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Impact of coronavirus pandemic on sharing mode of manufacturer

Zhenzhen Mao a, Weisi Zhang a, b, *, Bin Yang a, Tao Zhang a

a Logistics Research Center, Shanghai Maritime University, Shanghai 201306, China
b School of Management, Fudan University, Shanghai 200433, China

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ABSTRACT

Service platform has developed rapidly in car-sharing, consumers often buy or own cars but not fully utilize and share them. Since the coronavirus pandemic has affected sales and people’s attitudes towards car-sharing, which brought both opportunities and challenges to the platform and changed the operating mode of manufacturers, some traditional manufacturers have motivated to cooperate with third-party platform. In this paper, we develop an analytical framework to examine the pricing decisions and optimal mode selection of manufacturer under the COVID-19 epidemic. Considering the supply chain consists of a manufacturer and a third-party sharing platform. We analyze three scenarios including no sharing, customers-to-customers, and mixed sharing, then employ a game theoretic approach to get equilibrium solutions and analytically derive the optimal mode choice. Our analysis shows that when the operation and maintenance cost is low, manufacturer will join the third-party platform, and the sharing price increase in operation and maintenance cost, while the selling price decrease in operation and maintenance cost. When the value perception factor less than the threshold, the manufacturer will retain sales channel, and the selling demand decrease in value perception factor in the growing market, the sharing demand has the same trend, vice versa. Furthermore, we find that if the operation and maintenance cost is low and value perception factor is high, mixed sharing is the best choice for the manufacturer, while the manufacturer will choose no car-sharing when the value perception factor is relatively low.

1. Introduction

Over the past decades, with the improvement of Internet technology, service platform business mode has received a rapidly development in sharing economy, especially in car-sharing. Traditionally, manufacturers produce cars and retailers sell them, consumers purchase cars for their own use. However, due to the consumption trends shift to more emphasis on sustainable products and services, the emergence of car-sharing service platform (e.g., Uber, Didi) has provided a viable alternative to car ownership. Therefore, customers buy car and share their idle part, users use shared cars to meet their travel needs by paying car sharing price, and the platform matches supply and demand between owners and users. In order to reduce the loss for sales decline and regain market opportunities, some traditional manufacturers actively have provided car-sharing services through self-built mode or joined mode (the manufacturer joins a third-party platform). Daimler and BMW, integrate their own sharing business of Car2Go and Reach Now by establishing joint venture (i.e., Share Now1). Ford and Toyota implemented a car-sharing program by teaming up with Getaround, America’s largest car-sharing platform. Similarly, there are 12 automakers have signed cooperation agreements with Didi (i.e., a third-party platform) up to 2018.

Currently, despite the rapid development of car-sharing, it also faces many problems and challenges, especially in the case of coronavirus pandemic. Due to strict lockdown, the impact of the COVID-19 epidemic on the global car-sharing industry has soared (Ivanov, 2020; Scharf, Heide, Grahle, Syre, & Goehlich, 2020), in order to reduce the risk of infection, many people shift away from car-sharing2, according to sources from Fortune, the global pandemic has pummeled Uber’s passenger-trip volumes by 80%3. However, under the expectation of long-term economic downturn, many consumers are also worried about their own financial situation, some potential buyers embrace car-sharing to reduce the expenditure on car purchase. As for manufacturers, they are facing tremendous financial pressure due to declining sales and...
rising costs. Globally, the profit margin of manufacturers has dropped from 6% in 2018 to 3% in early 2020.¹

Faced with ever-changing market scenarios, manufacturers consider whether joining a third-party service platform, and need to tradeoff the benefits of car-sharing and the losses caused by reduced sales (Belloso, Ferguson, & Toktay, 2017). In addition, inappropriate pricing will result in loss of users, making service platform difficult to continue operating and have to exit sharing market eventually, like ToGo, EZZY. Because increased in sharing price reduce the consumer’s willingness to switch from ownership to car-sharing (de Luca & Di Pace, 2015), or changes in service fee also affects supply side’s enthusiasm. In literature, a few literatures have studied the manufacture involves in car-sharing (e.g., Belloso et al., 2017; Tian & Jiang, 2018). They however consider the product-sharing is provided by owners or manufacturer. Although, the business mode of owners and manufacturer both join the sharing market has been considered in Wang, Ng, and Dong (2020). But we focus on business modes selection, which is different with the study where they examine the implication of firm’s involvement. Thus, the above cases occurring in reality raises some intriguing issues that have not been well understood in literature. Motivated by practice observations and the unclear implications, we try to answer the following questions: (1) What are the impacts of the manufacturer’s involvement in the third-party platform on pricing decisions? (2) What are the impacts of Coronavirus pandemic on car-sharing? (3) What is the optimal mode chosen by the manufacturer?

To address the aforementioned research issues, we divide into three models as following. (i) No sharing (Model N). In this (benchmark) case, where the manufacturer selling his cars to consumers, while consumers decide to buy or not; (ii) Customer-to-customer (Model C). In this case, the manufacture provides car selling, consumers decide to buy or share, and the owners can share an idle part of car via the third-party platform; (iii) Mixed sharing (Model M). In view of a high costs of constructing and operating a platform, we consider the manufacture joins in a third-party platform to share cars with users, where shared cars in platform are provided from the manufacturer and owners. Then, the manufacture needs to formulate a reasonable price in sales channel and input quantity in third-party platform.

After studying the above three sharing modes, our work contributes to the current literature in three ways. First, since the continued changes in consumption and utility patterns, the study of car-sharing problem contributes to the concern of sustainability products and services, and fills gaps in literature stream of the sharing economy. Second, most previous researchers examine product-sharing is provided from owners or manufacturer, we further explore a novel sharing economy model, where shared cars are offered by the manufacturer and individuals. By comparing the proposed three car-sharing modes, members in the supply chain can strategically choose the optimal operation mode. Third, this work distinct from previous studies is that we consider the impact of Coronavirus pandemic on the consumers’ decisions. Some consumers may choose car-sharing to reduce a large payment for car ownership, others however concern about physical distancing and feel car ownership is more valuable.

The remainder of this paper is organized as follows. In Section 2, we present related literature of our paper. The model and the equilibrium outcomes are presented in Section 3 and Section 4. In Section 5, we implemented a data-driven comprehensive numerical study to explore the optimal equilibrium decisions, the mode selection of the manufacturer and main challenges faced by car-sharing under the COVID-19 pandemic. Finally, we summarize the conclusions and outline the possible directions for future research in Section 6.

¹ https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/moving-forward-how-covid-19-will-affect-mobility-in-the-united-kingdom

2. Literature review

As consumption changes and sustainable development needs, sharing economy has received significant attention from scholars, managers, as well as individuals in recent years. Our work is primarily related to the literatures on the three streams: car-sharing, pricing decision, and modes selection.

