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The Competition Between Taxi Services and On-Demand Ride-Sharing Services: A Service Quality Perspective

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Abstract: On-demand ride-sharing services change our travel behavior, which threatens the survival of taxi services. Motivated by this, this paper examines the impact of on-demand ride-sharing services on taxi services and how to achieve the coexistence of two services from a service quality perspective. This paper analyzes the coexistence condition of two services considering the network effect. First, the profit target for taxi drivers is nonnegative. A Stackelberg model is built in which the taxi service is the leader and the on-demand ride-sharing service is the follower. Then, the reference dependency theory is introduced to modify the profit target of taxi drivers. And the new coexistence condition is compared with the benchmark status. The results find that the coexistence of the two services depends on the type of riders and the quality difference in both cases. When two services and riders are highly heterogenous, two services are more likely to coexist. Services with different qualities could better satisfy the diverse preferences of riders. Considering taxi profit without competition as the profit reference point, the requirement of service quality difference and the diversity of rider composition is increased. In terms of the network effect, the negative network effect is more beneficial to the coexistence of two services.

Keywords: on-demand ride-sharing service; service quality; network effect; regulation policy

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1. Introduction

On-demand ride-sharing services have expanded significantly and gained popularity during the past several years worldwide [1]. It has altered the way people travel and benefits the riders with a lower fare [2,3], higher operational agility [4,5], more responsiveness [6,7], and because of psychological constructs [8]. In addition, on-demand ride-sharing services establish a sustainable competitive advantage compared with taxi services [9]. For example, carpooling service slashes CO_2 emissions by 50% per passenger mile [10].

By linking passengers with local drivers, on-demand ride-sharing services like Didi and Uber upended the taxi industry's traditional economic model [11]. Rather than hailing a regular taxi, riders may simply use the on-demand ride-sharing applications on their smartphones to order a ride, which will be accessible within minutes [5]. Moreover, the on-demand ride-sharing platform offers different services according to the cost and quality of service to better satisfy heterogenous ride requirements. High-end service such as UberBlack is known for a high-quality service experience. Low-end services such as carpooling cost less, but riders may wait a long time for the car's arrival or be impacted by the other riders' behavior when sharing a ride. Thus, the service quality of ride-hailing services is related to the service type.

The need for taxis decreased significantly once on-demand ride-sharing services were introduced [12–14]. The global taxi drivers' protest was sparked by the competition between on-demand ride-sharing services and taxi services. Researchers and practitioners highlight the plight of taxi drivers and the potential extinction of these legacy services [15]. In addition, studies generally focus on ride-hailing's low trip prices as the main reason for declining taxi rides [16]. Therefore, regulatory policies such as entry restrictions and regulated prices are implemented in several countries to realize the survival of taxis. For instance, in Edmonton, Canada, Uber was granted authorization to operate under a novel type of license known as a private transportation provider (PTP) [17]. Regulations in China are concerned with limitations on vehicle models and driver qualifications [18]. However, these restrictions are considered to be discriminatory and aggravate the difficulty of hailing a car [19]. Fewer studies have considered how to achieve the coexistence of on-demand ride-sharing services and taxi services from the perspective of service quality. Moreover, the regulatory policies rarely differ based on the type of services the platform offers.

Riders usually regard wait times as the performance index of ride services [20,21]. Hence, wait times are a significant factor in the rivalry between on-demand ride-sharing services and taxi services [22]. Intuitively, it seems that the quality of the new service is better than the taxi service. In normal conditions, this is the case because of information technology's benefits. The average wait times may be shorter compared to taxi services [4]. But sometimes there exists a long wait before being assigned to a vehicle [23], or riders experience a long pick-up time after being assigned a vehicle, especially for carpooling service. Therefore, the comparison results of service quality between taxi services and on-demand ride-sharing services are uncertain. This will impact the coexistence condition of the two services.

For observing the regulatory polices (e.g., regulated pricing, a complete ban, and entry limitation) in different countries, several papers focus on designing the regulation policy to make it possible for on-demand ride-sharing services and taxi services to coexist. Ref. [24] compared several supervisory measures, including the driving cap, the minimum wage, and the congestion tax, using queuing theory. Ref. [25] built a multi-stage game-theoretic model and compared the effect of regulation policies such as limiting the amount of time users could spend online. However, fewer studies have considered how to achieve the coexistence of two services from the perspective of service quality. Furthermore, the regulatory policies rarely change based on the type of service the platform offers.

Thus, this paper attempts to provide insight into how to regulate the on-demand ride-sharing service, highlighting the role of service quality and service type. The principal objective of this research is to analyze the coexistence condition of on-demand ride-sharing services and taxi services and the price strategy of two services under the coexistence condition. Note that the coexistence target implies a positive profit margin for both services. The price decision of two services is explored according to the Stackelberg game method of modeling, where taxi service is the leader and on-demand ride-sharing service is the follower. Specifically, this paper takes into account different types of on-demand ride-sharing services, i.e., high-end service (e.g., UberBlack) and low-end service (e.g., carpooling), based on the service quality. There are two cases, i.e., the competition between high-end service and taxi service (H case) and low-end service and taxi service (L case). Riders' utility is affected by the service quality, the price, and the network effect. To examine the impact of network effect on the pricing decisions and coexistence condition of two services, this paper compares the coexistence conditions under positive/negative network effects. It also extends the model considering the coexistence target based on reference dependency theory, taking into account the operating cost and different network effect coefficients.

The results and managerial implications are summarized as follows. First, the coexistence of the two services depends on the type of riders and the quality difference in both cases. When two services and riders are highly heterogenous, two services are more likely to coexist. Services with different qualities could better satisfy the diverse preferences of riders. More homogenous services imply that they compete fiercely. Thus, it is difficult for the low-quality service to survive. Comparing the H case with the L case, this paper finds that, in order to ensure coexistence, the requirements for riders' diversity and quality difference are more strict in the H case than in the L case. This result indicates that the taxi industry is impacted by the low-end service slightly. The government needs to strengthen supervision on the platform offering high-end services. In terms of the network effect, interestingly, the negative network effect is more beneficial to the coexistence of two services. Both the requirements of the type of riders and the quality difference are lower in the scenario with the negative network effect. The negative network effect means that more riders choosing the same service will reduce the riders' utility. Thus, the negative network effect automatically drives rational riders to choose different services to maximize their own utility. Both services set higher prices and achieve higher demand when they have a competitive advantage by comparing the pricing decisions of both services. The player with a competitive advantage in the L case sets a higher price than that in the H case. Due to a smaller potential market share in the L case, the taxi service needs to improve its quality to attract more riders. Intuitively, a higher price covers the expense of high quality.

According to numerical analysis, consumer surplus benefits from the improvement of the average service quality. Given the taxi service quality, enhancing the on-demand ride-sharing service quality benefits the consumer surplus in both cases. However, in the L case, an increment of consumer surplus leads to fierce competition. This needs a tradeoff between the consumer surplus and the coexistence of two services. The results also demonstrate that the consumer surplus is increasing in the network effect due to a higher rider utility. Note that the consumer surplus decreases with the absolute value of the negative network effect. Thus, the platform may subsidize riders for non-peak hours to reduce the impact of the negative network effect. The consumer surplus in both cases is increasing in the riders' homogeneity. Counterintuitively, more diverse rider types or larger market share may hurt the consumer surplus. To satisfy the various riders' requirements of service quality, two services in both cases set a higher price. This has a significant impact on consumer surplus, even exceeding the increment of consumer surplus brought by a larger market share.

The requirement of the difference in service quality between two services and the diversity of rider composition are enhanced in order to ensure the coexistence of two services when taxi drivers view profit as the reference point without competition. For high-end service, the platform could improve service quality through information technology. If the platform offers low-end services, the government is supposed to endeavor to improve the quality of taxi services, which also differentiates the two services. The government can promote the collaboration of taxi services between on-demand ride-sharing services and taxi services.

In the extension, considering the operating cost does not change the main result. It just increases the requirement for a difference in service quality. If the network effect coefficients are different, the network effect of on-demand ride-sharing service exerts over the coexistence condition more than that of taxi services. Therefore, to achieve the coexistence target, the government may pay attention to the network effect of on-demand ride-sharing services, such as controlling the promotion strategy of on-demand ride-sharing services.

The rest of this paper is structured as follows. An overview of the literature is given in Section 2. A game-theoretic model of the competition between on-demand ride-sharing services and taxi services is developed in Section 3. Section 4 presents the pricing decisions of on-demand ride-sharing service and taxi service, and compares the optimal decisions in two cases. Section 5 discusses an analysis of the effects of exogenous parameters on consumer surplus and social welfare in various scenarios. Section 6 extends the model in Section 3 considering the operating cost and different network effect coefficients, respectively. The primary findings and the model's limitations are outlined in Section 7.

2. Literature Review

First, this paper reviews the literature focusing on the price strategy of on-demand ride-sharing services. Subsequently, the research on on-demand ride-sharing service operations management in a competitive market and on-demand ride-sharing service regulatory methods are reviewed. Lastly, the primary contributions are given.

The on-demand ride-sharing service has given rise to a burgeoning body of literature [26–30], especially the pricing strategy adopted by the platforms. Static pricing and dynamic pricing to balance supply and demand have been widely investigated. Ref. [31] studied the dynamic pricing strategy of on-demand ride-sharing services and obtained the optimal platform's price with increasing/decreasing demand. They found that the platform used dynamic pricing to decrease the excess supply capacity/demand under the decreasing/increasing market demand. In order to compare dynamic pricing with static pricing, [32] developed a queueing-theoretic model and discovered that the static pricing policy outperforms the dynamic pricing policy from the platform's perspective. Ref. [33] established a two-period model with uncertain demand and supply in two adjacent areas. Their results contrasted with [32] and suggested that dynamic pricing could improve the platform's profitability even in areas where there is more demand than supply. Similarly, [34] focused on the platform's pricing strategy in two adjacent zones. Different from [33], they also take into account the cross-regional demand. The result showed that dynamic pricing or bonus incentives in the region adjacent to the supply shortage zone could achieve a balance of demand and supply. Ref. [35] considered a revenue maximization problem in a model that accounts for the stochastic and nonstationary character of demands as well as the nontrivial distance between locations. They verified that the revenue improvement brought by the dynamic pricing strategy is predominantly driven by an increase in the number of consumers serviced rather than an increase in average price. In addition, researchers investigated the pricing policies considering the riders' and drivers' behavior, e.g., riders' delay sensitivity and drivers' idle-time sensitivity [32,36,37].

Our research concentrates on the ride service market including taxi services and ride-hailing services. Numerous research concluded that the growth of on-demand ride-sharing services significantly impacted the taxi industry. However, researchers failed to reach a consensus. Using the user data of on-demand ride-sharing and taxi services in Chicago, [38] compared the usage patterns for two services and explored the underlying determinants of usage patterns. Ref. [19] took New York and Istanbul as examples on which to study the impact of on-demand ride-sharing services on taxi services and provided suggestions for the regulation of the new service. Ref. [12] claimed that the competition from on-demand ride-sharing services has led to a significant fall in taxi demand, utilizing the data from Shenzhen. According to [39], on-demand ride-sharing services have startled the taxi business. They discovered that the introduction of Uber has cut the income of taxi drivers by about 10%. Similarly, [40] examined data from 44 Chinese cities between 2010 and 2016 using multiperiod DID. The result showed that there was a 17.83% decline in taxi riding after the entry of ride-hailing service. Furthermore, the rise of on-demand ride-sharing services caused a drop in the number of taxi customers, especially among young and well-off riders [13,14]. However, [41] focused on the competition between two services within the resort corridor and across the valley in Las Vegas. They found that on-demand ride-sharing services could complement taxi ridership. Ref. [42] stated that from the perspective of service quality, on-demand ride-sharing services benefited taxi services. They found that the taxi service is motivated to improve the service quality to compete with Uber. Considering the service quality, [4] analyzed the impact of on-demand ride-sharing service on taxi service based on data from 1680 ride-hailing and taxi trips in Los Angeles. Their results showed that ride-hailing riders only need to wait about one-quarter of the time compared to taxis and approximately one in five taxi riders were never picked up. Different from the above literature, this paper uses a decision model to examine the effects of various on-demand ride-sharing services on the taxi industry and attempt to find out the coexistence condition of the two services.

