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Original Research

Understanding Optimal Business Model of Free-Floating Bike-Sharing Platform in the Context of Low-Carbon City

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Abstract

Free-floating bike-sharing is characterized by environmental-friendly and a sustainable form of urban transportation, which becomes increasingly popular globally. To achieve sustainable development, we establish an analytical framework to explore the optimal business models of free-floating bike-sharing platforms (FBSPs) including ordinary, premium, and hybrid that are three business models often employed by FBSPs. This paper aims to address the platform's optimal business decision, and to characterize the conditions under which business model can achieve Pareto improvement for the platform and users. Our results reveal that both user's heterogeneity on service quality sensitivity and time for searching a bike play critical roles in deciding platform's optimal business model. If the platform only provides premium service, high operating costs lead to lower profit than that of hybrid strategy. Furthermore, the hybrid service model is optimal when platform overall performance (the ratio of the time to searching a bike and the platform service quality) is either sufficiently high or low, and Pareto improvement for the platform and users are also achieved under this condition. Otherwise, the ordinary service model should be implemented when platform overall performance is moderate. Service quality has also found having a non-monotonic effect on social welfare under premium service model.

Keywords: free-floating bike-sharing platform, sustainable development, business model, pricing strategy, sharing economy

Introduction

Bike-sharing activity has generally been seen as a sustainable mobility promoting low-carbon city building, considering huge transport sector carbon emissions [1]. Mobike, one of the global bike-sharing giants, reported that its service contributes to reducing carbon dioxide by 540,000 tonnes a year in China [2]. The recent increase in popularity of bike-sharing exhibits the great attractiveness of this innovative and effective way in satisfying a particular demand for transportation through a production and consumption platform [3, 4]. Free-floating bike-sharing platforms (FBSPs) as an environmentally sustainable transport which has shown wide-spread adoptions in many

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countries, and bike-share activity is most popular in China [5, 6]. To be specific, in the middle of 2017, there have been approximately 16 million free-floating bikes available with over 106 million users [7]. Different from the bike rental service offered by traditional public bike-sharing systems, free-floating bike-sharing service offered by BSPs can be seen as a digital innovation that heavily depends on technologies for tracking and billing user journeys [8]. Bikes can be picked up and left anywhere at users' convenience to complete their part or the whole journeys, and then paid by their smartphone [7, 9]. Therefore, bike-sharing can better address inner-city traffic congestion and environmental problems [10-13], considered as a sustainable practice by providing alternatives to auto commuting [14, 15].

However, as new ventures in the emerging market, FBSPs are facing a high death rate and are keen to know how to make a profit and achieve sustainable development. In fact, one platform often occupies the market of an individual region in China. For instance, Luoyang, one of the Chinese cities which has near seven million residents, decided to keep only one FBSP through public bidding, and "Hellobike" wins the bid. In this sense, the characteristic of the business model of the service that the focal platform offers is critical in increasing market demand and platform profit. Importantly, a bike-sharing platform can provide both premium service and ordinary service, which makes the bike-sharing market extraordinarily complicated. The premium service of a FBSP is to offer those upgraded bikes that bring high quality service enabled by more technology elements (e.g., electric bike) and advanced material (e.g., carbon fiber). The ordinary service is to provide those bikes that have relatively low quality. The hybrid service model, which combines the features of the premium and ordinary service models, is gaining popularity among bike-sharing platforms. For example, Hellobike uses this strategy to enable its users to use either the premium or ordinary service.

Bike-sharing platform can be seen as a one-side platform, in which suppliers put bikes into the market through the platform [16]. At present, the business model of bike-sharing platforms in the market differs. The user experience of the service is also significantly affected by the searching time of a bike since the main purpose of FBSP is to solve short distance transport issue. The goal of this study is to explore which business model a FBSP should adopt in such a monopoly market and how the searching time of a bike affects FBSPs' profit. In particular, we seek to deal with the following research issues. First, what is the optimal price-setting and business model decision for the FBSP? Second, how does users' heterogeneous sensitivity of quality affect market outcomes under different models of the FBSP? Third, how do differences in searching time between the premium service and ordinary service affect the profit of FBSP? Fourth, how user surplus and social welfare changes under different business model and searching time?

With the features of FBSPs, we address the research question by building a three-stage model in a game with complete information considering vertically differentiated FBSPs which offer nondurable product i.e., free-floating bike rental service. Platform users differ in sensitivity of service quality (bike quality). In the first period, the FBSP determines the type of business model it will launch, that is, service quality. In the second stage, the platform sets the charging price for users. In the third stage, users choose the services based on their utility.

This research is expected to contribute to the FBSP studies by helping to determine which business model is optimal for FBSP to adopt, and the findings are instructive for both FBSPs and the policymakers. In this sense, this study makes a significant contribution to the literature by filling the gap of identifying optimal business model choice for a monopoly FBSP. Second, prior research on FBSP focus on balancing the availability of bikes through inventory management [17, 18]. Unlike these studies, we consider user's heterogeneity in service quality sensitivity and the user's time for searching a bike because it is important to anticipate customers' reactions to different pricing strategies in different scenarios. Further, extant studies on pricing strategies mainly focus on traditional industry, with little effort applied in the emerging market [19-21]. Our study provides a useful extension of pricing strategy for traditional industry and offer guidance to help platforms to better understand the needs of users and develop appropriate pricing strategies by capturing the features of FBSP. Finally, since developing alternatives of road infrastructure and helping to relieve traffic congestion are good for improving the convenience of transportation, our findings also provide evidence for policymakers as key stakeholders to support the sustainable development of platform considering the benefits it brings to users and society.

Literature Review

Our work contributes to three strands of literature. First, highlighting the vertical differentiation of bike-sharing platforms. Second, the heterogeneity of customers with different quality sensitivity. Third, customer's time value.

First, vertical differentiation refers to the difference in quality of the product [22], which is first proposed by Gautschi and Lancaster [23] and has been widely used and extended. Parker and Alstyne [24] first applied it in the software differentiation model. Hernandez [25] uses the vertical differentiation theory to the duopoly market to study the price strategy of high-quality and low-quality companies, and finds that when market competition is lower, the price ratio of high-quality products to low-quality products will decrease. Qian and Dan [26] incorporate consumer strategic behavior in the process of analyzing the profits of quality differentiated enterprises, and find that as consumers become more strategic, the loss of profits on low-quality platforms is larger. The theory of vertical differentiation has been expanded in different fields such as software operations [27], express service [28], etc. In sharing economy context, Yu et al. [29] study the optimal pricing of vertical differentiation between car rental service and sales services in car-sharing. They prove that offering products with a relatively high (low) quality in per-use rental services (sales) is highly profitable for product categories with a strong pooling effect or when there are high firm-side benefits from ownership. Prior research also examined the vertical differentiation in ride-hailing industry. Wei et al. [30] find that the time sensitivity of passengers has a critical impact on a ride-hailing platform in choosing strategy through comparing the pooling, premier and hybrid service strategies. Qian and Ukkusuri [31] model the taxi market as a multi-leader-follower game, and study the equilibrium under competition between offline hailing and online hailing in the ride-hailing market. They find that the pricing policy are related to the competition level, and also have impacts on the total passenger cost, average waiting time, and fleet utilization.

