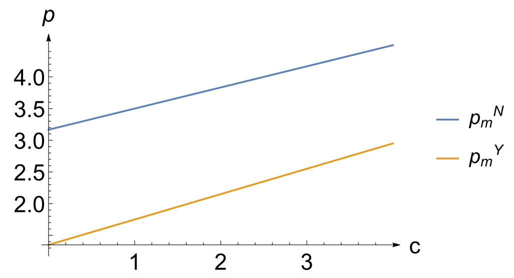

FIGURE 9. **The effect of travel cost c on price p in mobile charging vehicles($\theta = 0.5$).**

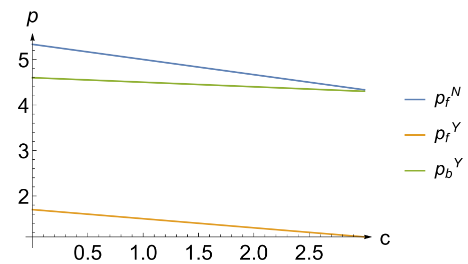

FIGURE 10. **The effect of travel cost c on price p in charging providers ($\theta = 0.5$).**

Next, we focus on the impact of consumer time cost and travel cost on charging service competition decisions and thus draw Proposition 1-3.

Proposition 1: For the prices of the fixed charging and mobile charging vehicles, with $t_2 > t_1$, the following equilibrium solutions hold.

1) $p_f^N, \pi_f^N, p_f^Y, p_b^Y, \pi_f^Y$, and π_b^Y decrease with c, while p_m^N, p_m^Y, π_m^N, and π_m^Y increase with c.

2) $p_f^N, p_f^Y, p_b^Y, p_m^N$, and p_m^Y increase with Θ. Besides, π_f^N, $\pi_m^N, \pi_f^Y, \pi_m^Y$, and π_b^Y also increase with Θ.

We prove Proposition 1 based on the first-order derivatives of p (π) with respect to c (θ) (see Proof A-C in Appendix A-C

When consumers' travel cost c increases, the prices of fixed charging and mobile charging robots decrease, while the price and demand for mobile charging vehicles increase as shown in Figure 9-10. This is because when consumers drive to charging stations, they will afford road costs and deal with risks such as traffic congestion. As travel cost c rise, fixed-charging consumers will turn to mobile-charging vehicles,

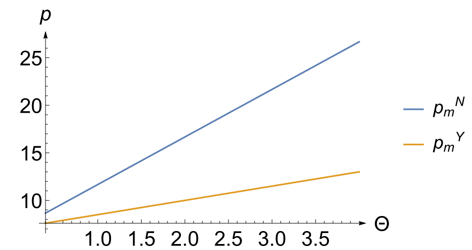

FIGURE 11. **The effect of time cost θ on price $p$in mobile charging vehicles provider($c = 10$).**

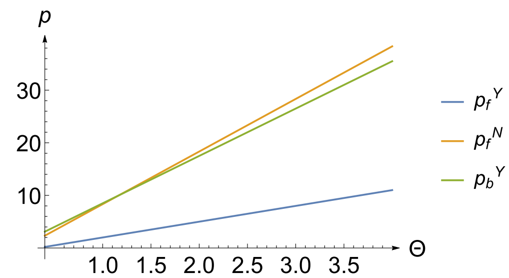

FIGURE 12. **The effect of time cost θ on price p in charging providers($c = 10$).**

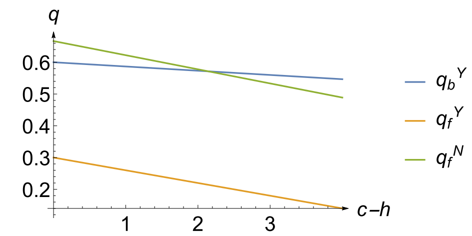

FIGURE 13. **The effects of $c - h$ on charging providers' quantity q ($\theta = 0.5$).**

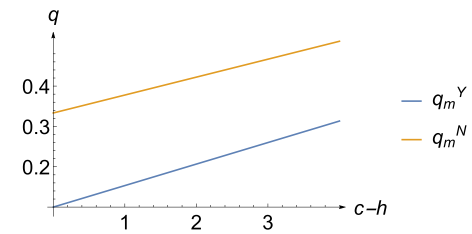

FIGURE 14. **The effects of $c - h$ on charging providers' quantity q ($\theta = 0.5$).**

thereby increasing the demand for mobile-charging services. This phenomenon is particularly evident in areas with urban congestion or insufficient coverage of fixed charging stations. Therefore, in these areas, The market for mobile charging vehicles has the potential to expand. In addition, the profits of fixed charging stations may be affected by external factors, such as traffic congestion and inaccurate map navigation. For mobile charging vehicles, it will be more advantageous to deploy mobile charging vehicles in areas with high travel cost (e.g., urban centers). In addition, fixed charging location choices and accurate address navigation are beneficial for both fixed charging stations and mobile charging robots. As the consumer time cost Θ increases, charging service pricing and benefits also increase as shown in Figure11-12. Specifically, a larger Θ is the higher the opportunity cost of consumers. At this time, charging service providers have an incentive to raise prices to obtain more profits.

Proposition 2: The effect of consumer time cost on demand is as follows:

1) When $h > c$, q_f^N, q_f^Y, q_b^Y decrease with Θ, q_m^N, q_m^Y increase with Θ.

2) When $c > h$, q_f^N, q_f^Y, q_b^Y increase with Θ, q_m^N and q_m^Y decrease with Θ.