Car-sharing is a strategy for retaining benefits of car use by sharing vehicles, individuals gain benefits of private cars without costs and responsibilities of ownership (Geum, Lee, & Park, 2014). Studies on car-sharing has shown that shift from ownership to membership often promoted in conception of sustainability (Cohen & Kietzmann, 2014; Pretenthaler & Steiner, 1999). Researches also have focus on issues in the implications of car-sharing on consumers and incumbent firms (or manufacturers). Baltus-Armet, Shaheen, Clonts, and Weinzimmer (2014), Wirtz, So, Mody, Liu, and Chun (2019) conducted a survey about car-sharing and find that financial benefits, contribution to sustainability, convenience are the main motivations of car-sharing participants (Lemoi, Baker, Bolton, Gruber, & Kandampully, 2017; Hessani, 2020). Via an empirical analysis of platform (i.e., Didi), Guo, Xin, Barnes, and Li (2020) find that the entry of sharing platform will positively impacts new car sales in short running. Different with Guo et al. (2020), Tian and Jiang (2018) develop an analytical framework to study the implications of P2P sharing on the manufacturer’s distribution channel. They find that sharing economy is benefit to manufacturer and retailer when the platform exists and marginal cost is relatively high, but lose-lose when the marginal cost is very low. Unlike the above-referenced researches, we construct an analytical framework and explore the decision-making of the manufacturer, where car-sharing is offered by individual or both of the owners and manufacturer in the third-party platform.

Pricing decision has been widely examined from the supply chain operation (de Luca & Di Pace, 2015; Duncan, 2011). For example, Jiang and Tian (2018) find platform’s fee is non-monotonic to the manufacturer’s profit and consumer surplus. In practice, some firms apply dynamic pricing theory (Gibbs, Gutten-tag, Gretzel, Yao, & Morton, 2018), Ren, Luo, Lin, Hsu, and Li (2019) consider the sharing platform may shift the usage of shared EVs by designing a dynamic pricing scheme. Studies have considered the surge pricing on on-demand service platforms (Chen, Zheng, Ke, & Yang, 2020), this pricing strategy can achieve platform revenue and social welfare maximization. Further, Yang, Shao, Wang, and Ye (2020) proposed a novel reward scheme to reduce the potential negative impacts of surge pricing. In addition, Cachon, Daniels, and Lobel (2017), Chen, Zhang, and Liu (2020) both compare two pricing schemes of static pricing and dynamic pricing. Cachon et al. (2017) find that dynamic pricing is better off, while Chen, Zhang, and Liu (2020) find that fixed pricing is better than dynamic pricing under certain conditions. In this paper, we assume that the car-sharing price is the equilibrium price (market clearing price) to make match the supply and demand in sharing platform, which is consistent with the assumption in Jiang and Tian (2018), Tian and Jiang (2018). In addition, we focus on the transaction-based pricing strategy about the third-party platform’s service fee.

The third stream in the literature related to our paper concerns mode selection in sharing economy. Robust supply chain policies under deep uncertainties are developed for minimizing the impact of an epidemic. Paul and Venkateswaran (2020) choose Exploratory Modelling and Analytical Methodology car-sharing to find the ensemble of all plausible behaviors of an epidemic. Under the pandemic, countries make calls to stay at home to ensure that people are least affected by the virus (Güler & Geçici, 2020). In addition, for the sharing economy provides more choice for consumers and manufacturers, such as some traditional manufacturers have motivated to conduct the shared manufacturing to get involved in manufacturing activities via P2P collaborations (Yu et al., 2020). Mobility solution like ride-sharing are becoming popular in many urban areas worldwide recently (Martins, de
Several manufacturers have begun introducing car-sharing schemes besides sales channel (Bellos et al., 2017), the manufacturers need to contemplate whether joins car-sharing and how its product line design. Researchers have studied on the manufacturer’s selection of sharing mode (Li, Bai, & Xue, 2020; Zhang, Huang, Tian, Jin, & Cai, 2020). Specifically, Li et al. (2020) consider OEM’s selection between cooperation with third-party B2C platforms and third-party P2P platform. However, Zhang et al. (2020) investigate the manufacturer’s choice over joined mode or built mode. Of the studies noted above, we also contribute to mode selection what is similar to Li et al. (2020) and Zhang et al. (2020). However, considering the impact of a pandemic on the consumer’s attitude towards car-sharing, we develop a novel sharing economy mode where sharing products are offered by owners and the manufacturer in a third-party platform.

Our work differs from the above papers in three aspects. First, although several studies focus on the challenges and disruptions of supply chain under the pandemic (Govindan, Mina, & Alavi, 2020; Guler & Gocci, 2020; Queiroz, Ivanov, Dolgui, & Fosso Wamba, 2020), few existing studies has examined the sharing mode selection facing to influence of outbreak by employing game theory analytical method. Second, Banerjee, Riquelme, and Johari (2015) find that the platform can maximize its revenue by charging a marked-up price relative to the market-clearing price. We follow the market clearing mechanism in sharing market (Jiang & Tian, 2018; Tian & Jiang, 2018; Wang et al., 2020), and maximize the profits of supply chain members. Third, our paper is most related to Li et al. (2020) and Zhang et al. (2020). They both consider the manufacturer’s sharing mode selection to answer the following question: should a manufacturer cooperate with the P2P platform or third-party B2C platforms if there exists sharing economy. Similar with them, we also study the mode choice. However, we develop mixed sharing mode where car-sharing offered by owners and manufacturer, and consider the consumers’ value perception factor with two opposite attitudes towards car-sharing facing to the pandemic.

3. The model

3.1. Notations and assumptions

We consider a supply chain consists of a monopolist manufacturer (he) and a third-party car-sharing platform. When the manufacturer does not join in the third-party platform, he only produces and sells products to consumers. Meanwhile facing the upsurgence of sharing economy, some traditional manufacturers have provided sharing services. They not only sell cars to consumers, but also cooperate with third-party platform to provide shared cars. The third-party platform provides sharing service to match supply and demand. Consumers need to decide whether to buy or share according to their utility. Therefore, we consider the following three scenarios: No sharing (Model N), Customer-to-customer (Model C), and Mixed sharing (Model M), as illustrated in Fig. 1.

(1) No sharing (Model N): The base scenario, in which the manufacturer produces cars and sells them at price \( p \). Consumers decide whether to buy a car according to their utility.

(2) Customer-to-customer (Model C): The shared cars in the third-party platform are provided solely by car owners. The manufacturer does not directly participate in car-sharing, and produces and sells cars at price \( p \). The third-party platform provides car-sharing service to match the supply and demand. For simplicity, we assume the car-sharing price is \( r \), the car-sharing revenue of owners is \( r - f_o \), in which \( f_o \) is the owner’s service fee per transaction that need to pay for third-party platform.