Second, the research on bike sharing mainly focuses on platform operation and factors affecting the user's willingness to use it. In terms of operation, Schuijbroek et al. [17] use clustering and heuristic algorithms to determine the service level requirements of bike-sharing stations and the optimal vehicle routes involved. Caggiani et al. [32] propose a new dynamic bicycle redistribution method by predicting the number of bicycles in different area. Lu et al. [33] design systems for assisted bike sharing based on big data modeling. Pal and Zhang [34] solve the static complete-rebalancing problem of bike sharing platform based on a new hybrid integer linear program and neighborhood drop algorithm. In empirical studies, Bachand-Marleau et al. [35] analyze characteristics of bike sharing usage (e.g., the frequency of rides) based on 1432 travel survey data in Canada. Fishman et al. [36] find that the convenience of sharing bikes pays an important role in users' intention through survey. Jia and Fu [37] analyze residents' willingness to use bike sharing platforms, and find that the emergence of bikes is critical in increasing the proportion of residents (commuting and non-commuting) using BSP. Wu et al. [38] also reveal that perceived usefulness and enjoyment have the significant impacts on the users' riding intention. In addition to these factors, price and time savings are also key elements that affect user's transport choices [39-41]. There are some studies that investigate factors that may affect people's willingness in adopting BSP through analyzing their influence in different price strategies. Cheng and Gao [42] consider the availability of monopoly bike sharing platforms to analyze price strategies, find that while high availability leads to high usage willingness of people while bringing high costs. At the same time, they explore the impact of government subsidy strategies on platform profits and consumer surplus. Zhang et al. [43] propose a special price strategy that riding a particular bike can be rewarded with monetary rewards in order to facilitate the balance of distribution of free-floating bikes across different regions. However, the extant literature rarely involves differentiated service quality. In real life, we find that Mobike is committed to providing a higher level service, while ofo offers a relatively low level service [42]. Specifically, compared with ofo, Mobike invest substantially in bike manufacturing and technology costs than ofo in their early stage, thus leading to higher service quality and price. However, the trade-off between the price and the level of service quality is under-researched, and the business model for bike-sharing platform has not been clarified. In this sense, our research helps to fill this gap and provides insight for the business model selection of BSP.Another stream of literature related to this study is time value, and there are many studies investigating the influence of time value on consumer decision-making. Leclerc et al. [44] explore whether consumers think of time as money when making decisions based on prospect theory. Liu et al. [45] develop a decentralized supply chain model based on price and delivery time sensitivity, exploring consumer time and price decisions. Shang and Liu [46] adopt a two-stage game to study the time-sensitive and quality-sensitive customer, and prove that quality differentiation plays a dual role in the time-based competition, either helping companies with larger time competitive advantage compete more effectively, or helping companies with smaller time competitive advantage seize the market and protect their market advantages. Zhang et al. [47] study the strategy of monopolizing the service industry segment based on customer's time-sensitivity, compare the most profitable of the two strategies and find that the optimal profit of providing one service is always lower than the differentiation strategy. Li et al. [48] study the impact of price sensitivity and delivery time on demand based on the supermodular game theory. The prior research mainly focuses on firm in traditional industry, rarely investigating platform venture in emerging market. This study innovatively considers the user's searching time of a bike and platform business model, and investigates pricing strategy of bike sharing platform with those two factors, provides insights for the future research.

Method

There is a bike-sharing platform B in the market, and users can get riding service by renting bicycles on the platform. The platform can provide either ordinary service or premium service for users. Therefore, the platform has three service strategies to choose from. First, the platform can employ the ordinary service model, in which the platform only provides users with low quality cycling experience. Second, it can adopt the premium service model, under which bicycles provided by the platform have been integrated more technology elements (electric bike), lighter material to offer a comfortable high quality cycling experience. Finally, it can provide hybrid service model, in which the platform not only provides users with ordinary service, but also provides users with premium service.

We assume that the platform B does not fully occupy the market, which indicates that users can choose not to join the platform. Considering the users' heterogeneous sensitivity of quality, we use θ to reflect the differences of users. Users are uniformly distributed along a unit line with respect to service quality sensitivity. The market is standardized between 0 and 1, while the demand for users to use service quality i is denoted by d_i. We use S_i to represent the service quality, then the platform can choose different service quality level S_H and S_L prior to setting the price in each period, where $0<S_L<S_H$. The platform set the price P_i in each model. Considering that users will spend time looking for bikes before riding, we set ωt_i to represent time cost of users, where ω is a constant that refers to the user's time value and t_i denotes user's time to find a bike. What needs to be noted is that the searching time of the platform with premium service model is not necessarily lower than that with ordinary service model.

Let

$$r=\frac{S_L}{S_H} \tag{1}$$

r denotes the service quality similarity, where $0<r<1$. The more r tends to be 0, the greater the difference in service quality between two types of service, and the more it tends to 1, the smaller the difference of them in service quality.

Let

$$d_s=\frac{t_L-t_H}{S_H-S_L} \tag{2}$$

d_s denotes the platform overall performance. When d_s is greater than 0, the increase in d_s signifies that the difference in searching time between both low and high service quality is greater than the quality difference between the two types of service, which may indicate that the platform pays more attention to the impact of the searching time for users on profits, while the decrease of d_s shows that the difference in service quality is greater than the difference in searching time between two types of service, which may imply that the platform pays more attention to the impact of service quality on platform profit. When d_s is less than 0, the opposite is true.

For a bike-sharing platform, it often requires more investment and other resources to enhance its service quality, which will inevitably increase the platform's operating costs. In our research, the cost of the ordinary service model occurs in all three modes, for the sake of simplicity, we do not consider the cost in this strategy. We assume that the operating costs kS_i^2 incurred by the platform in improving the service quality level are marginally incremental, where k is a constant that refers to the cost for the service quality of the platform. A similar cost structure is found in Ha et al. [49], Dou et al. [50]. The game is as follows. In period 1, the platform decides to launch the service quality mode. In period 2, the platform decides the pricing strategy for users. In period 3, users choose the product according

Table 1. List of decision variables and parameters.

Notation	Description
S	Service quality level
H	Superscript to indicate the business model of premium service
L	Superscript to indicate the business model of ordinary service
HL	Superscript to indicate the business model of hybrid service
θ_i	User's service quality sensitivity
ω	The value of time
t_i	The user's time to search a bike
d_i	The demand of users
d_s	Platform overall performance
r	Similarity of the service quality
$C(S_i)$	Platform operating cost
P_i	Platform B's price
π	Platform's profit

to their sensitivity. Table 1 shows the parameters of this paper and its description.

Ordinary Service Model

We first analyze the platform provides only an ordinary service to users. Under this strategy, each user needs to pay P_L to enjoy this service and costs ωt_L to search a bike for each trip. Therefore, the gross utility of a user at θ_L uses the service from platform B can be formulated as:

$$U_L = \begin{cases} \theta S_L - P_L - \omega t_L, \text{ Users join the platform} \\ 0, \text{ Users do not join the platform} \end{cases} \tag{3}$$

Fig.1 shows the utility function of users. A user $\theta \in [\theta_L, 1]$ choose to enjoy the ordinary service, since they are more effective than not use it. The user at θ_L is indifferent between using platform B and doing without, and thus the indifference point is

$$\theta_L = \frac{P_L + \omega t_L}{S_L} \tag{4}$$

The demand for platform B is $1 - \theta_L$. To ensure users' non-negative demand for using the ordinary service, the price needs to satisfy $0 \le P_L \le S_L - \omega t_L$. Similar constraints are found in Wei and Nault [51].