We prove Proposition 2 based on the first-order derivatives of $p\ (\pi)$ with respect to $c\ (\theta)$ (see Proof A-C in Appendix A-C

Fixed charging has more advantages than mobile charging vehicles when $h > c$. As the consumer time cost Θ increases, there will be a decrease in the demand for both fixed charging services and mobile charging robots. This is because an increase in Θ narrows the cost difference between mobile charging vehicles and fixed charging options, including mobile charging robots. Both fixed charging services and mobile charging robot operations require consumers to drive themselves, leading to an increase in opportunity costs. Consequently, consumers prefer mobile charging vehicles, thus increasing their demand. When $c > h$, mobile charging vehicles outperform fixed charging in terms of advantages. However, as Θ increases, the demand for mobile charging vehicles tends to decrease. Despite the low service costs, rising time cost narrow the gap between fixed and mobile charging, making the benefits of mobile charging less obvious and leading to reduced demand.

During periods of elevated consumer time cost, such as peak demand periods like holidays when fixed charging stations on motorways experience congestion, strategically deploying certain mobile charging vehicles in charging queues waiting for areas can prove advantageous. This allows consumers to utilize mobile charging vehicles more conveniently and decrease their waiting time, thereby enhancing the appeal of the service. For both fixed charging and mobile charging robots, the adoption of super-fast charging technology and scheduled charging services is recommended. Super-fast charging technology has the potential to reduce charging time and enhance user experience, while scheduled charging services enable better resource planning and help avoid resource wastage. Consequently, this enhances operational efficiency and boosts profitability.

Proposition 3: The effect of the difference between travel cost and charging delivery costs on demand is as follows: When $c > h$, the following statements hold.

1) $q_f^N, q_f^Y, q_b^Y, \pi_f^Y, \pi_b^Y$, and π_f^N decrease with $c - h$.

2) q_m^N, q_m^Y, π_m^Y, and π_m^N increase with $c - h$.

We prove Proposition 3 based on the first-order derivatives of $p\ (\pi)$ with respect to $c\ (\theta)$ (see Proof A-C in Appendix A-C

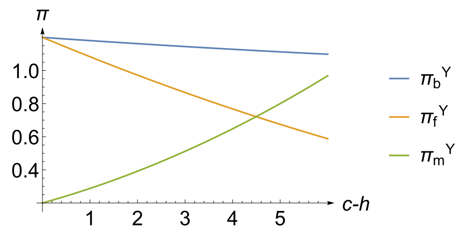

FIGURE 15. The effects of $c - h$ on charging providers' profits π ($\theta = 0.5$).

The gap between travel cost and mobile charging vehicle service costs $c - h$ will have an impact on the equilibrium demand of the participants. Specifically, when $c-h$ increases, that is, travel cost for consumers increase or the cost of mobile charging vehicle services decreases, the demand for fixed charging stations and mobile charging robots decreases, while the demand for mobile charging vehicles increases, thereby improving the mobility and profit level of charging vehicles. Therefore, for mobile charging vehicles, on the one hand, profits can be increased by operating in areas where consumer travel cost are high. However, smart technology and battery recycling can be considered to reduce service costs. We consider the impact of the difference between travel cost and mobile charging vehicle service costs on the profits of charging service providers, as shown in Figure 13-15. As $c-h$ increases, for example, the higher the cost of travel or the lower the service cost, the profits of fixed charging will decrease, while the profits of mobile charging vehicles will increase. This shows that mobile charging reduces service costs through battery recycling and vehicle dispatching, etc., which is conducive to improving profitability.

V. CONCLUSION

Our study focuses on the competition in charging services and pricing changes based on differences in the development of charging technology. We considered two modes: fixed charging and mobile charging vehicles (Mode N) and mobile charging robots, fixed charging and mobile charging vehicles (Mode Y). In Mode N, consider static games of complete information in which fixed charging and mobile charging vehicles make pricing decisions simultaneously. However, in Mode Y, the fixed charging and mobile charging vehicles decide the price first, and then the mobile charging robot makes pricing decisions in the two-stage Stackelberg game. This study analyzes the limitations of mobile charging vehicles and explains why they have not gained popularity in Mode N. Additionally, it examines the service approach and pricing strategy of mobile charging robots in Mode Y and analyzes the impact of new technologies on the equilibrium of the charging market. The main findings of the study are as follows:

First, mobile charging vehicles are generally less profitable and less efficient than fixed charging stations. Mobile charging incurs service costs, primarily because of the requirement of offering charging delivery service, which

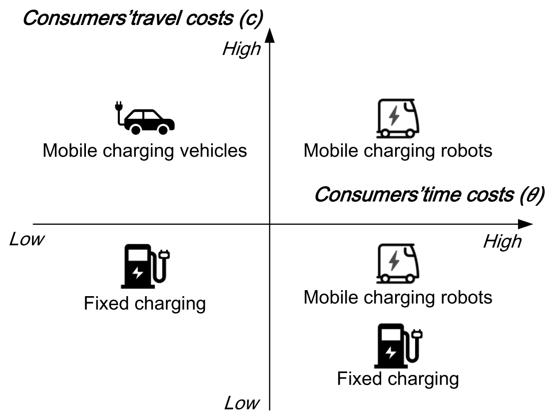

FIGURE 16. Strategy options for new entrant charging service providers.

encompasses labor and energy expenditures. Moreover, inherent journey risks such as traffic further escalate these expenses. By contrast, fixed charging stations, are devoid of such costs and expanding their infrastructure. Consequently, consumers embraced fixed charging services. Second, the pricing strategy of mobile charging robots is intricately tied to travel cost and consumers' time valuations. Mobile charging robots combine the stability inherent in fixed charging stations with the flexibility characteristics of mobile charging services. Consequently, the pricing of charging robots is inversely correlated with travel cost and positively correlates with consumers' time valuation. Finally, the advent of mobile charging robots intensify market competition, precipitating downward pressure on pricing for both fixed and mobile charging services. As mobile charging robots develop, they may potentially decrease the demands for fixed charging services, expediting the obsolescence of the mobile charging vehicle market.

