12-2019

Urban consolidation center or peer-to-peer platform? The solution to urban last-mile delivery

Qiyuan DENG
Singapore Management University, qiyuan.deng.2015@pbs.smu.edu.sg

Xin FANG
Singapore Management University, xfang@smu.edu.sg

Yun Fong LIM
Singapore Management University, yflim@smu.edu.sg

Urban Consolidation Center or Peer-to-Peer Platform?

The Solution to Urban Last-Mile Delivery

Qiyuan DENG • Xin FANG • Yun Fong LIM

Lee Kong Chian School of Business, Singapore Management University

December 19, 2019

Abstract

The growing population in cities creates huge demand for urban last-mile delivery. Booming e-commerce activities further increase this demand, exerting intense pressure on the cities' well-being. To build a city with congestion and pollution under control, a consolidator can operate an urban consolidation center (UCC) to bundle shipments from multiple carriers before the last-mile delivery. Alternatively, the consolidator can operate a peer-to-peer platform for the carriers to share their delivery capacity. Our objective is to compare the performance of these two business models. Under each business model, we study the interactions between a consolidator and multiple carriers using a two-period game-theoretical model. In each period, the consolidator first chooses a delivery fee to maximize her expected profit. Each carrier then observes his task volume, and decides whether to deliver on his own or use the consolidator's service to minimize his expected cost. Under the UCC model, the carriers become more dependent on the UCC to deliver their tasks as their variable delivery cost increases or their logistics reestablishment cost decreases. Under the platform model, the carriers generally keep their logistics capability (even if they purchase capacity from the platform) in equilibrium to ensure their flexibility of selling capacity on the platform. Between the two business models, it is generally more profitable for the consolidator to operate the UCC than the platform if the carriers' fixed delivery cost is large. Furthermore, the UCC becomes more dominant as there are more carriers. If the number of carriers is large, it is also more efficient for the consolidator to operate the UCC than the platform to reduce the expected social-environmental cost. Otherwise, the platform is more efficient.

Keywords: last-mile delivery, collaborative logistics, urban consolidation center, peer-to-peer platform, game theory

1 Introduction

Last-mile delivery is the last leg of a supply chain that transfers freight or packages from a distribution center to a receiver. It comprises up to 28% of the total delivery cost of a supply chain (Lopez, 2017, Wang et al., 2016). Managing last-mile delivery becomes especially challenging if it is performed in an urban area, where congestion increases fuel consumption, causes delay of delivery, and lowers delivery efficiency (Ranieri et al., 2018). In addition, last-mile delivery is the most expensive and critical operation for companies engaged in e-commerce (Lee and Whang, 2001). Due to the continuous growth of urban population and e-commerce activities, last-mile delivery to a city center exerts intense pressure on the city's economic, social, and environmental well-being (Quak and Tavasszy, 2011).

The economic impact of urban last-mile delivery includes the waste of resources due to extra waiting in traffic congestion and low utilization of uncoordinated vehicles transporting freight to the city center. The large number of small, individual customer orders in e-commerce further complicates urban last-mile delivery and incurs significant costs. The social-environmental impact includes the vicious effect of the increasing traffic incidents and pollution due to transport vehicles, which degrades the quality of life in the city. For example, based on the Beijing Municipal Environmental Monitoring Center's statistics, emissions of transport vehicles are the main source of PM2.5 that causes hazardous haze in Beijing (`http://www.bjmemc.com.cn/`).

To build a smart city with congestion and pollution under control, an *urban consolidation center* (UCC) is a potential solution to mitigate the repercussion of urban last-mile delivery. Also known as a *city distribution center* (van Duin et al., 2008) or an *urban distribution center* (Boudoin et al., 2014), a UCC consolidates shipments from multiple carriers and then delivers them to the city center using the UCC's own fleet of trucks. A consolidator operating a UCC usually requires a facility to sort the shipments according to their destinations before they are delivered. As a result of the consolidation with fewer trucks, higher truck utilization can be achieved, leading to a lower delivery cost. This shipment consolidation not only economically benefits stakeholders, including the consolidator, the carriers, and the public authorities (Ambrosini and Routhier, 2004), but also mitigates the social-environmental impact because of reduced traffic. Ideally, the resultant cost savings can be shared among the carriers, motivating them to use the UCC's service.

Despite the potential benefits, many UCC projects in practice are not successful. The UCCs of the Port Authority of New York and New Jersey were closed after five years of operations (Doig, 2001). Dablanc (2011) reports that 150 UCC projects were started in Europe during the last 25 years, but only five projects survive. Even if they survive, they usually have difficulty to break even and require significant subsidies from the government. For example, it costs a UCC in La Rochelle 3.8€ to deliver a parcel to a customer who is charged only 1.7–3€. A UCC in Monaco charges her customers 2.30€/100Kg, and receives 2.59€/100Kg as a subsidy from the local government (Dablanc, 2005). Many UCC projects failed because the carriers were reluctant to use their service. This is supported by a survey in the NYC metro, which reveals that less than 20% of the carriers would like to participate in a UCC project (Holguin-Veras et al., 2008). Their reluctance to participate is mainly due to a common concern that they may over rely on the UCCs. Many carriers reduce their own logistics capacity after using a consolidation service (Snapp, 2012, Vivaldini et al., 2012, Choe et al., 2017). For example, the logistics department of GOME, a Chinese retailer for electrical appliances, reduces its investment in delivery trucks and drivers after engaging a consolidation service (National Express, 2010). The substantial cost of reestablishing the logistics capability, which includes the costs to purchase trucks, recruit drivers, obtain licenses, and gain knowledge about local clients (Browne et al., 2005), makes the carriers reluctant to rely on a UCC's service.

More recently, some peer-to-peer platforms have been established for carriers to share their delivery capacity. Notable examples include Saloodo! by DHL, Freightos and Convoy in Europe, Loadsmart in U.S., and Cainiao and Truck Alliance in China. On such a platform, a carrier can sell his unused capacity to another carrier to fulfill the latter's delivery needs. It is attractive for a consolidator to operate a platform because it requires neither a sorting facility nor a fleet of delivery trucks. The peer-to-peer platform business model typically follows a sharing-economy approach: The platform takes a revenue share from each transaction of capacity for providing market access to the carriers and for processing the transaction (Gesing, 2017). In contrast to the UCCs' low success rate, the emergence of the capacity sharing platforms motivates us to investigate whether the latter can be a better alternative for a city to address the challenges of urban last-mile delivery.

Although bearing the delivery costs, a UCC can achieve a larger economy of scale as each truck of the UCC may consolidate the tasks of many carriers. In contrast, a capacity sharing platform does not incur any delivery cost, but each individual carrier on the platform has only very limited delivery capacity compared to the UCC's fleet. In this paper, we compare the above two business models for urban last-mile delivery in terms of the consolidator's profit and the social-environmental cost. Specifically, the consolidator can either operate a UCC to bundle shipments from multiple carriers before the last-mile delivery, or operate a peer-to-peer platform for the carriers to share their delivery capacity. For each business model, we develop a two-period game-theoretical model to capture the interactions between the consolidator and the carriers. In each period, knowing that each carrier has a delivery task with a random volume to fulfill, the consolidator first determines the delivery fee to maximize her expected profit. Then, after knowing his task volume, each carrier decides whether to deliver his task to the city center on his own or use the consolidator's service such that his expected cost is minimized. By identifying subgame perfect Nash Equilibrium with rational expectations, we have obtained the following insights.

(i) If the consolidator operates a UCC, we observe the trade-off faced by the carriers in practice: The carriers can potentially save their delivery costs by using the UCC's service, while they face the risk of eliminating their logistics capability. As their variable delivery cost increases, the carriers become more dependent on the UCC to deliver their tasks to the city center. On the other hand, as the cost to reestablish their logistics capability increases, the carriers become less dependent on the UCC.

(ii) If the consolidator operates a capacity sharing platform, we find that the carriers generally have their logistics capability on hand (even if they purchase capacity from the platform) in equilibrium. This ensures sufficient capacity available on the platform to facilitate successful transactions. Since the platform can always earn a positive profit from each successful transaction, it can be more financially sustainable in the long run. Our results explain the increasing popularity of the capacity sharing platforms in practice.

(iii) Comparing the UCC and the platform in terms of the consolidator's expected profit, we find that it is generally more profitable for the consolidator to operate the UCC than the platform if the carriers' fixed delivery cost is large. Moreover, it is easier for the UCC to dominate as the number of carriers becomes larger. In terms of reducing the expected social-environmental cost, our comparison between the UCC and the platform shows that if the number of carriers is large, then it is more efficient for the consolidator to operate the UCC than the platform. Furthermore, the condition for the UCC to outperform the platform varies with the distribution of the carriers' task volumes.

After reviewing the related literature in §2, we formulate the problem between the consolidator and the carriers in §3. We analyze the business models in which the consolidator operates a UCC and a capacity sharing platform in §4 and §5 respectively. We compare the two business models in terms of the consolidator's expected profit and the expected social-environmental cost in §6. We study two extensions of our models in §7, before we provide concluding remarks in §8. All proofs are provided in the online supplement.

2 Related literature

This paper is mainly related to two streams of literature. The first stream consists of papers on UCCs and the second stream is about peer-to-peer platforms. The majority of studies on UCCs is conceptual and descriptive. McDermott (1975) shows in a survey conducted in Columbus, Ohio that operating a UCC could bring substantial benefits to the shippers, carriers, consumers, society, and government. Based on a program in the European network, Dablanc (2007) concludes that the provision of urban logistics services emerges slowly despite their growing demand. Allen et al. (2012) review the feasibility studies, trials, and fully operational schemes of UCCs in 17 countries in the last 40 years.

Some analytical papers on UCCs focus on planning and allocation of delivery jobs among the carriers. For example, Crainic et al. (2009) consider a two-tier distribution structure and propose an optimization model to deal with job scheduling, resource management, and route selection. Handoko et al. (2016) propose an auction mechanism for last-mile delivery to match a UCC's truck capacity to the shipments such that the UCC's profit is maximized. Wang et al. (2015) study a rolling-horizon auction mechanism with virtual pricing of shipping capacity. Wang et al. (2018) consider cost uncertainty in last-mile delivery through a UCC, and propose approaches to solve the winner determination problem of an auction. Özener and Ergun (2008) study a logistics network in which shippers collaborate and bundle their shipment requests to negotiate better rates with a common carrier. They determine an optimal route covering all the demands such that the total cost is minimized. To the best of our knowledge, no papers have formally analyzed the stakeholders' incentives for a UCC project. Our paper fills the gaps in the literature by providing a game-theoretical analysis of the carriers' incentive to participate in a UCC project.

The ideas of the capacity sharing platform relate our paper to the literature on two-sided markets (Rochet and Tirole, 2006, Weyl, 2010, Hagiu and Wright, 2015). A typical setting of a two-sided market involves two types of players. On a platform, independent providers (such as drivers) offer service to consumers (such as riders). See, for example, Cachon et al. (2017), Bai et al. (2018), Taylor (2018), Bimpikis et al. (2016), Cohen and Zhang (2017), and Hu and Zhou (2017). In contrast, a carrier on the platform in our paper is flexible to choose either to sell his remaining capacity like a service provider or to buy capacity like a consumer.

Several papers in operations management deal with peer-to-peer rental platforms, which are similar to our capacity sharing platform in spirit. For example, Fraiberger and Sundararajan

(2015) analyze a peer-to-peer rental market where each consumer is either a supplier or a buyer. Benjaafar et al. (2018) analyze a model where players with different usage levels make decisions on whether to own a product. Non-owners can access the product through renting from owners on a needed basis. Jiang and Tian (2016) consider a setting in which consumers who purchased a product can derive different usage values and generate income by renting out their purchased product through a third-party sharing platform. Tian and Jiang (2018) further study how this consumer-to-consumer product sharing affects a distribution channel. Abhishek et al. (2016) consider a setting in which a consumer decides whether to purchase a durable good and whether to rent it when the rental market is available. In the stream of literature above, if an owner decides to rent out his product, he cannot use the product during the rental period. In contrast, a carrier on our capacity sharing platform does not rent out his entire truck. Instead, he uses his remaining truck capacity to deliver goods for another carrier to earn extra revenue. Benjaafar et al. (2017) consider a ride sharing platform on which individuals may rent out empty seats from their cars or find a ride. However, different from ride sharing, the carriers' random task volumes play a significant role in matching supply with demand of capacity on our capacity sharing platform. Furthermore, the carriers' task volumes in our paper can change over time, which also affect their incentive to use the platform.

The collaboration among the carriers considered in our paper shares some similarity with the paper by Agarwal and Ergun (2010), which considers the alliance formation among carriers. They study the design of large-scale networks and the allocation of limited capacity on a transportation network among the carriers in the alliance. Our paper is also related to the literature of inventory transshipment, which typically considers a wholesaler distributes inventory to multiple retailers and the inventory can be transshipped among the retailers to fulfill demand. Papers most relevant to our work include Rudi et al. (2001) and Dong and Rudi (2004), where both the wholesaler's and the retailers' profits are considered. However, in this stream of literature, a player with demand must work with another player with supply to generate profits. In contrast, the carriers on our platform have the option to deliver by themselves and sell their remaining capacity to the platform, allowing them to be a seller or a buyer. Our platform model is also related to the literature of secondary markets, where resellers can buy and sell excess inventory (see, for example, Lee and Whang (2002), Mendelson and Tunca (2007), Milner and Kouvelis (2007), Broner et al. (2010), and Chen et al. (2013)). This stream of research focuses on the impact of secondary markets on supply chains' or firms' performance. In contrast, our paper compares the UCC with the capacity sharing platform. We do not see such a comparison in this stream of literature.

3 Problem formulation

We consider a consolidator interacts with carriers $i = 1, 2, \ldots, n$ in a two-period setting, where period $t = 1$ captures the short-term impact of the consolidation in practice, and period $t = 2$ captures the long-term impact. In period $t = 1, 2$, carrier i has a delivery task with volume v_{it}. We assume v_{it} equals v_L with a probability λ, or equals v_H $(> v_L)$ with a probability $1 - \lambda$, where $\lambda \in [0, 1]$. All the delivery tasks in each period must be fulfilled within the period. We assume each carrier is initially equipped with logistics capability that has a limited delivery capacity sufficient for his own task in each period.

In each period, the consolidator first decides the pricing of the delivery service and each carrier then decides whether to deliver on his own or outsource his task to the consolidator. If carrier i delivers on his own, then the carrier incurs a fixed cost $c > 0$ and a variable cost per unit volume $m > 0$. The fixed cost c includes the maintenance cost for the trucks, the license and permit fees for the trucks, and the salary of drivers. The variable cost includes the fuel cost and the loading-unloading cost.

In period 1, if a carrier decides to outsource his task, then he can also choose to eliminate or keep his logistics capability for the future. It incurs a fixed holding cost $h \in (0, c)$ to the carrier if he chooses to keep his logistics capability. The holding cost h includes the costs to maintain the unused trucks and to keep some relevant staff. In period 2, if a carrier decides to deliver on his own, then he needs to reestablish his logistics capability if it is eliminated in period 1. This incurs a *reestablishment cost* $f > 0$ which includes the costs to purchase trucks, to recruit drivers, and to learn about and reconnect with local clients. Let $\delta \in (0, 1)$ denote a discount factor across the two periods. To rule out uninteresting cases, such as the carriers never keep their logistics capability, we assume $h < \delta f$ and $f > c(v_H - v_L)/v_L$.

Based on the above problem setting, we analyze and identify the equilibrium decisions of the consolidator and the carriers under each business model. We first provide the details and insights of our analyses in §4 and §5 when the consolidator operates a UCC and a capacity sharing platform respectively. We then compare the two business models in terms of maximizing the consolidator's expected profit and minimizing the expected social-environmental cost in §6.