A user who chooses an ordinary service pays P_L for each trip. According to the indifference point, the demand for users equals $d_L = 1 - \frac{P_L + \omega t_L}{S_L}$. Since the service quality provided by the platform is low and is included in the premium service model, the operating cost of the platform can be ignored. Thus, the platform profit is as follows:

$$\pi_L = P_L d_L \tag{5}$$

Premium Service Model

The premium service strategy provides bicycles with more technology elements (electric bike) and lighter material to offer a comfortable cycling experience. The user at θ_H pay P_H for each trip, meanwhile spends the time t_H searching a bike. In this case, the solution of optimal profit for the platform is similar to the ordinary service model. Thus, the utility of each user can be expressed as:

$$U_L = \begin{cases} \theta S_H - P_H - \omega t_H, \text{ Users join the platform} \\ 0, \text{ Users do not join the platform} \end{cases} \tag{6}$$

Similar to the ordinary service model, a user $\theta \in [\theta_H, 1]$ choose to join the platform. Fig. 2 shows the utility function of users. Setting the user's utility function $U_H = 0$ we obtain the market division point. Thus, the indifference point is

$$\theta_H = \frac{P_H + \omega t_H}{S_H} \tag{7}$$

In order to ensure the demand be non-negative, the platform price needs to satisfy $0 \le P_H \le S_H - \omega t_H$, which indicates that there is an upper limit on pricing. When it exceeds the upper bound, no users join the platform.

Under this strategy, the platform invests more design insights, manufacturing, and R&D resources, which can lead to operational costs kS_H^2, where k is a constant, and S_H represents the level of service quality. According to the above description, the platform profit equation is

$$\pi_H = P_H d_H - C(S_H) \tag{8}$$

Hybrid Service Model

Under this strategy, the bike-sharing platform provides users with both premium service and ordinary service. For example, Hellobike introduced electric bikes and normal bikes to solve the problem

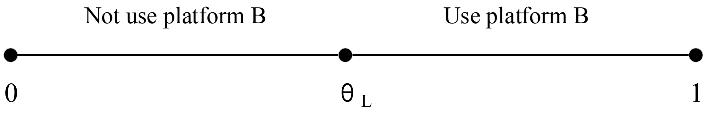

Fig. 1. User choices under ordinary service model.

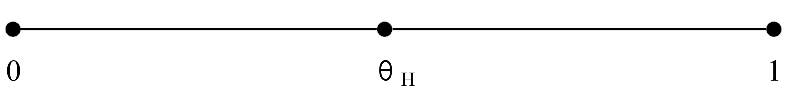

Fig. 2. User choices under premium service model.

of short-distance travel, but users have a different perception of travel experience. In this section, we use *hL* and *hH* to distinguish ordinary service and premium service in analysing the hybrid strategy. The utility of each user can be written as follows:

$$U_{HL}=\begin{cases}\theta S_{hH}-P_H-\omega t_H\,, & \textit{Users choose premium service}\\ \theta S_{hL}-P_L-\omega t_L, & \textit{Users choose ordinary service}\\ 0, & \textit{Neither}\end{cases} \tag{9}$$

In Fig. 3, users are divided into three parts based on their service quality sensitivity. Users at $\theta \in [\theta_1, 1]$ prefer to use the premium service, and those who at $\theta \in [\theta_2, \theta_1)$ enjoy the ordinary service. Therefore, θ_1 is the indifference point of using the two services. Users located at $\theta \in [0, \theta_2)$ do not join the platform, since they find it is optimal for them to choose another way to travel. To ease exposition, let $\Delta S = S_H - S_L$ ($\Delta S>0$), and $\Delta t = t_L - t_H$. We have $U_{hL} = U_{hH}$, $U_{hL} = 0$, and thus

$$\theta_1=\frac{P_{hH}-P_{hL}-\omega\Delta t}{\Delta S} \tag{10}$$

$$\theta_2=\frac{P_{hL}+\omega t_L}{S_L} \tag{11}$$

Based on the results, it can be concluded that the demand for users with premium service and those with ordinary service are as follows:

$$d_{hH}=1-\theta_1=\frac{\Delta S-P_{hH}+P_{hL}+\omega\Delta t}{\Delta S} \tag{12}$$

$$d_{hL}=\theta_1-\theta_2=\frac{S_L P_{hH}-S_H P_{hL}+\omega\left(t_H S_L-t_L S_H\right)}{S_L\Delta S} \tag{13}$$

In order to ensure the demand be non-negative, that is $0<\theta_2<\theta_1$, we need $\omega\Delta t\le P_{hH}-P_{hL}\le\omega\Delta t+\Delta S$ and $\frac{P_{hL}}{S_L}-\frac{P_{hH}}{S_H}<\frac{\omega t_H}{S_H}-\frac{\omega t_L}{S_L}$.

The platform profit consists of two parts: users using the ordinary service and users enjoying the premium service. We obtain the profit function is as follows:

$$\pi_{HL}=P_{hH}d_{hH}+P_{hL}d_{hL}-C\left(S_{HL}\right) \tag{14}$$

Results and Discussion

In this section, we analyze the optimal choice for the platform. We first use backward induction to derive the optimal pricing strategy of the FBSP under three service models. We then compare the equilibrium profits resulted from the three strategies and investigate the best business model for the platform. Finally, we explore the impact of the optimal model on user surplus and social welfare.

Optimal Pricing under Ordinary Service Strategy

We first analyze the users' participation decisions. Recall that $d_L=1-\frac{P_L+\omega t_L}{S_L}$ denotes the number of users. We substitute d_L into Equation (5) then we obtain the platform's profit function as

$$\pi_L=P_L\left(1-\frac{P_L+\omega t_L}{S_L}\right) \tag{15}$$

The optimal price and maximum profit can be obtained by solving the first-order condition of Equation (15). Then we obtain $P_L^*=\frac{S_L-\omega t_L}{2}$, $d_L^*=\frac{S_L-\omega t_L}{2S_L}$.

Therefore, the total profit of platform B is $\pi_L^*=\frac{(S_L-\omega t_L)^2}{4S_L}$, when the cost of searching a bike satisfies $0\le\omega\Delta t_L\le S_L$. Combined with the previous condition, we can obtain that the price should satisfy $0\le P_L\le S_L-\omega t_L$ to achieve optimal profit. The specific reasoning process can be found in Proposition 1 in the appendix.

COROLLARY 1: Platform's profit and user demand decrease with the increase of searching time for users.

Based on the above analysis, it is clear that if the service quality provided by the platform matches the user's expectation, the platform will be more profitable. Users will only choose this mode when they are less sensitive to the service quality provided by the platform, while the increase in the searching time will decrease the positive effect of cost-effective travel on users' demand. Consequently, the profit of the platform is reduced, which indicates that the ordinary service with high searching time cannot meet the needs of users perfectly. The result shows that the platform

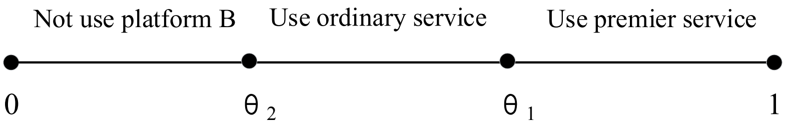

Fig. 3. User choices under hybrid service model.

should distribute the bike appropriately and reduce the searching time to users as much as possible.

For clarity, we set the value of time $\omega = 0.2$, $t_L \in [1, 2]$, and service quality $S_L = 1.4, 1.6, 1.8$. We plot the influence of searching time for a bike between platform equilibrium profit and user demand, as shown in Fig. 4 (a-b).

COROLLARY 2: An increase in service quality promotes profit growth and increases user surplus.

In this case, the platform and users reach a win-win situation. An increase of ordinary service leads to the increase of platform price for users, which is consistent with the situations in reality. When the level of bike sharing service quality increases, the platform will invest more operating resources, and they are reasonable to set higher prices for users to make more profit. Although the increase of platform charges will lead to a decrease in user utility, the increase of service quality reduces the extent of user utility reduction, which ultimately increases the user surplus. Thus, it provides a win-win situation for both the platform and users.

We set $\omega = 0.2$, $S_L \in [1, 2]$ and $t_L = 1.2, 1.4, 1.6$, platform profits vary with the service quality as shown in Fig. 5.