As the EV market continues to expand, charging service providers face the challenge of strategically setting their pricing and service offerings to attract and retain customers. One key consideration is the trade-off between consumer time and travel cost, which varies based on both consumer and city characteristics. To assist new entrants in making informed decisions, we propose the use of a coordinate diagram, as depicted in Figure 16, to visualize these factors. It illustrates a coordinate diagram where the consumer time cost is plotted on one axis and the travel cost on the other. The diagram serves as a tool to analyze how different consumer and city characteristics intersect and influence the optimal pricing and service strategies for charging providers.

By analyzing the distribution of consumer and city characteristics on the coordinate diagram, new charging service providers can identify clusters or patterns that indicate potential market segments. For example, developing a mobile charging robot service is advisable in regions where both consumer time cost and travel cost are high. This is because the mobile charging robot exhibits superior performance in terms of service efficiency and traffic cost control,

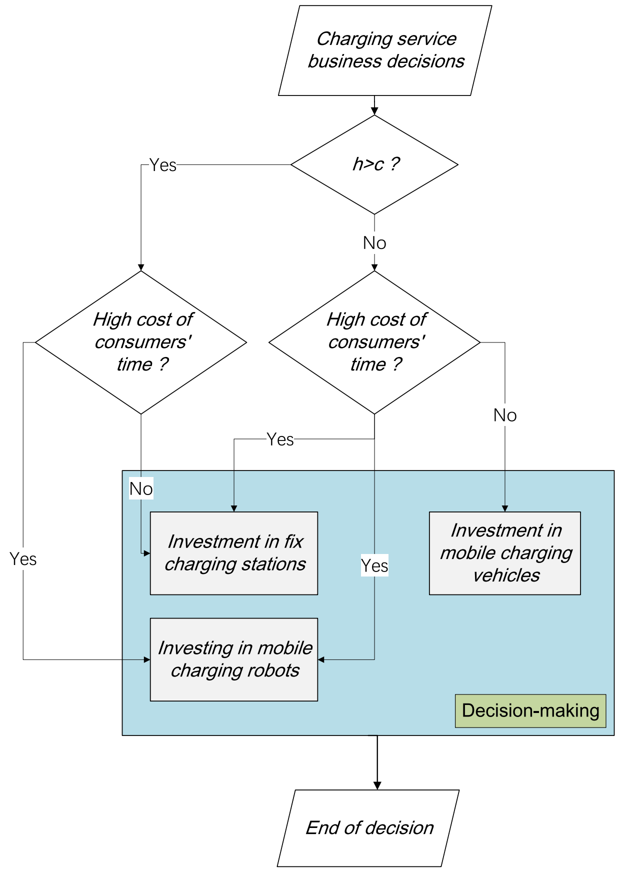

FIGURE 17. Decision process for new entrant charging service providers.

as demonstrated in Theorem2. Conversely, fixed charging is preferable in regions where consumer time cost and travel cost are low, as indicated in Theorem 1. This preference stems from the higher stability of fixed charging and its ability to provide continuous power supply over extended periods. In situations where consumer time cost is low but travel cost is high, mobile charging is favored, as evidenced by Propositions 1 and 2 which arises from the high flexibility of mobile charging, making it suitable for various emergencies.

In addition, we propose a decision-making flowchart tailored for the three distinct charging services within the EV (EV) sector in Figure 17. Our study integrates the cost characteristics of EV charging technology to compare the unit service cost (h) associated with mobile charging vehicles with the unit trip cost (c) borne by consumers. Furthermore, the accompanying Figure 17 analyzes the reference significance of consumer time cost within the decision-making process, delineated through propositions 1-3. By utilizing this flowchart, charging service providers can more accurately identify optimal operating conditions, leading to improved profitability.

In conclusion, our study proposes a coordinate diagram that provides a visual framework for new charging service providers to strategically assess the trade-off between consumer time cost and travel cost based on varying consumer and city characteristics. By leveraging this tool, charging providers can tailor their pricing and service offerings to meet the needs of diverse market segments effectively, ultimately maximizing competitiveness and profitability in the rapidly evolving EV market. With the development of mobile charging technology, mobile charging robots are expected to replace the original traditional charging methods gradually. To improve charging service, providers should consider the following measures:

- Fixed charging service providers need to carry out optimized site planning, precise navigation charging, and other new service methods to reduce the cost of charging for consumers.
- Mobile charging vehicles must focus on reducing the costs of charging delivery service. For example, EVs can be used to recycle batteries and optimize charging vehicle routes to reduce operating costs. Mobile charging vehicles are more suitable for areas with insufficient fixed charging coverage and high transportation costs for consumers to drive themselves.
- To enhance competitiveness and reduce costs, it is crucial to develop advanced automatic navigation and energy distribution algorithms for mobile charging robots.

In the paper, we propose a utility model considering the consumer perspective. Although our research is forward-looking and advantageous for the EV market, there still exist some limitations summarized as follows. Firstly, in this paper, we innovatively consider the differences among the three charging services from the perspective of consumers. To better profile different consumers (i.e., users), more information about users' preferences is needed to improve the utility model in the future. It is better to use the investigation results of user satisfaction factors to establish the relationship between consumer satisfaction and the charging demand function. Secondly, this paper lacks of discussion of the alliances of charging service providers with different charging technologies. Although there are some differences between mobile charging technologies, the charging services will consider to acquisition or merger of different charging technologies to enhance competitiveness. It can investigate the cooperation in charging service providers alliances. Finally, more research on the impact of policy subsidies on charging infrastructure is needed to encourage the advancement of the EV market. It can compare the different subsidy impacts on three charging technologies and discuss the impact on social welfare.