Finally, this paper is pertinent to the regulation of on-demand ride-sharing services to achieve the coexistence of two services. According to [43], rather than attempting to regulate ride-hailing services, communities that use a taxicab medallion system should lower the cost of taxi services. Previous studies have suggested several regulatory policies, such as partnerships with official platforms, a cap on the number of drivers, and a minimum wage [24,25,44–46]. Ref. [24] compared several supervisory measures, including the driving cap, the minimum wage, and the congestion tax, using queuing theory. They discovered that the minimum wage policy helped drivers and riders but hurt platform interests. The effect of the type of services the platform offers on the coexistence condition of two services is investigated in this paper, which is different from [24]. Ref. [45] took into account the different modes of services the platform provides and found that the platform should offer driver subsidies in order to accomplish the first-best scenario. In a similar way, this paper also considers high-end and low-end services, but investigates the coexistence of two services based on the service quality. Ref. [16] developed a Stackelberg game model to examine the impact of a regulated platform's price on the competition between on-demand ride-sharing services and taxi services. The result indicated that both the platform's price and profit are higher without regulation. Despite both our work and [15] considering the competition between ride-hailing services and taxi services, this paper focuses on the influence of service quality and the network effect on the coexistence condition. To investigate the impact of platform subsidy methods on drivers' and riders' choices during surge and normal periods with government regulation, [25] built a multi-stage game-theoretic model. The findings showed that the regulation policy, which limited the amount of time users could spend online, had no impact on the platform's optimal profit. However, the regulation policy about the cap on total online time may be severely detrimental to both the platform and drivers.

Unlike these studies, this paper developed a Stackelberg game model to address the coexistence of on-demand ride-sharing service and taxi service considering the service quality and network effect. Specifically, the coexistence condition with different types of on-demand ride-sharing services and positive/negative network effects is examined, and the optimal platform's pricing strategy under the coexistence condition is explored. In addition, this paper compares and analyzes the price and profit of two services and consumer surplus with respect to the difference in service quality of the two services. Finally, the cases with capacity cost and the different network effect coefficients are studied, respectively.

3. Problem Description

In a ride service market, on-demand ride-sharing service denoted as R competes with traditional taxi service denoted as T. The platform could offer high-end services, such as UberBlack, which matches riders with top-rated drivers driving luxury vehicles. It works better than a taxi service and costs more for a 5-star experience. In other words, the service quality of high-end service is higher than that of taxi service. Some on-demand ride-sharing platforms may focus on carpooling services (low-end services) such as BlaBla Car, which shares a vehicle between riders who have similar commutes or destinations. While more riders are taking the same car, the wait time for individual riders will increase, thus reducing the service quality. In this regard, the taxi service could outperform the low-end service. Therefore, this paper considers two cases, i.e., high-end service vs. taxi service (H case) and low-end service vs. taxi service (L case), based on the relationship between the service quality of on-demand ride-sharing service and taxi service.

3.1. Rider Side

The ride service market comprises a diverse range of riders. They differ in the valuation of ride services, ϕ. ϕ is assumed to follow the uniform distribution, i.e., $\phi \sim U(\widetilde{\phi}, 1)$. $\widetilde{\phi}$ indicates the type of riders with the minimum willingness to pay and the indifference point between choosing either service or outside options. Then, the total demand for two services is $1 - \widetilde{\phi}$. Larger $\widetilde{\phi}$ implies a fiercer competition. On the contrary, smaller $\widetilde{\phi}$ means the ride market has highly heterogenous riders and they have more various requirements for service quality.

One of the characteristics of ride service is the network effect. The same-side network effect means with the change in the number of users using the same product or service, the utility of each user from consuming the product or service changes [47]. Therefore, the impact of the same-side network effect on the riders' utility is considered in this paper. On the one hand, considering taxi drivers searching behavior, for example, the residential area is the most frequent place for drivers to search for customers [48]. It implies that more riders could attract more drivers to provide service and thus reduce the wait times. It will improve the service quality and increase the rider's utility. On the other hand, if the service supply is relatively stable, more riders using on-demand ride-sharing services at the same time will decrease the service availability. For example, in the holiday season, more riders on Uber will lead to a long wait time or pay more for rapid service [49]. And, it is hard to take a ride in the rush hour in Hong Kong. The waiting time for a ride may be more than 15 min, which affects the riders' utility significantly [50]. A large number of riders means riders may compete with each other to obtain the service and may increase the wait times. In consequence, the service quality is reduced. It implies that a higher number of riders has a more negative impact on demand. As a result, there exist positive and negative network effects for the ride service. Similar to the research on the network effect such as [51,52], it is assumed that the demand for on-demand ride-sharing services is linearly related to the network effect, i.e., $e_R(n_R) = \alpha n_R$. Moreover, the impact of network effect coefficients on the on-demand ride-sharing service demand and the taxi demand are the same. Similarly, the network effect of using taxi services is $e_T(n_T) = \alpha n_T$. Note that whether the network effect is positive or negative is unclear. $\alpha > 0$ means adding one rider increases riders' utility, while $\alpha < 0$ implies that riders' utility is reduced with the increase in demand.

Riders with service valuation ϕ obtain the utilities from two services that are $U_R = \phi q_R - p_R + \alpha n_R$ and $U_T = \phi q_T - p_T + \alpha n_T$, respectively, where p_R and p_T represent the platform's price and taxi price. Service quality is regarded as a determinant of increasing rider satisfaction. Therefore, the increase in service quality could improve the ride's utility [53]. Let G represent the difference in service quality, i.e., $G = q_R - q_T$. Therefore, $G > 0$ in the H case and $G < 0$ in the L case. Let $\widehat{\phi}$ denote the indifference point of choosing an on-demand ride-sharing service or taxi service. It means the utilities of the rider with $\widehat{\phi}$ for two services are the same, i.e., $U_R\left(\widehat{\phi}\right) = U_T\left(\widehat{\phi}\right)$. As mentioned, two cases are considered according to the services offered by the platform. In the H case, the demand for high-end service and taxi service is $1 - \widehat{\phi}$ and $\widehat{\phi} - \widetilde{\phi}$, respectively. In contrast, the demand for low-end services and taxi services are $\widehat{\phi} - \widetilde{\phi}$ and $1 - \widehat{\phi}$ in the L case.

3.2. Profit Function of the Platform and Taxi Service

Similar to [44], this paper first focuses on the revenue of two services, and later in the extension, it considers the platform's profit and explores the impact of the operating cost on the pricing strategy. The revenues of on-demand ride-sharing services and taxi services are $\pi_R = p_R n_R$ and $\pi_T = p_T n_T$, respectively. The on-demand ride-sharing service and taxi service form price competition. Considering the service offered by the platform as an entrant, this paper regards the taxi service as the leader in the Stackelberg game.

4. Analysis

4.1. H Case

In the H case, the platform provides a premium service, which performs better than the taxi service. According to $U_{R1}\left(\widehat{\phi}_1\right) = U_{T1}\left(\widehat{\phi}_1\right)$, $\widehat{\phi}_1 = \frac{p_{R1} - p_{T1} - \alpha\left(1 + \widetilde{\phi}\right)}{q_{R1} - q_{T1} - 2\alpha}$ is obtained, which implies the rider with service value $\widehat{\phi}_1$ is indifferent to choosing either service. Therefore, given the taxi price and the platform's price, the demand for high-end service and taxi services are $n_{R1} = 1 - \frac{p_{R1}-p_{T1}-\alpha(1+\widetilde{\phi})}{q_{R1}-q_{T1}-2\alpha}$ and $n_{T1} = \frac{p_{R1}-p_{T1}-\alpha(1-\widetilde{\phi})-\widetilde{\phi}(q_{R1}-q_{T1})}{q_{R1}-q_{T1}-2\alpha}$. Then, Proposition 1 is derived.

Proposition 1. *In H case, given the taxi price, the optimal platform's price is* $p_{R1}(p_{T1}) = \frac{G-\alpha(1-\widetilde{\phi})+p_{T1}}{2}$, *and the indifference point of riders' utility is* $\widehat{\phi}_1(p_{T1}) = \frac{G-p_{T1}-(3+\widetilde{\phi})\alpha}{2(G-2\alpha)}$.

All the proofs are shown in Appendix A.

Proposition 1 indicates that the price of the platform is rising in the difference between the service qualities. Since the high-end service outperforms the taxi service, better service costs more, intuitively. Note that condition $G > 2|\alpha|$ is assumed. It suggests that riders' decisions are more influenced by service quality than by the network effect.

Theorem 1. *The optimal price and demand for high-end service and taxi services are as follows:*

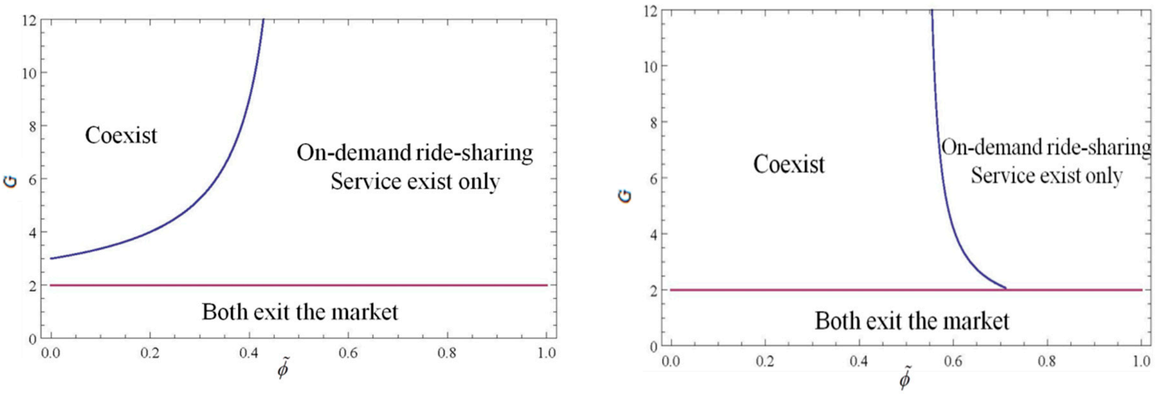
(1) (*Positive network effect*) *if and only if* $0 < \widetilde{\phi} < \phi_1$ *and* $G > A$, *two services coexist, where* $\phi_1 = \frac{1}{2}$, $A = \frac{3\alpha(1-\widetilde{\phi})}{1-2\widetilde{\phi}}$. *The optimal prices for high-end service and taxi services are* $p_{R1}{}^* = \frac{(3-2\widetilde{\phi})G-5\alpha(1-\widetilde{\phi})}{4}$ *and* $p_{T1}{}^* = \frac{(1-2\widetilde{\phi})G-3\alpha(1-\widetilde{\phi})}{2}$. *The demand for two services are* $n_{R1}{}^* = \frac{(3-2\widetilde{\phi})G-5\alpha(1-\widetilde{\phi})}{4(G-2\alpha)}$ *and* $n_{T1}{}^* = \frac{(1-2\widetilde{\phi})G-3\alpha(1-\widetilde{\phi})}{4(G-2\alpha)}$. *If* $\phi_1 \le \widetilde{\phi} < 1$ *and* $G > 2\alpha$, *taxi service will exit the market.*