4 Business model 1: An urban consolidation center

In this section, we consider the consolidator operates a UCC to serve the carriers for their last-mile deliveries to the city center. We assume that the UCC owns a fleet of vehicles with a total capacity that is sufficiently large to accommodate all the carriers' tasks in each period.

The decision process is as follows. At the start of period $t = 1, 2$, the UCC first decides the price per unit volume $\bar{p}_t$ of her delivery service. After observing $\bar{p}_t$, each carrier i waits until his delivery task volume is realized. We assume each carrier i only knows his own realized task volume and decides independently on how to deliver his task to the city center. Let $\bar{d}_{it}$ denote the decision of carrier i for period $t = 1, 2$. In period 1, each carrier i has three possible options defined as follows. (i) $\bar{d}_{i1} = -1$: Carrier i delivers on his own. (ii) $\bar{d}_{i1} = 0$: Carrier i uses the UCC's service and eliminates his logistics capability. (iii) $\bar{d}_{i1} = 1$: Carrier i uses the UCC's service and keeps his logistics capability. We assume that each carrier's delivery capacity has no value after period 2. Thus, each carrier i has only two possible options in period 2 defined as follows. (i) $\bar{d}_{i2} = -1$: Carrier i delivers on his own. (ii) $\bar{d}_{i2} = 0$: Carrier i uses the UCC's service. As a result, we have $\bar{d}_{i1} \in \{-1, 0, 1\}$ and $\bar{d}_{i2} \in \{-1, 0\}$, for $i = 1, \ldots, n$. Figure 1 shows the sequence of decisions in the two periods.

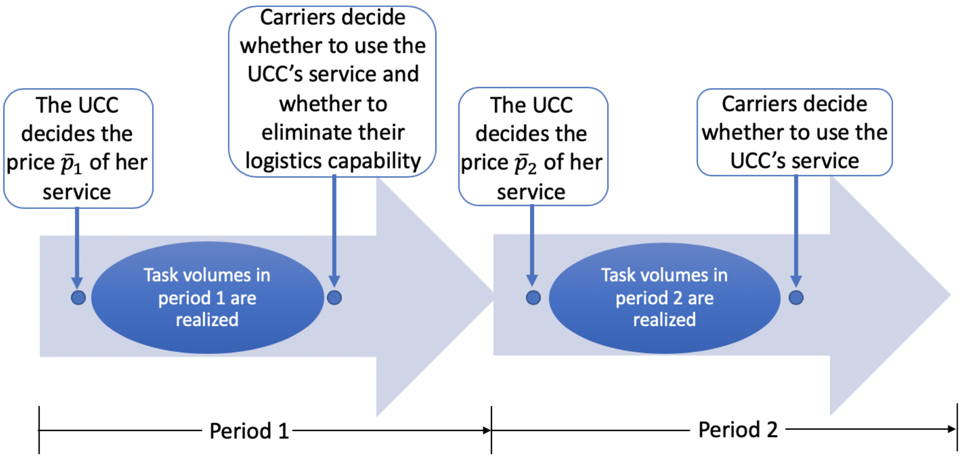


Figure 1: The sequence of decisions in the two periods under the UCC business model

Let n_t denote the expected number of carriers who use the UCC's delivery service in period t. To serve these carriers, the UCC incurs a fixed delivery cost that depends on n_t. Taking economies of scale into consideration, we assume that the fixed delivery cost equals $\sqrt{n_t}C > 0$ (Steinerberger, 2015). Furthermore, the UCC also incurs a variable cost per unit volume $M > 0$. To be consistent with reality, we assume the UCC receives a subsidy $S > 0$ per unit volume of shipments from the local government or authority.

In each period t in Figure 1, the UCC first sets the price per unit volume $\bar{p}_t$ for her service to maximize her expected profit. Given the price $\bar{p}_t$ and the realized task volume v_{it}, each carrier i determines his decision $\bar{d}_{it}$ to minimize his cost. We solve the problem in Figure 1 backward by first determining the optimal decisions of the carriers and the UCC in period 2, before we find their optimal decisions in period 1 in the following sections.

4.1 Analysis

We first find the optimal decision of each carrier i in period 2. Given the decision $\bar{d}_{i1}$ in period 1 and the price $\bar{p}_2$ in period 2, carrier i determines his optimal decision $\bar{d}_{i2}^*$ to minimize his cost in period 2. After that we substitute the optimal responses of all the carriers into the UCC's problem to find her optimal price $\bar{p}_2^*$.

Define $\bar{\phi}_{i2}\left(\bar{d}_{i2};\bar{d}_{i1},\bar{p}_2\right)$ as the cost of carrier i in period 2, which is a function of $\bar{d}_{i2}$ given $\bar{d}_{i1}$ and $\bar{p}_2$. Each carrier i minimizes his cost $\bar{\phi}_{i2}\left(\bar{d}_{i2};\bar{d}_{i1},\bar{p}_2\right)$ by comparing the following two options: (i) $\bar{d}_{i2}=-1$: Carrier i delivers on his own in period 2, which incurs a cost $\bar{\phi}_{i2}\left(-1;\bar{d}_{i1},\bar{p}_2\right) = c+mv_{i2}-\left(\left|\bar{d}_{i1}\right|-1\right)f$. (ii) $\bar{d}_{i2}=0$: Carrier i uses the UCC's service in period 2, which incurs a cost $\bar{\phi}_{i2}\left(0;\bar{d}_{i1},\bar{p}_2\right)=\bar{p}_2 v_{i2}$. The following lemma shows the optimal decision of each carrier i in period 2.

Lemma 1. (Optimal decision of carrier i in period 2)

1. If carrier i delivers on his own or uses the UCC's service and keeps his logistics capability in period 1 ($\bar{d}_{i1}=-1$ or 1), then in period 2, carrier i uses the UCC's service ($\bar{d}_{i2}^*=0$) if $\bar{p}_2\le m+c/v_{i2}$, or delivers on his own ($\bar{d}_{i2}^*=-1$) otherwise.

2. If carrier i uses the UCC's service and eliminates his logistics capability in period 1 ($\bar{d}_{i1}=0$), then in period 2, carrier i uses the UCC's service ($\bar{d}_{i2}^*=0$) if $\bar{p}_2\le m+(c+f)/v_{i2}$, or delivers on his own ($\bar{d}_{i2}^*=-1$) otherwise.

Part 1 of Lemma 1 shows that the carriers in period 1 who deliver on their own ($\bar{d}_{i1}=-1$), or who use the UCC's service and keep their logistics capability ($\bar{d}_{i1}=1$) will make the same decision in period 2. This is because in both cases, the carriers own their logistics capability in period 2, leading to the same delivery cost. Furthermore, Lemma 1 also shows that carrier i is more likely to use the UCC's service in period 2 if his task volume in the period is smaller (because $\bar{p}_2\le m+c/v_{i2}$ and $\bar{p}_2\le m+(c+f)/v_{i2}$ are more likely to hold if v_{i2} is smaller). In this case, it is not worthwhile to pay the fixed cost c to deliver on his own. It is also worth noting that if carrier i uses the UCC's service and eliminates his logistics capability in period

1 ($\bar{d}_{i1} = 0$), then he is more likely to engage the UCC in period 2 because of the additional reestablishment cost f.

Let V_2 denote the expected total task volume of the carriers who use the UCC's service in period 2. Given the carriers' optimal responses in Lemma 1, the UCC chooses the price $\bar{p}_2$ to maximize her expected profit in period 2:

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)V_2 - \sqrt{n_2}C. \quad (1)$$

Note that it is non-trivial to optimize $\bar{p}_2$ because it affects not only the unit profit $\bar{p}_2 + S - M$ and volume V_2, but also the fixed cost $\sqrt{n_2}C$. Although lowering $\bar{p}_2$ will attract more carriers to use the UCC's service and increase the volume V_2, it will also increase the fixed cost $\sqrt{n_2}C$.

Define n_e as the number of carriers who use the UCC's service and eliminate their logistics capability in period 1 (that is, the carriers with $\bar{d}_{i1} = 0$). Note that n_e is known in period 2. The following lemma shows the UCC's optimal pricing decision in period 2.

Lemma 2. (Optimal decision of the UCC in period 2)

1. If $n_e > 0$, the optimal price of the UCC's service in period 2 is

$$\bar{p}_2^* = \begin{cases} m + (c+f)/v_L, & \text{if } m < \min\{b_1, b_2, b_3\}; \\ m + (c+f)/v_H, & \text{if } b_1 \le m < \min\{b_4, b_5\}; \\ m + c/v_L, & \text{if } \max\{b_2, b_4\} \le m < b_6; \\ m + c/v_H, & \text{if } m \ge \max\{b_3, b_5, b_6\}. \end{cases}$$

2. If $n_e = 0$, the optimal price of the UCC's service in period 2 is

$$\bar{p}_2^* = \begin{cases} m + c/v_L, & \text{if } m < b_7; \\ m + c/v_H, & \text{if } m \ge b_7. \end{cases}$$

The terms $b_j, j = 1, \ldots, 7$, are defined in the proof of Lemma 2 in the online supplement. Lemma 2 shows that if no carriers eliminate their logistics capability ($n_e = 0$), then the UCC is forced to charge lower prices to attract the carriers. Note that the proof of Lemma 2 shows that $b_j, j = 1, \ldots, 7$, decrease as the subsidy S increases. Thus, Lemma 2 implies that if the government provides a higher subsidy to the UCC, the latter can afford to charge a lower price $\bar{p}_2^*$ for her service.

After obtaining the optimal decisions $\bar{d}_{i2}^*$ and $\bar{p}_2^*$, we use them to find the carriers' and the UCC's optimal decisions in period 1. Similar to the analysis of period 2, we first determine the optimal decision of each carrier i in period 1. Given $\bar{p}_1$, each carrier i chooses $\bar{d}_{i1}$ to minimize his expected total discounted cost $\bar{\Phi}_i(\bar{d}_{i1}; \bar{p}_1)$ over the two periods by comparing the three options: $\bar{d}_{i1} = -1, 0$, or 1. Note that, to evaluate $\bar{\Phi}_i(\bar{d}_{i1}; \bar{p}_1)$, one needs to form some belief about the number of carriers who use the UCC's service and eliminate their logistics capability in period 1 (that is, the value of n_e). Following Su and Zhang (2008) and Cachon and Swinney (2009), we seek to identify a subgame perfect Nash Equilibrium with rational expectations. This means that each player (including the carriers and the UCC) chooses their optimal action given their belief about how the others will play. Furthermore, these beliefs are correct, which are identical to the corresponding actions in equilibrium. In our context, all the carriers and the UCC form the same rational belief $\tilde{n}_e$ about n_e when they optimize their decisions in period 1, and in equilibrium, $\tilde{n}_e = n_e\left(\bar{p}_1^*; \bar{d}_{i1}^*, i = 1, 2, \ldots, n\right)$.

For notational convenience, given $\bar{d}_{i1}$, define $\bar{\phi}_{i2}^*\left(\bar{d}_{i1}\right) = \bar{\phi}_{i2}\left(\bar{d}_{i2}^*\left(\bar{d}_{i1}\right); \bar{d}_{i1}, \bar{p}_2^*\left(\bar{d}_{i1}\right)\right)$ as the optimal cost of carrier i in period 2. Given $\bar{p}_1$, each carrier i minimizes $\bar{\Phi}_i\left(\bar{d}_{i1}; \bar{p}_1\right)$ by choosing one of the following options: (i) $\bar{d}_{i1} = -1$: Carrier i delivers on his own, which incurs an expected total discounted cost $\bar{\Phi}_i\left(-1; \bar{p}_1\right) = c + mv_{i1} + \delta\bar{\phi}_{i2}^*(-1)$. (ii) $\bar{d}_{i1} = 0$: Carrier i uses the UCC's service and eliminates his logistics capability, which incurs an expected total discounted cost $\bar{\Phi}_i\left(0; \bar{p}_1\right) = \bar{p}_1 v_{i1} + \delta\bar{\phi}_{i2}^*(0)$. (iii) $\bar{d}_{i1} = 1$: Carrier i uses the UCC's service and keeps his logistics capability, which incurs an expected total discounted cost $\bar{\Phi}_i\left(1; \bar{p}_1\right) = \bar{p}_1 v_{i1} + h + \delta\bar{\phi}_{i2}^*(1)$. The following lemma shows the optimal decision of carrier i in period 1.

Lemma 3. (Optimal decision of carrier i in period 1)

1. If $\tilde{n}_e > 0$, the optimal decision of carrier i is determined as follows.

(a) If $m < \min\left\{\tilde{b}_1, \tilde{b}_2, \tilde{b}_3\right\}$, then

$$\bar{d}_{i1}^* = \begin{cases} 1, & \text{if } \bar{p}_1 \le m + (c-h)/v_{i1}; \\ -1, & \text{otherwise.} \end{cases}$$

(b) If $\tilde{b}_1 \le m < \min\left\{\tilde{b}_4, \tilde{b}_5\right\}$, then

$$\bar{d}_{i1}^* = \begin{cases} 1, & \text{if } \bar{p}_1 \le m + (c-h)/v_{i1} \text{ and } h \le \delta(c+f)(\lambda v_L/v_H + 1 - \lambda) - \delta c; \\ 0, & \text{if } \bar{p}_1 \le m + (1+\delta)c/v_{i1} - \delta(c+f)(\lambda v_L/v_H + 1 - \lambda)/v_{i1} \\ & \quad \text{and } h > \delta(c+f)(\lambda v_L/v_H + 1 - \lambda) - \delta c; \\ -1, & \text{otherwise.} \end{cases}$$

(c) If $\max\left\{\tilde{b}_2, \tilde{b}_4\right\} \le m < \tilde{b}_6$, then

$$\bar{d}_{i1}^* = \begin{cases} 1, & \text{if } \bar{p}_1 \le m + (c-h)/v_{i1} \text{ and } h \le \delta c(\lambda + (1-\lambda)v_H/v_L) - \delta c; \\ 0, & \text{if } \bar{p}_1 \le m + (1+\delta)c/v_{i1} - \delta c(\lambda + (1-\lambda)v_H/v_L)/v_{i1} \\ & \quad \text{and } h > \delta c(\lambda + (1-\lambda)v_H/v_L) - \delta c; \\ -1, & \text{otherwise.} \end{cases}$$

(d) If $m \ge \max\left\{\tilde{b}_3, \tilde{b}_5, \tilde{b}_6\right\}$, then

$$\bar{d}_{i1}^* = \begin{cases} 0, & \text{if } \bar{p}_1 \le m + c/v_{i1}; \\ -1, & \text{otherwise.} \end{cases}$$

2. If $\tilde{n}_e = 0$, the optimal decision of carrier i is determined as follows.

(a) If $m < b_7$, then

$$\bar{d}_{i1}^* = \begin{cases} 1, & \text{if } \bar{p}_1 \le m + (c-h)/v_{i1} \text{ and } h \le \delta c(\lambda + (1-\lambda)v_H/v_L) - \delta c; \\ 0, & \text{if } \bar{p}_1 \le m + (1+\delta)c/v_{i1} - \delta c(\lambda + (1-\lambda)v_H/v_L)/v_{i1} \\ & \quad \text{and } h > \delta c(\lambda + (1-\lambda)v_H/v_L) - \delta c; \\ -1, & \text{otherwise.} \end{cases}$$

(b) If $m \ge b_7$, then

$$\bar{d}_{i1}^* = \begin{cases} 0, & \text{if } \bar{p}_1 \le m + c/v_{i1}; \\ -1, & \text{otherwise.} \end{cases}$$

The terms $\tilde{b}_j$, $j = 1, \ldots, 6$, are defined in the proof of Lemma 3 in the online supplement. Lemma 3 shows that if the task volume v_{i1} of carrier i becomes smaller in period 1, then the carrier is more likely to use the UCC's service to avoid the fixed cost c. In case carrier i chooses to use the UCC's service in period 1, he will eliminate his logistics capability ($\bar{d}_{i1}^* = 0$) if m is sufficiently large (that is, if $m \geq \max\left\{\tilde{b}_3, \tilde{b}_5, \tilde{b}_6\right\}$ or $m \geq b_7$); otherwise, he will keep his logistics capability ($\bar{d}_{i1}^* = 1$) if the holding cost h is sufficiently small.