APPENDIX A
THEORETICAL ANALYSIS

A. THE DETAILED SOLVING PROCESS OF MODE N

In order to derive the equilibrium of Mode N. By using the backward induction method, the first-order and second-order derivatives of π with respect to p can also be obtained as follows:

$$\frac{\partial^2 \pi_f^N}{\partial {p_f^N}^2} = \frac{2}{\Theta t_1 - \Theta t_2} < 0,$$

$$\frac{\partial \pi_f^N}{\partial p_f^N} = \frac{c + 2p_f - p_m + \Theta t_1 - \Theta t_2}{\Theta t_1 - \Theta t_2},$$

$$\frac{\partial^2 \pi_m^N}{\partial {p_m^N}^2} = \frac{2}{\Theta t_1 - \Theta t_2} < 0,$$

$$\frac{\partial \pi_m^N}{\partial p_m^N} = \frac{c + h + p_f - 2p_m}{\Theta t_2 - \Theta t_1}.$$

We have $t_2 > t_1$, $\frac{\partial^2 \pi_f^N}{\partial {p_f^N}^2} < 0$, $\frac{\partial^2 \pi_m^N}{\partial {p_m^N}^2} < 0$, the optimal strategy needs to satisfy:

$$\frac{\partial \pi_f^N}{\partial p_f^N} = 0, \frac{\partial \pi_m^N}{\partial p_m^N} = 0.$$

Therefore, we can get

$$p_f^N = \frac{1}{3}\left(-c + h - 2\Theta t_1 + 2\Theta t_2\right),$$

the demand of fixed charging is

$$q_f^{N*} = \frac{(c - h - \Theta t_1 + \Theta t_2)^2}{9\Theta\left(t_2 - t_1\right)},$$

the profit of fixed charging is

$$\pi_f^N = \frac{(c - h + 2\Theta t_1 - 2\Theta t_2)^2}{9\Theta\left(t_2 - t_1\right)}.$$

Similarly, we can get

$$p_m^N = \frac{1}{3}\left(c + 2h - \Theta t_1 + \Theta t_2\right),$$

$$q_m^N = \frac{c - h + 2\Theta t_1 - 2\Theta t_2}{3\Theta t_1 - 3\Theta t_2},$$

$$\pi_m^N = \frac{(c - h - \Theta t_1 + \Theta t_2)^2}{9\Theta\left(t_2 - t_1\right)}.$$

B. THE DETAILED SOLVING PROCESS OF MODE Y

Using the backward induction method, the first-order and second-order derivatives of π with respect to p can also be obtained as follows:

$$\frac{\partial^2 \pi_b^Y}{\partial {p_b^Y}^2} = -\frac{2}{\Theta t_1} < 0,$$

the optimal strategy needs to satisfy the following equation:

$$\frac{\partial \pi_b^Y}{\partial p_b^Y} = \frac{-2p_b + p_f + \Theta t_1}{\Theta t_1} = 0,$$

so we can formulate the mobile robot price:

$$p_b^Y = \frac{1}{2}\left(p_f + \Theta t_1\right).$$

We can substitute p_b^Y into π_m^Y and π_f^Y. By using the backward induction method, the first-order and second-order derivatives of π_m^Y (π_f^Y) with respect to p_m^Y (p_f^Y) can also be obtained as follows:

$$\frac{\partial^2 \pi_f^Y}{\partial {p_f^Y}^2} = \frac{t_1 + t_2}{\Theta t_1 (t_1 - t_2)} < 0,$$

$$\frac{\partial^2 \pi_m^Y}{\partial {p_m^Y}^2} = \frac{2}{\Theta t_1 - \Theta t_2} < 0.$$

Then, we have $t_2 > t_1$, the optimal strategy needs to satisfy:

$$\frac{\partial \pi_f^Y}{\partial p_f^Y} = \frac{\Theta t_1^2 + 2p_f t_2 + t_1\left(2c + 2p_f - 2p_m - \Theta t_2\right)}{2\Theta t_1\left(t_1 - t_2\right)} = 0,$$

$$\frac{\partial \pi_m^Y}{\partial p_m^Y} = \frac{c + h + p_f - 2p_m}{\Theta t_2 - \Theta t_1} = 0.$$

Therefore, we can get

$$p_f^Y = \frac{t_1\left(-c + h - \Theta t_1 + \Theta t_2\right)}{t_1 + 2t_2},$$

$$p_m^Y = \frac{-\Theta t_1^2 + 2\left(c + h\right) t_2 + t_1\left(2h + \Theta t_2\right)}{2\left(t_1 + 2t_2\right)},$$

$$p_b^Y = \frac{t_1\left(-c + h + 3\Theta t_2\right)}{2\left(t_1 + 2t_2\right)}.$$

The demand for fixed charging is

$$q_f^Y = \frac{\left(t_1 + t_2\right)\left(c - h + \Theta t_1 - \Theta t_2\right)}{2\Theta\left(t_1 - t_2\right)\left(t_1 + 2t_2\right)},$$

the profit of fixed charging is

$$\pi_f^Y = \frac{t_1\left(t_1 + t_2\right)\left(c - h + \Theta t_1 - \Theta t_2\right)^2}{2\Theta\left(t_2 - t_1\right)\left(t_1 + 2t_2\right)^2}.$$