(2) (*Negative network effect*) *if* $0 < \widetilde{\phi} < \phi_1$ *and* $G > 2|\alpha|$, *or* $\phi_1 \le \widetilde{\phi} < \frac{5}{7}$ *and* $2|\alpha| < G < \frac{3\alpha(1-\widetilde{\phi})}{1-2\widetilde{\phi}}$, *two services coexist. The optimal prices for high-end service and taxi services are* $p_{R1}{}^* = \frac{(3-2\widetilde{\phi})G-5\alpha(1-\widetilde{\phi})}{4}$ *and* $p_{T1}{}^* = \frac{(1-2\widetilde{\phi})G-3\alpha(1-\widetilde{\phi})}{2}$. *The demand for two services are* $n_{R1}{}^* = \frac{(3-2\widetilde{\phi})G-5\alpha(1-\widetilde{\phi})}{4(G-2\alpha)}$ *and* $n_{T1}{}^* = \frac{(1-2\widetilde{\phi})G-3\alpha(1-\widetilde{\phi})}{4(G-2\alpha)}$; *if* $\frac{5}{7} < \widetilde{\phi} < 1$, $G > 2|\alpha|$, *taxi service will exit the market.*

From Theorem 1, when two services and riders are highly heterogenous, two services could coexist. More specifically, when $\alpha > 0$, $0 < \widetilde{\phi} < \frac{1}{2}$ means there exists not only a high type of rider, but also a low type of rider. In other words, riders have various requirements of service quality. In addition, a significant gap in quality prompts both services to coexist, as demonstrated in Figure 1a. If riders or services are more homogeneous (i.e., $\widetilde{\phi} > \frac{1}{2}$ or $2\alpha < G < A$), the optimal taxi price is 0. It suggests that taxi services will withdraw from the ride market. When two services are highly homogenous, high-end service competes fiercely with taxi service. The entry of the platform makes it difficult for taxi services to survive, although taxi service is the leader. This result is consistent with the regulation, which encourages a clearly differentiated development between two services, to form a complementary relationship.

The positive network effect indicates that more riders choosing the same service will increase the riders' utility. Therefore, riders are more likely to make the same choice, which could also be interpreted as herding behavior. Such behavior aggravates the disadvantage of the player with low service quality. If two services are highly homogeneous, the market segments have a high degree of overlap. In addition, if the types of riders are less varied, high types of riders (i.e., $\frac{1}{2} < \widetilde{\phi} < 1$) will choose the service with high quality. Taxi service is faced with the threat of exiting the market.

Compared with the positive network effect, two services are more likely to coexist with the negative network effect, as shown in Figure 1b. Similar to $\alpha > 0$ scenario, when $0 < \widetilde{\phi} < \frac{1}{2}$, both services gain positive revenue as long as the difference in service quality is larger than the network effect. Whereas the type of riders is less diverse, i.e., $\frac{1}{2} < \widetilde{\phi} < \frac{5}{7}$, the difference in service quality should satisfy $2|\alpha| < G < \frac{3\alpha(1-\widetilde{\phi})}{1-2\widetilde{\phi}}$ to achieve the coexistence of two services. This result suggests that the quality difference should not be too great. More heterogenous services in the H case imply that the high-end service can much better meet the service quality requirement of the high type of riders. Note that the negative network effect means that more riders choosing the same service will reduce the riders' utility. Thus, the negative network effect automatically drives rational riders to choose different services to maximize their own utility. However, the relatively homogeneous riders and a large difference in the service quality enable the high-end service to capture the entire market share despite the negative network effect.



(**a**) positive network effect (**b**) negative network effect

Figure 1. The coexistence of two services in H case.

Despite the negative network effect, the high-end service is able to take up the full market share due to relatively homogeneous riders and a significant difference in service quality.

Corollary 1. *When two services coexist in the H case, the impact of the quality difference G and the network effect coefficient α on optimal price and demand is shown in Table 1.*

Table 1. The impact of the quality difference G and the network effect coefficient α on optimal price and demand.

α	$\frac{\partial p_1{}^*}{\partial G}$	$\frac{\partial p_{T1}{}^*}{\partial G}$	$\frac{\partial n_{R1}{}^*}{\partial G}$	$\frac{\partial n_{T1}{}^*}{\partial G}$	$\frac{\partial p_{R1}{}^*}{\partial \alpha}$	$\frac{\partial p_{T1}{}^*}{\partial \alpha}$	$\frac{\partial n_{R1}{}^*}{\partial \alpha}$	$\frac{\partial n_{T1}{}^*}{\partial \alpha}$	$\frac{\partial \pi_{R1}{}^*}{\partial \alpha}$	$\frac{\partial \pi_{T1}{}^*}{\partial \alpha}$	$\frac{\partial \pi_{R1}{}^*}{\partial G}$	$\frac{\partial \pi_{T1}{}^*}{\partial G}$
$\alpha > 0$	↑	↑	↓	↑	↓	↓	↑	↓	↓	↓	↑	↑
$\alpha < 0$	↑	↑	↑	↓	↓	↓	↑	↓	↓	↓	↑	↑

Note that ↑ represents an increasing relationship. ↓ represents an decreasing relationship.

The greater difference in service quality usually drives a higher price for high-quality service. However, low-quality service adopts a low-price strategy to gain a competitive price advantage and compensate for the disadvantage in quality. Counterintuitively, in this paper, the prices of both services increase with the difference in service quality. Taxi service quality, such as wait times, is usually more stable, while the wait times of on-demand ride-sharing services are highly variable because drivers are self-scheduling staff. As a result, changes in the quality difference depend on the quality of the entrant. To achieve a short waiting time, the platform needs to raise the price to attract a large number of drivers. In practice, the surge price of Uber or the prime price of Lyft is the means to improve the riders' service experience by increasing the price. Riders not only focus on the service quality, but they also consider the price. Therefore, riders who are price-conscious will turn to taxi services due to a relatively low price. The demand of the entrant is decreasing in its service quality. In contrast, the taxi demand is increasing in the rival's service quality. It enables taxi services to set a higher price at a large difference in service quality. $\frac{\partial p_R{}^*}{\partial G} > \frac{\partial p_T{}^*}{\partial G}$ implies that the quality difference impacts the platform's price more significantly. Using a lower price rise, taxi services could realize the increase in both demand and price. Therefore, the revenue of taxi services is increasing in the quality difference. For the platform, improving its service quality leads to a greater quality difference. It takes the quality advantage and sets a higher price. Although the high price forces the riders who are indifferent to choosing between both services to switch to taxi services, the price is high enough to compensate for the reduced revenue caused by demand reduction. The improvement of on-demand ride-sharing service quality benefits itself and the taxi service, resulting in the spillover effect of service quality.

The positive network effect represents the rider's utility increase brought by riders using the same service. A more significant positive network effect will attract more riders to choose the same service. However, to some extent, this will aggregate the difficulty of hailing a car. For example, many riders send orders downtown for a ride. But they need to wait for a while for a car to arrive. Therefore, the platform uses a high price to reduce the riders' "herding behavior". In contrast, a low-price strategy is adopted to offset the negative network effect. Although the taxi price is decreasing in positive network effect and its reduction is even higher than the rival's, taxi service is still unable to make up for its service quality disadvantage. As a result, the demand for taxi services decreases with the positive network effect. Under the condition of a negative network effect, the platform lessens the impact of a negative network effect by raising the price. This leads to a decrease in demand.

4.2. L Case

In the L case, the platform offers low-end service. Thus, the service quality of taxi service is higher. According to $U_{R2}\left(\widehat{\phi}_2\right) = U_{T2}\left(\widehat{\phi}_2\right)$, $\widehat{\phi}_2 = \frac{p_{T2}-p_{R2}-\alpha\left(1+\widetilde{\phi}\right)}{q_{T2}-q_{R2}-2\alpha}$ is derived, which suggests that the rider with service value $\widehat{\phi}$ is indifferent to choosing taxi services and low-end services. Therefore, given the taxi price and the platform's price, the demand for low-end service and taxi services are $n_{R2} = \frac{p_{T2}-p_{R2}-\alpha\left(1-\widetilde{\phi}\right)-\widetilde{\phi}(q_{T2}-q_{R2})}{q_{T2}-q_{R2}-2\alpha}$ and $n_{T2} = 1 - \frac{p_{T2}-p_{R2}-\alpha\left(1+\widetilde{\phi}\right)}{q_{T2}-q_{R2}-2\alpha}$. Then, Proposition 2 is derived.

Proposition 2. *In the L case, given the taxi price, the optimal platform's price is* $p_{R2} = \frac{p_{T2}+\widetilde{\phi}G-\alpha\left(1-\widetilde{\phi}\right)}{2}$, *and the indifference point of riders' utility is* $\widehat{\phi}_2(p_{T2}) = \frac{p_{T2}-\widetilde{\phi}G-\left(1+3\widetilde{\phi}\right)\alpha}{2(-G-2\alpha)}$.

Note that this paper defines the difference between service qualities as $G = q_R - q_T$. Consequently, $G < 0$ in the L case. Different from the H case, the platform's price is decreasing in $|G|$. This suggests that if the service quality of taxi service far exceeds that of low-end service, the platform will choose a lower price. The platform sets a lower price as a result of the low service quality and attempts to gain a competitive advantage through a low-price strategy. However, the demand for low-end service is increasing in $|G|$. The two services differ greatly from one another due to the lower quality of on-demand ride-sharing services. Therefore, the platform could pay attention to the low type of riders and adopt a low price to compensate for the disadvantage of the service quality. Similar to the H case, the condition $|G| > 2\alpha$ is assumed.

Theorem 2. *The optimal price and demand for the low-end service and the taxi service are as follows:*

(1) (*Positive network effect*) *if and only if* $0 < \widetilde{\phi} < \phi_2$ *and* $|G| > B$, *two services coexist, where* $\phi_2 = \frac{2}{3}$, $B = \frac{5\alpha\left(1-\widetilde{\phi}\right)}{2-3\widetilde{\phi}}$. *The optimal prices for low-end service and taxi services are* ${p_{R2}}^* = \frac{\left(3\widetilde{\phi}-2\right)G-5\alpha\left(1-\widetilde{\phi}\right)}{4}$ *and* ${p_{T2}}^* = \frac{\left(\widetilde{\phi}-2\right)G-3\alpha\left(1-\widetilde{\phi}\right)}{2}$. *The demands of the two*

services are $n_{R2}{}^* = \frac{(3\tilde{\phi}-2)G-5\alpha(1-\tilde{\phi})}{4(-G-2\alpha)}$ *and* $n_{T2}{}^* = \frac{(\tilde{\phi}-2)G-3\alpha(1-\tilde{\phi})}{4(-G-2\alpha)}$*. If* $\phi_2 < \tilde{\phi} < 1$ *and* $|G| > 2\alpha$*, on-demand ride-sharing services will exit the market.*

(2) (*Negative network effect*) *if* $0 < \tilde{\phi} < \phi_2$ *and* $|G| > 2|\alpha|$*, or* $\phi_2 \le \tilde{\phi} < \frac{9}{11}$ *and* $2|\alpha| < |G| < \frac{5|\alpha|(1-\tilde{\phi})}{|2-3\tilde{\phi}|}$*, two services coexist. The optimal prices for low-end service and taxi services are* $p_{R2}{}^* = \frac{(3\tilde{\phi}-2)G-5\alpha(1-\tilde{\phi})}{4}$ *and* $p_{T2}{}^* = \frac{(\tilde{\phi}-2)G-3\alpha(1-\tilde{\phi})}{2}$*. The demand for the two services are* $n_{R2}{}^* = \frac{(3\tilde{\phi}-2)G-5\alpha(1-\tilde{\phi})}{4(-G-2\alpha)}$ *and* $n_{T2}{}^* = \frac{(\tilde{\phi}-2)G-3\alpha(1-\tilde{\phi})}{4(-G-2\alpha)}$*; if* $\frac{9}{11} < \tilde{\phi} < 1,\ |G| > 2|\alpha|$*, on-demand ride-sharing services will exit the market.*

From Theorem 2, the coexistence condition of two services in the L case is similar to that in the H case, which depends on the type of riders and the quality difference. In terms of the positive network effect, highly heterogenous riders ensure the coexistence of two services. However, the diversity of riders' type is lower than that in the H case (i.e., $\phi_1 < \phi_2$). Different from the H case, on-demand ride-sharing services leave the market as the riders or services become more uniform. The taxi service as the incumbent enjoys the dominant advantage. In addition, the taxi service performs better. It is difficult for the platform to enter the market by providing a homogeneous service. And $\frac{2}{3} < \tilde{\phi} < 1$ means that the market includes only high-type riders. Since taxi service has advantages in quality, riders prefer it more. Meanwhile, the positive network effect drives more riders to choose taxi services. As a result, only the taxi service survives. The results with negative network effects are also similar to those in the H case, but the conditions for the coexistence of two services are relaxed.