(3) Mixed sharing (Model M): Facing the upsurgence of sharing economy, traditional manufacturer that sells products at price \( p \) in the market may also join the sharing market in order to gain more profits, and \( q_m \) is the sharing quantity. Therefore, the shared cars in the third-party platform are offered by owners and the manufacturer. As mentioned above, the car-sharing price is \( r \), the car-sharing revenue of manufacturer is \( r - f_m \), in which \( f_m \) is the manufacturer’s service fee per transaction that need to pay for third-party platform.

Without loss of generality, we assume the manufacturer is more likely to join the third-party sharing platform, note that self-build platform requires a lot of construction costs in the early stage. In practice, consumer’s estimate of valuation varies from person to person. For simplicity, we use the parameter \( \tau \) to represent the valuation per use, which is uniformly distributed in the interval \([0, 1]\) (Jiang, Tian, & Xu, 2018; Lim, Mak, & Rong, 2015). As we discussed above, consumers may have two different behaviors in choosing car-sharing due to the impact of a pandemic, we use \( \beta \) to denote the value perception factor for using car-sharing. Some consumers may prefer car ownership due to health concern, where \( 0 < \beta < 1 \); however, others may choose car-sharing to avoid a large payment for car ownership, where \( \beta > 1 \). Thus, the users can get the value perception factor \( \beta \) per car-sharing use. Similar to Bellos et al. (2017), we also normalize the useful life to one period, and denote the consumer’s use fraction as \( d \). At a given sharing price \( r \) (i.e., market-clearing price that to make the supply match the demand), the consumers who did not buy but use shared car if \( d(\beta r - r) > 0 \). These assumptions are consistent with Jiang et al. (2018).

Sequence of events. In model N, the manufacturer first decides his selling price \( p \), the consumers then make their decisions of buy or not. In model C, the manufacturer first decides his selling price \( p \), then the third-party sharing platform sets \( f_o \), and finally consumers decide to become owners or users. In model M, the manufacturer first decides his selling price and sharing quantity \( q_m \), then the sharing platform sets \( f_o \), and finally consumers decide to become owners or users.

Note that we use the superscript \( j = N, C, M \) to represent these three sharing modes, and subscript \( i = m, t, o, u \) to denote the manufacturer, third-party platform, owners and users, respectively. All of the parameters and variables are listed in Table 1.
3.2. Benchmark: No sharing (Model N)

In this section, we begin our analysis by considering the benchmark case of no car-sharing service, and exists sole sale channel. The manufacturer first sets the selling price \( p \), and then the customers choose whether to buy a car or not. Therefore, consumer’s utility can be expressed as \( U_0 = d(v - c) - p \), in order to satisfy the participation constraint of consumers, the condition \( U_0 \geq 0 \) must be met, then we can get the threshold \( v_0^N = (p/d + c) \). Thus, the sales demand function is \( D_0^N = 1 - (p/d + c) \). And the profit function of manufacturer can be expressed as:

\[
x_o^N(p) = (p - c_o)D_o^N
\]

(1)

It can be verified that the above objective function is concave in \( p \), that is, \( \partial^2 x_o^N / \partial p^2 = -2/d < 0 \). According to the first-order condition, we obtain the optimal selling price \( p^N \), then substitute it into demand and profit expressions. As a result, we summarize the equilibrium outcomes at below.

**Theorem 1.** In the Benchmark, there exists a unique equilibrium. The equilibrium selling price and the expected profit of the manufacturer are as follows:

\[
p^N = (c_o + d - cd)/2
\]

(2)

\[
x_o^N = (c_o - (1-c)d)^2/4d
\]

(3)

And the excepted demand is \( D_0^N = ((1-c)d - c_o)/2d \), it should be noted that for manufacturers pursuing profit maximization, we need to consider the participation constraint, which means that the condition \( (1-c)d - c_o > 0 \) needs to be established to ensure that \( D_0^N > 0 \). All proofs of Theory 1 are provided in Appendix.

4. Analysis of the car-sharing modes

In this section, based on the benchmark, we first analyze the customer-to-customer car-sharing, the customers who own the car but do not fully utilize them, may share their cars with some users who do not own car (Model C). Then we consider a novel sharing economy model in which the manufacturer not only sells cars to consumers, but also considers providing shared cars for users in sharing market, so the shared cars in the third-party platform are offered by owners and manufacturer (Model M).

4.1. Customer-to-customer (Model C)

Customer-to-customer product-sharing is widely adopted in various industries in the world, due to recent technological advancements. In sharing market under model C, the shared cars in the third-party platform are provided solely by car owners. Therefore, the utility of owners can be expressed as \( U_o = d(v - c) + (1-d)(r - f_o - c) - p \), and \( U_n = d(\beta r - r) \) as the utility of users. There exists a threshold \( v_0^C = (p - r + (1-d)(f_o + c))/(d(1-\beta)) \), such that \( U_o = U_n \). When \( U_o \geq U_n \), which means consumers tend to be an owner rather than a user. Therefore, the demand function for the owners can be expressed as \( D_o^C = v_0^C - v_o^C \) according to \( v_0^C \). Similarly, for the consumers decide to be a user when \( U_o < U_n \), and in order to ensure the utility of user is larger than zero, i.e., \( U_o > 0 \), there exists a threshold \( v_0^C = r/\beta \), so the demand function for the user is expressed as \( D_o^C = v_o^C - v_0^C \). The profit functions of manufacturer and the third-party platform are expressed as follow:

\[
x_o^C(p) = (p - c_o)(1 - v_0^C)
\]

(4)

\[
x_o^C(f_o) = f_od(v_0^C - v_o^C)
\]

(5)

According to the market clearing mechanism, we can get the equilibrium car-sharing price \( r^C \). Then, substitute \( r^C \) into profit functions and get the equilibrium solutions of Stackelberg game through backward induction. Firstly, the third-party decides the optimal service fee \( f_o^C \) by considering the first-order condition. Secondly, substitute the platform’s best response function into profit function of the manufacturer, we can get the equilibrium selling price. Finally, we updated the \( f_o^C \), and substitute them into Equations (4), (5), we can obtain the equilibrium profits of the manufacturer and the third-party platform. As a result, we summarize the equilibrium outcomes at below.

**Theorem 2.** In Model C, there exists a unique equilibrium. The equilibrium results are as follows:

\[
p^C = \frac{\beta(1-d) + d - c + c_o}{2}
\]

(6)

\[
f_o^C = \frac{\beta(1-d) + d - c_o - c}{4(1-d)}
\]

(7)

\[
x_o^C = \frac{(c + c_o - \beta(1-d) - d)^2}{16\beta + 16(1-\beta)d^2}
\]

(8)

\[
x_o^C = \frac{(c + c_o - \beta(1-d) - d)^2}{8\beta + 8(1-\beta)d^2}
\]

(9)

All proofs of Theory 2 are provided in Appendix. The demand of the owners and users present as follow.

\[
D_o^C = \frac{\beta(1-d) + d - c_o - c}{4\beta + 4(1-\beta)d^2}
\]

(10)

\[
D_n^C = \frac{\beta(1-d) + d - c_o - c}{4\beta + 4(1-\beta)d^2}
\]

(11)

Considering participation concerns (i.e., \( D_o^C > 0, D_n^C > 0 \), the operation and maintenance cost should not excessively high (i.e., \( c < \beta(1-d) + d - c_o \)), the sum of marginal cost and the operation and maintenance cost should less than 1 (i.e., \( c + c_o < 1 \)). Otherwise, the manufacturer will withdraw from the sales channel, meanwhile it will not provide any car-sharing services in the third-party platform. Therefore, we focus on the suitable parameter range in the rest of the paper.