Let V_1 denote the expected total task volume of the carriers who use the UCC's service in period 1. Recall that $\bar{\pi}_2(\bar{p}_2^*)$ is the UCC's expected profit in period 2 given by Equation (1). Assuming all the carriers respond optimally according to Lemma 3, the UCC optimizes her price $\bar{p}_1$ to maximize her expected total discounted profit over the two periods:

$$\bar{\Pi}\left(\bar{p}_1\right) = \left(\bar{p}_1 + S - M\right) V_1 - \sqrt{n_1} C + \delta \bar{\pi}_2\left(\bar{p}_2^*\left(\bar{p}_1\right)\right). \tag{2}$$

4.2 Equilibrium decisions

The following theorem determines the rational expectation equilibrium. To rule out uninteresting cases in which the carriers never keep their logistics capability, we assume $h \leq \min\{\delta(c+f)(\lambda v_L/v_H + 1 - \lambda) - \delta c, \delta c(\lambda + (1-\lambda) v_H/v_L) - \delta c\}$.

Theorem 1. (Equilibrium decisions of the UCC model) *There are three candidates of the equilibrium characterized as follows.*

1. *If $m < \min\{b_7, m_1\}$, then we have the following candidate of the equilibrium.*

   Period 1: The UCC's equilibrium price is $\bar{p}_1^* = m + (c-h)/v_L$. Under this price, each carrier i uses the UCC's service and keeps his logistics capability if $v_{i1} = v_L$, and delivers on his own otherwise.

   Period 2: The UCC's equilibrium price is $\bar{p}_2^* = m + c/v_L$. Under this price, each carrier i uses the UCC's service if $v_{i1} = v_L$, and delivers on his own otherwise.

2. *If $\min\{b_7, m_1\} \leq m < b_7$, then we have the following candidate of the equilibrium.*

   Period 1: The UCC's equilibrium price is $\bar{p}_1^* = m + (c-h)/v_H$. Under this price, all the carriers use the UCC's service and keep their logistics capability.

   Period 2: The UCC's equilibrium price is $\bar{p}_2^* = m + c/v_L$. Under this price, each carrier i uses the UCC's service if $v_{i1} = v_L$, and delivers on his own otherwise.

3. *If $m \geq \max\{m_2, m_3, m_4\}$, then we have the following candidate of the equilibrium.*

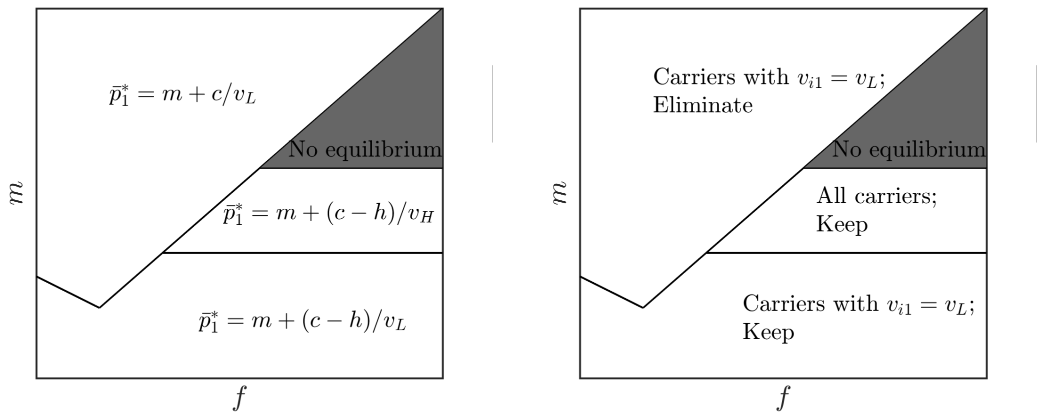
   Period 1: The UCC's equilibrium price is $\bar{p}_1^* = m + c/v_L$. Under this price, each carrier i uses the UCC's service and eliminates his logistics capability if $v_{i1} = v_L$, and delivers on his own otherwise.

   Period 2: The UCC's equilibrium price is $\bar{p}_2^* = m + c/v_H$. Under this price, all the carriers use the UCC's service.

The terms $m_j, j = 1, \ldots, 4$, are defined in the proof of Theorem 1 in the online supplement. Note that the three intervals of m in Theorem 1 may overlap. Given a set of parameters (including

m), the equilibrium is the candidate with the highest expected total discounted profit for the UCC. According to the proof of Theorem 1, $m_j, j = 1, \ldots, 4$, decrease as the subsidy S increases. Thus, if the government provides a higher subsidy S to the UCC, then the third equilibrium in Theorem 1 becomes more likely to exist (that is, $m \geq \max\{m_2, m_3, m_4\}$ becomes easier to hold). Since all the carriers will use the UCC's service in period 2 in this equilibrium, the UCC is more likely to sustain in the long run. This result is aligned with the observation that many UCC projects require government subsidies in practice.

The equilibrium of the UCC model can be characterized by the reestablishment cost f and the variable delivery cost m. Figure 2(a) shows the UCC's equilibrium price in period 1. If f is sufficiently small (corresponding to the left end of Figure 2(a)), then the UCC's price $\bar{p}_1^*$ increases as m increases. This is because if m is getting larger, the carriers are more likely to use the UCC's service. Anticipating this, the UCC charges a higher price in period 1.

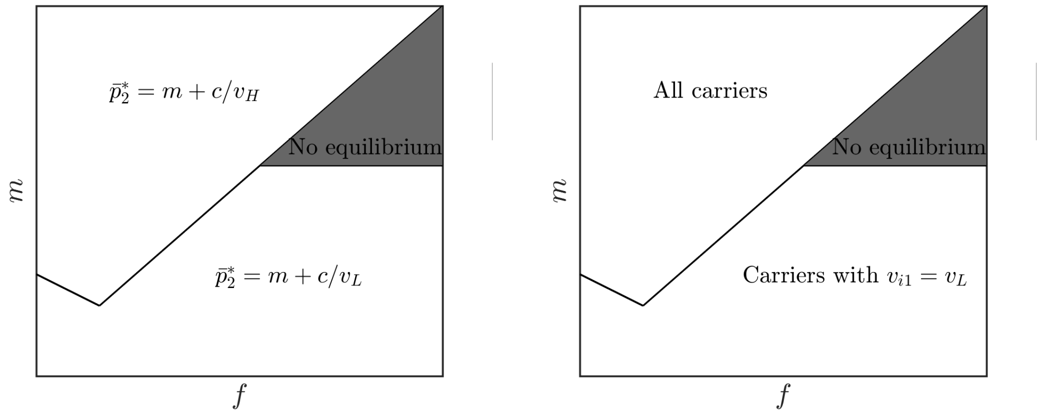


(a) The UCC's equilibrium pricing strategy (b) The equilibrium decisions of the carriers using the UCC's service

Figure 2: The equilibrium decisions in period 1 under the UCC model

Figure 2(b) illustrates the equilibrium decisions of the carriers who use the UCC's service in period 1. If f is sufficiently small and m is sufficiently large (corresponding to the top-left corner of Figure 2(b)), then the carriers who use the UCC's service will eliminate their logistics capability. This is because the carriers anticipate that they are likely to continue to use the UCC's service in period 2. Even if they need to deliver on their own in period 2, it is affordable to reestablish their logistics capability. In contrast, if f is sufficiently large and m is sufficiently small (corresponding to the bottom-right corner of Figure 2(b)), the carriers who use the UCC's service will keep their logistics capability. Furthermore, as m increases all the carriers will use the UCC's service and keep their logistics capability.

Figures 3(a) and (b) show the UCC's equilibrium price and the carriers who use the UCC's



(a) The UCC's equilibrium pricing strategy (b) Carriers using the UCC's service in equilibrium

Figure 3: The equilibrium decisions in period 2 under the UCC model

service, respectively, in period 2. If f is sufficiently small and m is sufficiently large, all the carriers will use the UCC's service (see the top-left corner of Figure 3(b)). However, as f increases and m decreases, the carriers will keep their logistics capability in period 1 (see the bottom-right corner of Figure 2(b)), thus fewer carriers will use the UCC's service in period 2 (see the bottom-right corner of Figure 3(b)).

In general, as m increases, the carriers are more dependent on the UCC to deliver their tasks. That is, in period 1 the carriers who use the UCC's service will eliminate their logistics capability, and in period 2 more carriers will use the UCC's service. However, as f increases, the carriers become less dependent on the UCC. That is, in period 1 the carriers who use the UCC's service will keep their logistics capability, and in period 2 fewer carriers will use the UCC's service.

5 Business model 2: A capacity sharing platform

In this section, instead of having a physical UCC, we consider the consolidator operates a platform for the carriers to share their delivery capacity. On the platform, a carrier delivering by himself to the city center can sell his remaining truck capacity to another carrier, so that the latter can outsource his delivery task by paying a fee. If the transaction is successful, then the platform retains a portion of this fee as her revenue. Motivated by the fact that the delivery capacity of each individual carrier is usually very limited compared to the UCC's fleet, we assume that a high task volume means a full or nearly-full truckload for a carrier. Thus, in contrast to the UCC model, if $v_{it} = v_H$, then carrier i has to deliver by himself to the city center in period t (the other carriers cannot help him) and his remaining capacity is insufficient to help any other carrier to deliver. Thus, in each period t, only carrier i with $v_{it} = v_L$ will participate (purchase or sell capacity) in the capacity sharing platform. We assume that each carrier participating in the platform can serve (or can be served by) at most one other carrier on the platform. For convenience, define $\mathcal{N} = \{1, 2, \ldots, n\}$, $\mathcal{N}_{L,t} = \{i | v_{it} = v_L, i \in \mathcal{N}\}$, and $\mathcal{N}_{H,t} = \{i | v_{it} = v_H, i \in \mathcal{N}\}$, for $t = 1, 2$.

The decision process is as follows. At the start of each period t, the platform first decides the price per unit volume $\hat{p}_t$ of the delivery service. After observing the price $\hat{p}_t$, each carrier i waits until his delivery task volume v_{it} is realized, and decides independently on how to deliver his task to the city center. Let $\hat{d}_{it}$ denote the decision of carrier i for period $t = 1, 2$. In period 1, each carrier $i \in \mathcal{N}_{L,1}$ has three possible options. (i) $\hat{d}_{i1} = -1$: Carrier i delivers on his own and sells his remaining capacity to the platform. (ii) $\hat{d}_{i1} = 0$: Carrier i purchases capacity from the platform and eliminates his logistics capability. (iii) $\hat{d}_{i1} = 1$: Carrier i purchases capacity from the platform and keeps his logistics capability. In consistent with the UCC model, we assume that all the delivery capacity has no value after period 2. Thus, in period 2 each carrier $i \in \mathcal{N}_{L,2}$ has only two possible options defined as follows. (i) $\hat{d}_{i2} = -1$: Carrier i delivers on his own and sells his remaining capacity to the platform. (ii) $\hat{d}_{i2} = 0$: Carrier i purchases capacity from the platform. As a result, for $i \in \mathcal{N}_{L,1}$, we have $\hat{d}_{i1} \in \{-1, 0, 1\}$, and for $i \in \mathcal{N}_{L,2}$, we have $\hat{d}_{i2} \in \{-1, 0\}$. Figure 4 shows the sequence of decisions in the two periods.

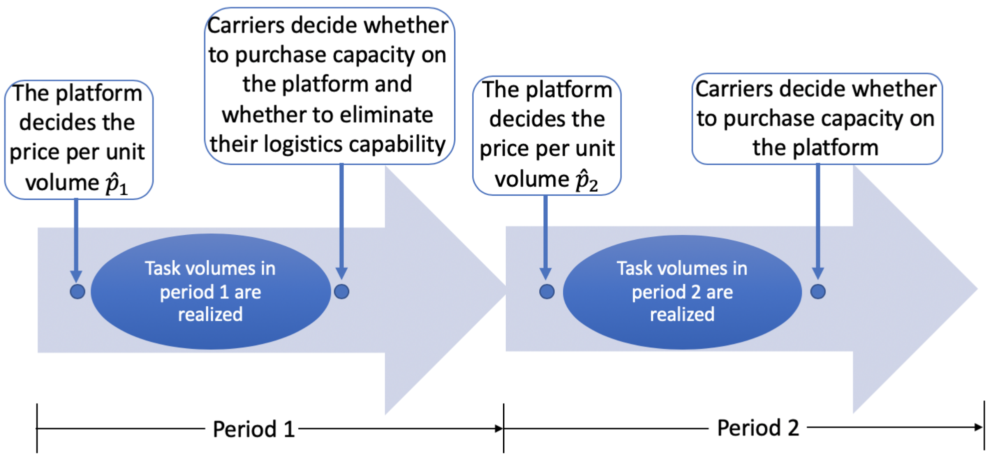


Figure 4: The sequence of decisions in the two periods under the platform business model

If carrier $i \in \mathcal{N}_{L,t}$ wants to sell his remaining capacity to the platform, whether his capacity can be successfully sold depends on the demand and the supply of capacity on the platform. If the demand is no less than the supply, then all the carriers who wish to sell their remaining capacity can successfully sell it. However, if the demand is less than the supply, then only a subset of these carriers can sell their remaining capacity. In this situation, the platform will randomly distribute the tasks with an equal probability to the carriers willing to sell their remaining capacity.

Given that all the delivery tasks must be fulfilled in each period t, if carrier $i \in \mathcal{N}_{L,t}$ wants to purchase capacity from the platform, we assume the carrier can always obtain the required capacity v_L. The platform can guarantee this by outsourcing the delivery task of carrier i to an external party, if necessary. We assume that the platform does not make any profit in this outsourcing process. If carrier $i \in \mathcal{N}_{L,t}$ purchases capacity in period t ($\hat{d}_{it} = 0$ or 1), then he pays $\hat{p}_t v_L$. If there is enough supply on the platform, the platform receives a portion $\alpha \hat{p}_t v_L$, where $\alpha \in (0, 1)$ represents the platform's *revenue share*. The remaining portion $(1 - \alpha)\hat{p}_t v_L$ goes to the other carrier on the platform who serves carrier i. To ensure that selling capacity on the platform is profitable, we assume $(1 - \alpha)\hat{p}_t > m$.

For notational convenience, define $n_{s,t}$ as the expected number of carriers who deliver on their own and sell their remaining capacity to the platform in period t (that is, the carriers who choose $\hat{d}_{it} = -1$). Define $n_{p,t}$ as the expected number of carriers who purchase capacity from the platform in period t (that is, the carriers who choose $\hat{d}_{i1} = 0$ or 1 in period 1, and the carriers who choose $\hat{d}_{i2} = 0$ in period 2). Therefore, the supply and the demand of capacity on the platform in period t are propotional to $n_{s,t}$ and $n_{p,t}$ respectively.

For each period t in Figure 4, the platform first sets the price per unit volume $\hat{p}_t$ to maximize her expected profit. Given the price $\hat{p}_t$ and the realized task volume v_{it}, each carrier $i \in \mathcal{N}_{L,t}$ determines his decision $\hat{d}_{it}$ to minimize his expected cost. We solve the problem in Figure 4 backward by first identifying the optimal decisions of each carrier $i \in \mathcal{N}_{L,2}$ and the platform in period 2, before we find their optimal decisions in period 1 in the following sections.