Corollary 2. *When two services coexist in the L case, the relationship between optimal price and demand with respect to the difference in service quality* $|G|$ *and the network effect coefficient* α *is as follows:*

(1) $\frac{\partial p_R{}^*}{\partial |G|} > 0$; $\frac{\partial p_T{}^*}{\partial |G|} > 0$; $\frac{\partial n_R{}^*}{\partial |G|} > 0$, *if* $\alpha > 0$ ($\frac{\partial n_R{}^*}{\partial |G|} < 0$, *if* $\alpha < 0$); $\frac{\partial n_T{}^*}{\partial |G|} < 0$, *if* $\alpha > 0$ ($\frac{\partial n_T{}^*}{\partial |G|} < 0$, *if* $\alpha < 0$);

(2) $\frac{\partial p_R{}^*}{\partial \alpha} < 0$; $\frac{\partial p_T{}^*}{\partial \alpha} < 0$; $\frac{\partial n_R{}^*}{\partial \alpha} < 0$; $\frac{\partial n_T{}^*}{\partial \alpha} > 0$.

Corollary 2 indicates the impact of the quality difference and network effect on the optimal price and demand of two services, which is similar to the results in the H case. Note that the taxi service outperforms the on-demand ride-sharing service in the L case.

4.3. Comparison of H Case and L Case

Based on Theorem 1 and Theorem 2, both of the coexistence requirements of riders' diversity and the quality difference are more stringent in the H case than in the L case, i.e., $\phi_1 < \phi_2$ and $B < A$, under the condition of a positive network effect, as shown in Table 2. It implies that two services are more likely to survive in the L case. Specifically, in the H case, taxi service is at a disadvantage in terms of service quality. Only low-type riders will choose it. Although taxi service is considered the market leader, the quality advantage of high-end service weakens its first mover advantage. Therefore, it needs a more diverse rider composition to ensure taxi profitability. In the L case, the taxi service performs better. However, the difference in service quality is relatively small, resulting in a lower requirement for riders' heterogeneity.

When two services coexist, comparing the results in the H and L cases, Proposition 3 is derived.

Proposition 3. (*a*) *The relationship between the prices of two services are as follows:*

(1) *If* $\frac{G_1}{G_2} \le Y_1$*, then* $p_{R1}{}^* < p_{R2}{}^*$, $p_{T1}{}^* < p_{T2}{}^*$*, and* $p_{T1}{}^* < p_{R1}{}^* < p_{R2}{}^* < p_{T2}{}^*$;

(2) *If* $Y_1 < \frac{G_1}{G_2} \le Y_2$*, then* $p_{R1}{}^* > p_{R2}{}^*$, $p_{T1}{}^* < p_{T2}{}^*$;

(3) *If* $\frac{G_1}{G_2} > Y_2$, *then* $p_{R1}{}^* > p_{R2}{}^*, p_{T1}{}^* > p_{T2}{}^*$, *and* $p_{R2}{}^* < p_{T2}{}^* < p_{T1}{}^* < p_{R1}{}^*$;
(*b*) *The relationship between demand of two services:* $n_{R1}{}^* > n_{R2}{}^*, n_{T1}{}^* > n_{T2}{}^*$;
where G_1 *and* G_2 *denote the absolute value of the quality difference in the H case and L cases,* $G_1 > 0$ *and* $G_2 > 0$, *and* $Y_1 = \frac{2-3\widetilde{\phi}}{3-2\widetilde{\phi}}$ *and* $Y_2 = \frac{2-\widetilde{\phi}}{1-2\widetilde{\phi}}$.

Table 2. The comparison results of coexistence condition in H and L case.

	$\lvert G\rvert$	$\widetilde{\phi}$				
		$\left(0, \frac{1}{2}\right]$	$\left(\frac{1}{2}, \frac{2}{3}\right]$	$\left(\frac{2}{3}, \frac{5}{7}\right]$	$\left(\frac{5}{7}, \frac{9}{11}\right]$	$\left(\frac{9}{11}, 1\right)$
positive network effect	$\frac{5\alpha(1-\widetilde{\phi})}{2-3\widetilde{\phi}} < \lvert G\rvert \le \frac{3\alpha(1-\widetilde{\phi})}{1-2\widetilde{\phi}}$	(N,Y)	(N,Y)	(N,N)	(N,N)	(N,N)
	$\lvert G\rvert > \frac{3\alpha(1-\widetilde{\phi})}{1-2\widetilde{\phi}}$	(Y,Y)	(N,Y)	(N,N)	(N,N)	(N,N)
negative network effect	$\lvert G\rvert > 2\lvert\alpha\rvert$	(Y,Y)	(N,Y)	(N,N)	(N,N)	(N,N)
	$2\lvert\alpha\rvert < \lvert G\rvert < \frac{3\lvert\alpha\rvert(1-\widetilde{\phi})}{1-2\widetilde{\phi}}$	--	--	(Y,Y)	(N,Y)	(N,N)
	$\frac{3\lvert\alpha\rvert(1-\widetilde{\phi})}{1-2\widetilde{\phi}} < \lvert G\rvert < \frac{5\lvert\alpha\rvert(1-\widetilde{\phi})}{2-3\widetilde{\phi}}$	--	--	(N,Y)	(N,Y)	(N,N)

Note that (i_H, i_L) $(i_H, i_L = Y, N)$ denotes the status of coexistence in H and L cases.

Both services set a higher price in the case with a higher quality difference. For example, the H case has a significantly larger quality differential than the L case. As mentioned, the taxi service quality is relatively stable. Therefore, the quality difference is determined by the platform. The larger quality difference corresponds to a higher service quality offered by the platform in the H case. As a result, a higher price is used to make up for the effort to maintain the service quality. However, because of the high platform's price, some riders move to the taxi service, making it possible for the taxi service to increase its price, even exceeding the taxi price in the L case. As the difference in service quality in the H case is slightly higher or slightly lower than that in the L case, correspondingly, a higher service quality costs more. In terms of demand, the service with advantages in quality attracts more riders in both cases. This result suggests that the service should improve the service experience and gain more market share.

Then, the relationship between the prices and demand is analyzed more specifically, when the absolute values of quality difference are the same in both cases, as shown in Table 3. The players with a competitive advantage in the H case are on-demand ride-sharing services, and the players with a competitive advantage L case are taxi services. Both services set higher prices and achieve higher demand when they have a competitive advantage. The results show that two services should be concerned about improving service quality. For example, the platform can efficiently match service supply and demand through big data analysis, in order to shorten the waiting time.

Table 3. The comparison results of the optimal price and demand between the players with a competitive advantage and competitive disadvantage.

		H Case	
		Player with Competitive Advantage	**Player with Competitive Disadvantage**
L case	player with competitive advantage	$p_{R1}{}^* < p_{T2}{}^*, n_{R1}{}^* > n_{T2}{}^*$	$p_{T1}{}^* < p_{T2}{}^*, n_{T1}{}^* < n_{T2}{}^*$
	player with competitive disadvantage	$p_{R1}{}^* > p_{R2}{}^*, n_{R1}{}^* > n_{R2}{}^*$	$p_{T1}{}^* < p_{R2}{}^*, n_{T1}{}^* < n_{R2}{}^*$

The price comparison between the players with competitive advantage indicates that the taxi service in the L case sets a higher price. Considering $\phi_1 < \phi_2$, the riders in the L case focus more on the service quality. Therefore, in the L scenario, the service quality by the taxi service will be higher than in the H case by the on-demand ride-sharing service.

Its price will be high correspondingly. Furthermore, due to $\phi_1 < \phi_2$, the total demand is lower in L case $(1 - \phi_2)$ than that in H case $(1 - \phi_1)$. Thus, the demand of the player with a competitive advantage is lower in the L case than in the H case. Based on the comparison results of the price and the demand in both cases, the result shows that $\pi^*_{T1} < \pi^*_{R2} < \pi^*_{R1}$ and $\pi^*_{T1} < \pi^*_{R2} < \pi^*_{T2}$. The comparison between the revenue of the players with a competitive advantage is given in Corollary 3.

Corollary 3. *When the absolute values of quality difference are the same in both cases,*

(*a*) (*positive network effect*) *there exists* ϕ_3 *and* G_3 *such that* (1) *if* $0 < \widetilde{\phi} < \phi_3$ *and* $2\alpha < |G| < G_3$, $\pi^*_{R1} < \pi^*_{T2}$; *if* $0 < \widetilde{\phi} < \phi_3$ *and* $|G| \geq G_3$, $\pi^*_{R1} \geq \pi^*_{T2}$; (2) *if* $\phi_3 < \widetilde{\phi} < \phi_1$ *and* $2\alpha < |G| < G_3$, $\pi^*_{R1} > \pi^*_{T2}$; *if* $\phi_3 < \widetilde{\phi} < \phi_1$ *and* $|G| \geq G_3$, $\pi^*_{R1} \leq \pi^*_{T2}$;

(*b*) (*negative network effect*) *there exists* ϕ_3 *and* G_4 *such that* (1) *if* $0 < \widetilde{\phi} < \phi_3$, $\pi^*_{R1} < \pi^*_{T2}$; (2) *if* $\phi_3 < \widetilde{\phi} < 1$ *and* $2|\alpha| < |G| \leq G_4$, $\pi^*_{R1} \geq \pi^*_{T2}$; (3) *if* $\phi_3 < \widetilde{\phi} < 1$ *and* $|G| > G_4$, $\pi^*_{R1} < \pi^*_{T2}$, *where* $\phi_3 = 0.292$, $G_3 = \frac{\alpha}{1-4\widetilde{\phi}+2\widetilde{\phi}^2}\left(3 - 7\widetilde{\phi} + 4\widetilde{\phi}^2 + \sqrt{2}(1-\widetilde{\phi}^2)\right)$ *and* $G_4 = \frac{\alpha}{1-4\widetilde{\phi}+2\widetilde{\phi}^2}\left(3 - 7\widetilde{\phi} + 4\widetilde{\phi}^2 - \sqrt{2}(1-\widetilde{\phi}^2)\right)$.

Under the condition of positive network effect, if the type of riders is more diverse, but the two services are more homogenous, the player with the competitive advantage in the L case, i.e., taxi service, will earn more profit. As shown in Table 2, in the H case, the platform's price is lower than the taxi's in the L case. Consumers use price to signal their perception of quality [54,55]. In other words, people believe higher prices as a signal of greater quality. Thus, riders question the service quality offered by the platform in the H case due to a low price when they are faced with two homogeneous services. This will reduce the gap between taxi demand in the L case and demand in the H case. With a larger quality difference, riders could easily distinguish between the two services. This weakens the role of price as a quality signal. Higher prices will drive riders to choose the service with lower quality but acceptable price. As a result, the demand for the taxi service in the L case is relatively low. However, the platform in the H case adopts a low-price strategy to attract riders and improve its profitability. Riders are more homogenous, which indicates the proportion of high-type riders increases. If the quality difference is small, the price of taxi services in the L case is so high that the demand for on-demand ride-sharing services in the H case is significantly higher than that of taxi services in the L case. Consequently, the platform in the H case gains more profit.