Similarly, we can get

$$q_f^Y = \frac{\left(t_1 + t_2\right)\left(c - h + \Theta t_1 - \Theta t_2\right)}{2\Theta\left(t_1 - t_2\right)\left(t_1 + 2t_2\right)},$$

$$q_b^Y = \frac{h + 3\Theta t_2 - c}{2\Theta t_1 + 4\Theta t_2},$$

$$\pi_b^Y = \frac{1}{4\Theta(t_1 + 2t_2)^2}\Big[-4k\Theta t_1^2 - 16k\Theta t_2^2 + t_1\Big((c - h)^2 + \Theta t_2\left(-6c + 6h - 16k + 9\Theta t_2\right)\Big)\Big].$$

C. PROOF OF PROPOSITION

Here we present detailed proof of Proposition 1, Proposition 2, and Proposition 3.

Proof: **(Proof of Proposition 1)** We prove Proposition 1 through the following first-order derivatives.

For the statement (1) of Proposition 1, the first-order derivatives of p_f^N, π_f^N, p_f^Y, p_b^Y, π_f^Y, and π_b^Y are shown as follows:

$$\frac{\partial p_f^N}{\partial c} = -\frac{1}{3} < 0,$$

$$\frac{\partial \pi_f^N}{\partial c} = \frac{2\left(-c + h + \Theta t_1 - \Theta t_2\right)}{9\Theta\left(t_1 - t_2\right)} < 0,$$

$$\frac{\partial p_f^Y}{\partial c} = -\frac{t_1}{t_1 + 2t_2} < 0,$$

$$\frac{\partial p_b^N}{\partial c} = -\frac{t_1}{2(t_1+2t_2)} < 0,$$
$$\frac{\partial \pi_f^Y}{\partial c} = \frac{t_1(t_1+t_2)(c-h+\Theta t_1-\Theta t_2)}{\Theta(t_2-t_1)(t_1+2t_2)^2} < 0,$$
$$\frac{\partial \pi_b^Y}{\partial c} = -\frac{t_1(-c+h+3\Theta t_2)}{2\Theta(t_1+2t_2)^2} < 0.$$

Besides, the first-order derivatives of p_m^N, p_m^Y, π_m^N, and π_m^Y in the statement (1) of Proposition 1 are shown as follows:

$$\frac{\partial p_m^N}{\partial c} = \frac{1}{3} > 0,$$
$$\frac{\partial p_m^Y}{\partial c} = \frac{t_2}{t_1+2t_2} > 0,$$
$$\frac{\partial \pi_m^N}{\partial c} = \frac{2c-2h+4\Theta t_1-4\Theta t_2}{9\Theta t_2-9\Theta t_1} > 0,$$
$$\frac{\partial \pi_m^Y}{\partial c} = \frac{t_2\left(\Theta t_1^2+2(-c+h)t_2-\Theta t_1 t_2\right)}{\Theta(t_1-t_2)(t_1+2t_2)^2} > 0.$$

For the statement (2) of Proposition 1, the first-order derivatives of p_f^N, p_f^Y, p_b^Y, p_m^N, and p_m^Y are shown as follows:

$$\frac{\partial p_f^N}{\partial \Theta} = \frac{2}{3}(t_2-t_1) > 0,$$
$$\frac{\partial p_f^Y}{\partial \Theta} = \frac{t_1(-t_1+t_2)}{t_1+2t_2} > 0,$$
$$\frac{\partial p_b^Y}{\partial \Theta} = \frac{3t_1t_2}{2t_1+4t_2} > 0,$$
$$\frac{\partial p_m^N}{\partial c} = \frac{1}{3}(-t_1+t_2) > 0,$$
$$\frac{\partial p_m^Y}{\partial \Theta} = \frac{t_1(-t_1+t_2)}{2(t_1+2t_2)} > 0.$$

Besides, the first-order derivatives of in the statement (2) of π_f^N, π_m^N, π_f^Y, π_m^Y, and π_b^Y in Proposition 1 are shown as follows:

$$\frac{\partial \pi_f^N}{\partial \Theta} = \frac{(c-h+2\Theta t_1-2\Theta t_2)(c-h-2\Theta t_1+2\Theta t_2)}{9\Theta^2(t_1-t_2)} > 0,$$
$$\frac{\partial \pi_m^N}{\partial \Theta} = \frac{(c-h+\Theta t_1-\Theta t_2)(c-h-\Theta t_1+\Theta t_2)}{9\Theta^2(t_1-t_2)} > 0,$$
$$\frac{\partial \pi_f^Y}{\partial \Theta} = \frac{t_1(t_1+t_2)\left[(\Theta t_1-\Theta t_2)^2-(c-h)^2\right]}{2\Theta^2(t_2-t_1)(t_1+2t_2)^2} > 0,$$
$$\frac{\partial \pi_m^Y}{\partial \Theta} = \frac{1}{4\Theta^2(t_1-t_2)(t_1+2t_2)^2}\Big\{[\Theta t_1^2+2(c-h)t_2 - \Theta t_1 t_2]\left(\Theta t_1^2+2(-c+h)t_2-\Theta t_1 t_2\right)\Big\} > 0,$$
$$\frac{\partial \pi_b^Y}{\partial \Theta} = -\frac{t_1\left((c-h)^2-9\Theta^2 t_2^2\right)}{4\Theta^2(t_1+2t_2)^2} > 0.$$

Therefore, Proposition 1 is proved. ■

Proof: **(Proof of Proposition 2)** We prove Proposition 2 through the following first-order derivatives.