**Property 1.** The selling price increase in production cost, and the slope is the same under the model no sharing and customer-to-customer. In addition, the third-party platform’s optimal service fee is decrease in customer-to-customer scenario. Mathematically, \( \frac{d f_o^C}{d c_o} = -\frac{1}{4(1-\beta)} \).

Property 1 indicates that the selling price is increase and the service fee is decrease in production cost \( c_o \). As increase in production cost, the selling price set by the manufacturer will be higher, leading to declination in car sales, which will eventually reduce the quantity of car-
sharing. Therefore, in order to attract owners to join the sharing market, the third-party platform charges lower service fee. These intuitive conclusions can be used to test the validity of the model, the findings are consistent with the existing literature of car-sharing and pricing mode. Next, we analyze the impact of value perception factor on the expected demand, and get the following result.

**Proposition 1.** The relationship between the demand and the value perception factor depends on the use fraction. When the use fraction larger than a threshold, the selling demand decrease in value perception factor, and the sharing demand has the same trend, vice versa. Mathematically, if \( d > d_1 = \frac{1}{1 - (\sigma_o - \sigma_u)} - 1 \), \( \frac{\partial df}{\partial \beta} < 0, \frac{\partial df}{\partial \beta} < 0 \); otherwise, \( \frac{\partial df}{\partial \beta} > 0 \).

Proposition 1 indicates that the demand has a opposite tendency as value perception factor increase under different use fraction. Specifically, when the consumers’ use fraction is higher a certain threshold \( d_1 \), the selling demand and sharing demand will decrease in value perception factor, while increases in value perception factor if use fraction is lower the threshold. The reason lies that use fraction is large (i.e., the consumers are in the growing market like China), as value perception factor increases, consumers are more inclined to the car-sharing service instead of owning one, especially under the impact of the coronavirus pandemic. Leading the selling demand decrease in value perception factor in the growing market, the sharing demand has the same trend, vice versa. As for \( d_1 = \frac{1}{1 - (\sigma_o - \sigma_u)} - 1 \), note that the higher the cost (i.e., production cost, the operation and maintenance cost), the larger the threshold of the use fraction, which means that it is a growing market.

### 4.2. Mixed sharing (Model M)

In this scenario, the shared cars in the third-party platform are provided by a mixture of owners and the manufacturer. Consumers need to decide to become owners or users, and we denote \( U_o = d(y - c + (1 - d)(r - f_o - c) - p) \), \( U_u = d(\beta y - r) \) as the utility function of the owners and users, respectively. Similar as model \( C \), the consumer will choose to buy a car, when the utility of the owner is larger than that of user, i.e., \( U_o \geqslant U_u \). Otherwise, vice versa. Therefore, we can obtain the two thresholds \( v_{o}^* = (p - r + (1 - d)f_o + c)/(d(1 - \beta)) \) and \( v_u^* = \frac{r}{\beta} \), according to the conditions \( U_o = U_u = U_o = 0 \), respectively. According to the customer utility theory, the demand functions of the owners and the users are expressed as \( D_o^M = 1 - v_{o}^* \), \( D_u^M = v_u^* - v_{o}^* \) respectively. The manufacturer decides selling price \( p \) and sharing quantity \( q_m \), then the third-party platform sets \( f_o \), and finally consumers decide to become owners or users. Therefore, the profit functions of manufacturer and third-party platform as follow:

\[
\kappa^M_o(p, q_m) = (p - c_o)(1 - v_{o}^*) + q_m(r - f_o - c - c_o) \\
\kappa^M_u(f_o) = f_o(1 - d)(1 - v_{o}^*) + f_m q_m
\]

Manufacturer and owners can share their idle cars through the third-party platform and get sharing price \( p^M \) per transaction. Similarly, the market-clearing price obtained by matching car-sharing supply and demand, users who have not bought the cars can receive the car-sharing service. Substituting \( p^M \) into the demand and profit expressions, we use the backward induction approach to solve the problem. First, it can be verified that the profit function of the third-party car-sharing platform is concave in \( f_o \). By considering the first-order condition, we obtain the optimal service fee per transaction of owners \( f^M_o \). Then, by substituting the third-party platform’s best response function into the equation (12), according to the Hessian Matrix, it is easy to verify that the profit function is joint concave in \( p \) and the sharing quantity \( q_m \). Therefore, we can get the optimal selling price \( p^M \) and sharing quantity \( q^M_m \). Finally, equilibrium decisions and outcomes are summarized as below.

**Theorem 3.** In Model M, there exists a unique equilibrium. The equilibrium outcomes are as follows:

\[
p^M = \frac{\beta + (1 - \beta)d - c + c_o}{2} \\
f^M_o = \frac{(\beta + (1 - \beta)d^2)((1 - \beta)d - f_o)}{2(\beta + 2(1 - \beta)d^2)} \\
f^M_u = \frac{d(\beta - f_o - c - c_u)(\beta + 2(1 - \beta)d^2) - \beta f_o(1 - \beta)d}{2\beta(\beta + 2(1 - \beta)d^2)} \\
q^M_m = \frac{\beta f_o}{2\beta + 2(1 - \beta)d^2}
\]

We present the specific analysis process and proofs in appendix. The demand of owners and users can be expressed as follow.

\[
D_o^M = \frac{d(1 - \beta)d + f_o}{2\beta + 4(1 - \beta)d^2} \\
D_u^M = \frac{(\beta - f_o - c - c_u)(\beta + 2(1 - \beta)d^2) - \beta f_o(1 - \beta)d}{2\beta(\beta + 2(1 - \beta)d^2)}
\]

Generally, the manufacturer has two distribution channels (i.e., sales channel & car-sharing channel) in this scenario. One may wonder how the manufacturer will operate both of the two channels, or if he will launch the car-sharing program but close sales channel. To answer this question, it needs to identify the conditions of to make sure \( D_o^M > 0 \) and \( q_m > 0 \). Otherwise, \( D_o^M < 0, q_m < 0 \) indicate the two channels are closed. The following proposition gives the answer.

**Proposition 2.** The manufacturer will join the third-party platform, if the operation and maintenance cost is lower a certain threshold, and he will retain sales channel, if the value perception factor is lower a certain threshold. Mathematically, if \( c < c_1 = \beta - c_o - f_o - \frac{d f_o (1 - \beta)}{2\beta + 2(1 - \beta)d^2} \), then \( q_m > 0 \); in addition, if \( \beta < \beta_1 = 1 + \frac{d}{\beta} \), then \( D_o^M > 0 \).