When the types of riders are more diverse, the total demand increases, while riders do not concentrate on the same service due to the negative network effect. Thus, the excess demand for the entrant in the H case compared with that for taxi service in the L case is reduced. The platform's price is lower and does not have a significant demand advantage. This leads to a lower platform's profit. If riders are more homogeneous, the comparison result is similar to that with the positive network effect. But with a negative network effect, the platform's profit is more likely to be higher than that of taxi services due to a lower requirement of the quality difference $(G_4 > G_3)$.

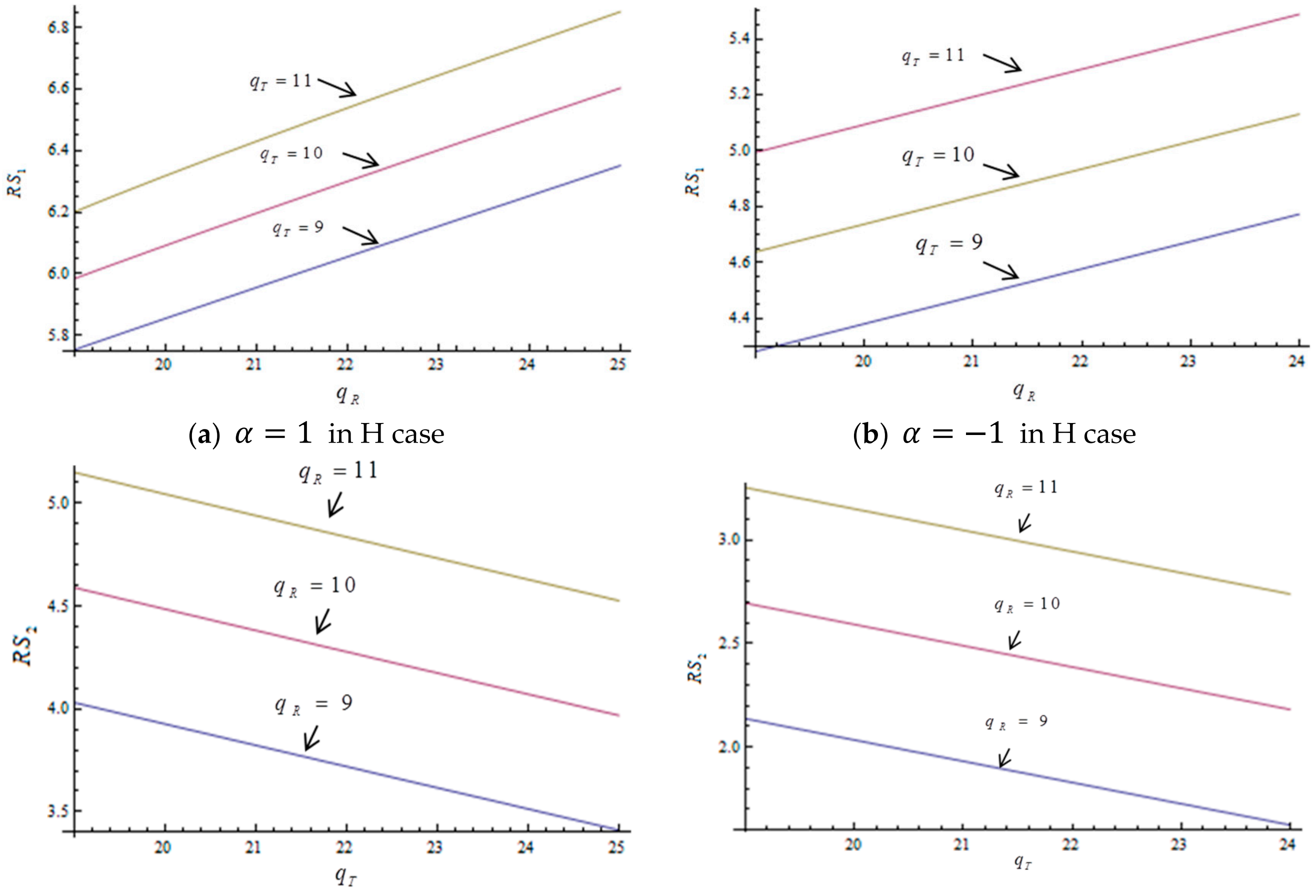
5. Numerical Analysis

Based on the results in Section 4, this section uses numerical analysis to explore the impact of various parameters on consumer surplus and the coexistence conditions of two services.

5.1. Consumer Surplus

The policy makers are concerned with consumer surplus. Thus, this paper further compares consumer surplus in two cases.

The consumer surpluses in both cases are as follows: $RS_1 = \int_{\widehat{\phi}_1}^{1} \left(\phi q_{R1} - p_{R1} + \alpha\left(1 - \widehat{\phi}_1\right)\right) d\phi + \int_{\widetilde{\phi}}^{\widehat{\phi}_1} \left(\phi q_{T1} - p_{T1} + \alpha\left(\widehat{\phi}_1 - \widetilde{\phi}\right)\right) d\phi$ and $RS_2 = \int_{\widetilde{\phi}}^{\widehat{\phi}_2} \left(\phi q_{R2} - p_{R2} + \alpha\left(\widehat{\phi}_2 - \widetilde{\phi}\right)\right) d\phi + \int_{\widehat{\phi}_2}^{1} \left(\phi q_{T2} - p_{T2} + \alpha\left(1 - \widehat{\phi}_2\right)\right) d\phi$. Given $\widetilde{\phi} = 0.3$, the relationship between consumer surplus and the service quality of both services is illustrated in Figure 2. From Figure 2, consumer surplus benefits from the improvement of the average service quality. The improvement of average service quality could be achieved by (1) increasing the quality of the on-demand ride-sharing service; (2) increasing the quality of the taxi service; and (3) increasing the quality of both services.



(**a**) $\alpha = 1$ in H case (**b**) $\alpha = -1$ in H case

(**c**) $\alpha = 1$ in L case (**d**) $\alpha = -1$ in L case

Figure 2. The relationship between consumer surplus and the service quality of both services.

As shown in Figure 2a,c, given the service quality of taxi service, the consumer surplus of riders in both cases is increasing in the service quality provided by the platform with the positive network effect. To be specific, on the one hand, riders benefit more from heterogenous services due to the high-end service offered by the platform. The high service experience could satisfy the requirements of riders better. On the other hand, the demand for taxi service is increasing in the quality difference according to Corollary 1. Although the taxi price also increases, it is still lower than the platform's price. Therefore, the consumer surplus of taxi services increases with the improvement of the rival's quality. Different from the H case, the taxi service takes advantage of service quality in the L case. The improvement of service quality offered by the platform will increase the average service quality. Finally, it will boost the consumer surplus, given the taxi service quality.

Figure 2a shows that the consumer surplus increases with the taxi service quality given the service quality of the entrant. Intuitively, the improvement of taxi service quality could enhance the riders' experience. Nevertheless, the result shows that under this condition, the difference between the two services is smaller in the H case. In other words, more homogenous services operate in favor of riders. This result may contradict the coexistence condition discussed in the H case previously. It suggests that more heterogenous services are good for coexistence. But note that riders could benefit from the increase in average service quality, which is not the case for the L case. In the L case, the increase in taxi service quality reduces the consumer surplus. The taxi price rises to compensate for the cost of the service quality. Higher taxi prices will reduce riders' utility. Meanwhile, consider the positive network effect on the riders' utility. With the increase in quality differentiation, the decrease in demand for taxi services further reduces consumer surplus. The result shows that when the platform provides low-end service, the consumer surplus could be improved by increasing the quality of the entrant. Note that only enhancing the taxi service quality could obtain the opposite result.

Given the same quality difference, the consumer surplus is higher when the service qualities of both services are higher, that is, the consumer surplus is higher at (22, 10) than (21, 9) in Figure 2. It implies that the government could advocate the improvement of both services, which will benefit riders more. This result is similar to [38] They argue that both the taxi industry and on-demand ride-sharing services must enhance service quality to remain competitive and efficient. Additionally, when the players with competitive advantage or disadvantage in both cases achieve the same service quality, for example, service qualities in the H case and the L case (20, 9), consumer surplus is much higher in the H case. It indicates that the platform provides a high-end service that is beneficial for not only itself but also for riders. This result may relate to the decision sequence. In the L case, the leader is the player with quality advantage (i.e., taxi service) and has the first mover advantage. As a result, the taxi price in the L case is much higher than the platform's price in the H case. It also brings about a higher price for the player with a quality disadvantage in the L case. Therefore, the average price of services is lower in the H case than in the L case. This enables riders to obtain more consumer surplus in the H case.

The impact of positive or negative network effects on the consumer surplus is similar. The consumer surplus is increasing in the network effect, as shown in Figure 3. Note that the consumer surplus is decreasing in the absolute value of the negative network effect. The consumer surplus is much higher when the network effect is positive due to a higher utility. In addition to a higher price, the platform should effectively guide riders through information technology and avoid using the service during peak hours. It may also increase the subsidy for non-peak hours to reduce the impact of the negative network effect. As shown in Figure 3, the consumer surplus in both cases is increasing in the rider's homogeneity. Not that riders have similar preferences for service quality, which means a smaller market share. In other words, the consumer surplus is decreasing in market share. The result indicates that more diverse riders in service quality or larger market share may hurt the consumer surplus. As discussed previously, more heterogenous riders could be beneficial for the coexistence of two services. However, to satisfy the various riders' requirements of service quality, both services in both cases set a higher price. It has a significant impact on consumer surplus, even exceeding the increment of consumer surplus brought by a larger market share.

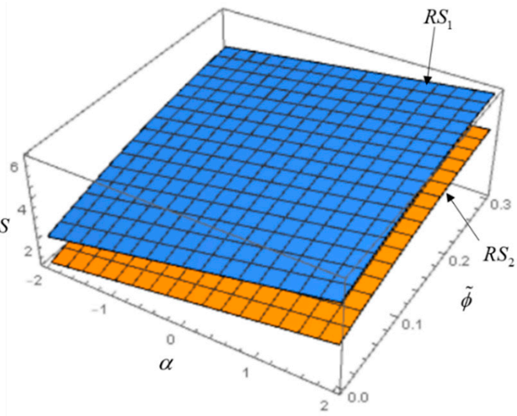
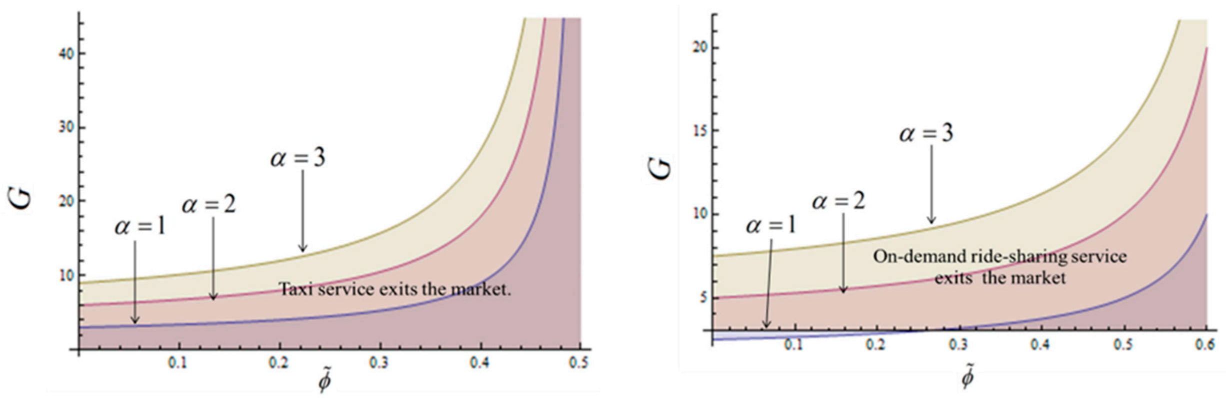


Figure 3. The relationship between consumer surplus and network effect.