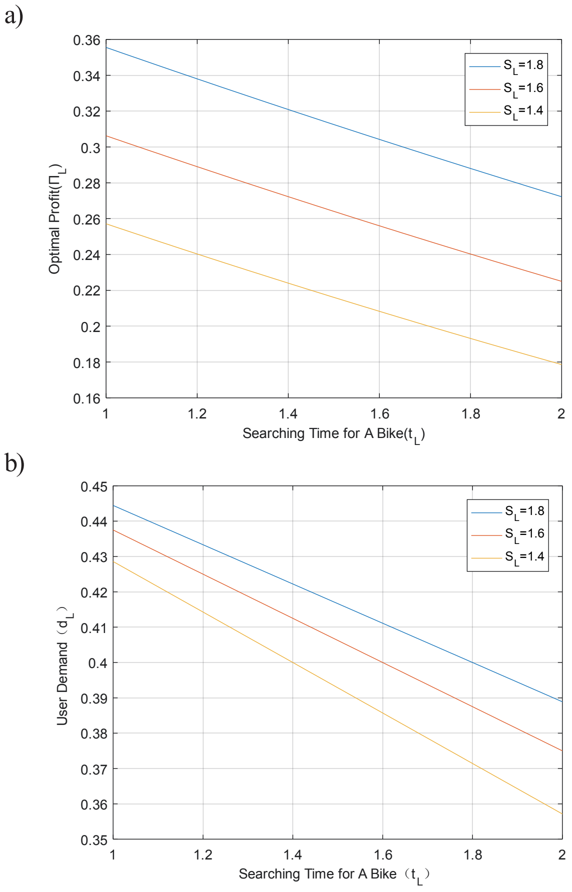

Fig. 4. The impact of t_L on d_L and π_L: a) the impact of t_L on π_L, b) the impact of t_L on d_L.

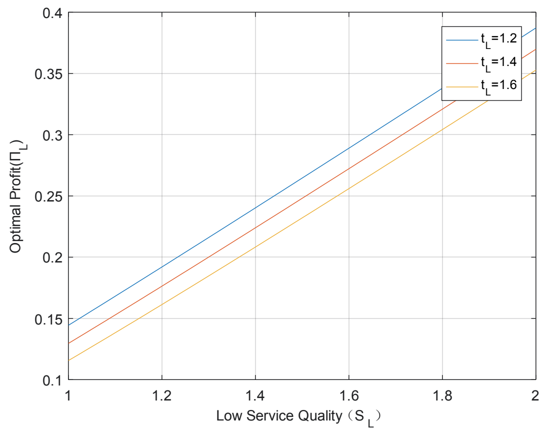

Fig. 5. The impact of S_L on π_L.

Optimal Pricing under Premium Service Strategy

We characterize the equilibrium and provide some detailed derivations of the user's travel decision making, which illustrates how the service quality of bike-sharing service affects the travel behavior of the users. Thus, we describe the optimal travel behavior of users in the following proposition. Similar to the ordinary service model, we substitute d_H and $C(S_H)$ into Equation (8). Then we have

$$\pi_H = P_H\left(1-\frac{P_H+\omega t_H}{S_H}\right)-kS_H^2 \tag{16}$$

Solving the first-order condition of the profit Equation (16), we obtain $P_H^* = \frac{S_H-\omega t_H}{2}$, $d_H^* = \frac{S_H-\omega t_H}{2S_H}$.

Therefore, the total profit of platform B is $\pi_H^* = \frac{(S_H-\omega t_H)^2}{4S_H}-kS_H^2$, when the cost of searching a bike satisfies $0 \le \omega t_H \le S_H$. Combined with the previous constraint, we summarize that the price should satisfy $0 \le P_H \le S_H - \omega t_H$ to achieve equilibrium profit. The specific reasoning process can be found in Proposition 2 in the appendix.

COROLLARY 3: Platform's profit and user demand decrease with the increase of searching time for users.

With the increase of bike searching time, users will be less willing to use the premium service, resulting in lower demand and lower profits. This corollary is similar to COROLLARY 1, and it is not described here.

COROLLARY 4: The increase of service quality leads to a positive influence on both the platform's price. Platform's profit increases as the service quality increases, if and only if $k < \frac{(S_H-\omega t_H)(S_H+\omega t_H)}{8S_H^3}$.

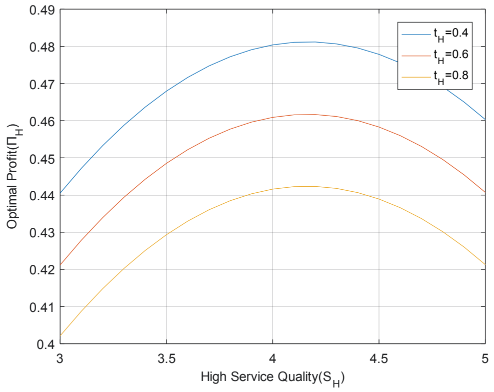

Fig. 6. The impact of S_H on π_H.

When the platform improves the service quality, considering its operation situation, it is reasonable to charge users for a high price, which increases the platform profit. However, due to the increased cost, the platform blindly pursuing high quality service will be harmful to the platform. Thus, the threshold for premium service needs to be clarified. When it exceeds the threshold, improving the service quality will have a negative influence on the profit as shown in Fig. 6. Therefore, the platform needs to balance premium service and platform operation costs. Fig. 6 also indicates that reducing the time to search a bike to a certain range can increase the profits of the platform. There, the time to find a bike and the investment of service quality are critical factors that need to be paid more attention by the platform.

We set the value of time ω = 0.2, $S_R \in [3,5]$, t_H = 0.4, 0.6, 0.8 and k = 0.03, platform's profit varies with the service quality as shown in Fig. 6.

Optimal Pricing under Hybrid Service Strategy

In this case, the platform profit consists of two aspects. Substituting d_{hH}, d_{hL} and $C(S_{HL})$ into the equation (14), we obtain

$$\pi_{HL}=P_{hH}\frac{\Delta S-P_{hH}+P_{hL}+\omega\Delta t}{\Delta S}+P_{hL}\frac{S_L P_{hH}-S_H P_{hL}+\omega(t_H S_L-t_L S_H)}{S_L\Delta S}-kS_H^2 \quad (17)$$

Since we have $\frac{\partial^2\pi_{HL}}{\partial P_{hL}^2}=A<0,\frac{\partial^2\pi_{HL}}{\partial P_{hH}^2}=C<0,\frac{\partial^2\pi_{HL}}{\partial P_{hH}P_{hL}}=B>0$ and $B^2-AC<0$, which ensures the existence of optimal profits. Solving the first-order conditions of the profit function, we obtain the optimal prices: $P_{hH}{}^*=\frac{S_H-\omega t_H}{2}$, $P_{hL}{}^*=\frac{S_L-\omega t_L}{2}$.

Thus, we obtain the demand for users, respectively, $d_{hH}{}^*=\frac{\Delta S+\omega\Delta t}{2\Delta s}$, $d_{hL}{}^*=\frac{\omega(S_L t_H-S_H t_L)}{2S_L\Delta S}$.

According to the analysis, the platform's profit is $\pi_L{}^*=\frac{S_H S_L\Delta S-2\omega S_L t_H\Delta S-\omega^2 S_L t_H\Delta t+\omega^2 t_L(S_H t_L-S_L t_H)}{4S_L\Delta S}-kS_H^2$.

The detailed derivation process can be found in Proposition 3 in the appendix.

We set the value of time ω = 0.7, $t_H \in [0,2]$, t_L = 1 and S_L = 1, 1.5, 2, 1, and S_H = 2, 2.5, 3, 3, and S_L = 1, 1.5, 1, and S_H = 2, 2.5, 3. Thus, the change in profits is shown in Fig. 7 (a-b).