Proposition 2 shows channel choice of the manufacturer when he can join the third-party platform. Note that if the manufacturer joins the platform, he becomes a supplier of car-sharing, and he is responsible for the operation and maintenance cost, as well as the service fee for car-sharing. According to Theorem 3, it can be verified that the manufacturer’s sharing quantity is decrease in \( c \) (i.e., \( \partial q_m/\partial c = - d/(2\beta) < 0 \)). When the operation and maintenance cost is low, the manufacturer joins the platform, otherwise he will not participate the car-sharing market. It means higher costs to launch a car-sharing program will adversely affect the profits of manufacturer, and accelerate to exit from the platform.
Furthermore, when the value perception factor is lower a threshold $\beta_1$, the manufacturer will keep the sales channel. However, he will abandon the sales channel and embrace the car-sharing, if the operation and maintenance cost is lower the threshold, but the value perception factor is larger than the threshold. In this case, we denote the manufacturer’s service fee should pay to platform is zero, i.e., $f_m = 0$. Then, the threshold equal one means that consumers incline to choose car-sharing than ownership. Hence, the manufacturer will join the platform, and pay all attentions to car-sharing program. Leading to the manufacturer be the single supplier in the third-party platform, and there is in no owners in this case for they incline to shared cars. Under the pandemic, many people are unemployed because of the downturn economy, considering the worry about their financial well-being, they prefer to use car-sharing.

After studying the manufacturer’s channel choice when there exists car-sharing platform, we consider the manufacturer holds two both channels in mixed sharing. Then, we examine the impact of the operation and maintenance cost on the pricing decisions, the following result can be derived.

**Property 2.** The selling price decrease in the operation and maintenance cost, and the customer-to-customer and mixed sharing scenarios have the same slope. The platform’s optimal service fee is decrease in customer-to-customer, but the service fee is not related to $c$ in mixed sharing. In addition, the sharing price is increase in operation and maintenance cost.

We summarize the Property 2 in Table 2. Property 2 indicates that selling price and service fee both decrease in the operation and maintenance cost, while the sharing price increase. The key reason to explain as follow, since owners are responsible for higher daily costs, which makes the manufacturer decides to reduce selling price to maintain a certain sales demand. As for the platform, as the operation and maintenance cost increases, leading the platform to set a lower service fee and a higher sharing price to encourage owners to join car-sharing market. However, in mixed sharing mode, we find that the third-party platform’s optimal service fee is not affected by $c$, but related to the manufacturer’s service fee $f_m$.

### 5. Analytical and numerical comparison

Having analyzed equilibrium solutions of the three scenarios, in this section, considering the impact of coronavirus pandemic on car-sharing, the three main factors (i.e., operation and maintenance cost, value perception factor, use needs) are important for the manufacturer’s decision-making. Therefore, we make a comparison about the pricing decisions and examine the optimal mode selection of manufacturer under different conditions. At the end of this section, we discuss several main challenges for car-sharing facing to the pandemic on the basis of combining real data and model analysis.

In order to explore the performance of the optimal solutions in three scenarios, we use numerical analysis to compare the pricing and profits of the manufacturer under different sharing modes. As discussed in Section 3.1, we denote the consumer’s car use fraction as $d$ and normalize its whole life to one period. In practice, statistics from BTS\(^5\) shows that the transit ridership was down 65% during the pandemic. More and more young people have gradually accepted the car-sharing where nearly 80% may consider such travel mode, according to the reports from Deloitte.\(^6\) In addition, generally the production costs account for 40–50% of car’s total costs and car-sharing platform (i.e., Uber) charges its service suppliers 20–25% of sharing revenue (Cachon et al., 2017). In sum up, based on the practice and for the convenience of the model analysis, without loss of generality we consider that all parameters in the model are unitized to 1. Then, we conducted numerical experiment and selected a relatively representative group as the parameter values. Therefore, based on the above discussion and previous researches (Bellos et al., 2017; Li et al., 2020; Wang et al., 2020), the parameters are set as $c_m = 0.25$, $c = 0.03$, $\beta = 0.95$, $d = 0.6$ and $f_m = 0.1$.

5.1 Pricing decisions

As given above, we focus on the suitable parameter range to make sure positive market demand. By comparing pricing decisions in the three scenarios, the following proposition can be derived. Table 3 summarizes the equilibrium price decisions.

**Proposition 3.** Focus on pricing decisions, there exist $p^M < p^C = p^M$ if $\beta \geq c$; otherwise, $p^M > p^C = p^M$. Manufacturer joins the third-party platform will not change the optimal selling price, but lead to a lower sharing price and service fee, i.e., $p^M = p^C$, $r^M < r^C$ and $f^M < f^C$.

Proposition 3 indicates that the car-sharing mode will affect the pricing decisions of manufacturer and third-party platform. In sales channel, when value perception factor is lower the operation and maintenance cost, the selling price in no car-sharing is larger than the corresponding price in sharing modes; however, if the operation and maintenance cost is low, the manufacturer will charge higher price in model C & M. For the sharing price increase in operation and maintenance cost, while the selling price decrease in $c$. When the value perception factor smaller than the threshold, the manufacturer will retain sales channel, and the selling demand decrease in value perception factor in the growing market, leading the manufacturer sets higher selling price to maximize profits. By comparing the sharing price and service fee in sharing modes, the manufacturer joins the platform will induce a lower sharing price in sharing platform, as illustrate in Fig. 2. This finding is consistent with Jiang et al. (2018). It means the manufacturer will adjust the sharing quantity in platform instead of selling price to maximize his profits. Note that the third-party makes match between supply and demand to obtain equilibrium sharing price. The manufacturer’s involvement in the platform will cannibalize his sales channel, but also increase suppliers in car-sharing. Thus, the total supply of sharing products will increase, leading to a lower sharing price. For the third-party platform, on one hand, the platform obtains a part of profits from the manufacturer’s involvement. On other hand, there exists competitions between the owners and manufacturer in sharing market, leading to the owners’ willingness of car-sharing drop down due to a lower sharing price. Therefore, to motivate the owners join the platform, the third-party platform will set a lower service fee.