5.2. The Impact of Parameters on the Coexistence Condition

According to Theorem 1, when the network effect is positive, the coexistence condition of two services in the H case is $G \geq A$. As shown in Figure 4, when riders are more homogeneous (a higher $\widetilde{\phi}$), both services could survive only with a larger quality difference. If the two services are similar in service quality and riders also have similar requirements of service quality, the player with the quality advantage will dominate the market, forcing the player with a disadvantage in quality to withdraw from the market. Meanwhile, the quality difference changes slightly under the condition of extremely homogenous riders or extremely heterogenous riders. Given the composition of riders, higher quality difference is required when the network effect exerts a significant influence on the condition of coexistence. Considering the positive network effect, riders tend to choose the same service to increase the utility, whereas more differences in service quality could weaken the trend of riders making the same choice.



(**a**) H case (**b**) L case

Figure 4. The relationship between the coexistence of the two services, the difference in the service quality, and the composition of riders ($\alpha > 0$).

When the network effect is positive, the relationships among the coexistence of the two services, the difference of the service quality, and the composition of riders the relationship in the L case are similar to those in the H case. But the requirement of riders' diversity has been reduced, that is, expanding $\widetilde{\phi}$ from 0.5 to 0.667. In addition, the threshold of the quality difference for the coexistence in the L case varies relatively smoothly with the type of riders, $\widetilde{\phi}$. In contrast, this threshold in the H case is more variable when the riders' composition is at a medium level. This result implies that the government should focus on the service type offered by the platform to facilitate the coexistence of the two services.

6. Regulation of On-Demand Ride-Sharing Service

When there is only a taxi service, the optimal taxi price is ${p_T}^{N*} = \frac{q_T}{2}$ and the optimal profit is ${\pi_T}^{N*} = \frac{{q_T}^2}{4(q_T-\alpha)}$. The introduction of an on-demand ride-sharing service has captured the market share of taxi services and reduced taxi profits. As a consequence, the survival of the taxi industry continues to be a challenge. Regulation policies such as entry limitations are adopted by countries worldwide to alleviate the effect of the entrant on the incumbent. The introduction of regulation reduces the service supply of the entrant to facilitate the coexistence of two services. Our findings imply that offering distinct services can enable the coexistence of two services. The coexistence of services in this paper means taxi profit is nonnegative.

As noted by [56], people not only consider their final economic outcome, but also consider changes in the outcome relative to the reference point when people make decisions. Reference dependency influences taxi drivers' decisions. Therefore, even if taxi services could gain profit in a competitive market, taxi drivers may still feel dissatisfied if their profit is lower than the profit they could obtain without the entrant. In other words, taxi drivers consider the profit without competition as the reference point of the profit with competition. Thus, based on the reference dependency theory, this paper further analyzes the impact of on-demand ride-sharing services on taxi profits, so as to provide some guidance for the regulation of the entrant.

6.1. H Case

Firstly, this paper discusses the case that taxi drivers accept the entrant if the taxi profit in the competitive market could not be less than that in the noncompetitive market, ${\pi_T}^N$. When there is only a taxi service, the optimal taxi profit is ${\pi_T}^N = \frac{{q_T}^2}{4(q_T-\alpha)}$. The taxi profit in the H case is ${\pi_T}^* = \frac{1}{8(G-2\alpha)}\left(3\alpha\left(-1+\widetilde{\phi}\right)+G-2\widetilde{\phi}G\right)^2$. The relationship between the difference in taxi service before and after the introduction of the entrant ($\Delta\pi = {\pi_T}^* - {\pi_T}^N$) and service quality of the entrant is shown in Figure 5, given $q_T = 7$.

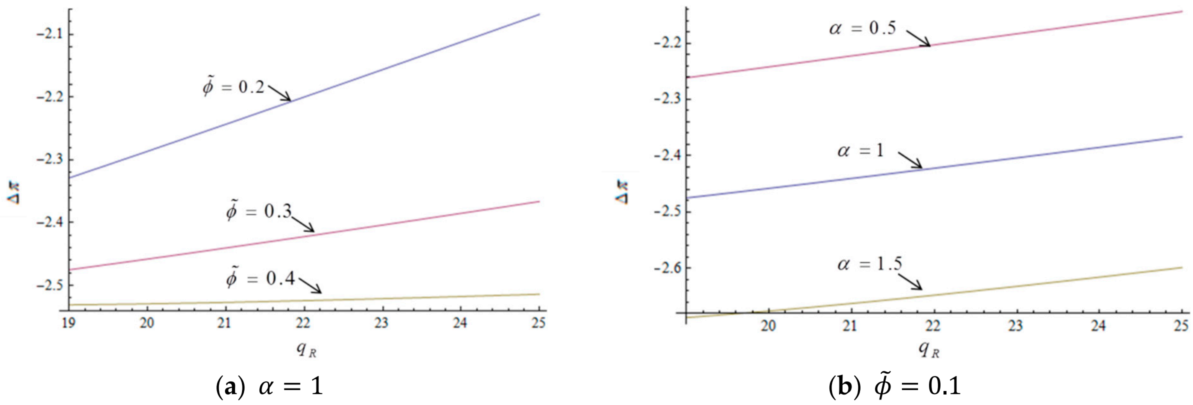


Figure 5. The relationship between the profit difference of taxi service and the quality of on-demand ride-sharing service in H case.

From Figure 5a, the difference in taxi profit is increasing in the service quality of the entrant given the network effect. The more homogeneous the two services are, the more taxi profit is reduced due to the competition. Although the two services are of high homogeneity, the entrant still outperforms the taxi service in the H case. Thus, the on-demand ride-sharing service attracts more riders and decreases the taxi profit dramatically. This result indicates that if two services exhibit heterogeneity, the competition could only result in a lesser reduction in taxi profit, which can alleviate the dissatisfaction of taxi drivers to a certain extent. This requires the platform to exert its advantages in information technology to provide services with shorter waiting times. Given the service quality of the entrant, the taxi profit is increasing in the diversity of rider composition types $(1-\widetilde{\phi})$. A more diversified rider composition indicates an increase in the total market share. Taxi services can still maintain a certain market share in the competition scenario, and thus reduce the impact of the entrant on taxi profit. Meanwhile, Figure 5a illustrates that when $\widetilde{\phi}$ is smaller, the profit difference of taxi service is more sensitive to changes in service quality of on-demand ride-sharing service. Smaller $\widetilde{\phi}$ implies greater diversity of riders, which increases the potential market share of taxi service after the introduction of the entrant, and therefore likely increases taxi profit.

Given the service quality of the entrant, the profit difference of taxi service is decreasing in the network effect, as shown in Figure 5b. This result indicates that on-demand ride-sharing service impacts taxi profit significantly with a higher network effect. High-type riders prefer the premium service offered by the platform due to a higher service quality, while higher network externalities enable lower-type riders also choose the premium service to achieve higher utility. Consequently, the taxi demand decreases sharply. Moreover, taxi price decreases with the network effect according to Corollary 1. Therefore, the taxi profit is reduced by a large margin when the network effect is high. This paper assumes that taxi drivers consider the profit without competition as the reference point of the profit with competition. If the taxi profit in the competitive market is larger than the reference point, i.e., ${\pi_T}^* \geq {\pi_T}^N$, the drivers will allow the entrant to enter the ride market. Then, when the quality difference between two services G is no less than $\underline{G}$, where $\underline{G} = \frac{\alpha^2(-3+9\widetilde{\phi}-6\widetilde{\phi}^2)+3\alpha(1-3\widetilde{\phi}+2\widetilde{\phi}^2)q_{T1}+{q_{T1}}^2+\sqrt{{q_{T1}}^2(2\alpha^2(-1+\widetilde{\phi}^2+2\widetilde{\phi}^2)-2\alpha(-1+\widetilde{\phi}^2+2\widetilde{\phi}^2)q_{T1}+{q_{T1}}^2)}}{(1-2\widetilde{\phi})^2(q_{T1}-\alpha)}$, the two services can coexist. However, $\underline{G}$ is extremely high. It is difficult to satisfy the condition of $G \geq \underline{G}$. Thus, it is more likely that the taxi profit decreased in the competition scenario. Based on the survey in Ghana and sub-Saharan Africa, the emergence of the service mode that hails a car online brought a dramatic decrease in taxi service [13]. Ref. [16] consider ride-hailing's low trip prices as the main reason for declining taxi rides, while the result in this paper provides a new explanation for the decline in taxi service from the service difference between the two services. The result once again highlights that the government should be concerned about the difference in service quality in order to establish the coexistence of the two services. The regulation can be established to encourage the platform to provide better service. On the one hand, the platform can improve the service quality by providing a more comfortable car or high-quality drivers. On the other hand, the platform can further use the advantages of information technology to match supply and demand accurately and shorten waiting times. Then, the two services can be more heterogenous.

Note that in the above analysis, the optimal taxi price in the competitive market ${p_T}^*$ is higher than the optimal taxi price without competition ${p_T}^{N*}$ under the condition of $G \geq \underline{G}$. This result suggests that taxi services cannot maximize their profit if they maintain their original price in the noncompetitive market. However, in practice, the taxi price has not been adjusted; that is, the taxi service still adopts the same price as before, $\widetilde{p}_T$. The taxi price without competition may not be the price to realize the maximum profit, i.e., $\widetilde{p}_T \neq {p_T}^{N*}$. This paper considers the scenario that the taxi price, $\widetilde{p}_T$, is unchanged in the noncompetitive and competitive market. Then, the taxi profit with and without competition is $\widetilde{p}_T\left(\frac{G-\widetilde{p}_T-(3+\widetilde{\phi})\alpha}{2(G-2\alpha)}-\widetilde{\phi}\right)$ and $\widetilde{p}_T\left(1-\frac{\widetilde{p}_T-\alpha}{q_{T1}-\alpha}\right)$, respectively. When taxi price exceeds p_{T0}, where $p_{T0} = G(1-2\widetilde{\phi})-\alpha(3-\widetilde{\phi})$, taxi prices are not profitable in the competitive market. This suggests that if the original taxi price is relatively high, on-demand ride-sharing service plunders all demands of taxi service because of its favorable price and high service quality. When taxi prices are lower than p_{T0}, taxi services gain profit in the competition scenario, but their profit is less than the profit without competition.

The difference in taxi profit is $\Delta\pi = \pi_T - {\pi_T}^N$. Given $\widetilde{\phi} = 0.4$, $\alpha = 1$, $q_{T1} = 9$, the relationship between the difference in taxi profit, taxi price, and the service quality of the entrant is shown in Figure 6, where $\Delta\pi < 0$. It implies that the competition reduces the taxi profit. The difference in taxi profit is decreasing in taxi price and increasing in the service quality of the entrant. As mentioned before, the original taxi price $\widetilde{p}_T$ is less than the optimal taxi price with competition. With the increase in $\widetilde{p}_T$, the taxi profit π_T is closer to the maximum profit, and thus $\Delta\pi$ is decreased.