For the statement (1) of Proposition 2, with $h > c$, the first-order derivatives of q_f^N, q_f^Y, q_b^Y, q_m^N, and q_m^Y are shown as follows:

$$\frac{\partial q_f^N}{\partial \Theta} = \frac{-c+h}{3\Theta^2(t_1-t_2)} < 0,$$
$$\frac{\partial q_f^Y}{\partial \Theta} = -\frac{(c-h)(t_1+t_2)}{2\Theta^2(t_1-t_2)(t_1+2t_2)} < 0,$$
$$\frac{\partial q_b^Y}{\partial \Theta} = \frac{c-h}{2\Theta^2(t_1+2t_2)} < 0,$$
$$\frac{\partial q_m^N}{\partial \Theta} = \frac{c-h}{3\Theta^2(t_1-t_2)} > 0,$$
$$\frac{\partial q_m^Y}{\partial \Theta} = \frac{(c-h)t_2}{\Theta^2(t_1-t_2)(t_1+2t_2)} > 0.$$

Particularly, the statement (2) is the same as the statement (1) in Proposition 2. Thus, the same expressions of the first-order derivatives of q_f^N, q_f^Y, q_b^Y, q_m^N, and q_m^Y are shown above. While the results of them with $c > h$ are shown as follows: $\frac{\partial q_f^N}{\partial \Theta} > 0$, $\frac{\partial q_f^Y}{\partial \Theta} > 0$, $\frac{\partial q_b^Y}{\partial \Theta} > 0$, $\frac{\partial q_m^N}{\partial \Theta} < 0$, $\frac{\partial q_m^Y}{\partial \Theta} < 0$.

Therefore, Proposition 2 is proved. ■

Proof: **(Proof of Proposition 3)** We prove Proposition 3 through the following first-order derivatives.

For the statement (1) of Proposition 3, with $c > h$, the first-order derivatives of q_f^N, q_f^Y, q_b^Y, π_f^Y, π_b^Y, and π_f^N are shown as follows:

$$\frac{\partial q_f^N}{\partial (c-h)} = \frac{1}{3\Theta t_1-3\Theta t_2} < 0,$$
$$\frac{\partial q_f^Y}{\partial (c-h)} = \frac{t_1+t_2}{2\Theta t_1^2+2\Theta t_1t_2-4\Theta t_2^2} < 0,$$
$$\frac{\partial q_b^Y}{\partial (c-h)} = -\frac{1}{2\Theta t_1+4\Theta t_2} < 0,$$
$$\frac{\partial \pi_f^Y}{\partial (c-h)} = -\frac{t_1(t_1+t_2)(c-h+\Theta t_1-\Theta t_2)}{\Theta(t_1-t_2)(t_1+2t_2)^2} < 0,$$
$$\frac{\partial \pi_b^Y}{\partial (c-h)} = -\frac{t_1(-2(c-h)+\Theta t_2)}{4\Theta(t_1+2t_2)^2} < 0,$$
$$\frac{\partial \pi_f^N}{\partial (c-h)} = \frac{2}{9}\left(-2+\frac{c-h}{\Theta(-t_1+t_2)}\right) < 0.$$

For the statement (2) of Proposition 3, with $c > h$, the first-order derivatives of q_m^N, q_m^Y, π_m^Y, and π_m^N are shown as follows:

$$\frac{\partial q_m^N}{\partial \Theta} = \frac{1}{3\Theta t_2-3\Theta t_1} > 0,$$
$$\frac{\partial q_m^Y}{\partial \Theta} = -\frac{t_2}{\Theta\left(t_1^2+t_1t_2-2t_2^2\right)} > 0,$$
$$\frac{\partial \pi_m^Y}{\partial (c-h)} = \frac{t_2\left(\Theta t_1^2-(2(c-h)+\Theta t_1)t_2\right)}{\Theta(t_1-t_2)(t_1+2t_2)^2} > 0,$$
$$\frac{\partial \pi_m^N}{\partial (c-h)} = \frac{2}{9}\left(1+\frac{c-h}{\Theta(-t_1+t_2)}\right) > 0.$$

Therefore, Proposition 3 is proved. ■

REFERENCES

[1] A. Rohr and J. McDonald, "Health effects of carbon-containing particulate matter: Focus on sources and recent research program results," *Crit. Rev. Toxicology*, vol. 46, no. 2, pp. 97–137, Feb. 2016.

[2] J. Milner, I. Hamilton, J. Woodcock, M. Williams, M. Davies, P. Wilkinson, and A. Haines, "Health benefits of policies to reduce carbon emissions," *BMJ*, vol. 368, p. l6758, Mar. 2020.

[3] X. Xia, P. Li, Z. Xia, R. Wu, and Y. Cheng, "Life cycle carbon footprint of electric vehicles in different countries: A review," *Separat. Purification Technol.*, vol. 301, Nov. 2022, Art. no. 122063.

[4] T. A. Jacobson, J. S. Kler, M. T. Hernke, R. K. Braun, K. C. Meyer, and W. E. Funk, "Direct human health risks of increased atmospheric carbon dioxide," *Nature Sustainability*, vol. 2, no. 8, pp. 691–701, Jul. 2019.

[5] H. Ritchie. (2020). *Cars, Planes, Trains: Where Do Co2 Emissions From Transport Come From?*. Our World Data. [Online]. Available: https://ourworldindata.org/co2-emissions-from-transport

[6] K. Abnett. *Eu Lawmakers Approve Effective 2035 Ban on New Fossil Fuel Cars*. Accessed: Feb. 14, 2023. [Online]. Available: https://www.reuters.com/business/autos-transportation/eu-lawmakers-approve-effective-2035-ban-new-fossil-fuel-cars-2023-02-14/

[7] H. Boushey. *Full Charge: The Economics of Building a National Ev Charging Network*. Accessed: Dec. 11, 2023. [Online]. Available: https://www.whitehouse.gov/briefing-room/blog/2023/12/11/full-charge-the-economics-of-building-a-national-ev-charging-network/

[8] S. Xu, "China's climate governance for carbon neutrality: Regulatory gaps and the ways forward," *Humanities Social Sci. Commun.*, vol. 10, no. 1, pp. 1–10, Nov. 2023.