Next, in order to visually understand the result above, we use numerical analysis to make comparison under different sharing modes. Fig. 3 illustrates the impact of value perception factor on selling demand with different use fraction, which is consistent with Proposition 1. Further, by comparing selling demand with the same $d$ in three scenarios, we can find that the selling demand always larger in no car-sharing than in sharing modes, if the operation and maintenance cost

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5. https://data.bts.gov/stories/s/m9eb-yevh
6. https://www2.deloitte.com/cn/zh/pages/consumer-industrial-product\_s/solutions/publication-future-of-mobility.html

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| Equilibrium solutions | $N$ | $C$ | $M$ |
|-----------------------|-----|-----|-----|
| $p^*$                 | $\frac{d}{2}$ | $\frac{1}{2}$ | $\frac{1}{2}$ |
| $p_m$                | $-$ | $\frac{1}{4(1-\beta^2)}$ | $-$ |
| $r^*$               | $-$ | $\frac{1}{4(1-\beta^2)-\beta d}$ | $\frac{1}{2}$ |

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Table 2: Impact of $c$ on equilibrium solutions.
is low. The finding means that car-sharing will cannibalize the demands for car ownership in this case, because when the operation and main-tenance cost is low, the users need to pay for car-sharing mobility is low. Therefore, it can attract some potential buyers to choose car-sharing mobility mode, leading the manufacturer to set a higher selling price in sales channel to maximize his profit.

### 5.2. Modes selection of the manufacturer

Note that the customer-to-customer sharing will change the consumers’ purchase decisions and manufacturer’s decisions-making. Hence, the manufacturer considerate whether provides car-sharing services via the third-party, and what is the optimal sharing mode choice. By comparing the optimal solutions of the three scenarios, the following results can be derived. The selection is illustrated in **Fig. 4**. As is given above, the consumer has two attitudes towards car-sharing facing to the pandemic. We picture the value perception factor in range $0 < \beta < 1$ and $\beta > 1$ to denote the two types of users.

First, considering participation concerns in all models, when the operation and maintenance cost is low and value perception factor is high, mixed sharing is the best choice for the manufacturer. According to **Proposition 3**, in such case the manufacturer will set higher selling price in sharing modes than no car-sharing, and the manufacturer’s involvement in the platform will induce a lower sharing price. Leading more people to choose car-sharing, then the sharing demand will increase. Further, when the operation and maintenance cost is very low, the second model choice is model N (i.e., $\pi_M > \pi_C > \pi_N$); however, model C is better than model N when the operation and maintenance cost is relatively high (i.e., $\pi_M > \pi_C > \pi_N$). The rationale hinges on that car-sharing has two effects on the manufacturer. On one hand, the car-sharing will cannibalize the sales demand as some potential buyers choose car-sharing. On other hand, car-sharing will provide a positive

### Table 3

Summary of equilibrium pricing solutions.

| Equilibrium solutions | N | C | M |
|-----------------------|---|---|---|
| $p^*$                 | $(1 - c)d + c_m$ | $\frac{\beta(1 - d) + d - c + c_m}{2}$ | $\frac{\beta(1 - d) + d - c + c_m}{2}$ |
| $f_c$                 | $\frac{\beta(1 - d) + d - c - c_m}{2}$ | $\frac{\beta(1 - d) + d - c - c_m}{2}$ | $\frac{\beta(1 - d) + d - c - c_m}{2}$ |
| $r^*$                 | $\frac{\beta^2(3 + 4d + \beta(c + c_m + d(-1 + 4d))}{(4d + 4\beta d^2)}$ | $\frac{\beta^2(3 + 4d + \beta(c + c_m + d(-1 + 4d))}{(4d + 4\beta d^2)}$ | $\frac{\beta^2(3 + 4d + \beta(c + c_m + d(-1 + 4d))}{(4d + 4\beta d^2)}$ |

**Fig. 2.** Sharing price & service fee in different models.

**Fig. 3.** Impact of $\beta$ on selling demand with different $d$.

**Fig. 4.** Optimal mode choice of the manufacturer.
effect on the manufacturer, whereby some consumers have motivations to own a car for a financial benefit from sharing idle parts of car. When the owner’s car operation and maintenance is low, the service fee \( f_s \) is high, whereby the owners have little motivations to provide car-sharing services. Meanwhile, some people tend to use shared car, leading to a decline in sales channel. At this case, the third-party platform brings negative effect and the manufacturer will gain more profit under no car-sharing. However, the car-sharing is very attractive to consumers with high value perception, the owners can balance their own cost due to additional benefits from sharing. Thereby consumers’ willingness to purchase cars increase, the platform brings positive effect and the manufacturer will benefit more profits under customer-to-customer. However, when the operation and maintenance cost is low and the value perception factor is relatively low, it can benefit more under no car-sharing than mixed sharing, and the customer-to-customer mode is the manufacturer’s last choice (i.e., \( x_M^N > x_M^C > x_C^N \)).

Second, if the operation and maintenance cost, and value perception factor is low or very high, only Model N & C exist, i.e., mixed sharing mode cannot implement in this condition. Since the existence of car-sharing will cannibalize the manufacturer’s sales demands, many consumers will choose to buy cars for the low cost of car ownership and lead to more potential sharing providers in such case. Furthermore, the car-sharing price is low if the consumers with low value perception for car-sharing. In this condition, the manufacturer’s sharing income in car-sharing will not be enough to offset its loss in profits of sales channel. Thus, the manufacturer will not offer any cars in platform. Likewise, when the operation and maintenance cost is moderate and value perception factor is very low, the third-party platform will exit from the market. Because there are no owners willing to share their idle part of car under high service fee and additional operation costs for car-sharing. When the operation and maintenance cost and value perception factor is high, the sales channel will close in model N. In this case, the car-sharing platform brings the positive effect to the manufacturer, which makes the manufacturer still to operate in sales channel under customer-to-customer mode.

**Proposition 4.** Only when the operation and maintenance cost is low and value perception factor is high, the three models can be implemented. When the operation and maintenance cost is very low and value perception factor is high, it exists \( x_M^N > x_M^C > x_C^N \). As the operation and maintenance cost increase, it exists \( x_M^N > x_M^C > x_C^N \) as the decrease in value perception factor, it exists \( x_M^N > x_M^C > x_C^N \).

5.3. Main challenges for car-sharing facing to pandemic

Due to transportation ground to a halt under the COVID-19 pandemic, many automobile players faced with plunging demands and their revenues. On the basis of the real-elements of car-sharing context, we discuss several main challenges facing to the pandemic by associating real data and model analysis.

First, the transit systems faced with drastically plummeting ridership amid global pandemic. Statistics from the US DOT and other sources shown that the transit ridership was down 65% and the sharing platform’s (i.e., Uber) passenger-trip volumes pummeled by 80% during the pandemic period. Under the pandemic, the selling demand drops down with the consumers’ travel needs \( d \), as shown in Fig. 3. This trend is the same as the practice that some manufactures and car dealerships closed due to a disruption in supply chain, with sale plummeting 47% in US in April 7. In such case, Fig. 5 indicates that the expected demand in selling channel and sharing market will decrease in the reduction of car’s usage needs. This is because, many people changed to work from home and others have shifted away from shared mobility to reduce risk of infection, leading to reduction in themselves travel needs and car-sharing time.