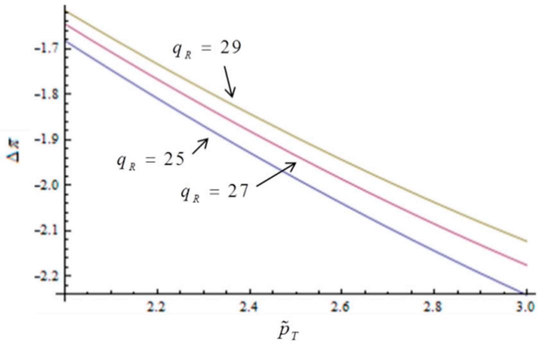


Figure 6. The relationship among the difference of taxi profit, taxi price, and the service quality of ride-hailing service in H case.

From Proposition 3, the taxi price is lower than the platform's in the H case. When taxi prices are at a level, the taxi service uses its price advantage to weaken its disadvantage in service quality. As a result, the entrant has little impact on the taxi profit. With the increase in the service quality of the entrant, the difference in service quality increases. Based on Corollary 1, taxi prices and demand benefit from the increase in quality difference. Therefore, given the taxi price, the difference in taxi profit increases with the service quality of the entrant. This result indicates that the taxi service has enjoyed the spillover effect brought by the entrant. In consequence, similar to the case of $p_T = {p_T}^*$, the government could start with expanding the difference in service quality between the two services, that is, promoting the platform to provide more convenient services, so as to realize the coexistence of the two services.

6.2. L Case

Similar to the analysis above, we explore the taxi profit with the taxi price in the non-competitive market, ${p_T}^{N*}$, and with the taxi price, ${p_T}^*$, which is adjusted in the competitive market. The taxi profits with and without competition are $\frac{{q_{T2}}^2}{4(q_{T2}-\alpha)}$ and $\frac{\left(\left(\widetilde{\phi}-2\right)G-3\alpha\left(1-\widetilde{\phi}\right)\right)^2}{8(-G-2\alpha)}$, respectively, where $G = q_{R2} - q_{T2} < 0$. Given $q_{T2} = 7$, the relationship between the profit difference of taxi service and the service quality of the entrant is shown in Figure 7.

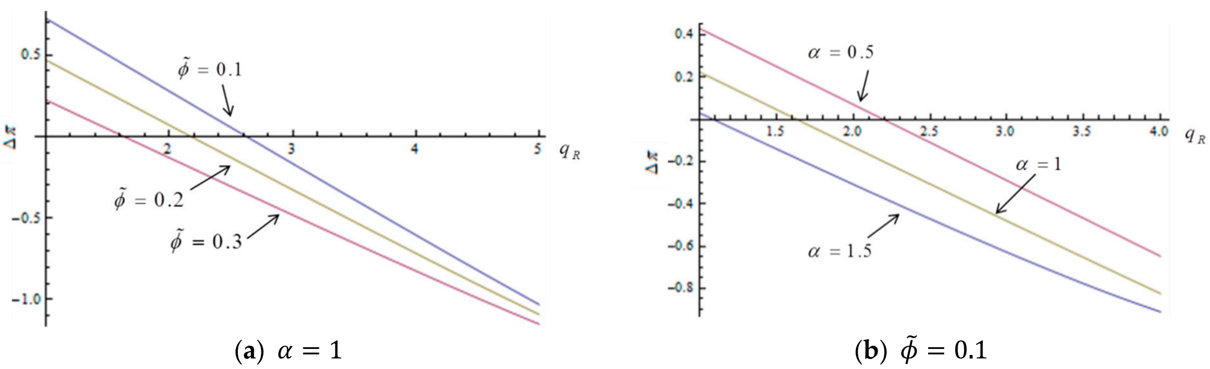


Figure 7. The relationship between the quality of on-demand ride-sharing service and the difference in taxi profit in L case.

Distinct from the result in the H case, the difference in taxi profit decreases with the quality of the entrant in the L case. This result implies that the difference in taxi profit is increasing in $|G|$. From the perspective of the quality difference, the relationship between the difference in taxi profit and the service quality of the entrant is the same in the H case and the L case. This result shows that if the two services are more heterogenous, the taxi service is less vulnerable to the entrant. Given the quality of the entrant, the relationships between the difference in taxi profit and the diversification of rider composition as well as the network effect are similar to the results in the H case.

In the L case, if $|G|$ satisfies the condition, $|G| \geq \underset{-1}{G}$, where $\underset{-1}{G} = \frac{-3\alpha^2\left(2-3\widetilde{\phi}+\widetilde{\phi}^2\right)+3\alpha\left(2-3\widetilde{\phi}+\widetilde{\phi}^2\right)q_{T2}+{q_{T2}}^2+\sqrt{{q_{T2}}^2\left(\alpha^2\left(4+2\widetilde{\phi}-2\widetilde{\phi}^2\right)+2\alpha\left(-2-\widetilde{\phi}+\widetilde{\phi}^2\right)q_{T2}+{q_{T2}}^2\right)}}{\left(2-\widetilde{\phi}\right)^2\left(q_{T2}-\alpha\right)}$, the competition has not weakened the profitability of taxi services. A larger difference in service quality brings about a lower taxi price and higher taxi demand, according to Corollary 3. Although the taxi price is higher than the platform's price, the advantage in terms of service quality still leads more riders to choose the taxi service. Here, the increase in taxi demand has a greater impact on profits than the decrease in taxi prices. Therefore, as $|G|$ increases, taxi services earn more.

If the taxi price, $\widetilde{p}_T$, does not change with and without competition, the profits are $\widetilde{p}_T\left(1-\frac{\widetilde{\phi}|G|+\widetilde{p}_T-\left(1+3\widetilde{\phi}\right)\alpha}{2(|G|-2\alpha)}\right)$ and $\widetilde{p}_T\left(1-\frac{\widetilde{p}_T-\alpha}{q_{T2}-\alpha}\right)$, respectively. The relationship between the difference in taxi profit and the taxi price is illustrated in Figure 8. The difference in taxi profit is decreasing in taxi price, which is similar to the result in the H case, and also decreasing in the service quality of the entrant, which differs from the result in the H case. Note that the reduction of the quality of on-demand ride-sharing service enlarges the difference of two services. Lower taxi prices are more likely to achieve the reference point of the taxi profit when the two services are more heterogenous. Therefore, the government should be concerned about expanding the service quality of the two services. However, it is inappropriate to reduce the service quality of the entrant to realize the coexistence of the two services, since this decreases the consumer surplus. The government can strive to improve the quality of taxi services, which also differentiates the two services. E-hailing taxi service is possible from the technology perspective [57]. In Germany, taxi companies have offered their service online to improve the service quality to face the competition [58]. Additionally, the government might encourage collaboration between two services to improve service responsiveness. DiDi announced that it has reached cooperation with more than 150 taxi enterprises in China. Didi sent orders based on big data analysis, improving taxi drivers' income and operating efficiency.

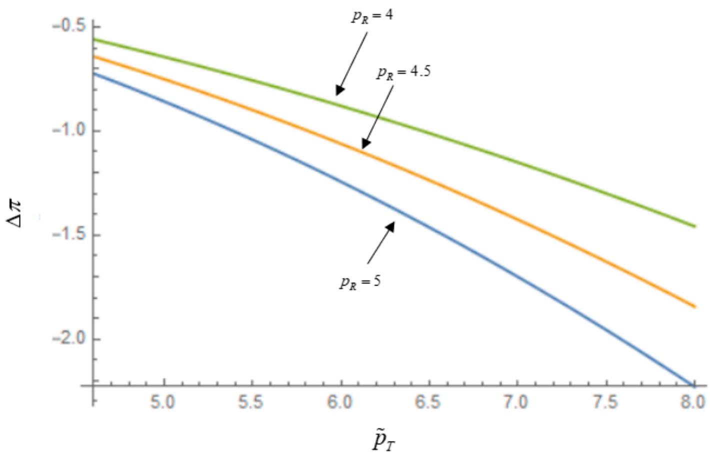


Figure 8. The relationship among the difference in taxi profit, taxi price, and the quality of on-demand ride-sharing service in L case ($\widetilde{\phi} = 0.4$, $\alpha = 1$, $q_{T2} = 9$).

7. Extension

7.1. Considering the Operating Cost

This paper did not consider the operating cost in the profit function in the previous model. Then, this paper extends the model and adds the operating cost (c_R and c_T) in the profit function of two services, i.e., $\Pi_R = (p_R - c_R)n_R$ and $\Pi_T = (p_T - c_T)n_T$. Information technology facilitates the platform to efficiently connect drivers with riders nearby. It reduces the amount of "empty cruising". Thus, this paper assumes that the operating cost of an on-demand ride-sharing service is lower than that of a taxi service, $c_R < c_T$. This paper only takes the H case with the positive network effect as an example to discuss the impact of operating cost on the coexistence conditions and pricing decisions of the two services.

Proposition 4. *If and only if* $0 < \widetilde{\phi} < \phi_1$ *and* $G > A + \frac{\Delta c}{1-2\widetilde{\phi}}$*, two services coexist. The optimal prices for high-end service and taxi services are* $p_{R3}{}^{**} = \frac{(3-2\widetilde{\phi})G-5\alpha(1-\widetilde{\phi})+3c_R+c_T}{4} = p_{R1}{}^* + \frac{3c_R+c_T}{4}$*, and* $p_{T3}{}^* = \frac{(1-2\widetilde{\phi})G-3\alpha(1-\widetilde{\phi})+c_R+c_T}{2} = p_{T1}{}^* + \frac{c_R+c_T}{2}$*. The demand for the two services are* $n_{R3}{}^* = \frac{(3-2\widetilde{\phi})G-c_R+c_T-5\alpha(1-\widetilde{\phi})}{4(G-2\alpha)} = n_{R1}{}^* + \frac{c_T-c_R}{4(G-2\alpha)}$ *and* $n_{T3}{}^* = \frac{(1-2\widetilde{\phi})G-3\alpha(1-\widetilde{\phi})+c_R-c_T}{4(G-2\alpha)} = n_{T3}{}^* - \frac{c_T-c_R}{4(G-2\alpha)}$*. If* $\phi_1 \le \widetilde{\phi} < 1$ *and* $G > 2\alpha$*, taxi service will exit the market.*

In this scenario, taxi service is at a disadvantage in terms of quality and operating cost. Therefore, Proposition 4 indicates that the coexistence of two services requires a larger difference in service quality when this paper considers the operating cost. This is because taxi services are not only at a disadvantage in terms of quality, but also in terms of service costs. The service demand for both services decreases with the operating cost of itself and increases with the operating cost of the competitor. The prices of both services increase with the operating cost of both services. Note that that operating costs have a more significant impact on the price of itself ($\frac{\partial p_R}{\partial c_R} > \frac{\partial p_T}{\partial c_R}, \frac{\partial p_T}{\partial c_T} > \frac{\partial p_R}{\partial c_T}$). The increase in the operating cost of the platform leads to an increase in prices of both prices. However, the taxi price is much lower than the platform's price, which weakens the service quality advantage of the platform. As a result, the taxi demand increases under this condition.

7.2. Different Network Effect Coefficients

In the basic model, this paper considers the network effect coefficients of on-demand ride-sharing services and taxi services are the same. However, on-demand ride-sharing service exhibits higher network effects facilitated by information technology. Therefore, in this section, this paper extends the basic model to explore the effect of difference network effect coefficients on the coexistence condition, taking the H case with positive network effect as an example.