5.1 Analysis

Given the decision $\hat{d}_{i1}$ in period 1 and the price $\hat{p}_2$ in period 2, we first determine the optimal decision $\hat{d}^*_{i2}$ of each carrier $i \in \mathcal{N}_{L,2}$ to minimize his expected cost. After that we substitute the carriers' optimal responses into the platform's problem to find her optimal price $\hat{p}^*_2$.

Each carrier $i \in \mathcal{N}_{L,2}$ minimizes his expected cost $\hat{\phi}_{i2}\left(\hat{d}_{i2}; \hat{d}_{i1}, \hat{p}_2\right)$ in period 2 by comparing the two options: $\hat{d}_{i2} = -1$ or 0. If carrier i delivers by himself and sells his remaining capacity to the platform ($\hat{d}_{i2} = -1$), then the expected revenue generated from selling his remaining capacity depends on the supply (proportional to $n_{s,2}$) and the demand (proportional to $n_{p,2}$) of capacity on the platform in period 2. Following Su and Zhang (2008) and Cachon and Swinney (2009), we aim to identify a subgame perfect Nash Equilibrium with rational expectations. We assume all the carriers in $\mathcal{N}_{L,2}$ form the same rational beliefs $\tilde{n}_{s,2}$ and $\tilde{n}_{p,2}$ about $n_{s,2}$ and $n_{p,2}$, respectively, when they optimize their decisions in period 2. Furthermore, $\tilde{n}_{s,2} = n_{s,2}\left(\hat{d}_{i2}^*, i \in \mathcal{N}_{L,2}\right)$ and $\tilde{n}_{p,2} = n_{p,2}\left(\hat{d}_{i2}^*, i \in \mathcal{N}_{L,2}\right)$ in equilibrium. Define $\theta_t = \min\{\tilde{n}_{p,t}/\tilde{n}_{s,t}, 1\}$, for $t = 1, 2$.

Specifically, each carrier $i \in \mathcal{N}_{L,2}$ minimizes $\hat{\phi}_{i2}\left(\hat{d}_{i2}; \hat{d}_{i1}, \hat{p}_2\right)$ by comparing the following options. (i) $\hat{d}_{i2} = -1$: Carrier i delivers on his own and sells his remaining capacity to the platform, which incurs an expected cost $\hat{\phi}_{i2}\left(-1; \hat{d}_{i1}, \hat{p}_2\right) = c + mv_L - \left(\left|\hat{d}_{i1}\right| - 1\right) f - \theta_2\left[(1-\alpha)\hat{p}_2 - m\right] v_L$. (ii) $\hat{d}_{i2} = 0$: Carrier i purchases capacity from the platform, incurring a cost $\hat{\phi}_{i2}\left(0; \hat{d}_{i1}, \hat{p}_2\right) = \hat{p}_2 v_L$. Note that for both periods 1 and 2, if the cost of delivering by himself is identical to the cost of purchasing capacity from the platform, we assume that carrier i will choose either option with an equal probability. This random tie-breaking rule is to avoid the extreme situation where the carriers with identical costs choose the same option on the platform.

After we determine the optimal decision $\hat{d}_{i2}^*$ of carrier $i \in \mathcal{N}_{L,2}$, we can substitute it into the platform's problem to find her optimal price in period 2. The platform chooses $\hat{p}_2$ to maximize her expected profit in period 2:

$$\hat{\pi}_2(\hat{p}_2) = \alpha \hat{p}_2 v_L \min\{n_{s,2}, n_{p,2}\}. \tag{3}$$

After obtaining the optimal decisions $\hat{d}_{i2}^*$ and $\hat{p}_2^*$ in period 2, we use them to find the carriers' and the platform's optimal decisions in period 1.

Each carrier $i \in \mathcal{N}_{L,1}$ in period 1 minimizes his expected total discounted cost $\hat{\Phi}_i\left(\hat{d}_{i1}; \hat{p}_1\right)$ over the two periods by comparing the three options: $\hat{d}_{i1} = -1, 0$, or 1. If $\hat{d}_{i1} = -1$, then the expected cost of carrier i in period 1 depends on $n_{s,1}$ and $n_{p,1}$. Similar to period 2, we assume all the carriers in $\mathcal{N}_{L,1}$ form the same rational beliefs $\tilde{n}_{s,1}$ and $\tilde{n}_{p,1}$ about $n_{s,1}$ and $n_{p,1}$ respectively. Furthermore, $\tilde{n}_{s,1} = n_{s,1}\left(\hat{d}_{i1}^*, i \in \mathcal{N}_{L,1}\right)$ and $\tilde{n}_{p,1} = n_{p,1}\left(\hat{d}_{i1}^*, i \in \mathcal{N}_{L,1}\right)$ in equilibrium. For notational convenience, given $\hat{d}_{i1}$, define $\hat{\phi}_{i2}^*\left(\hat{d}_{i1}\right) = \hat{\phi}_{i2}\left(\hat{d}_{i2}^*\left(\hat{d}_{i1}\right); \hat{d}_{i1}, \hat{p}_2^*\left(\hat{d}_{i1}\right)\right)$ as the optimal expected cost of carrier i in period 2. Given $\hat{p}_1$, carrier $i \in \mathcal{N}_{L,1}$ minimizes $\hat{\Phi}_i\left(\hat{d}_{i1}; \hat{p}_1\right)$ by choosing one of the following options:

(i) $\hat{d}_{i1} = -1$: Carrier i delivers on his own and sells his remaining capacity to the platform, which incurs an expected total discounted cost $\hat{\Phi}_i(-1; \hat{p}_1) = c + mv_L - \theta_1\left[(1-\alpha)\hat{p}_1 - m\right] v_L + \delta \hat{\phi}_{i2}^*(-1)$.

(ii) $\hat{d}_{i1} = 0$: Carrier i purchases capacity from the platform and eliminates his logistics capability, which incurs an expected total discounted cost $\hat{\Phi}_i(0; \hat{p}_1) = \hat{p}_1 v_L + \delta \hat{\phi}_{i2}^*(0)$.

(iii) $\hat{d}_{i1} = 1$: Carrier i purchases capacity from the platform and keeps his logistics capability, which incurs an expected total discounted cost $\hat{\Phi}_i(1;\hat{p}_1) = \hat{p}_1 v_L + h + \delta\hat{\phi}^*_{i2}(1)$.

We then substitute all the carriers' optimal responses $\hat{d}^*_{i1}$ into the platform's problem to find her optimal price $\hat{p}^*_1$ that maximizes her expected total discounted profit:

$$\hat{\Pi}(\hat{p}_1) = \alpha\hat{p}_1 v_L \min\{n_{s,1}, n_{p,1}\} + \delta\hat{\pi}_2(\hat{p}^*_2(\hat{p}_1)), \tag{4}$$

where $\hat{\pi}_2(\hat{p}^*_2(\hat{p}_1))$ represents the platform's optimal expected profit in period 2 given $\hat{p}_1$ (see Equation (3)).

5.2 Equilibrium decisions

The following theorem summarizes the platform's and the carriers' decisions for each period in the equilibrium with rational expectations. Define $\underline{f} = \frac{(2-2\lambda+\frac{\alpha\lambda^2}{4})mv_L+(1-\frac{3\lambda}{2}+\frac{\lambda(\lambda+\alpha)}{4})c}{(2-\alpha)\frac{\lambda}{2}(1-\frac{\lambda}{4})}$ and $\underline{f}' = \frac{(2-3\lambda+\frac{\alpha\lambda^2}{2})mv_L+(1-\frac{5\lambda}{2}+\lambda^2+\frac{\alpha\lambda(2-\lambda)}{4})c}{(2-\alpha)\frac{\lambda}{2}(2-\lambda)}$.

Theorem 2. (Equilibrium decisions of the platform model)

1. *If $f \geq \frac{h}{\delta(1-\lambda)}$, then we have the following results.*

   Period 1: The platform's equilibrium price is $\hat{p}^*_1 = (c + 2mv_L - h)/[(2-\alpha)v_L]$. Under this price, each carrier $i \in \mathcal{N}_{L,1}$ chooses $\hat{d}^*_{i1} = -1$ or $\hat{d}^*_{i1} = 1$ with an equal probability.

   Period 2: The platform's equilibrium price is $\hat{p}^*_2 = (c + 2mv_L)/[(2-\alpha)v_L]$. Under this price, each carrier $i \in \mathcal{N}_{L,2}$ chooses $\hat{d}^*_{i2} = -1$ or $\hat{d}^*_{i2} = 0$ with an equal probability.

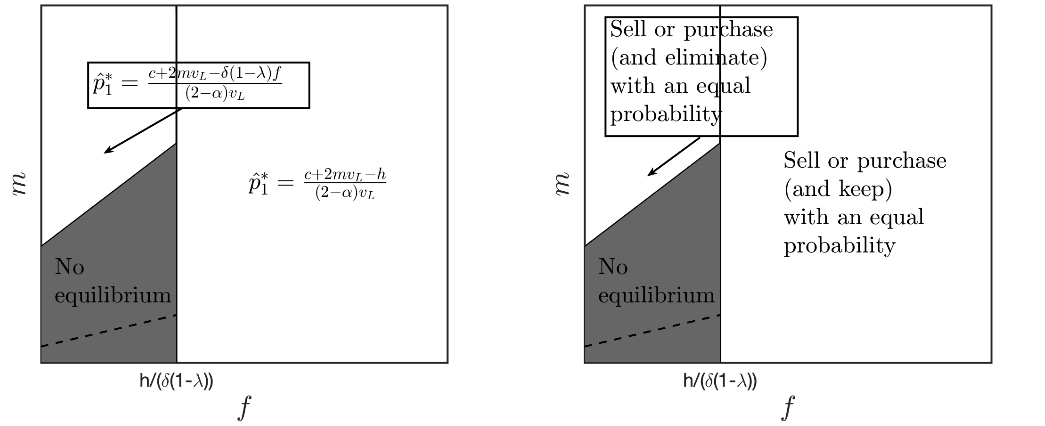
2. *If $f < \min\left\{\frac{h}{\delta(1-\lambda)}, \underline{f}, \underline{f}'\right\}$, then we have the following results.*

   Period 1: The platform's equilibrium price is $\hat{p}^*_1 = [c + 2mv_L - \delta(1-\lambda)f]/[(2-\alpha)v_L]$. Under this price, each carrier $i \in \mathcal{N}_{L,1}$ chooses $\hat{d}^*_{i1} = -1$ or $\hat{d}^*_{i1} = 0$ with an equal probability.

   Period 2: The platform's equilibrium price is $\hat{p}^*_2 = (c + 2mv_L)/[(2-\alpha)v_L]$. Under this price, carrier $i \in \mathcal{N}_{L,2}$ chooses $\hat{d}^*_{i2} = -1$ or $\hat{d}^*_{i2} = 0$ with an equal probability, if $\hat{d}^*_{i1} = -1$; or chooses $\hat{d}^*_{i2} = 0$, if $\hat{d}^*_{i1} = 0$.

Theorem 2 shows that, in general, the platform sets the prices to match the supply and demand of capacity so that a carrier chooses to sell or purchase capacity from the platform with an equal probability. Theorem 2 is illustrated by Figures 5 and 6. Figure 5(a) shows the platform's equilibrium price in period 1. Figure 5(b) shows that each carrier $i \in \mathcal{N}_{L,1}$ sells or purchases capacity on the platform in period 1 with an equal probability. If the reestablishment cost f is sufficiently large ($f \geq h/[\delta(1-\lambda)]$), then the carriers who purchase capacity from the platform should keep their logistics capability. Otherwise, these carriers should eliminate their logistics capability.

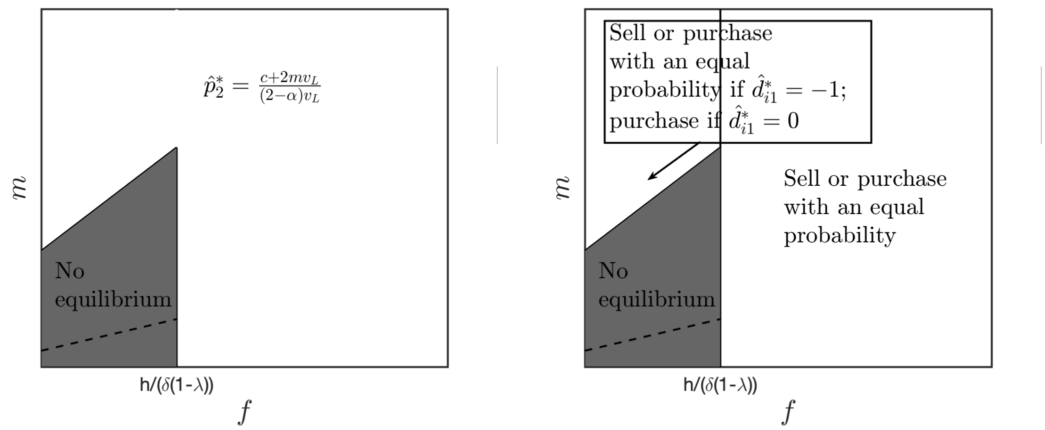
Figures 6(a) and (b) show the equilibrium decisions of the platform and each carrier $i \in \mathcal{N}_{L,2}$, respectively, in period 2. Figure 6(b) shows that if $f \geq h/[\delta(1-\lambda)]$, then each carrier i sells



(a) The platform's equilibrium pricing strategy (b) The equilibrium decision of each carrier

Figure 5: The equilibrium decisions of the platform and each carrier i in period 1

or purchases capacity on the platform in period 2 with an equal probability. Otherwise, the carrier's decision depends on his decision in period 1. If he delivers on his own in period 1 (that is, $\hat{d}_{i1}^* = -1$), then he sells or purchases capacity on the platform in period 2 with an equal probability. On the other hand, the carriers who purchase capacity and eliminate their logistics capability in period 1 (that is, $\hat{d}_{i1}^* = 0$) will continue to purchase capacity from the platform in period 2. In this situation, although the reestablishment cost f is affordable, but with a large variable delivery cost m, it is expensive to make their own delivery.



(a) The platform's equilibrium pricing strategy (b) The equilibrium decision of each carrier

Figure 6: The equilibrium decisions of the platform and each carrier i in period 2

6 Comparing the UCC and the capacity sharing platform

We compare the performance of the UCC and the capacity sharing platform in terms of the expected profit and the expected social-environmental cost. We focus on three regions where the equilibria exist in both models: (i) When f is sufficiently small and m is sufficiently large:

$f < \min\left\{\frac{h}{\delta(1-\lambda)}, f_1, f_2\right\}$ and $m > \max\{b_7, m_4, m_5, m_6\}$. (ii) When f is sufficiently large and m is intermediate: $f > \max\left\{\frac{h}{\delta(1-\lambda)}, f_1, f_2, f_3, f_4\right\}$ and $\min\{b_7, m_1\} \leq m < b_7$. (iii) When f is sufficiently large and m is sufficiently small: $f > \max\left\{\frac{h}{\delta(1-\lambda)}, f_1, f_2, f_3, f_4\right\}$ and $m < \min\{b_7, m_1\}$. The terms m_5, m_6, and $f_j, j = 1, \ldots, 4$ are defined in the proof of Theorem 3 in the online supplement.

6.1 Expected profit

Between the UCC and the platform, which business model is more profitable for the consolidator? As discussed in Section 1, it is important to make the consolidator financially sustainable in order to achieve the benefits of consolidation. We determine the consolidator's preference by comparing the equilibrium profits $\bar{\Pi}(\bar{p}_1^*)$ of the UCC in §4 and $\hat{\Pi}(\hat{p}_1^*)$ of the capacity sharing platform in §5. The following theorem identifies the conditions under which the UCC (or the platform) is more profitable for the consolidator.