Second, the pandemic may cause uncertainty in the consumer’s preference for car-sharing. Consumers across the globe continue to face severe health and financial concerns, they have worked at home or shift to use private car to reduce the risk of infection. However, statistics from BLS 8 indicated that the unemployment rate figure stood around 11.1% as of June in 2020, leading some people suffer economic hardship and turn to embrace the car-sharing. In the analysis of our model, the expected profit of manufacture increase as the value perception factor increases, as illustrate in Fig. 6. Furthermore, when value perception factor is relatively low, the manufacturer faced with low operation and maintenance cost will obtain more profits under the no car-sharing mode. However, when the consumer with high value perception for car-sharing, the manufacturer can benefit from car-sharing economy and mixed-sharing mode is the optimal choice. Therefore, we conclude the result in Proposition 5 as follow.

**Proposition 5.** The manufacturer’s expected profit increase in the value

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7 https://www.mckinsey.com/business-functions/marketing-and-sales/our -insights/how-consumers-behavior-in-car-buying-and-mobility-changes-amid -covid-19

8 https://usafacts.org/articles/unemployment-rate-dropped-to-69-in-october /
3. Sharing costs

The operation cost increases in the sharing mode, as well as wear a mask to reduce the risk of infection, which means more operation costs will pay for sharing their car. In this paper, we consider these costs as the operation and maintenance cost. Then, as shown in Fig. 2, we find that the sharing price will increase in the operation and maintenance cost, leading to a reduction in the car-sharing demand and selling demand. Finally, the manufacturer’s expected profit will decrease in the operation and maintenance cost, as well as the service fee \( f_m \), as illustrates in Fig. 7. Further, when the operation and maintenance cost is low, the manufacturer will join the third-party platform and gain more profits in mixed sharing mode under high value perception factor of consumers. Therefore, we conclude the result in Proposition 6 as follow.

**Proposition 6.** The manufacturer’s expected profit decrease in the operation and maintenance cost, and his profit decrease in the service fee \( f_m \) in mixed sharing. Further, if the value perception factor is high, the manufacturer faced with low operation and maintenance cost will join the third-party platform, and obtain more profits in mixed sharing than the benchmark and customer to customer scenarios.

6. Conclusions

Car-sharing has changed the way people travel from point A to point B, which provides more travel options customers, and also affected the operation mode of manufacturer, especially under the new coronavirus epidemic. Recently, the coronavirus pandemic has affected sales and people’s attitudes towards car-sharing. In this paper, we develop an analytical framework consists of a manufacturer and a third-party platform, and take the impact of COVID-19 pandemic on car-sharing as a key factors. We analyze three scenarios including no sharing, customers-to-customers, and mixed sharing, then employ a game theoretic approach to get equilibrium solutions and analytically derive the optimal mode choice. The unique contributions of our work lie in three aspects. First, since the continued changes in consumption and utility patterns, the study of car-sharing problem contributes to the concern of sustainability products and services. Second, most previous researches consider product-sharing is provided from owners or manufacturer, we further explore a novel sharing economy model, where shared cars are offered by the manufacturer and individuals. Third, our research considers the impact of COVID-19 pandemic on consumer behavior, thereby affecting car-sharing.

Our analysis shows that when the operation and maintenance cost is low, manufacturer will join the third-party platform, and the sharing price increase in operation and maintenance cost, while the selling price decrease in operation and maintenance cost, and the selling price holds the same under customers-to-customers and mixed sharing scenarios. When the value perception factor smaller than the threshold, the manufacturer will retain sales channel, and the selling demand decrease in value perception factor in the growing market, the sharing demand has the same trend, vice versa. Furthermore, we find that if the operation and maintenance cost is low and value perception factor is high, mixed sharing is the best choice for the manufacturer, while the manufacturer will choose no car-sharing when the value perception factor is relatively low.

Based on the analysis of this paper, our findings provide executable managerial insights for the manufacturer and the third-party platform in the car-sharing market with the COVID-19 pandemic. When the operation and maintenance cost is low, the manufacturer chooses to join the third-party platform, otherwise he will not participate the car-sharing. Furthermore, he will keep the sales channel when the value perception factor is low, otherwise he will abandon the sales channel and embrace the car-sharing. In addition, the manufacturer will choose mixed sharing, if the operation and maintenance cost is low and value perception factor is high, while the manufacturer will choose no car-sharing when the value perception factor is relatively low. Contrary to the intuitive feelings, with the increase in operation and maintenance cost, third-party platform needs to reduce the service fee under the customer-to-customer scenario, however the service fee remains unchanged under the mixed sharing.

This paper has some limitations that provide potential directions for future research. First, for the simplicity of the model, we examine the pandemic mainly with the value perception factor. It would be very meaningful to verify whether the main insights are robust with the influence of other factors in the future. Furthermore, this paper focuses on the impact of pandemic on car-sharing, and regards the sharing market as an ordinary commodity market. Platform transactions, with the characteristics of two-sided market with network effects, which will be the future extensions.

CRediT authorship contribution statement

Zhenzhen Mao: Conceptualization, Writing - review & editing, Visualization. Weisi Zhang: Conceptualization, Writing - review & editing, Supervision. Bin Yang: Conceptualization, Methodology, Supervision. Tao Zhang: Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

**Proof of Theory 1.** From Eqs. (1), we get the second-order condition is $\frac{\partial^2 \pi_c^M}{\partial p^2} = -2/d < 0$, therefore the profit function of manufacturer is concave in $p$, the manufacturer obtain maximum profit when $p^M$ satisfies $\frac{\partial \pi_c^M}{\partial p^2} = 0$. By substituting $p^M$ into $D_c^M$ and $\pi_c^M(p)$, we can easily obtain optimal sales demand $D_c^M$ and the manufacturer’s profits $\pi_c^M$. Note that the condition $(1 - c - c_m \pi_d < 0$ needs to be established to ensure that $D_c^M > 0$.

**Proof of Property 1.** From (1), we get the second-order condition as follows: $\frac{\partial^2 \pi_c^M}{\partial p^2} = -2/(1 + d)2d/(\beta + (1 - \beta)d^2) < 0$, the third-party platform’s profit is strictly concave to service fee $f_o$. We can get the optimal service fee $f_{\text{o}}^c$ from $\frac{\partial \pi_c^M}{\partial f_o} = 0$.

Second, we solve the manufacturer’s optimal decision $p$. Substitute the third-party platform’s best response function into eq. (4), the second order derivative is $\frac{\partial^2 \pi_c^M}{\partial p^2} = -d/(\beta + (1 - \beta)d^2) < 0$, the third-party platform’s profit is strictly concave to $p$. By considering the first-order condition $\frac{\partial \pi_c^M}{\partial p} = 0$, we obtain the optimal selling price $p_c^M$.

Finally, the optimal selling price $p_c^M$ is substituted into the demand functions and the profits functions to derive $f_{\text{o}}^c$, $D_c^M$, $D_s^c$, $\pi_c^M$, $\pi_s^M$. Note that the condition $\beta(1 - d) + (1 - c - c_m \pi_d < 0$, respectively.