Fig. 7 offers insights on how the optimal profit is affected by the relative levels of searching time and service quality. We set t_L at 1 and let t_H keep changing. We compare four situations in Fig. 7a). When S_L remains unchanged, the platform profit increases significantly with the increase of S_H, which indicates that the platform profit is highly sensitive to the change of S_H. When S_H remain unchanged, the platform profit decreases little with S_L, which indicates that the platform profit is insensitive to the change of S_L. When S_H is higher and S_L is lower, platform profit is the largest, and when S_H is lower and S_L is lower,

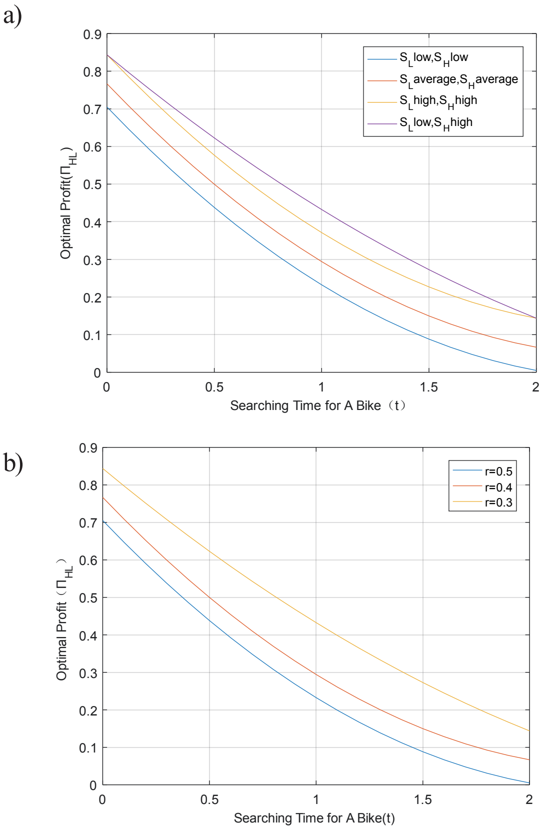

Fig. 7. The impacts of t, S and r on platform profits: a) the impacts of t and S on platform profits, b) the impacts of t and r on platform profits.

platform profit is the smallest. When $t_H<t_L$, that is to the left of $t_L = 1$ in the Fig. 7a), we find that platform profits decline faster because this part of the user is more sensitive to the time and premium service. In the hybrid service model shown in Fig. 7b), the platform will get more profits when the two service levels differ greatly, since the greater the difference between the two levels of service, the more it will meet the needs of the heterogeneous users. Therefore, the platform not only needs to use the mixed service level but also needs to consider the service level and the time to search a bike at the same time to improve the profit.

Business Model Decision

In this section, we discuss which model brings greater profit to the platform. For the sake of clarity, we conclude equilibrium points and maximum profits available to the platform in Table 2.

Comparing the profits of the three models, the optimal choice of platform is made under the different conditions of service quality input and time input for heterogeneous users. The optimal decision-making results of the platform are as follows:

– Proposition 4: Optimal Business Model Decisions

(a) If and only if $\underline{d_1}<d_s<\overline{d_1}$, the ordinary service is the best choice for the platform;

(b) If and only if $d_s<\underline{d_1}$ or $d_s>\overline{d_1}$, the hybrid service is the best choice for the platform;

where $\underline{d_1}=-\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}$, $\overline{d_1}=\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}$.

Proposition 4 shows that the platform prefers different strategies under different d_s (platform overall performance). Proposition 4a) shows that under certain conditions the ordinary service becomes the best choice. When d_s less than 0 but moderate, the bike searching time of ordinary service is shorter, which helps to expand market share and gain more profit.

On the contrary, as indicated in Proposition 4b), when the platform overall performance is sufficiently low or high, the platform should employ a hybrid model in order to make more profit. Specifically, when d_s is low, there is little difference in the high and low service quality, and the higher service quality needs a longer time to find a bike. Thus, providing an ordinary service seems to be the best choice for the platform. However, if the platform only provides ordinary service, it will not meet the individual needs of users, which will reduce the platform's profit. Further, when d_s is high, it indicates that high service quality takes less time to search a bike, thus higher service quality is the best choice. However, if the platform only provides premium service, high operating costs may reduce profits. Therefore, the platform should choose a hybrid service model to meet the needs of heterogeneous users.

User Surplus and Social Welfare

We have discussed the optimal profit and business model in the prior analysis. Considering that platform should not merely pursue the maximization of self-interest, it also needs to pay attention to the user surplus affected by strategy choice. This section explores the impact of platform overall performance on user surplus and social welfare. The CS for users is defined as the area to the right of the price under the demand curve [52]. Thus, the user surplus formula is shown as follows:

$$CS_i=\int_{\theta}^{1} U_i d\theta \left(i=H,L,HL\right) \tag{18}$$

According to Propositions 1, 2 and 3, the optimal user surplus under the three strategies is $CS_L=\frac{\left(S_L+\omega t_L\right)^2-4\omega S_L t_L}{8S_L}$, $CS_H=\frac{\left(S_H+\omega t_H\right)^2-4\omega S_H t_H}{8S_H}$ and $CS_{HL}=\frac{\left(\Delta S+\omega\Delta t\right)^2}{8\Delta S}+\frac{\left(S_L+\omega t_L\right)^2}{8S_L}-\frac{\omega t_H}{2}$. By comparing user surplus, we summarize the results in proposition 5.

Table 2. Equilibrium solution of bike sharing platform providing differentiated services.

Models	Equilibrium price	Equilibrium quantity	Optimal profit
1	$P_L^*=\frac{S_L-\omega t_L}{2}$	$d_L^*\frac{S_L-\omega t_L}{2S_L}$	$\frac{\left(S_L-\omega t_L\right)^2}{4S_L}$
2	$P_H^*=\frac{S_H-\omega t_H}{2}$	$d_H^*=\frac{S_H-\omega t_H}{2S_H}$	$\frac{\left(S_H-\omega t_H\right)^2}{4S_H}-kS_H^2$
3	$P_{hH}^*=\frac{S_H-\omega t_H}{2}$, $P_{hL}^*=\frac{S_L-\omega t_L}{2}$	$d_{hH}^*=\frac{\Delta S+\omega\Delta t}{2\Delta s}$, $d_{hL}^*=\frac{\omega\left(S_L t_H-S_H t_H\right)}{2S_L\Delta S}$	$\frac{S_H S_L\Delta S-2\omega S_L t_H\Delta S-\omega^2 S_L t_H\Delta t+\omega^2 t_L\left(S_H t_L-S_L t_H\right)}{4S_L\Delta S}-kS_H^2$

- Proposition 5: User Surplus in three strategies

(a) If $t_L \geq t_H$, user surplus in the hybrid service model is higher than that in the ordinary service model;

(b) If $t_L < t_H$ and $\overline{d}_2 < d_s < 0$, or $t_L \leq t_H$ and $d_s < \underline{d}_2$, user surplus in the hybrid service model is higher than that in the ordinary service model;

(c) If $t_L < t_H$ and $\underline{d}_2 < d_s < \overline{d}_2$, user surplus in the ordinary service model is higher than that in the hybrid service model;

where $\underline{d_2} = -\frac{2\sqrt{2}+3}{\omega}$, $\overline{d_2} = \frac{2\sqrt{2}-3}{\omega}$.

Through the above analysis, we find that when the platform overall performance under specific conditions, user surplus and platform profit will achieve optimal at the same time, that is, the platform and users obtain a win-win strategy. Combining Proposition 4 with Proposition 5, we summarize Proposition 6.