Theorem 3. (Comparing the UCC's and the platform's profits) *In each region, the UCC is more profitable than the platform ($\bar{\Pi}(\bar{p}_1^*) > \hat{\Pi}(\hat{p}_1^*)$) if and only if*

Region (i): $c > c_1$;

Region (ii): one of the following conditions holds: (a) $c > c_2$ and $\delta > \delta_1$, (b) $c < c_2$ and $\delta < \delta_1$;

Region (iii): one of the following conditions holds: (a) $c > c_3$, (b) $h < h_1$.

In Region (i), the UCC is more profitable than the platform if the carriers' fixed delivery cost $c > c_1$. This is because when c is large, the carriers are more likely to outsource their delivery tasks to avoid the fixed cost. This will benefit the consolidator if she operates a UCC because there will be many carriers using her service. On the other hand, if the consolidator operates a platform, there will not be many successful transactions because the supply of capacity is low. This reduces her profit. Furthermore, the proof of Theorem 3 shows that c_1 decreases with n and S. As n increases, the carriers enjoy more savings by using the UCC because of the economies of scale in shipment consolidation, making the UCC more likely to outperform the platform. The UCC also becomes more dominant as the government subsidy S increases. If $c < c_1$, then the carriers are more likely to deliver on their own. Thus, more capacity will be available on the platform, making the platform more profitable than the UCC.

In Region (ii), the UCC is more profitable than the platform if both the fixed delivery cost c and the discount factor δ are large ($c > c_2$ and $\delta > \delta_1$). A large c pushes more carriers to outsource their delivery tasks. Furthermore, a large reestablishment cost f persuades the carriers who eliminate their logistics capability to continue outsourcing the delivery in the long run. A large δ magnifies this effect. Under the platform model, these carriers are less likely to supply capacity in period 2. This creates excessive demand for capacity on the platform, leading to a severe imbalance of supply and demand, which yields a lower profit for the platform. On the other hand, if δ is small ($c > c_2$ and $\delta < \delta_1$), the carriers are less sensitive to their costs in period 2 and become more likely to do their own delivery. This mitigates the supply-demand imbalance on the platform, making the platform more profitable than the UCC.

In contrast, if both c and δ are small ($c < c_2$ and $\delta < \delta_1$), the affordable delivery costs (small c and intermediate m) attract more carriers to deliver on their own. This is especially so for a small δ, which encourages the carriers, who eliminate their logistics capability in period 1, to deliver on their own in period 2. This creates excessive supply of capacity on the platform, which reduces the number of successful transactions, making the platform less profitable than the UCC. However, if δ is large ($c < c_2$ and $\delta > \delta_1$), the large f makes the carriers, who eliminate their logistics capability in period 1, to outsource their delivery tasks in period 2. This increases the demand for capacity on the platform, which mitigates the imbalance of supply and demand, leading to a higher profit for the platform than the UCC.

Lastly, in Region (iii), the UCC is more profitable than the platform if $c > c_3$ because of the same reason mentioned in Region (i). The second condition ($h < h_1$) for the UCC to outperform the platform needs more explanations. We first consider the opposite case with $h > h_1$. If the holding cost h is large, the carriers are less likely to hold their logistics capability in period 1. Meanwhile, the large f deters the carriers from eliminating their logistics capability. Therefore, more carriers will deliver on their own to avoid these large costs, reducing the UCC's profit. However, if h is small, then the carriers can always use the UCC's service and hold their logistics capability in period 1, avoiding a costly reestablishment in the next period. This makes the UCC more profitable than the platform. Furthermore, the proof of Theorem 3 shows that c_3 decreases and h_1 increases with n, making it easier for the UCC to dominate as n increases.

6.2 Expected social-environmental cost

Between the UCC and the platform, which business model is more efficient for the consolidator to reduce the social-environmental cost? As a result of the consolidation, both the UCC and the platform yield higher truck utilization with fewer trucks used. This not only economically benefits the consolidator and the carriers, but also mitigates the social-environmental impact (in terms of reduced congestion and pollution) because of reduced traffic to the city center. In this section, we compare the UCC and the platform with respect to their impact to the society and the environment.

To quantify the impact, define ψ as the social-environmental cost associated with a carrier's delivery to the city center. This includes, for example, the cost to the society due to congestion and the cost to the environment due to pollution. Define $\bar{\Delta}_\psi$ and $\hat{\Delta}_\psi$ as the *expected total social-environmental cost reduction* achieved by the UCC and the platform respectively. Under the UCC model, although additional trucks are required, each UCC's truck can potentially consolidate multiple tasks. In contrast, under the platform model, although no additional trucks are required, each carrier can at most serve one other carrier's task. It is unclear that which business model is more effective in reducing the social-environmental cost.

We first analyze the expected total social-environmental cost reduction achieved by the UCC. Recall that n_t represents the expected number of carriers served by the UCC in period $t = 1, 2$. Using the same setup cost's formula due to the consolidation by the UCC in §4, the expected total social-environmental cost in each period t is reduced from $n\psi$ to $\sqrt{n_t}\psi + (n - n_t)\psi$. This leads to $\bar{\Delta}_\psi = n\psi - [\sqrt{n_1}\psi + (n - n_1)\psi] + n\psi - [\sqrt{n_2}\psi + (n - n_2)\psi]$.

In contrast, the task of a carrier who purchases capacity from the platform is fulfilled by another carrier, leading to a social-environmental cost reduction ψ. In case the platform does not have sufficient supply of capacity, we assume that the unmatched delivery tasks are outsourced to a third party without incurring any additional social-environmental cost. Recall that $n_{p,t}$ represents the expected number of carriers who purchase capacity from the platform in period t. The expected total social-environmental cost reduction in each period t is $n_{p,t}\psi$. Thus, we have $\hat{\Delta}_\psi = n_{p,1}\psi + n_{p,2}\psi$.

The following theorem compares $\bar{\Delta}_\psi$ and $\hat{\Delta}_\psi$. We focus on the same three regions in Theorem 3 where the equilibria exist in both models.

Theorem 4. (Comparing the UCC's and the platform's social-environmental cost reductions) *In each region, the UCC is more efficient than the platform in reducing the expected total social-environmental cost ($\bar{\Delta}_\psi > \hat{\Delta}_\psi$) if and only if*
Region (i): $n > \left(\frac{1+\sqrt{\lambda}}{1-\lambda/4}\right)^2$;
Region (ii): $n > \left(1 + \sqrt{\lambda}\right)^2$;
Region (iii): $n > 4/\lambda$.

Theorem 4 shows that if the number of carriers n is large, then the UCC is more efficient in reducing the social-environmental cost than the platform. This is because if n is large, the UCC's trucks (each can serve multiple tasks) can achieve a larger economy of scale in shipment consolidation. This significantly reduces the traffic congestion and pollution caused by the last-mile delivery. On the other hand, if n is small, the UCC may not be efficient in reducing the social-environmental cost. In contrast, the platform, which matches a carrier's task with another carrier without employing any additional trucks, becomes more efficient.

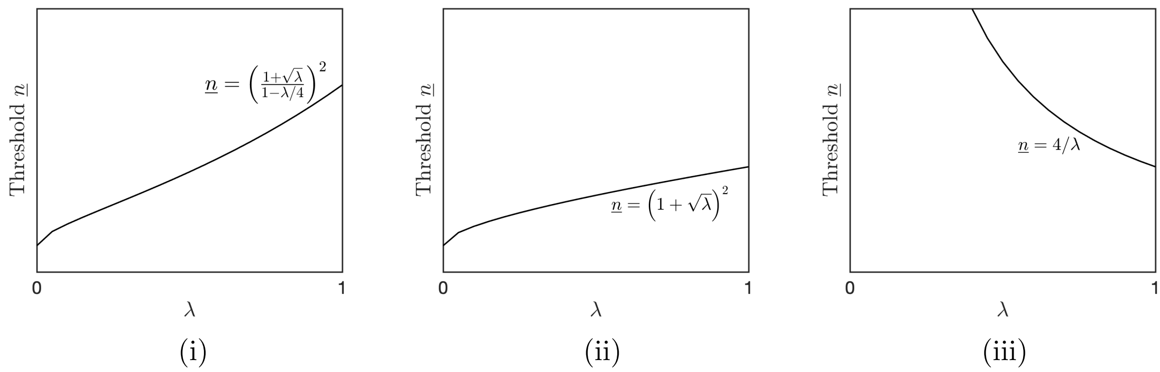


Figure 7: Thresholds of n in Regions (i), (ii), and (iii)

Figure 7 shows how the threshold of n in each region varies with the probability of low task volume λ. In Regions (i) and (ii), as λ increases, the thresholds $\left(\frac{1+\sqrt{\lambda}}{1-\lambda/4}\right)^2$ and $\left(1+\sqrt{\lambda}\right)^2$ also increase, making the platform more likely to outperform the UCC in reducing the social-environmental cost. As λ increases, more carriers will engage the platform. Many of these carriers want to purchase capacity from the platform because of the large and intermediate variable delivery cost m in Regions (i) and (ii). This significantly reduces the social-environmental cost, making the platform more efficient than the UCC.

In Region (iii), as λ increases, the threshold $4/\lambda$ decreases, making the UCC more likely to outperform the platform in reducing the social-environmental cost. This is because as λ increases, more carriers will engage the platform. However, the large f and small m in Region (iii) make the carriers more likely to deliver on their own. This is especially so under the platform model because the carriers can earn extra revenue by selling their remaining capacity. In contrast, the UCC can achieve a larger scale of shipment consolidation, which reduces the social-environmental cost more efficiently than the platform.

Table 1 shows the consolidator's preferred business model with respect to the profit and the social-environmental impact. To maximize the expected profit, the consolidator should choose the UCC if the carriers' fixed delivery cost c is large in general. Otherwise, the capacity sharing platform is preferred. To minimize the expected social-environmental cost, the UCC is preferred if the number of carriers n is large. Otherwise, the consolidator should choose the platform.

Table 1: The preferred business model of the consolidator

	small c **small** n	**small** c **large** n	**large** c **small** n	**large** c **large** n
To maximize expected profit	platform	platform	UCC	UCC
To minimize expected social-environmental cost	platform	UCC	platform	UCC

7 Extensions

7.1 A hybrid model

We consider the consolidator operates a hybrid business model that combines the ideas of both the UCC and the capacity sharing platform. In this hybrid model, the consolidator simultaneously operates a UCC, which fulfills the carriers' delivery tasks, and a platform, which matches supply and demand for capacity among the carriers. This hybrid model is inspired by Amazon that sells products to consumers by itself, and also allows peer-to-peer selling on its platform.

For analytical tractability, we consider a one-period model in which the consolidator operates both the UCC and the platform. Through the UCC, the consolidator charges the carriers for her delivery service. Through the platform, the consolidator receives a revenue share $\alpha \in (0, 1)$ from each successful transaction of capacity. The consolidator first chooses the prices $\bar{p}$ and $\hat{p}$ per unit volume of delivery service for the UCC and the platform, respectively, to maximize her expected profit.

After observing the prices $\bar{p}$ and $\hat{p}$, each carrier i waits until his delivery task volume v_i is realized. Depending on v_i, each carrier i has different options to fulfill his task. If $v_i = v_L$ (which occurs with a probability λ), then carrier i has three possible options: (i) He delivers on his own and sells his remaining capacity to the platform. (ii) He uses the UCC's service. (iii) He purchases capacity from the platform. If $v_i = v_H$ (which occurs with a probability $1 - \lambda$), then carrier i has two possible options: (i) He delivers on his own. (ii) He uses the UCC's service. Each carrier independently decides how to fulfill his task to minimize his expected cost. To ensure that selling capacity on the platform is profitable and the options do not always dominate each other, we assume $m < (1 - \alpha)\hat{p} < (1/v_L - 1/v_H)\, c$. The following theorem summarizes the consolidator's and the carriers' equilibrium decisions.

Theorem 5. (Equilibrium decisions of the hybrid model)

1. If $m < \min\{m_7, m_8\}$, then it is optimal for the consolidator to charge any $\bar{p}^* > (c + 2mv_L)/((2-\alpha)v_L)$ and $\hat{p}^* = (c + 2mv_L)/((2-\alpha)v_L)$. Under these prices, each carrier i with $v_i = v_H$ delivers on his own, and each carrier i with $v_i = v_L$ delivers on his own (and sells his remaining capacity to the platform) or purchases capacity from the platform with an equal probability.

2. If $m_7 \leq m < m_9$, then it is optimal for the consolidator to charge $\bar{p}^* = m + c/v_L$ and any $\hat{p}^* \geq m + c/v_L$. Under these prices, each carrier i with $v_i = v_H$ delivers on his own, and each carrier i with $v_i = v_L$ uses the UCC's service.

3. If $m \geq \max\{m_8, m_9\}$, then it is optimal for the consolidator to charge $\bar{p}^* = m + c/v_H$ and any $\hat{p}^* \geq m + c/v_L$. Under these prices, all the carriers use the UCC's service.

The terms $m_j, j = 7, \ldots, 9$, are defined in the proof of Theorem 5 in the online supplement.

The conditions of the above equilibrium result determine the source from which the consolidator generates her profit. If the carriers' variable delivery cost m is small ($m < \min\{m_7, m_8\}$), then the consolidator will generate profit from the platform. This is because the affordable delivery cost m makes it difficult to attract the carriers to use the UCC's service. However, as m becomes moderate or large ($m_7 \leq m < m_9$ or $m \geq \max\{m_8, m_9\}$), more carriers would like to outsource their delivery tasks. Specifically, if $m_7 \leq m < m_9$, then only the carriers with a high task volume will deliver on their own. If $m \geq \max\{m_8, m_9\}$, then no carriers will make their own delivery. Both cases eliminate the supply of capacity on the platform. Thus, the consolidator will optimize her prices to induce the carriers to engage the UCC (rather than the platform), such that her expected profit is maximized. In both cases, the consolidator generates profit from the UCC.

Note that some equilibrium in Theorem 5 leads to a lower social-environmental cost than the others. For example, it is straightforward to show that if $n > 1/(1 - \lambda/2)^2$, then the third equilibrium (when $m \geq \max\{m_8, m_9\}$) results in the lowest expected total social-environmental cost. In this equilibrium, all the carriers use the UCC's service. The government can promote the third equilibrium by increasing the variable delivery cost m, such as imposing variable tax to the carriers who deliver on their own. Furthermore, the proof of Theorem 5 shows that m_7, m_8, and m_9 decrease with the government subsidy S for the UCC's service. Thus, to make the third equilibrium more achievable, the government can provide a higher subsidy to the consolidator for the UCC's service. Conversely, if $n \leq 1/(1 - \lambda/2)^2$, then the first equilibrium (when $m < \min\{m_7, m_8\}$) yields the lowest social-environmental cost. In this equilibrium, all the carriers with a low task volume sell or purchase capacity on the platform. In this situation, the government can act in a reverse manner to make the first equilibrium more attainable.

7.2 Demand correlation

In the UCC and the platform models, some carriers are reluctant to eliminate their logistics capability in period 1 because of the reestablishment cost f. This decision depends on the carrier's delivery task volume in the next period. In practice, each carrier's demands across the periods are sometimes correlated such that the carriers can roughly predict their task volumes in the near future. This helps them plan ahead with their logistics requirement.

In this section, we analyze the UCC model with correlated demands for each carrier between the two periods. Specifically, we assume the demands for each carrier in the two periods are positively correlated. That is, if the carrier's task volume is low (high) in period 1, then his task volume is also low (high) in period 2. The rest of the model is identical to that of §4. The following theorem summarizes the equilibrium results.