[9] Z. Wei, B. Li, R. Zhang, and X. Cheng, "Contract-based charging protocol for electric vehicles with vehicular fog computing: An integrated charging and computing perspective," *IEEE Internet Things J.*, vol. 10, no. 9, pp. 7667–7680, May 2023.

[10] F. Chen, S. Xu, and Y. Zhai, "Electric vehicle subsidy structure considering network externality under carbon neutrality constraints," *Kybernetes*, p. 1, Jan. 2024, doi: 10.1108/K-07-2023-1185.

[11] A. Nath, Z. Rather, I. Mitra, and L. Sahana, "Multi-criteria approach for identification and ranking of key interventions for seamless adoption of electric vehicle charging infrastructure," *IEEE Trans. Veh. Technol.*, vol. 72, no. 7, pp. 8697–8708, Jul. 2023.

[12] M. Abdolmaleki, N. Masoud, and Y. Yin, "Vehicle-to-vehicle wireless power transfer: Paving the way toward an electrified transportation system," *Transp. Res. C, Emerg. Technol.*, vol. 103, pp. 261–280, Jun. 2019.

[13] D. Rempel, C. Cullen, M. M. Bryan, and G. V. Cezar, "Reliability of open public electric vehicle direct current fast chargers," *Hum. Factors*, Nov. 2022, Art. no. 00187208231215242.

[14] M. Kavianipour, F. Fakhrmoosavi, M. Shojaei, A. Zockaie, M. Ghamami, J. Wang, and R. Jackson, "Impacts of technology advancements on electric vehicle charging infrastructure configuration: A Michigan case study," *Int. J. Sustain. Transp.*, vol. 16, no. 7, pp. 597–609, Jul. 2022.

[15] S. Adak, H. Cangi, R. Kaya, and A. S. Yilmaz, "Effects of electric vehicles and charging stations on microgrid power quality," *Gazi Univ. J. Sci. A, Eng. Innov.*, vol. 9, no. 3, pp. 276–286, Sep. 2022.

[16] S. Acharya, Y. Dvorkin, H. Pandžic, and R. Karri, "Cybersecurity of smart electric vehicle charging: A power grid perspective," *IEEE Access*, vol. 8, pp. 214434–214453, 2020.

[17] N. Rotering and M. Ilic, "Optimal charge control of plug-in hybrid electric vehicles in deregulated electricity markets," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1021–1029, Aug. 2011.

[18] S. Powell, G. V. Cezar, L. Min, I. M. L. Azevedo, and R. Rajagopal, "Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption," *Nature Energy*, vol. 7, no. 10, pp. 932–945, Sep. 2022.

[19] H. Li, D. Son, and B. Jeong, "Electric vehicle charging scheduling with mobile charging stations," *J. Cleaner Prod.*, vol. 434, Jan. 2024, Art. no. 140162.

[20] H. Saboori and S. Jadid, "Mobile battery-integrated charging station for reducing electric vehicles charging queue and cost via renewable energy curtailment recovery," *Int. J. Energy Res.*, vol. 46, no. 2, pp. 1077–1093, Feb. 2022.

[21] M.-S. Răboacă, I. Băncescu, V. Preda, and N. Bizon, "An optimization model for the temporary locations of mobile charging stations," *Mathematics*, vol. 8, no. 3, p. 453, Mar. 2020.

[22] T. Gao and S. Bhattacharya, "Multirobot charging strategies: A game-theoretic approach," *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2823–2830, Jul. 2019.

[23] X. Duan, Z. Hu, Y. Song, K. Strunz, Y. Cui, and L. Liu, "Planning strategy for an electric vehicle fast charging service provider in a competitive environment," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 3, pp. 3056–3067, Sep. 2022.

[24] W. Lee, R. Schober, and V. W. S. Wong, "An analysis of price competition in heterogeneous electric vehicle charging stations," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3990–4002, Jul. 2019.

[25] J. Feng, S. X. Xu, and M. Li, "A novel multi-criteria decision-making method for selecting the site of an electric-vehicle charging station from a sustainable perspective," *Sustain. Cities Soc.*, vol. 65, Feb. 2021, Art. no. 102623.

[26] R. Wang, H. Wang, K. Zhu, C. Yi, P. Wang, and D. Niyato, "Mobile charging services for the Internet of Electric vehicles: Concepts, scenarios, and challenges," *IEEE Veh. Technol. Mag.*, vol. 18, no. 3, pp. 110–119, Sep. 2023.

[27] X. Zhang, Y. Cao, L. Peng, J. Li, N. Ahmad, and S. Yu, "Mobile charging as a service: A reservation-based approach," *IEEE Trans. Autom. Sci. Eng.*, vol. 17, no. 4, pp. 1976–1988, Oct. 2020.

[28] U. Qureshi, A. Ghosh, and B. K. Panigrahi, "Scheduling and routing of mobile charging stations with stochastic travel times to service heterogeneous spatiotemporal electric vehicle charging requests with time windows," *IEEE Trans. Ind. Appl.*, vol. 58, no. 5, pp. 6546–6556, Sep. 2022.