**Proof of Property 1.** According to the equilibrium outcome in Theory 1 and Theory 2, we can obtain the optimal pricing decision of the manufacturer and the third-party service platform $p^N = \frac{(1 - c - c_m \pi_d}{2}$, $\pi^N = \frac{\beta(1 - d)\beta + (1 - \beta)d^2}{\beta(1 - d) + (1 - c - c_m \pi_d}$. Obviously, $\frac{\partial \pi^N}{\partial c_m} = \frac{2}{\beta(1 - d)} > 0$, $\frac{\partial \pi^N}{\partial d} < 0$. Therefore, we can derive that the selling price is both increase in marginal production cost, while the service fee is decrease.

**Proof of Proposition 2.** We now focus on the influence of value perception factor on the expected selling demands and sharing demands in model C. Obviously, $\frac{\partial \pi^N}{\partial d} = \frac{(1 - c - c_m \pi_d}{2}/(\beta + (1 - \beta)d^2)$. Thus, we can obtain $d = \frac{\beta}{\beta(1 - d)} - 1 from \frac{\partial \pi^N}{\partial d} = 0$, and denote the threshold with $d_1 = \frac{1}{\beta(1 - d)} - 1$. When $d < d_1$, $\frac{\partial \pi^N}{\partial d} < 0$; otherwise, $\frac{\partial \pi^N}{\partial d} > 0$. In the same way, it easy obtain that when $d < d_1$, we have $\frac{\partial \pi^N}{\partial c_m} < 0$; otherwise, $\frac{\partial \pi^N}{\partial c_m} > 0$.

**Proof of Theory 3.** Similar to theory 2, we get $\pi^M = \beta(p + f_1 + c - d(1 - \beta)(1 - d + q_m - t_1))/(1 - \beta)d^2 + \beta$ from $(1 - d)D^M + q_m = dD^M$. By substituting $\pi^M$ into $\pi^M$ and the backward induction. First, we solve the third-party platform’s optimal service fee $f_o$. According to the second order derivative $\frac{\partial^2 \pi^M}{\partial p^2} = -2/(1 + d)2d/(\beta + (1 - \beta)d^2) < 0$, the third-party platform’s profit is strictly concave to service fee $f_o$. By considering the first-order condition $\frac{\partial \pi^M}{\partial f_o} = 0$, we can get the optimal service fee $f_{\text{o}}^M$.

Second, we solve the manufacturer’s optimal selling price $p$ and the quantity of car-sharing $q_m$. Substitute the platform’s best response function into eq. (12), we can obtain the second condition as follows: $\frac{\partial^2 \pi^M}{\partial q_m^2} = \frac{d}{\beta + (1 - \beta)d^2} < 0$, $\frac{\partial^2 \pi^M}{\partial p \partial q_m} = \frac{\beta(1 - c - c_m \pi_d}{2} = 0$.

Thus, the second-order Hessian Matrix can be expressed as:

$$H = \begin{bmatrix}
\frac{\partial^2 \pi^M}{\partial p^2} & \frac{\partial^2 \pi^M}{\partial p \partial q_m} \\
\frac{\partial^2 \pi^M}{\partial p \partial q_m} & \frac{\partial^2 \pi^M}{\partial q_m^2}
\end{bmatrix} = \begin{bmatrix}
\frac{d}{\beta + (1 - \beta)d^2} & 0 \\
0 & \frac{\beta(1 - c - c_m \pi_d}{2}
\end{bmatrix}
$$

As the first order principal minor determinant $\det \frac{d}{\beta + (1 - \beta)d^2} < 0$, the second order principal minor determinant $\det \frac{\beta(1 - c - c_m \pi_d}{2} > 0$. Therefore, the Hessian Matrix is negative definite. In addition, we use the numerical $(c_m = 0.25, c = 0.03, d = 0.6, \beta = 0.95, f_m = 0.1)$ to verify that it is a joint concave function as show in the following picture.

Therefore, the manufacturer’s profit is concave to $p$ and $q_m$. Then get the optimal selling price $p$ and the sharing quantity $q_m from \frac{\partial \pi^M}{\partial p} = 0$ and $\frac{\partial \pi^M}{\partial q_m} = 0$, respectively.

$$p^M = \frac{\beta(1 - c - c_m \pi_d}{2} \text{ (21)}$$
Finally, the preceding solutions are substituted into the demand functions and the profits functions to derive $f_1^{\text{eq}}, D_0^M, D_1^M, n_0^M, n_1^M$.

**Proof of Proposition 3.** The impact of the operation and maintenance cost $c$ on the pricing decision, we first obtain $\frac{\partial p^*}{\partial c} = -\frac{\partial d^*}{\partial p^*} = \frac{\partial d^*}{\partial c} = -\frac{\partial p^*}{\partial \beta}$. Then taking the derivative gives $\frac{\partial q^*}{\partial c} = -\frac{1}{\gamma_1 \gamma_2} < 0$, while the derivative $\frac{\partial q^*}{\partial N} = 0$ in model M. For sharing price, we have $\frac{\partial p^*}{\partial c} = \frac{\partial d^*}{\partial p^*} = \frac{\partial \beta}{\partial \gamma_1} > 0$, $\frac{\partial q^*}{\partial N} = \frac{1}{\gamma_1} > 0$.

**Proof of Proposition 2.** According to the equilibrium outcome in theory 3, we can obtain the optimal sharing quantity of the manufacturer $q_m^\beta = \frac{d\beta}{\gamma_1 \gamma_2 \gamma_3}$, it can be easily verified that $\frac{\partial q_m^\beta}{\partial \beta} = -\frac{\partial \beta}{\partial \gamma_1} < 0$. And focus on the condition that make sure the manufacturer sharing in the third-party platform, we can obtain $c = \beta - \gamma_1 \gamma_2 \gamma_3$, and $\frac{\partial q_m^\beta}{\partial \beta} = 0$. We denote the threshold with $c_1$, such that if $c < c_1$, then $q_m^\beta > 0$. Otherwise, $q_m^\beta = 0$.

Focus on the conditions in sales channel, we can obtain the selling quantity is $D_0^M = \frac{d\beta}{\gamma_1 \gamma_2 \gamma_3}$ in model M. Thus, we can obtain $\beta = 1 + \frac{\partial \beta}{\partial \gamma_1}$ from $D_0^M = 0$. And denote the threshold with $\beta_1 = 1 + \frac{1}{\gamma_1}$, there exists if $\beta < \beta_1$, then $D_0^M > 0$, $q_m^\beta > 0$ when $c < c_1$.

**Proof of Proposition 3.** According to Table 3, we can find that the equilibrium selling price in model C is equal to corresponding in model M. Therefore, the $p^N = p^M$ can be derived. Next, we examine the difference of the selling price between model N and model C (model M). Defining $\Delta p = p^N - p^M$, we can observe that when $\beta - c > 0$, $\Delta p > 0$, means that there exist $p^N \frac{\partial p^N}{\partial c} = p^M$; otherwise, $\Delta p < 0$, means that $p^N > p^M$. 

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