Theorem 6. (Equilibrium decisions of the UCC model with correlated demands) *Assume $h \le \min\{\delta(c+f)v_L/v_H - \delta c, \delta c(v_H/v_L - 1)\}$. There are three cases:*

1. *If $\max\{m_{11}, m_{12}\} \le m < \min\{m_4, m_{10}\}$, then we have the following results.*

   Period 1: The UCC's equilibrium price is $\bar{p}_1^* = m + c/v_L$. Under this price, each carrier i uses the UCC's service and eliminates his logistics capability if $v_{i1} = v_L$, and delivers on his own otherwise.

   Period 2: The UCC's equilibrium price is $\bar{p}_2^* = m + c/v_L$. Under this price, each carrier i uses the UCC's service if $v_{i1} = v_L$, and delivers on his own otherwise.

2. *If $\max\{m_{10}, m_{11}, m_{12}\} \le m < m_4$, then we have the following results.*

   Period 1: The UCC's equilibrium price is $\bar{p}_1^* = m + (c-h)/v_H$. Under this price, each carrier i uses the UCC's service and eliminates his logistics capability if $v_{i1} = v_L$, and uses the UCC's service and keeps his logistics capability otherwise.

   Period 2: The UCC's equilibrium price is $\bar{p}_2^* = m + c/v_L$. Under this price, each carrier i uses the UCC's service if $v_{i1} = v_L$, and delivers on his own otherwise.

3. *If $m \ge \max\{m_2, m_3, m_4\}$, then we have the following results.*

   Period 1: The UCC's equilibrium price is $\bar{p}_1^* = m + c/v_L$. Under this price, each carrier i uses the UCC's service and eliminates his logistics capability if $v_{i1} = v_L$, and delivers on his own otherwise.

   Period 2: The UCC's equilibrium price is $\bar{p}_2^* = m + c/v_H$. Under this price, all the carriers use the UCC's service.

The terms $m_j, j = 10, \ldots, 12$, are defined in the proof of Theorem 6. Note that the carriers eliminate their logistics capability in period 1 if they will continue to use the UCC's service in period 2. On the other hand, the carriers keep their logistics capability in period 1 if they will deliver on their own in period 2. This is because in period 1 the carriers already know their task volumes in the future, so they can plan ahead with their logistics capability.

We also analyze the platform model with positively correlated demands across the two periods for each carrier. We find that there is no Nash Equilibrium with rational expectations in that model. This is because if the *expected* number of carriers who eliminate their logistics capability in period 1 is small, then the carriers anticipate that the platform will charge a low price in period 2. This in turn encourages the carriers to eliminate their logistics capability in period 1, leading to deviations. Similar deviations exist if the expected number of carriers eliminating their logistics capability in period 1 is large. Therefore, there is no equilibrium.

We have also obtained the equilibrium results for the UCC and the platform models for a case where each carrier's task volumes across the two periods are negatively correlated. Compared to Theorem 6, the negative demand correlation induces more carriers to use the UCC's service. We omit the details here.

8 Conclusion

We study how a consolidator can make urban last-mile delivery more economically and social-environmentally sustainable. Specifically, the consolidator can choose to operate a UCC or a capacity sharing platform. Under the UCC business model, the consolidator requires a sorting facility and a fleet of trucks to deliver the tasks of carriers. The consolidator bears the delivery costs, but charges the carriers a service fee for the last-mile delivery. Under the capacity sharing platform business model, the consolidator operates a platform for the carriers to share their delivery capacity. The consolidator does not need a facility and trucks. There is no delivery cost incurred to the consolidator, who receives a revenue share from each successful transaction of capacity on the platform.

For each business model, we develop a two-period game-theoretical model capturing the interactions between the consolidator and the multiple carriers. In each period, the consolidator first determines the delivery fee per unit volume to maximize her expected profit. Then, after knowing his task volume, each carrier minimizes his expected cost by choosing to (i) deliver on his own, (ii) use the consolidator's service and eliminate his own logistics capability, or (iii) use the consolidator's service but keep his own logistics capability.

In practice, the carriers under the UCC business model face the following trade-off: They can potentially save their delivery costs by using the UCC's service, but they are subject to the risk of eliminating their logistics capability. Our game-theoretical model delicately demonstrates this trade-off through its equilibrium results (see Figures 2 and 3). As the carriers' variable delivery cost m increases, they become more dependent on the UCC: In period 1 the carriers who use the UCC's service will eliminate their logistics capability, and in period 2 more carriers will use the UCC's service. On the other hand, as the carriers' logistics reestablishment cost f increases, they become less dependent on the UCC: In period 1 the carriers who use the UCC's service will keep their logistics capability, and in period 2 fewer carriers will use the UCC's service. We also find that if the UCC receives a sufficient government subsidy, then all the carriers will use the UCC's service in period 2, making the UCC more sustainable in the long run. This echoes the phenomenon in practice that many UCC projects rely on government subsidies.

Under the capacity sharing platform model, the carriers generally have their logistics capability on hand in equilibrium (even if they purchase capacity from the platform). This ensures sufficient capacity available on the platform to facilitate successful transactions. Since the platform can always earn a positive profit (revenue share) from each successful transaction, our equilibrium results partially explain the increasing popularity of the capacity sharing platforms in practice. Only if f is sufficiently small and m is sufficiently large, the carriers who purchase capacity from the platform in period 1 will eliminate their logistics capability, and will purchase capacity again from the platform in period 2 (see Figures 5(b) and 6(b)).

We investigate which business model is more profitable for the consolidator. In general, the UCC is more profitable than the platform if the carriers' fixed delivery cost c is large. If c is large, the carriers are more likely to outsource their delivery service, leading to a low supply of capacity on the platform. Thus, there will not be sufficiently many successful transactions on the platform, causing it to be less profitable than the UCC. Moreover, it is easier for the UCC to dominate as the number of carriers n becomes larger because of her economy of scale in shipment consolidation. However, there is an exception if f is sufficiently large and m is intermediate (Region (ii) of §6.1). In this situation, the platform outperforms the UCC if the discount factor δ is small. Since the carriers are less sensitive to their costs in period 2, they become more likely to do their own delivery (and sell their remaining capacity to the platform). This mitigates the imbalance of supply and demand on the platform, and makes the platform more profitable than the UCC.

We also determine which business model is more efficient for reducing the social-environmental cost. Although additional trucks are required by the UCC model, each truck of the UCC can potentially consolidate multiple carriers' tasks. In contrast, no additional trucks are required by the platform model, but each carrier on the platform can only serve at most one other carrier because of his limited capacity. We find that if n is large, then the UCC is more efficient in reducing the expected social-environmental cost than the platform. This is because the UCC's trucks (each can serve multiple tasks) can achieve a larger economy of scale in shipment consolidation when n is large. This significantly reduces the traffic congestion and pollution of the last-mile delivery. Note that this is non-trivial because we have observed that the threshold of n for the UCC to outperform the platform varies with the probability λ of a low task volume in different manners under different situations (see Figure 7).

We study two extensions of our models. The first extension considers a hybrid model in which the consolidator concurrently operates a UCC and a platform. We also analyze an extension with correlated demands between two periods for each carrier. Other future research directions include endogenizing the government subsidy S and considering the construction costs of the UCC and the platform.

References

Abhishek V, Guajardo JA, Zhang Z (2016) Business models in the sharing economy: Manufacturing durable goods in the presence of peer-to-peer rental markets. Working paper, Carnegie Mellon University.

Agarwal R, Ergun Ö (2010) Network design and allocation mechanisms for carrier alliances in liner shipping. *Oper. Res.* **58**(6):1726–1742.

Allen J, Browne M, Woodburn A, Leonardi J (2012) The role of urban consolidation centres in sustainable freight transport. *Transport Rev.* **32**(4):473–490.

Ambrosini C, Routhier J (2004) Objectives, methods and results of surveys carried out in the field of urban freight transport: An international comparison. *Transport Rev.* **24**(1):57–77.

Bai J, So KC, Tang CS, Chen X, Wang H (2018) Coordinating supply and demand on an on-demand service platform with impatient customers. *Manufacturing Service Oper. Management*, forthcoming.

Benjaafar S, Bernhard H, Courcoubetis C (2017) Drivers, riders and service providers: The impact of the sharing economy on mobility. *Proceedings of the 12th workshop on the economics of networks, systems and computation*, 27 June 2017, pp.1-6.

Benjaafar S, Kong G, Li X, Courcoubetis C (2018) Peer-to-peer product sharing: Implications for ownership, usage and social welfare in the sharing economy. *Management Sci.* **65**(2):477–493.

Bimpikis K, Candogan O, Saban D (2016) Spatial pricing in ride-sharing networks. Working paper, Stanford University.

Boudoin D, Morel C, Gardat M (2014) Supply chains and urban logistics platforms, in Gonzalez-Feliu J, Semet F, Routhier J-L (eds), *Sustainable Urban Logistics: Concepts, Methods and Information Systems*, EcoProduction, Springer Berlin Heidelberg, pp. 1–20.

Broner F, Martin A, Ventura J (2010) Sovereign risk and secondary markets. *Amer. Econom. Rev.* **100**(4):1523–1555.

Browne M, Sweet M, Woodburn A, Allen J (2005) Urban Freight Consolidation Centres Final Report. Transport Studies Group, University of Westminster, London.

Cachon GP, Swinney R (2009) Purchasing, pricing, and quick response in the presence of strategic consumers. *Management Sci.* **55**(3):497–511.

Cachon GP, Daniels KM, Lobel R (2017) The role of surge pricing on a service platform with self-scheduling capacity. *Manufacturing Service Oper. Management* **19**(3):368–384.

Chen J, Esteban S, Shum M (2013) When do secondary markets harm firms? *Amer. Econom. Rev.* **103**(7):2911–2934.

Choe T, Scott A, Mauricio G, Jon W (2017) The future of freight: How new technology and new thinking can transform how goods are moved. *Deloitte Insights.*

Cohen M, Zhang R (2017) Coopetition and profit sharing for ride-sharing platforms. Working paper, New York University.

Crainic R, Ricciardi N, Storchi G (2009) Models for evaluating and planning city logistics systems. *Transportation Sci.* **43**(4):432–454.

Dablanc L (2005) French strategic approach to urban consolidation. *Bestufs II First Workshop 13th–14th January 2005*, London.

Dablanc L (2007) Goods transport in large European cities: Difficult to organize, difficult to modernize. *Transportation Res. Part A* **41**(3):280–285.

Dablanc L (2011) *City logistic best practices: A Handbook for Authorities*, SUGAR, Bologna, Italy.

Doig JW (2001) *Empire on the Hudson: Entrepreneurial Vision and Political Power at the Port of New York Authority.* Columbia University Press, New York.

Dong L, Rudi N (2004) Who benefits from transshipment? Exogenous vs. endogenous wholesale price. *Management Sci.* **50**:645–657.

Fraiberger S, Sundararajan A (2015) Peer-to-peer rental markets in the sharing economy. Working paper, New York University.

Gesing B (2017) Transport capacity sharing, in *Sharing Economy Logistics: Rethinking Logistics with Access over Ownership*, DHL Trend Research, pp. 21–22.

Hagiu A, Wright J (2015) Marketplace or reseller? *Management Sci.* **61**(1):184–203.

Handoko D, Lau HC, Cheng SF (2016) Achieving economic and environmental sustainability in urban consolidation center with bi-criteria auction. *IEEE Trans. Automation Science and Engineering* **13**(4):1471–1479.

Holguin-Veras J, Silas M, Polimeni J (2008) An investigation into the attitudinal factors determining participation in cooperative multi-carrier delivery initiatives, in Taniguchi E, Thomson R (eds), *Innovations in City Logistics IV*, Nova Science Publishers, pp. 55–68.

Hu M, Zhou Y (2017) Price, wage and fixed commission in on-demand matching. Working paper, University of Toronto.

Jiang B, Tian L (2016) Collaborative consumption: Strategic and economic implications of product sharing. *Management Sci.* **64**(3):1171–1188.

Lee H, Whang S (2001) Winning the last mile of e-commerce. *MIT Sloan Management Rev.* **42**(4):54–62.

Lee H, Whang S (2002) The impact of the secondary market on the supply chain. *Management Sci.* **48**(6):719–731.

Lopez E (2017) Why is the last mile so inefficient? *Supply Chain Dive.*

McDermott DR (1975) An alternative framework for urban goods distribution: Consolidation. *Transportation J.* **15**(1):29–39.

Mendelson H, Tunc T (2007) Strategic spot trading in supply chains. *Management Sci.* **53**(5):742–759.

Milner J, Kouvelis P(2007) Inventory, speculation, and sourcing strategies in the presence of online exchanges. *Manufacturing Service Oper. Management* **9**(3):312–331.

National Express (2010) National Express International Ltd case. http://www.ne56.com/experiential/ne56109111369BB3F5.html.

Özener OÖ, Ergun Ö (2008) Allocating costs in a collaborative transportation procurement network. *Transportation Sci.* **42**(2):146–165.

Quak H, Tavasszy L (2011) Customized solutions for sustainable city logistics: The viability of urban freight consolidation centres, in van Nunen JAEE, Huijbregts P, Rietveld P (eds), *Transitions Towards Sustainable Mobility*, Springer Berlin Heidelberg.

Ranieri L, Digiesi S, Silvestri B, Roccotelli M (2018) A review of last mile logistics innovations in an externalities cost reduction vision. *Sustainability* **10**(3):782.

Rochet JC, Tirole J (2006) Two-sided markets: A progress report. *The RAND J. Econom.* **37**(3):645–667.

Rudi N, Kapur S, Pyke D (2001) A two-location inventory model with transshipment and local decision making. *Management Sci.* **47**:1668–1680.

Snapp S (2012) The overestimation of the benefits of 3PL versus private fleets. *Brightwork research.*

Steinerberger S (2015) New bounds for the traveling salesman constant. *Advances Appl. Probability* **47**(1).

Su X, Zhang F (2008) Strategic customer behavior, commitment, and supply chain performance. *Management Sci.* **54**(10):1759–1773.

Taylor T (2018) On-demand service platforms. *Manufacturing Service Oper. Management*, **20**(4):704–720.

Tian L, Jiang B (2018) Effects of consumer-to-consumer product sharing on distribution channel. *Production Oper. Management* **27**(2):350–367.

van Duin R, Quak H, Munuzuri J (2008) Revival of the cost benefit analysis for evaluating the city distribution center concept? In Taniguchi E, Thompson RG (eds), *Innovations in City Logistics*, Nova Publishers, New York, pp. 97–114.

Vivaldini M, Pires S, de Souza F (2012) Improving logistics services through the technology used in fleet management. *J. Information Systems and Technology Management: JISTEM* **9**(3): 541–562.

Wang C, Lim YF, Lau HC (2018) An auction mechanism for last-mile delivery with cost uncertainty. Working paper, Singapore Management University.

Wang C, Lau HC, Lim YF (2015) A rolling horizon auction mechanism and virtual pricing of shipping capacity for urban consolidation centers, in Corman F, VoßS, Negenborn RR (eds), *Computational Logistics*, Springer International Publishing Switzerland, pp. 422-436.

Wang Y, Zhang D, Liu Q, Shen F, Lee LH (2016) Towards enhancing the last-mile delivery: An effective crowd-tasking model with scalable solutions. *Transportation Res. Part E* **93**:279–293.

Weyl EG (2010) A price theory of multi-sided platforms. *Amer. Econom. Rev.* **100**(4):1642–1672.