[29] B. Badia, R. A. Berry, and E. Wei, "Investment in EV charging spots for parking," *IEEE Trans. Netw. Sci. Eng.*, vol. 7, no. 2, pp. 650–661, Apr. 2020.

[30] A. K. Gupta and M. R. Bhatnagar, "A comprehensive pricing-based scheme for charging of electric vehicles," *IEEE Syst. J.*, vol. 17, no. 3, pp. 3492–3502, Aug. 2023.

[31] C. Wang, X. Lin, F. He, M. Z.-J. Shen, and M. Li, "Hybrid of fixed and mobile charging systems for electric vehicles: System design and analysis," *Transp. Res. C, Emerg. Technol.*, vol. 126, May 2021, Art. no. 103068.

[32] Z. Zhang, Z. Yang Dong, and C. Yip, "A new charging scheme based on mobile charging robots cluster: A three-level coordinated perspective," *IEEE Trans. Ind. Informat.*, vol. 20, no. 4, pp. 6900–6912, Apr. 2024.

[33] X. Hu, Z. Yang, J. Sun, and Y. Zhang, "Optimal pricing strategy for electric vehicle battery swapping: Pay-per-swap or subscription?" *Transp. Res. E, Logistics Transp. Rev.*, vol. 171, Mar. 2023, Art. no. 103030.

[34] S. Lai, J. Qiu, Y. Tao, and J. Zhao, "Pricing for electric vehicle charging stations based on the responsiveness of demand," *IEEE Trans. Smart Grid*, vol. 14, no. 1, pp. 530–544, Jan. 2023.

[35] X. Yang, T. Cui, H. Wang, and Y. Ye, "Multiagent deep reinforcement learning for electric vehicle fast charging station pricing game in electricity-transportation Nexus," *IEEE Trans. Ind. Informat.*, vol. 20, no. 4, pp. 6345–6355, Apr. 2024.

[36] Y. Zhao, Y. Guo, Q. Guo, H. Zhang, and H. Sun, "Deployment of the electric vehicle charging station considering existing competitors," *IEEE Trans. Smart Grid*, vol. 11, no. 5, pp. 4236–4248, Sep. 2020.

[37] M. Xu, H. Yang, and S. Wang, "Mitigate the range anxiety: Siting battery charging stations for electric vehicle drivers," *Transp. Res. C, Emerg. Technol.*, vol. 114, pp. 164–188, May 2020.

[38] S. Schoenberg, D. S. Buse, and F. Dressler, "Siting and sizing charging infrastructure for electric vehicles with coordinated recharging," *IEEE Trans. Intell. Vehicles*, vol. 8, no. 2, pp. 1425–1438, Feb. 2023.

[39] H.-M. Chung, W.-T. Li, C. Yuen, C.-K. Wen, and N. Crespi, "Electric vehicle charge scheduling mechanism to maximize cost efficiency and user convenience," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 3020–3030, May 2019.

[40] P. Tang, F. He, X. Lin, and M. Li, "Online-to-offline mobile charging system for electric vehicles: Strategic planning and online operation," *Transp. Res. D, Transp. Environ.*, vol. 87, Oct. 2020, Art. no. 102522.

[41] L. Liu, X. Qi, Z. Xi, J. Wu, and J. Xu, "Charging-expense minimization through assignment rescheduling of movable charging stations in electric vehicle networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 10, pp. 17212–17223, Oct. 2022.

[42] X. Fu, Z. Cheng, and J. Wang, "Research on online scheduling and charging strategy of robots based on shortest path algorithm," *Comput. Ind. Eng.*, vol. 153, Mar. 2021, Art. no. 107097.
[43] P.-Y. Kong, "Autonomous robot-like mobile chargers for electric vehicles at public parking facilities," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 5952–5963, Nov. 2019.
[44] Z. Zhang, Z. Yang Dong, and C. Yip, "When mobile energy meets active distribution networks: A security–economic coordination perspective," *IEEE Trans. Smart Grid*, vol. 15, no. 3, pp. 3126–3140, May 2024.

YATING DING received the degree in management from South China Normal University, Guangzhou, China, in 2021. She is currently pursuing the master's degree with the Department of Management Science and Engineering, Jinan University, Guangzhou, China. Her research interests include game theory and auction theory.

FENG CHEN received the bachelor's degree in industrial engineering from Anhui Polytechnic University, China, and the master's degree in management science and engineering from Nanjing University of Finance and Economics. He is currently pursuing the Ph.D. degree with the School of Management, Jinan University, Guangzhou, China. He has published several journal articles, such as *Water Supply*, *Urban Water Journal*, *Kybernetes*, and *Journal of Retailing and Consumer Services*. His major research interests include logistics and operations management and resources management.

JIANGHONG FENG received the Ph.D. degree from the Management School, Jinan University, Guangdong, China. He is currently an Associate Professor with the School of Economics and Management, South China Agricultural University, Guangdong. He has published several journal articles, such as *Transportation Research Part E: Logistics and Transportation Review*, *Applied Mathematical Modelling*, *Transportmetrica A: Transport Science*, *Computers and Industrial Engineering*, and *Sustainability*. His major research interests include ferry service operations, market design, and game theory.

HUIBING CHENG received the Ph.D. degree from the Management School, Jinan University, Guangdong, China. He is currently an Associate Professor with the Department of Transportation and Logistics, Guangzhou Railway Polytechnic, Guangdong. He has published several journal articles, such as *Transportation Research Part E: Logistics and Transportation Review*, *Applied Mathematical Modelling*, *Transportmetrica A: Transport Science*, *Computers and Industrial Engineering*, and *Sustainability*. His major research interests include ferry service operations, market design, and game theory.