- Proposition 6: Pareto improvement in three strategies

(a) i. If $r > 1 - \frac{kS_H}{3+2\sqrt{2}}$ and $d_s < \underline{d}_1$ or $r > 1 - \frac{kS_H}{3+2\sqrt{2}}$ and $d_s > \overline{d}_1$, the hybrid service model achieves Pareto improvement for the platform and the users.

ii. If $1 - \frac{kS_H}{3-2\sqrt{2}} \leq r \leq 1 - \frac{kS_H}{3+2\sqrt{2}}$ and $d_s < \underline{d}_2$ or $1 - \frac{kS_H}{3-2\sqrt{2}} \leq r \leq 1 - \frac{kS_H}{3+2\sqrt{2}}$ and $d_s > \overline{d}_1$, the hybrid service model achieves Pareto improvement for the platform and the users.

iii. If $0 < r < 1 - \frac{kS_H}{3-2\sqrt{2}}$ and $d_s < \underline{d}_2$ or $10 < r < 1 - \frac{kS_H}{3-2\sqrt{2}}$ and $d_s > \overline{d}_2$, the hybrid service model achieves Pareto improvement for the platform and the users.

(b) i. If $r > 1 - \frac{kS_H}{3+2\sqrt{2}}$ and $\underline{d}_2 < d_s < \overline{d}_2$, the ordinary service model achieves Pareto improvement for the platform and the users.

ii. If $1 - \frac{kS_H}{3-2\sqrt{2}} \leq r \leq 1 - \frac{S_H}{3+2\sqrt{2}}$ and $\underline{d}_1 < d_s < \overline{d}_2$, the ordinary service model achieves Pareto improvement for the platform and the users.

iii. If $0 < r < 1 - \frac{kS_H}{3-2\sqrt{2}}$ and $\underline{d}_1 < d_s < \overline{d}_1$, the ordinary service model achieves Pareto improvement for the platform and the users. According to prior analysis, Proposition 6 is verified.

where

$\underline{d_1} = -\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)} - \frac{1}{\omega}$, $\overline{d_1} = \frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)} - \frac{1}{\omega}$,

$\underline{d_2} = -\frac{2\sqrt{2}+3}{\omega}$ and $\overline{d_2} = \frac{2\sqrt{2}-3}{\omega}$.

Based on the similarity for the service quality provided by the platform, we find that when the platform overall performance is sufficiently low or high, the hybrid service achieves Pareto improvements in Proposition 6 (a-b). When the platform overall performance is moderate, the ordinary service enables the platform and users to achieve Pareto improvements regardless of the difference between premium and ordinary service, leading to a win-win situation.

For further analysis, we combine the previous findings with this section to discuss the impact of service quality and searching time of a bike on social welfare under different strategies. According to previous scholars, social welfare is the sum of platform profit and user surplus. We have the formula of social welfare as follows:

$$SW_i = PS_i + \pi_i (i = H, L, HL) \tag{19}$$

Under the ordinary service model, social welfare is $SW_L = PS_L + \pi_L = \frac{3(S_L - \omega t_L)^2}{8S_L}$, which indicates that social welfare of the ordinary service increases with the improvement of service level, which has been verified in COROLLARY 2, and decreases with the increase of searching time for users. For the premium service model, social welfare is $SW_H = PS_H + \pi_H = \frac{3(S_H - \omega t_H)^2}{8S_H} - kS_H^2$, which decreases with the increase of the searching time for users. Improved service quality of the platform can lead to a better experience for users, whin certain threshold for premium service model. When $k > \frac{3(S_H + \omega t_H)(S_H - \omega t_H)}{16S_H^3}$, high operating costs will lead to a greater loss to the platform than the increase in user surplus, thus social welfare is undermined.

Under the hybrid service model, social welfare is

$$SW_{HL} = PS_{HL} + \pi_{HL} = \frac{3S_H S_L \Delta S + 2\omega S_L \Delta S(2t_L - 5t_H) + 3\omega^2 t_L(S_H t_L - S_L t_H) - 3\omega^2 S_L t_H \Delta t}{8S_L \Delta S} - kS_H^2 \cdot$$

Given the complexity of SW_{HL}, we do not specifically explore any impacts on it under the hybrid service model, and leave this to future research.

Conclusions

Free-floating bike-sharing platforms born at a time when issues of environment conservation and public transportation are prominent challenges. It creates significant values in the aspects of reducing carbon-dioxide emissions, smoothing traffic flows and encouraging a healthier commute to and from work for people. In this sense, helping FBSPs to achieve sustainable development is important. In our research, we offer economic rationale for why FBSPs might adopt different business models in different scenario and also consider the user's heterogeneous characteristics and searching time of bikes. Besides, we analyze the impact of vertical differentiation pricing strategy on the platform's profit based on the status quo of FBSPs. In the monopoly, we use a three-stage game to compare the three models that the free-floating bike-sharing platform might provide, and then calculate the optimal price and equilibrium profit for each case. Finally, this paper also compares the user surplus based on three strategies.

Our study yields several interesting findings. First, both user's heterogeneity in service quality sensitivity and time for searching are able to greatly affect the platform's choice of optimal model. Adopting premium service solely results in lower profit than that of adopting hybrid strategy, since premium service requires high operating costs. Second, the platform is better adopting hybrid service model in the condition that platform overall performance (the ratio of the time to searching a bike and the platform service quality) is sufficiently high or low, and hybrid service model will also achieve Pareto improvement for the platform and users in the same condition. However, when the ratio is in the mid-range, ordinary service mode is more beneficial for platforms. More importantly, our finding suggests that under the premium service model, when the service quality is sufficiently high, the social welfare decreases as service quality increase due to the rising cost.

Our study can help to explain some observations. When the platform chooses premium service model, it should spend more effort in decreasing the searching time of bikes. Meanwhile, reducing searching time could help the platform obtain more profits under this strategy, thus contributing to higher user surplus and social warfare, and facilitate the development of green travel. For FBSPs, they take great effort to ensure the appropriateness of bike distribution in order to reduce the searching time for users [32, 43].

There are some policy recommendations based on our findings. First, to promote this green travel approach, policymakers need to offer more subsidies for those FBSPs, so that they can better manage their services and provide more high-quality service. Therefore, more users will be attracted, and platform adoption will be facilitated. Further, policies for managing the equal access to free-floating bike need to be introduced to avoid that platform intentionally targets to specific areas or socio-demographical groups. In this sense, unnecessary waste and unintentional social consequence can be effectively eliminated.

In addition, there are some suggestions for cities of different size. Although travel demand is higher in major cities with high population density, considering the issue of traffic safety and space limitation, premium service model is not recommended to the FBSPs in these major cities. The premium and hybrid service model are suggested to adopted by FBSPs in those small and medium cities, as transportation infrastructures and concerns of space limitation in these cities are at lower level. Therefore, providing premium and hybrid service could directly address public travel pain points by diversifying their travel alternatives.

Our research serves as the basis for the study of different attributes of FBSP. However, there are limitations in our analysis. To be specific, we only consider monopoly situations, which can be extended to competitive situations in the future, and it is interesting to study the product differentiation strategy between competitors. Second, we only take into account the impact of product differentiation and searching time of a FBSP. In practice, the attributes of bike sharing products that can affect users' decisions are diverse and complicated, such as the acceptability of bicycle platform technology, additional services and users' fair attention. Studying those factors that may affect users' travel behavior will provide useful insights for platforms. Third, it is interesting to analyze price discrimination in FBSP, which is outside the scope of this study but deserves detailed theoretical analysis in the future. Finally, the value we set for parameters in numerical illustration is mainly from prior literature, empirical research should be conducted in future work to accurately depict the characteristics of users and platforms.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

Appendix

– Proof of Proposition 1:

Under this strategy, we use $\pi_L = P_L\left(1 - \frac{P_L + \omega t_L}{S_L}\right)$ to find a first-order conductor for P_L, and obtain $P_L^* = \frac{S_L - \omega t_L}{2}$. Since we have $\frac{\partial^2 \pi_L}{\partial P_L^2} = -\frac{2}{S_L} < 0$, the first derivative solution must be the optimal solution. Then according to the non-negativity of user demand, we substitute P_L^* into the demand function of user, we have $0 \leq \omega t_L \leq S_L$. Combined with the original constraints of the user's demand, we finally obtain $0 \leq P_L \leq S_L - \omega t_L$. Therefore, the total profit of platform B in the ordinary service model is $\pi_L^* = \frac{(S_L - \omega t_L)^2}{4S_L}$ and the demand for users is $d_L^* = \frac{S_L - \omega t_L}{2S_L}$.