Similar to the basic model, riders with service valuation ϕ obtain the utilities from both services, which are $U_R = \phi q_R - p_R + \alpha_R n_R$ and $U_T = \phi q_T - p_T + \alpha_T n_T$, respectively. If $\alpha_R = \alpha_T$, then the model is reduced to the basic model. The optimal solutions are as follows: If, and only if, $0 < \widetilde{\phi} < \phi_1$ and $G > A_a$, two services could coexist, where $A_a = \frac{(2\alpha_R+\alpha_T)(1-\widetilde{\phi})}{1-2\widetilde{\phi}}$. The optimal prices for high-end service and taxi services are $p_{R5}{}^* = \frac{(3-2\widetilde{\phi})G-(2\alpha_R+3\alpha_T)(1-\widetilde{\phi})}{4}$ and $p_{T5}{}^* = \frac{(1-2\widetilde{\phi})G-(2\alpha_R+\alpha_T)(1-\widetilde{\phi})}{2}$. The demand for the two services are $n_{R5}{}^* = \frac{(3-2\widetilde{\phi})G-(2\alpha_R+3\alpha_T)(1-\widetilde{\phi})}{4(G-(\alpha_R+\alpha_T))}$ and $n_{R5}{}^* = \frac{(1-2\widetilde{\phi})G-(2\alpha_R+\alpha_T)(1-\widetilde{\phi})}{4(G-(\alpha_R+\alpha_T))}$; otherwise, taxi services will exit the market.

The result shows that the coexistence condition will be difficult to satisfy with the increase in the network effect of both services. Although a higher network effect is beneficial for the profit, it exacerbates the competition between the two services. Moreover, the network effect of the entrant exerts over the coexistence condition more than that of the taxi service. Therefore, to achieve the coexistence target, the government may pay attention to the network effect of on-demand ride-sharing services, such as reducing its promotion strategy.

8. Conclusions

In view of the operations practice of on-demand ride-sharing services and the conflict between this and taxis, this paper develops a game-theoretic framework to investigate the impact of on-demand ride-sharing services on taxi services. The pricing decisions of two services considering the service quality and network effect are studied. Then, this paper derives the coexistence condition of two services from the perspective of the difference in service quality. In the basic model, the coexistence of two services means that the profits of both services are nonnegative. Further, the case that taxi drivers regard taxi profit without competition as their reference point based on reference dependency theory is explored. Finally, this paper extends the basic model considering the operating cost and different network effect coefficients.

Our principle results and implications are outlined below. First, the coexistence of the two services depends on the type of riders and the quality difference in both cases. When two services and riders are highly heterogenous, two services are more likely to coexist. Services with different qualities could better satisfy the diverse preferences of riders. More homogenous services imply that they fiercely compete. Thus, it is difficult for the low-quality service to survive. This result is in contrast [16], who suggest that the government should encourage competition between platforms and the taxi industry. Comparing the H case with the L case, the results show that in order to achieve coexistence, both the requirements of riders' diversity and the quality difference are more stringent in the H case than in the L case. This result indicates that the taxi industry is slightly impacted by the low-end service. The government needs to strengthen supervision on the platform offering high-end service, which is similar to the suggestion by [18]. In terms of the network effect, interestingly, the negative network effect is more beneficial to the coexistence of two services. Both the requirement of the type of riders and the quality difference are lower in the scenario with the negative network effect. The negative network effect means that more riders choosing the same service will reduce the riders' utility. Thus, the negative network effect automatically drives rational riders to choose different services to maximize their own utility. Both services set higher prices and achieve higher demand when they have a competitive advantage by comparing the pricing decisions of both services. The player with a competitive advantage in the L case (i.e., taxi service) sets a higher price than that in the H case (i.e., on-demand ride-sharing service). Due to a smaller potential market share in the L case, the taxi service needs to improve its quality to attract more riders. Intuitively, a higher price covers the expense of high quality.

Numerical analysis shows that consumer surplus benefits from the improvement of the average service quality, which is similar to [38]. Given the taxi service quality, increasing the on-demand ride-sharing service quality benefits the consumer surplus in both cases. However, in the L case, the increment of consumer surplus leads to fierce competition. This needs to tradeoff between the consumer surplus and the coexistence condition of two services. The results also demonstrate that the consumer surplus is increasing in the network effect due to a higher rider's utility. Note that the consumer surplus decreases with the absolute value of the negative network effect. Thus, the platform may increase the subsidy for non-peak hours to reduce the impact of the negative network effect. The consumer surplus in both cases is increasing in the rider's homogeneity. Counterintuitively, more diverse rider types or larger market share may hurt the consumer surplus. To satisfy the various riders' requirements of service quality, two services in both cases set a higher price. It has a significant impact on consumer surplus, even exceeding the increment of consumer surplus brought by a larger market share.

When taxi drivers use the profit without competition as their benchmark, the requirement of the difference in service quality between two services and the diversity of rider composition is increased to facilitate the coexistence of the two services. For high-end service, the platform could improve the service quality through information technology. If the service quality offered by the platform is low, the government can strive to improve the quality of taxi services, which also differentiates the two services. The government can encourage on-demand ride-sharing services and taxi services to collaborate.

In the extension, considering the operating cost does not change the main result. It just increases the requirement for the difference in service quality. If the network effect coefficients are different, the network effect of the entrant exerts over the coexistence condition more than that of taxi services. Therefore, to achieve the coexistence target, the government may pay attention to the network effect of the entrant, such as controlling its promotion strategy.

Several extensions to our model are worth further investigation. First, currently, Urban Air Mobility (UAM) attracts a lot of attention. This new service will bring more competition between it and the existing mobility services such as taxi services and on-demand ride-sharing services. Comparing UAM and taxi service, the service quality such as waiting and boarding time is longer for UAM, but the in-vehicle time is much shorter for UAM [59]. Considering the service quality, the competition between Urban Air Mobility, taxi services, and on-demand ride-sharing services is unclear. Further study of the competition between these services from the passengers' willingness-to-pay perspective needs to be conducted. The game theory method is used in this paper to characterize the competition between taxi services and on-demand ride-sharing services. To some extent, the method lacks the application of the data from the practice. There are other methodologies such as aggression analysis and the logit model to conduct studies on the research topic in this paper using data from the real world. This will be future research that we will explore.

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Appendix A

Proof of Proposition 1. Based on $\overset{\frown}{\phi} q_{R1}(t) - p_{R1} + \alpha n_{R1} = \overset{\frown}{\phi} q_{T1}(\tilde{t}) - p_{T1} + \alpha n_{T1}$, the difference point of riders' utility is $\overset{\frown}{\phi} = \frac{p_{R1} - p_{T1} - \alpha(1+\tilde{\phi})}{G-2\alpha}$. Then, the demand for on-demand ride-sharing services $1 - \overset{\frown}{\phi}(p_{T1}) = \frac{G - p_{R1} + p_{T1} - (1+\tilde{\phi})\alpha}{G-2\alpha}$ and the profit of on-demand ride-sharing service $\frac{(G - p_{R1} + p_{T1} - (1+\tilde{\phi})\alpha) p_{R1}}{G-2\alpha}$ are obtained. From the first-order derivative condition, given the taxi price, the price of on-demand ride-sharing services is $p_{R1}(p_{T1}) = \frac{G - \alpha(1-\tilde{\phi}) + p_{T1}}{2}$. Substituting $\overset{\frown}{\phi}$ into $p_{R1}(p_{T1})$, $\overset{\frown}{\phi}(p_{T1}) = \frac{G - p_{T1} - (3+\tilde{\phi})\alpha}{2(G-2\alpha)}$ is derived. □

Proof of Theorem 1. In the scenario with a positive network effect:

Given the taxi price, substituting $\widehat{\phi} = \frac{p_{R1}-p_{T1}-\alpha\left(1+\widetilde{\phi}\right)}{q_{R1}-q_{T1}-2\alpha}$ into the profit of an on-demand ride-sharing service $\pi_{R1} = p_{R1}n_{R1}$, i.e., $\pi_{R1} = p_{R1}\left(1-\widehat{\phi}\right) = p_{R1}\left(1-\frac{p_{R1}-p_{T1}-\alpha\left(1+\widetilde{\phi}\right)}{q_{R1}-q_{T1}-2\alpha}\right)$. From the first-order derivative condition, $p_{R1} = \frac{G-2\alpha+p_{T1}+\alpha\left(1+\widetilde{\phi}\right)}{2}$ is obtained, where $G = q_{R1}-q_{T1}$. π_{R1} is concave in p_{R1}. Substituting $p_{R1} = \frac{G-2\alpha+p_{T1}+\alpha\left(1+\widetilde{\phi}\right)}{2}$ into $\widehat{\phi}$, $\widehat{\phi}(p_{T1}) = \frac{G-p_{T1}-\left(3+\widetilde{\phi}\right)\alpha}{2(G-2\alpha)}$ is obtained. Then, $p_{T1} = \frac{\left(1-2\widetilde{\phi}\right)G-3\alpha\left(1-\widetilde{\phi}\right)}{2}$ is derived from $\pi_{T1} = p_{T1}\left(\frac{G-p_{T1}-\left(3+\widetilde{\phi}\right)\alpha}{2(G-2\alpha)}-\widetilde{\phi}\right)$. Then, the price of on-demand ride-sharing services $p_{R1} = \frac{\left(3-2\widetilde{\phi}\right)G-5\alpha\left(1-\widetilde{\phi}\right)}{4}$ is obtained. ${p_{T1}}^* > 0$ and ${p_{R1}}^* > 0$ hold with the condition of $G \geq A$ and $G \geq H$, where $A = \frac{3\alpha\left(1-\widetilde{\phi}\right)}{1-2\widetilde{\phi}}$ and $H = \frac{5\alpha\left(1-\widetilde{\phi}\right)}{3-2\widetilde{\phi}}$. Comparing A with H, when $0 < \widetilde{\phi} < \frac{1}{2}$, $A-H > 0$ holds. When $\frac{1}{2} \leq \widetilde{\phi} < 1$, $A < 0 < H < 2\alpha$ holds, $G < A$ holds to assure ${p_T}^* > 0$. But under the condition of $A < 0 < H < 2\alpha$, $G < A$ contradicts with $G > 0$. Therefore, only on-demand ride-sharing services exist in the market. If $0 < \widetilde{\phi} < \frac{1}{2}$, $H < 2\alpha < A$. Therefore, two services can coexist if and only if $0 < \widetilde{\phi} < \frac{1}{2}$ and $G \geq A$. □

Similar to the scenario with a positive network effect, the proof in the scenario with a negative network effect is omitted here.

Proof of Proposition 2. Similar to the proof of Proposition 1. We omit here. □

Proof of Theorem 2. Similar to the proof of Theorem 1. We omit here. □

Proof of Proposition 3. In terms of the price comparison, $p_{R1}^* - p_{R2}^* = \frac{\left(3-2\widetilde{\phi}\right)G_1-\left(2-3\widetilde{\phi}\right)G_2}{4}$ is obtained. When $\frac{G_1}{G_2} > \frac{2-3\widetilde{\phi}}{3-2\widetilde{\phi}} \equiv Y_1 < 1$, $\left(3-2\widetilde{\phi}\right)G_1-\left(2-3\widetilde{\phi}\right)G_2 > 0$ is derived, then $p_{R1}-p_{R2} = \frac{\left(3-2\widetilde{\phi}\right)G_1-\left(2-3\widetilde{\phi}\right)G_2}{4} > 0$. Similarly, when $\frac{G_1}{G_2} > \frac{2-\widetilde{\phi}}{1-2\widetilde{\phi}} \equiv Y_2 > 1$, we have $p_{T1} > p_{T2}$. From $Y_1 - Y_2 = \frac{2-3\widetilde{\phi}}{3-2\widetilde{\phi}} - \frac{2-\widetilde{\phi}}{1-2\widetilde{\phi}} = \frac{-4\left(1-\widetilde{\phi}^2\right)}{\left(3-2\widetilde{\phi}\right)\left(1-2\widetilde{\phi}\right)} < 0$, the comparison results are obtained. The comparison of demand is similar to the comparison of price. We omit here. □

Proof of Proposition 4. Similar to the proof of Theorem 1. We omit here. □

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