A Online supplement

Proof of Lemma 1. By solving $\bar{\phi}_{i2}(0;\bar{d}_{i1},\bar{p}_2) \leq \bar{\phi}_{i2}(-1;\bar{d}_{i1},\bar{p}_2)$ for v_{i2}, we obtain that
1. $\bar{p}_2 \leq m + \frac{c}{v_{i2}}$ if $\bar{d}_{i1} = -1$ or 1. Thus, $\bar{d}^*_{i2} = 0$ if $\bar{p}_2 \leq m + \frac{c}{v_{i2}}$, and $\bar{d}^*_{i2} = -1$ otherwise.
2. $\bar{p}_2 \leq m + \frac{c+f}{v_{i2}}$ if $\bar{d}_{i1} = 0$. Thus, $\bar{d}^*_{i2} = 0$ if $\bar{p}_2 \leq m + \frac{c+f}{v_{i2}}$, and $\bar{d}^*_{i2} = -1$ otherwise. □

Proof of Lemma 2. Define $b_1 = M - S + \frac{\left(\sqrt{n_e}-\sqrt{\lambda n_e}\right)C+\left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right)(c+f)n_e}{(1-\lambda)n_e v_H}$,
$b_2 = M-S+\frac{\left(\sqrt{\lambda(n-n_e)+n_e}-\sqrt{\lambda n_e}\right)C+\lambda n_e f-\left((1-\lambda)n_e\frac{v_H}{v_L}+\lambda(n-n_e)\right)c}{(1-\lambda)n_e v_H+\lambda(n-n_e)v_L}$, $b_3 = M-S+\frac{\left(\sqrt{n}-\sqrt{\lambda n_e}\right)C+\lambda(c+f)n_e-\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)cn}{(1-\lambda)nv_H+\lambda(n-n_e)v_L}$,
$b_4 = M - S + \frac{\left(\sqrt{\lambda(n-n_e)+n_e}-\sqrt{n_e}\right)C+\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)(c+f)n_e-\left(\lambda n+(1-\lambda)n_e\frac{v_H}{v_L}\right)c}{\lambda(n-n_e)v_L}$,
$b_5 = M - S + \frac{\left(\sqrt{n}-\sqrt{n_e}\right)C+\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)(c+f)n_e-\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)cn}{\lambda(n-n_e)v_L+(1-\lambda)(n-n_e)v_H}$,
$b_6 = M-S+\frac{\left(\sqrt{n}-\sqrt{\lambda(n-n_e)+n_e}\right)C+\left(\lambda n\left(1-\frac{v_L}{v_H}\right)+(1-\lambda)n_e\frac{v_H}{v_L}-(1-\lambda)n\right)c}{(1-\lambda)(n-n_e)v_H}$, and $b_7 = M-S+\frac{\left(\sqrt{n}-\sqrt{\lambda n}\right)C+\left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right)nc}{(1-\lambda)nv_H}$.

To derive V_2 and n_2 in the UCC's expected profit function in Equation (1), we need to distinguish the following four types of carriers:
Type 1 ($\bar{d}_{i1} = -1$ or 1, and $v_{i2} = v_L$): Each carrier i of this type uses the UCC's service and eliminates his logistics capability in period 2 ($\bar{d}^*_{i2} = 0$) if $\bar{p}_2 \leq m + \frac{c}{v_L}$. The expected number of carriers of this type is $\lambda(n-n_e)$, and if those carriers use the UCC's service in period 2, then the expected task volumes served by the UCC are $\lambda(n-n_e)v_L$.
Type 2 ($\bar{d}_{i1} = -1$ or 1, and $v_{i2} = v_H$): Each carrier i of this type uses the UCC's service and eliminates his logistics capability in period 2 ($\bar{d}^*_{i2} = 0$) if $\bar{p}_2 \leq m + \frac{c}{v_H}$. The expected number of carriers of this type is $(1-\lambda)(n-n_e)$, and if those carriers use the UCC's service in period 2, then the expected task volumes served by the UCC in period 2 are $(1-\lambda)(n-n_e)v_H$.
Type 3 ($\bar{d}_{i1} = 0$, and $v_{i2} = v_L$): Each carrier i of this type uses the UCC's service in period 2 ($\bar{d}^*_{i2} = 0$) if $\bar{p}_2 \leq m+\frac{c+f}{v_L}$. The expected number of carriers of this type is λn_e, and if those carriers use the UCC's service in period 2, then the expected task volumes served by the UCC in period 2 are $\lambda n_e v_L$.
Type 4 ($\bar{d}_{i1} = 0$, and $v_{i2} = v_H$): Each carrier i of this type uses the UCC's service in period 2 ($\bar{d}^*_{i2} = 0$) if $\bar{p}_2 \leq m + \frac{c+f}{v_H}$. The expected number of carriers of this type is $(1-\lambda)n_e$, and if those carriers use the UCC's service in period 2, then the expected task volumes served by the UCC in period 2 are $(1-\lambda)n_e v_H$.

Note that the expected number of Type 3 and Type 4 carriers will be 0 if $n_e = 0$. We first analyze the UCC's optimal decision in the case that $n_e > 0$, before we analyze the case that $n_e = 0$. According to the assumption $f > \frac{c(v_H-v_L)}{v_L}$, we can derive $m + \frac{c+f}{v_L} > m + \frac{c+f}{v_H} > m + \frac{c}{v_L} > m + \frac{c}{v_H}$, so the optimal choice of the UCC is among the following four:

1. Choose a price $\bar{p}_2 \in \left(m + \frac{c+f}{v_H}, m + \frac{c+f}{v_L}\right]$ to attract type 3 carriers only, then n_2 and V_2 equal to the expected number and expected task volumes of type 3 carriers, that is $n_2 = \lambda n_e$ and $V_2 = \lambda n_e v_L$. Substituting them into Equation (1), the UCC's expected profit is

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)\lambda n_e v_L - \sqrt{\lambda n_e}C, \tag{5}$$

which increases in $\bar{p}_2$, so it is optimal for the UCC to choose $\bar{p}^*_2 = m+\frac{c+f}{v_L}$ to maximize profit. Substituting $\bar{p}^*_2 = m+\frac{c+f}{v_L}$ into Equation (5), we obtain that $\bar{\pi}_2\left(m + \frac{c+f}{v_L}\right) = \left(m + \frac{c+f}{v_L} + S - M\right)\lambda n_e v_L - \sqrt{\lambda n_e}C$.

2. Choose a price $\bar{p}_2 \in \left(m + \frac{c}{v_L}, m + \frac{c+f}{v_H}\right]$ to attract type 3 and type 4 carriers, then n_2 and V_2 equal to the total expected number and expected task volumes of those carriers, that is $n_2 = \lambda n_e + (1-\lambda)n_e$ and $V_2 = \lambda n_e v_L + (1-\lambda)n_e v_H$. Substituting them into Equation (1), the UCC's expected profit is

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)(\lambda n_e v_L + (1-\lambda)n_e v_H) - \sqrt{\lambda n_e + (1-\lambda)n_e}C, \tag{6}$$

which increases in $\bar{p}_2$, so it is optimal for the UCC to choose $\bar{p}^*_2 = m+\frac{c+f}{v_H}$ to maximize profit. Substituting $\bar{p}^*_2 = m + \frac{c+f}{v_H}$ into Equation (6), we obtain that $\bar{\pi}_2\left(m + \frac{c+f}{v_H}\right) = \left(m + \frac{c+f}{v_H} + S - M\right)(\lambda n_e v_L + (1-\lambda)n_e v_H) - \sqrt{n_e}C$.

3. Choose a price $\bar{p}_2 \in \left(m + \frac{c}{v_H}, m + \frac{c}{v_L}\right]$ to attract type 3, type 4, and type 1 carriers, then n_2 and V_2 equal to the total expected number and expected task volumes of those carriers, that is $n_2 = \lambda n_e + (1-\lambda)n_e + \lambda(n-n_e)$ and $V_2 = \lambda n_e v_L + (1-\lambda)n_e v_H + \lambda(n-n_e)v_L$. Substituting them into Equation (1), the UCC's expected profit is

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)(\lambda n_e v_L + (1-\lambda)n_e v_H + \lambda(n-n_e)v_L) - \sqrt{\lambda n_e + (1-\lambda)n_e + \lambda(n-n_e)}C, \tag{7}$$

which increases in $\bar{p}_2$, so it is optimal for the UCC to choose $\bar{p}^*_2 = m+\frac{c}{v_L}$ to maximize profit. Substituting $\bar{p}^*_2 = m+\frac{c}{v_L}$ into Equation (7), we obtain that $\bar{\pi}_2\left(m + \frac{c}{v_L}\right) = \left(m + \frac{c}{v_L} + S - M\right)(\lambda n v_L+(1-\lambda)n_e v_H)-$

$\sqrt{\lambda(n-n_e)+n_e}C$.

4. Choose a price $\bar{p}_2 \in \left(0, m+\frac{c}{v_H}\right]$ to attract all types of carriers, then $n_2 = n$ and V_2 equals to the total expected task volumes of all the carriers, that is $V_2 = \lambda n_e v_L + (1-\lambda)n_e v_H + \lambda(n-n_e)v_L + (1-\lambda)(n-n_e)v_H = \lambda n v_L + (1-\lambda)n v_H$. Substituting them into Equation (1), the UCC's expected profit is

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)(\lambda n v_L + (1-\lambda)n v_H) - \sqrt{n}C, \tag{8}$$

which increases in $\bar{p}_2$, so it is optimal for the UCC to choose $\bar{p}_2^* = m+\frac{c}{v_H}$ to maximize profit. Substituting $\bar{p}_2^* = m+\frac{c}{v_H}$ into Equation (8), we obtain that $\bar{\pi}_2\left(m+\frac{c}{v_H}\right) = \left(m+\frac{c}{v_H}+S-M\right)(\lambda n v_L + (1-\lambda)n v_H) - \sqrt{n}C$.

By comparing the profits of the UCC under choices 1, 2, 3, and 4, we can obtain that $\bar{\pi}_2\left(m+\frac{c+f}{v_L}\right)$ is the maximum if $m < \min\{b_1, b_2, b_3\}$; $\bar{\pi}_2\left(m+\frac{c+f}{v_H}\right)$ is the maximum if $b_1 \leq m < \min\{b_4, b_5\}$; $\bar{\pi}_2\left(m+\frac{c}{v_L}\right)$ is the maximum if $\max\{b_2, b_4\} \leq m < b_6$; and $\bar{\pi}_2\left(m+\frac{c}{v_H}\right)$ is the maximum if $m \geq \max\{b_3, b_5, b_6\}$. Therefore, the corresponding prices $\bar{p}_2^*$ under those choices are optimal for the UCC, and the results in Lemma 2 follow.

Similarly, we analyze the case that $n_e = 0$. Since there is only type 1 and type 2 carriers, the optimal decision of the UCC is among the following two:

1. Choose a price $\bar{p}_2 \in \left(m+\frac{c}{v_H}, m+\frac{c}{v_L}\right]$ to attract type 1 carriers only, then n_2 and V_2 equal to the expected number and expected task volumes of type 1 carriers, that is $n_2 = \lambda(n-n_e) = \lambda n$ and $V_2 = \lambda(n-n_e)v_L = \lambda n v_L$. Substituting them into Equation (1), the UCC's expected profit is

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)\lambda n v_L - \sqrt{\lambda n}C, \tag{9}$$

which increases in $\bar{p}_2$, so it is optimal for the UCC to choose $\bar{p}_2^* = m+\frac{c}{v_L}$ to maximize profit. Substituting $\bar{p}_2^* = m+\frac{c}{v_L}$ into Equation (9), we obtain that $\bar{\pi}_2\left(m+\frac{c}{v_L}\right) = \left(m+\frac{c}{v_L}+S-M\right)\lambda n v_L - \sqrt{\lambda n}C$.

2. Choose a price $\bar{p}_2 \in \left(0, m+\frac{c}{v_H}\right]$ to attract both types of carriers, then $n_2 = n$ and V_2 equals to the total expected task volumes of all the carriers, that is $V_2 = \lambda(n-n_e)v_L + (1-\lambda)(n-n_e)v_H = \lambda n v_L + (1-\lambda)n v_H$. Substituting them into Equation (1), the UCC's expected profit is

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)(\lambda n v_L + (1-\lambda)n v_H) - \sqrt{n}C, \tag{10}$$

which increases in $\bar{p}_2$, so it is optimal for the UCC to choose $\bar{p}_2^* = m+\frac{c}{v_H}$ to maximize profit. Substituting $\bar{p}_2^* = m+\frac{c}{v_H}$ into Equation (10), we obtain that $\bar{\pi}_2\left(m+\frac{c}{v_H}\right) = \left(m+\frac{c}{v_H}+S-M\right)(\lambda n v_L + (1-\lambda)n v_H) - \sqrt{n}C$.

By comparing the profits of the UCC under choices 1 and 2, we can obtain that $\bar{\pi}_2\left(m+\frac{c}{v_L}\right) > \bar{\pi}_2\left(m+\frac{c}{v_H}\right)$ if $m < b_7$. Therefore, it is optimal for the UCC to choose $\bar{p}_2^* = m+\frac{c}{v_L}$ if $m < b_7$, and $\bar{p}_2^* = m+\frac{c}{v_H}$ otherwise. The results in Lemma 2 thus follow.

□

Proof of Lemma 3. Define $\tilde{b}_1 = M - S + \frac{\left(\sqrt{\tilde{n}_e}-\sqrt{\lambda\tilde{n}_e}\right)C+\left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right)(c+f)\tilde{n}_e}{(1-\lambda)\tilde{n}_e v_H}$,
$\tilde{b}_2 = M-S+\frac{\left(\sqrt{\lambda(n-\tilde{n}_e)+\tilde{n}_e}-\sqrt{\lambda\tilde{n}_e}\right)C+\lambda\tilde{n}_e f-\left((1-\lambda)\tilde{n}_e\frac{v_H}{v_L}+\lambda(n-\tilde{n}_e)\right)c}{(1-\lambda)\tilde{n}_e v_H+\lambda(n-\tilde{n}_e)v_L}$, $\tilde{b}_3 = M-S+\frac{\left(\sqrt{n}-\sqrt{\lambda\tilde{n}_e}\right)C+\lambda(c+f)\tilde{n}_e-\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)cn}{(1-\lambda)n v_H+\lambda(n-\tilde{n}_e)v_L}$,
$\tilde{b}_4 = M - S + \frac{\left(\sqrt{\lambda(n-\tilde{n}_e)+\tilde{n}_e}-\sqrt{\tilde{n}_e}\right)C+\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)(c+f)\tilde{n}_e}{\lambda(n-\tilde{n}_e)v_L} - \frac{\left(\lambda n+(1-\lambda)\tilde{n}_e\frac{v_H}{v_L}\right)c}{\lambda(n-\tilde{n}_e)v_L}$,
$\tilde{b}_5 = M - S + \frac{\left(\sqrt{n}-\sqrt{\tilde{n}_e}\right)C+\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)(c+f)\tilde{n}_e-\left(\lambda\frac{v_L}{v_H}+(1-\lambda)\right)cn}{\lambda(n-\tilde{n}_e)v_L+(1-\lambda)(n-\tilde{n}_e)v_H}$,
and $\tilde{b}_6 = M - S + \frac{\left(\sqrt{n}-\sqrt{\lambda(n-\tilde{n}_e)+\tilde{n}_e}\right)C-\left(\lambda n\left(1-\frac{v_L}{v_H}\right)+(1-\lambda)\tilde{n}_e\frac{v_H}{v_L}-(1-\lambda)n\right)c}{(1-\lambda)(n-\tilde{n}_e)v_H}$.