– Proof of COROLLARY 1:

According to the results in Proposition 1, we differentiate π_L^* with respect to d_L and obtain that $\frac{\partial \pi_L^*}{\partial t_L} = -\frac{\omega(S_L - \omega t_L)}{2S_L} < 0$. We do the same for the demand d_L^* and find that $\frac{\partial d_L^*}{\partial t_L} = -\frac{\omega}{2S_L} < 0$. According to the above calculation results, COROLLARY 1 has been proved.

– Proof of COROLLARY 2:

According to the results in Proposition 1, we differentiate π_L^* with respect to S_L and obtain that $\frac{\partial \pi_L^*}{\partial S_L} = \frac{(S_L - \omega t_L)(S_L + \omega t_L)}{4S_L^2} > 0$. We do the same for the price P_L^* and find that $\frac{\partial P_L^*}{\partial S_L} = \frac{1}{2} > 0$. When other parameters remain unchanged, U_L is also monotonically increasing with S_L. According to the above calculation results, COROLLARY 2 has been proved.

– Proof of Proposition 2:

In the premium service model, we use $\pi_H = P_H\left(1 - \frac{P_H + \omega_H}{S_H}\right) - kS_H^2$ to find a first-order conductor for P_H. Solving the equation $\frac{\partial \pi_H}{\partial P_H} = 0$, we obtain $P_H^* = \frac{S_H - \omega t_H}{2}$. Since we have $\frac{\partial^2 \pi_H}{\partial P_H^2} = -\frac{2}{S_H} < 0$, the first derivative solution must be the optimal solution. The reasoning of constraints is similar to Proposition 1, and without going into detail here, then we find that $0 \le P_H \le S_H - \omega t_H$. We substitute P_H^* into π_H and d_H, we obtain the optimal profit of bike sharing platform $\pi_H^* = \frac{(S_H - \omega t_H)^2}{4S_H} - kS_H^2$ and the demand $d_H^* = \frac{S_H - \omega t_H}{2S_H}$.

– Proof of COROLLARY 3:

According to the results in Proposition 2, we differentiate π_H^* with respect to t_H and obtain that $\frac{\partial \pi_H^*}{\partial t_H} = -\frac{\omega(S_H - \omega t_H)}{2S_H} < 0$. We do the same for the demand d_H^* and find that $\frac{\partial d_H^*}{\partial t_H} = -\frac{\omega}{2S_H} < 0$. Thus, COROLLARY 3 has been proved.

– Proof of Proposition 3:

In the hybrid service model, for simplicity, we let $\Delta t = t_L - t_H$ and $\Delta S = S_H - S_L$ ($S_H > S_L$). We let $U_{hL} = U_{hH}$ and $U_{hL} = 0$ to obtain indifference point $\theta_1 = \frac{P_{hH} - P_{hL} - \omega \Delta t}{\Delta S}$ and $\theta_2 = \frac{P_{hL} + \omega t_L}{S_L}$. In order to meet $0 < \theta_2 < \theta_1 < 1$, we obtain two constraints, that is, $\omega \Delta t \le P_{hH} - P_{hL} \le \omega \Delta t + \Delta S$ and $\frac{P_{hL}}{S_L} - \frac{P_{hH}}{S_H} < \frac{\omega t_H}{S_H} - \frac{\omega t_L}{S_L}$. We use

$$\pi_{HL} = P_{HL}\left(1 - \frac{P_{hH} - P_{hL} - \omega \Delta t}{\Delta S}\right) + P_{hL}\frac{S_L P_{hH} - S_H P_{hL} + \omega(t_H S_L - t_L S_H)}{S_L \Delta S} - kS_H^2$$

to find a first-order conductor for P_{hH} and P_{hL}. Solving the equation $\frac{\partial \pi_{HL}}{\partial P_{hL}} = 0$ and $\frac{\partial \pi_{HL}}{\partial P_{hH}} = 0$, we obtain that $P^*_{hH} = \frac{S_H - \omega t_H}{2}$, $P^*_{hL} = \frac{S_L - \omega t_L}{2}$.

H

Since we have $\frac{\partial^2 \pi_{HL}}{\partial P_{hL}^2} = -\frac{2S_H}{S_L \Delta S} = A < 0$, $\frac{\partial^2 \pi_{HL}}{\partial P_{hH}^2} = -\frac{2}{\Delta S} = C < 0$, $\frac{\partial^2 \pi_{HL}}{\partial P_{hH} P_{hL}} = \frac{2}{\Delta S} = B > 0$, and

$B^2 - AC = \frac{4(S_L - S_H)}{\Delta S^2 S_L} < 0$, we obtain that the first derivative solution must be the optimal solution. Substituting P^*_{hH}, P^*_{hL} into π^*_{HL}, d_{hH} and d_{hL}, we obtain the optimal profit of bike sharing platform $\pi^*_{HL} = \frac{S_H S_L \Delta S - 2\omega S_L t_H \Delta S - \omega^2 S_L t_H \Delta t + \omega^2 t_L (S_H t_L - S_L t_H)}{4 S_L \Delta S} - kS_H^2$ and the demand $d^*_{hH} = \frac{\Delta S + \omega \Delta t}{2\Delta s}$, $d^*_{hL} = \frac{\omega(S_L t_H - S_H t_H)}{2 S_L \Delta S}$.

– Proof of COROLLARY 4:

According to the results in Proposition 2, we diP_H^*rentiate P^*_H with respect to S_H and obtain that $\frac{\partial P^{\sqcup}_H}{\partial S_H} = \frac{1}{2} > 0$. We do the same for the price π^*_H and find that when $k < \frac{(S_H - \omega t_H)(S_H + \omega t_H)}{8S_H^3}$, platform profit increases as the service quality improves. According to the above calculation results, the COROLLARY 4 has been proved.

– Proof of Proposition 4:

According to the previous analysis, the profits of the three models are

$$\pi^*_L = \frac{(S_L - \omega t_L)^2}{4S_L},$$

$$\pi^*_H = \frac{(S_H - \omega t_H)^2}{4S_H} - kS_H^2,$$

$$\pi^*_{HL} \frac{S_H S_L \Delta S - 2\omega S_L t_H \Delta S - \omega^2 S_L t_H \Delta t + \omega^2 t_L (S_H t_L - S_L t_H)}{4 S_L \Delta S} - kS_H^2.$$

By comparing the two, we get the best business model for the platform.

(1) By comparing the premium service model with the ordinary service model, we have

$$\pi^*_L - \pi^*_H = \frac{(S_L - \omega t_L)^2}{4S_L} - \frac{(S_H - \omega t_H)^2}{4S_H} + kS_H^2$$

(2) By comparing the hybrid service model with the ordinary service model, we have $\pi^*_L - \pi^*_{HL} =$

$$\frac{\left(S_L-\omega t_L\right)^2}{4S_L}-\frac{S_HS_L\Delta S-2\omega S_Lt_H\Delta S-\omega^2S_Lt_H\Delta t+\omega^2t_L\left(S_Ht_L-S_Lt_H\right)}{4S_L\Delta S}+kS_H^2$$

We let $\pi^*_L - \pi^*_{HL}>0$, then obtain $\frac{\left(\Delta S+\omega\Delta t\right)^2}{\Delta S}<4kS_H^2$, that is, $\frac{4kS_H}{\left(1+\omega d_s\right)^2}>1-r$. Then we have $\frac{-2\sqrt{kS_H\left(1-r\right)}}{\omega\left(1-r\right)}-\frac{1}{\omega}<d_s<\frac{2\sqrt{kS_H\left(1-r\right)}}{\omega\left(1-r\right)}-\frac{1}{\omega}$.

(3) By comparing the hybrid service model with the premium service model, we have $\pi^*_{HL} - \pi^*_H - =$

$$\frac{S_HS_L\Delta S-2\omega S_Lt_H\Delta S-\omega^2S_Lt_H\Delta t+\omega^2t_L\left(S_Ht_L-S_Lt_H\right)}{4S_L\Delta S}-\frac{\left(S_H-\omega t_H\right)^2}{4S_H}$$

We let $\pi^*_{HL} - \pi^*_H>0$, then obtain $\omega(S_Ht_L - S_Lt_H) >0$. This inequality is established in any case. In summary, we find that the platform always makes less profit on premium service than on hybrid service. Thus, we only need to compare the second case.

If the ordinary service is the strategy for the platform, it must have $\pi^*_L - \pi^*_{HL}>0$. This condition leads to the term $-\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}<d_s<\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}$.

If the hybrid service is the strategy for the platform, it must have $\pi^*_L - \pi^*_{HL}<0$. This condition leads to the term $d_s<-\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}$, $d_s>\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}$

Then we let $\underline{d_1}=-\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}$ and $\overline{d_1}=\frac{2\sqrt{kS_H(1-r)}}{\omega(1-r)}-\frac{1}{\omega}$.

- Proof of Proposition 5:

According to the previous analysis, we know that the user surplus for three strategies is shown below.

$$CS_L=\int_{\theta_L}^{1}\left(\theta S_L-P_L-\omega t_L\right)d\theta$$

$$CS_H=\int_{\theta_H}^{1}\theta S_H-P_H-\omega t_H\,d\theta$$

$$CS_L=\int_{\theta_2}^{\theta_1}\left(\theta S_L-P_L-\omega t_L\right)d\theta+\int_{\theta_1}^{1}\left(\theta S_H-P_H-\omega t_H\right)d\theta$$

where $\theta_L=\frac{P_L+\omega t_L}{S_L}$, $\theta_H=\frac{P_H+\omega t_H}{S_H}$, $\theta_1=\frac{P_{hH}-P_{hL}-\omega\Delta t}{\Delta S}$ and $\theta_2=\frac{P_{hL}+\omega t_L}{S_L}$. We substitute P^*_L, P^*_H, P^*_{hL} and P^*_{hH} into the equations, and we obtain that

$$CS_L=\frac{\left(S_L+\omega t_L\right)^2-4\omega S_Lt_L}{8S_L},$$

$$CS_H=\frac{\left(S_L+\omega t_H\right)^2-4\omega S_Ht_H}{8S_H}$$

$$CS_{HL}=\frac{\left(\Delta S+\omega\Delta t\right)^2}{8\Delta S}+\frac{\left(S_L+\omega t_L\right)^2}{8S_L}-\frac{\omega t_H}{2}$$

By comparing CS_{HL} and CS_L, we have

(a) If $t_L\geq t_H$, that is $\Delta t>0$, we obtain $CS_{HL}-CS_L=\frac{\left(\Delta S+\omega\Delta t\right)^2}{8\Delta S}+\frac{\omega\Delta t}{2}>0$. Therefore, user surplus in the hybrid service model is greater than that in ordinary service model.

(b) If $t_L<t_H$, that is $\Delta t>0$, we obtain $CS_{HL} - CS_L$ $(1 + \omega d_s)^2 + 4\omega d_s$. We let $(1 + \omega d_s)^2 + 4\omega d_s>0$, we have $\frac{2\sqrt{2}-3}{\omega}<d_s<0$ or $d_s<-\frac{2\sqrt{2}+3}{\omega}$. Therefore, user surplus in the hybrid service model is greater than that in ordinary service model. In summary, when $d_s>\frac{2\sqrt{2}-3}{\omega}$ or $d_s<-\frac{2\sqrt{2}+3}{\omega}$, that is $CS_{HL} - CS_L>0$, the platform employing hybrid service model will generate more user surplus. On the contrary, users use ordinary service remaining large. Then we let $\underline{d_2}=-\frac{2\sqrt{2}+3}{\omega}$ and $\overline{d_2}=\frac{2\sqrt{2}-3}{\omega}$.

- Proof of Proposition 6:

By comparing $\underline{d_1}$ and $\underline{d_2}$, we have $\underline{d_1}-\underline{d_2}=\frac{\left(2+2\sqrt{2}\right)\left(1-r\right)-2\sqrt{kS_H\left(1-r\right)}}{\omega\left(1-r\right)}$.

Letting $\underline{d_1}-\underline{d_2}<0$, we obtain that $r>1-\frac{kS_H}{3+2\sqrt{2}}$. By comparing $\overline{d_1}$ and $\overline{d_2}$, we have $\overline{d_1}-\overline{d_2}=\frac{2\sqrt{kS_H\left(1-r\right)}-\left(2\sqrt{2}-2\right)\left(1-r\right)}{\omega\left(1-r\right)}$.

Letting $\overline{d_1}-\overline{d_2}>0$ we obtain that $r>1-\frac{kS_H}{3-2\sqrt{2}}$.

In summary, when $r>1-\frac{kS_H}{3+2\sqrt{2}}$, we obtain $\underline{d_1}<\underline{d_2}$ and $\overline{d_1}>\overline{d_2}$

According to the solutions in Proposition 4 and 5, we know that if $r>1-\frac{kS_H}{3+2\sqrt{2}}$ and $d_s<\underline{d_1}$ or $r>1-\frac{kS_H}{3+2\sqrt{2}}$ and $d_s>\overline{d_1}$, the hybrid service model achieves Pareto improvement for the platform and the users. If $1-\frac{kS_H}{3-2\sqrt{2}}\leq r\leq 1-\frac{kS_H}{3+2\sqrt{2}}$ and $d_s<\underline{d_2}$ or $1-\frac{kS_H}{3-2\sqrt{2}}\leq r\leq 1-\frac{kS_H}{3+2\sqrt{2}}$ and $d_s>\overline{d_1}$, the hybrid service model achieves Pareto improvement for the platform and the users. If $0<r<1-\frac{kS_H}{3-2\sqrt{2}}$ and $d_s<\underline{d_2}$ or $10<r<1-\frac{kS_H}{3-2\sqrt{2}}$ and $d_s>\overline{d_2}$, the hybrid service model achieves Pareto improvement for the platform and the users. On the opposite, if $r>1-\frac{kS_H}{3+2\sqrt{2}}$ and

$\underline{d}_2 < d_s < \overline{d}_2$, the ordinary service model achieves Pareto improvement for the platform and the users. If $1 - \frac{kS_H}{3-2\sqrt{2}} \le r \le 1 - \frac{S_H}{3+2\sqrt{2}}$ and $\underline{d}_1 < d_s < \overline{d}_2$, the ordinary service model achieves Pareto improvement for the platform and the users. If $0 < r < 1 - \frac{kS_H}{3-2\sqrt{2}}$ and $\underline{d}_1 < d_s < \overline{d}_1$ the ordinary service model achieves Pareto improvement for the platform and the users. Thus, Proposition 6 is verified.

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