We first determine a carrier's optimal decision when $\tilde{n}_e > 0$. Note that $\tilde{n}_e$ is rational and hence is equal, in equilibrium, to the corresponding actual value n_e. Thus, according to case 1(a) of Lemma 2, if $m < \min\left\{\tilde{b}_1, \tilde{b}_2, \tilde{b}_3\right\}$, then $\bar{p}_2^* = m+\frac{c+f}{v_L}$. Given $\bar{p}_2^*$, each carrier i minimizes his total discounted cost $\bar{\Phi}_i(\bar{d}_{i1}; \bar{p}_1)$ by comparing the following 3 options:

1. $\bar{d}_{i1} = -1$: In this case, according to Lemmas 1 and 2, carrier i will deliver on his own in period 2. This incurs an expected cost $\bar{\Phi}_i(-1; \bar{p}_1) = c + m v_{i1} + \delta(\lambda(c + m v_L) + (1-\lambda)(c + m v_H))$.

2. $\bar{d}_{i1} = 0$: In this case, according to Lemmas 1 and 2, carrier i will use the UCC's service in period 2 if $v_{i2} = v_L$ and deliver on his own otherwise. This incurs an expected cost $\bar{\Phi}_i(0; \bar{p}_1) = \bar{p}_1 v_{i1} + \delta(\lambda\bar{p}_2^* v_L + (1-\lambda)(c + m v_H + f)) = \bar{p}_1 v_{i1} + \delta(\lambda(c + m v_L) + (1-\lambda)(c + m v_H) + f)$.

3. $\bar{d}_{i1} = 1$: In this case, according to Lemmas 1 and 2, carrier i will deliver on his own in period 2. This incurs an expected cost $\bar{\Phi}_i(1; \bar{p}_1) = \bar{p}_1 v_{i1} + h + \delta(\lambda(c + m v_L) + (1-\lambda)(c + m v_H))$.

By comparing the above three options, we obtain that $\bar{d}_{i1}^* = 1$ if $\bar{p}_1 \leq m + \frac{c-h}{v_{i1}}$, and $\bar{d}_{i1}^* = -1$ otherwise. This proves case 1(a) of Lemma 3. Next we determine the carrier's optimal decision in case 1(b) of

Lemma 3. Similarly, according to case 1 of Lemma 2, if $\tilde{b}_1 \le m < \min\left\{\tilde{b}_4, \tilde{b}_5\right\}$, then $\bar{p}_2^* = m + \frac{c+f}{v_H}$. Given $\bar{p}_2^*$, each carrier i minimizes his total discounted cost $\bar{\Phi}_i(\bar{d}_{i1}; \bar{p}_1)$ by comparing the following three options:

1. $\bar{d}_{i1} = -1$: In this case, according to Lemmas 1 and 2, carrier i will deliver on his own in period 2. This incurs an expected cost $\bar{\Phi}_i(-1; \bar{p}_1) = c + mv_{i1} + \delta(\lambda(c + mv_L) + (1-\lambda)(c + mv_H))$.
2. $\bar{d}_{i1} = 0$: In this case, according to Lemmas 1 and 2, carrier i will use the UCC's service in period 2. This incurs an expected cost $\bar{\Phi}_i(0; \bar{p}_1) = \bar{p}_1 v_{i1} + \delta(\lambda \bar{p}_2^* v_L + (1-\lambda)\bar{p}_2^* v_H) = \bar{p}_1 v_{i1} + \delta\left(m + \frac{c+f}{v_H}\right)(\lambda v_L + (1-\lambda) v_H)$.
3. $\bar{d}_{i1} = 1$: In this case, according to Lemmas 1 and 2, carrier i will deliver on his own in period 2. This incurs an expected cost $\bar{\Phi}_i(1; \bar{p}_1) = \bar{p}_1 v_{i1} + h + \delta(\lambda(c + mv_L) + (1-\lambda)(c + mv_H))$.

By comparing the above three options, we obtain that $\bar{d}_{i1}^* = 1$ if $\bar{p}_1 \le m + \frac{c-h}{v_{i1}}$ and $h \le \delta(c + f)\left(\lambda \frac{v_L}{v_H} + 1 - \lambda\right) - \delta c$, $\bar{d}_{i1}^* = 0$ if $\bar{p}_1 \le m + \frac{(1+\delta)c}{v_{i1}} - \frac{\delta(c+f)\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)}{v_{i1}}$ and $h > \delta(c+f)\left(\lambda \frac{v_L}{v_H} + 1 - \lambda\right) - \delta c$, and $\bar{d}_{i1}^* = -1$ otherwise. This proves case 1(b) of Lemma 3. The proofs of cases 1(c) and 2(a) are similar to the proof of case 1(b), and the proofs of cases 1(d) and 2(b) are similar to the proof of case 1(a), and thus omitted. □

Proof of Theorem 1. Define $m_1 = M - S + \frac{\left(\sqrt{n}-\sqrt{\lambda n}\right)C + \left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right)n(c-h)}{(1-\lambda)nv_H}$,
$m_2 = M - S + \frac{(1-\lambda)\sqrt{n}C + \lambda^2 nf - \left(\lambda\frac{v_L}{v_H} + (1-\lambda)^2\right)nc}{(1-\lambda)nv_H + \lambda(1-2\lambda)nv_L}$, $m_3 = M - S + \frac{\left(\sqrt{n}-\sqrt{\lambda n}\right)C + \left(\lambda\frac{v_L}{v_H}+1-\lambda\right)(c+f)\lambda n - \left(\lambda\frac{v_L}{v_H}+1-\lambda\right)nc}{(1-\lambda)(\lambda n v_L + (1-\lambda)nv_H)}$,
and $m_4 = M - S + \frac{\left(\sqrt{n}-\sqrt{\lambda(1-\lambda)n+\lambda n}\right)C + \left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\left(1-\lambda\frac{v_H}{v_L}\right)\right)nc}{(1-\lambda)^2 n v_H}$.

The UCC's expected profit $\bar{\Pi}(\bar{p}_1)$ in Equation (2) depends on V_1 and n_1. The different cases in Lemma 3 corresponding to different decisions of each carrier will lead to different values of V_1 and n_1. In the following, we analyze each case of Lemma 3 to derive V_1 and n_1 and obtain the UCC's expected total discounted profit and then determine the equilibrium price. To derive V_1 and n_1, we need to distinguish the following two typs of carriers:

Type A ($v_{i1} = v_L$): The expected number of carriers of this type is λn.

Type B ($v_{i1} = v_H$): The expected number of carriers of this type is $(1-\lambda)n$.

We first analyze the cases that $\tilde{n}_e > 0$ of Lemma 3, that is cases 1(a), 1(b), 1(c), and 1(d). Note that $\tilde{n}_e$ is rational and hence equal to to the corresponding actual value in equilibrium, and thus $\tilde{n}_e = n_e(\bar{p}_1^*, \bar{p}_2^*) > 0$, $\tilde{b}_1 = b_1$, $\tilde{b}_2 = b_2$, $\tilde{b}_3 = b_3$, $\tilde{b}_4 = b_4$, $\tilde{b}_5 = b_5$, and $\tilde{b}_6 = b_6$.

In case 1(a) ($\tilde{n}_e > 0$ and $m < \min\left\{\tilde{b}_1, \tilde{b}_2, \tilde{b}_3\right\}$), $\bar{d}_{i1}^* = 1$ if $\bar{p}_1 \le m + \frac{c-h}{v_{i1}}$, or $\bar{d}_{i1}^* = -1$ otherwise. Thus, type A carriers use the UCC's service and keep their logistics capability if $\bar{p}_1 \le m + \frac{c-h}{v_L}$, and type B carriers use the UCC's service and keep their logistics capability if $\bar{p}_1 \le m + \frac{c-h}{v_H}$. In this case, no carrier will use the UCC's service and eliminate logistics capability, which means $n_e = 0$, and thus cannot happen in equilibrium.

In cases 1(b) ($\tilde{n}_e > 0$ and $\tilde{b}_1 \le m < \min\left\{\tilde{b}_4, \tilde{b}_5\right\}$) and 1(c) ($\tilde{n}_e > 0$ and $\max\left\{\tilde{b}_2, \tilde{b}_4\right\} \le m < \tilde{b}_6$), since we focus on the case that $h \le \min\left\{\delta(c+f)\left(\lambda\frac{v_L}{v_H} + 1 - \lambda\right) - \delta c, \delta c\left(\lambda + (1-\lambda)\frac{v_H}{v_L}\right) - \delta c\right\}$, thus $\bar{d}_{i1}^* = 1$ if $\bar{p}_1 \le m + \frac{c-h}{v_{i1}}$, or $\bar{d}_{i1}^* = -1$ otherwise. Similar to the above case 1(a), these cases will never happen in equilibrium.

In case 1(d) ($\tilde{n}_e > 0$ and $m \ge \max\left\{\tilde{b}_3, \tilde{b}_5, \tilde{b}_6\right\}$), $\bar{d}_{i1}^* = 0$ if $\bar{p}_1 \le m + \frac{c}{v_{i1}}$, or $\bar{d}_{i1}^* = -1$ otherwise. Thus, type A carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \le m + \frac{c}{v_L}$, and type B carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \le m + \frac{c}{v_H}$. In case 1(d), we have obtained that $\bar{p}_2^* = m + \frac{c}{v_H}$ according to Lemma 2. The optimal choice of the retailer in period 1 is among the following two:

1. Choose a price $\bar{p}_1 \in \left(m + \frac{c}{v_H}, m + \frac{c}{v_L}\right]$ to attract type A carriers only, then n_1 and V_1 equal to the expected number and task volumes of type A carriers, that is $n_1 = \lambda n$ and $V_1 = \lambda n v_L$. Since type A carriers use the UCC's service and eliminate their logistics capability, thus $n_e = n_1 = \lambda n$. Substituting them into Equation (2), the UCC's expeted total discounted profit is

$$
\begin{aligned}
\bar{\Pi}(\bar{p}_1) &= (\bar{p}_1 + S - M)\lambda n v_L - \sqrt{\lambda n}C + \delta\bar{\pi}_2\left(m + \frac{c}{v_H}\right) \\
&= (\bar{p}_1 + S - M)\lambda n v_L - \sqrt{\lambda n}C + \delta\left[\left(m + \frac{c}{v_H} + S - M\right)(\lambda n v_L + (1-\lambda)nv_H) - \sqrt{n}C\right],
\end{aligned} \tag{11}
$$

which increases in $\bar{p}_1$, so it is optimal for the UCC to choose $\bar{p}_1^* = m + \frac{c}{v_L}$ to maximize profit. This could be in equilirbium only if $n_e = \lambda n$ satisfies the conditions that $n_e > 0$ (which is satisfied) and $m \ge \max\{b_3, b_5, b_6\}$. Substituting $n_e = \lambda n$ into b_3, b_5, and b_6, we can rewrite the latter conition as $m \ge \max\{m_2, m_3, m_4\}$. This leads to the results in case 3 of Theorem 1.

2. Choose a price $\bar{p}_1 \in \left(0, m + \frac{c}{v_H}\right]$ to attract both types of carriers, then $n_1 = n$ and V_1 equals to

the total expected task volumes of all the carriers, that is $V_1 = \lambda n v_L + (1-\lambda) n v_H$. Since all the carriers use the UCC's service and eliminate their logistics capability, thus $n_e = n_1 = n$. Substituting them into Equation (2), the UCC's expeted total discounted profit is

$$\begin{aligned} \bar{\Pi}(\bar{p}_1) &= (\bar{p}_1 + S - M)(\lambda n v_L + (1-\lambda) n v_H) - \sqrt{n}C + \delta \bar{\pi}_2 \left(m + \tfrac{c}{v_H}\right) \\ &= (\bar{p}_1 + S - M)(\lambda n v_L + (1-\lambda) n v_H) - \sqrt{n}C + \delta \left[\left(m + \tfrac{c}{v_H} + S - M\right)(\lambda n v_L + (1-\lambda) n v_H) - \sqrt{n}C\right], \end{aligned} \tag{12}$$

which increases in $\bar{p}_1$, so it is optimal for the UCC to choose $\bar{p}_1^* = m + \frac{c}{v_H}$ to maximize profit. This could be in equilirbium only if $n_e = n$ satisfies the conditions that $n_e > 0$ (which is satisfied) and $m \geq \max\{b_3, b_5, b_6\}$. Substituting $n_e = n$ into b_3, b_5, and b_6, we find that the latter condition can never be satisfied as b_5 and b_6 go to infinity.

Next we analyze the cases that $\tilde{n}_e = 0$ of Lemma 3, that is cases 2(a) and 2(b). Similarly, since $\tilde{n}_e$ is rational and hence equal to the corresponding actual value in equilibrium, and thus $n_e(\bar{p}_1^*, \bar{p}_2^*) = \tilde{n}_e = 0$.

In case 2(a) ($\tilde{n}_e = 0$ and $m < b_7$, since we focus on the case that $h \leq \min\left\{\delta(c+f)\left(\lambda \frac{v_L}{v_H} + 1 - \lambda\right) - \delta c, \delta c\left(\lambda + (1-\lambda)\frac{v_H}{v_L}\right) - \delta c\right\}$, thus $\bar{d}_{i1}^* = 1$ if $\bar{p}_1 \leq m + \frac{c-h}{v_{i1}}$, or $\bar{d}_{i1}^* = -1$ otherwise. Thus, type A carriers use the UCC's service and keep their logistics capability if $\bar{p}_1 \leq m + \frac{c-h}{v_L}$, and type B carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \leq m + \frac{c-h}{v_H}$. In case 2(a), we have obtained that $\bar{p}_2^* = m + \frac{c}{v_L}$ according to Lemma 2. The optimal choice of the retailer in period 1 is among the following two:

1. Choose a price $\bar{p}_1 \in \left(m + \frac{c-h}{v_H}, m + \frac{c-h}{v_L}\right]$ to attract type A carriers only, then n_1 and V_1 equal to the expected number and task volumes of type A carriers, that is $n_1 = \lambda n$ and $V_1 = \lambda n v_L$. Since no carrier will use the UCC's service and keeplogistics capability, thus $n_e = 0$. Substituting them into Equation (2), the UCC's expeted total discounted profit is

$$\begin{aligned} \bar{\Pi}(\bar{p}_1) &= (\bar{p}_1 + S - M)\lambda n v_L - \sqrt{\lambda n}C + \delta \bar{\pi}_2 \left(m + \tfrac{c}{v_L}\right) \\ &= (\bar{p}_1 + S - M)\lambda n v_L - \sqrt{\lambda n}C + \delta \left[\left(m + \tfrac{c}{v_L} + S - M\right)\lambda n v_L - \sqrt{\lambda n}C\right], \end{aligned} \tag{13}$$

which increases in $\bar{p}_1$, so it is optimal for the UCC to choose $\bar{p}_1^* = m + \frac{c-h}{v_L}$ to maximize profit. This could be in equilirbium only if $n_e = 0$ satisfies the conditions that $n_e = 0$ (which is satisfied) and $m - (M - S) < m_1$. Substituting $\bar{p}_1^* = m + \frac{c-h}{v_L}$ into Equation (13), we can obtain that $\bar{\Pi}\left(m + \frac{c-h}{v_L}\right) = (1+\delta)(m + S - M)\lambda n v_L + ((1+\delta)c - h)\lambda n - (1+\delta)\sqrt{\lambda n}C$.

2. Choose a price $\bar{p}_1 \in \left(0, m + \frac{c-h}{v_H}\right]$ to attract both types of carriers, then $n_1 = n$ and V_1 equals to the total expected task volumes of all the carriers, that is $V_1 = \lambda n v_L + (1-\lambda) n v_H$. Since no carrier will use the UCC's service and eliminate logistics capability, thus $n_e = 0$. Substituting them into Equation (2), the UCC's expeted total discounted profit is

$$\begin{aligned} \bar{\Pi}(\bar{p}_1) &= (\bar{p}_1 + S - M)(\lambda n v_L + (1-\lambda) n v_H) - \sqrt{n}C + \delta \bar{\pi}_2 \left(m + \tfrac{c}{v_L}\right) \\ &= (\bar{p}_1 + S - M)(\lambda n v_L + (1-\lambda) n v_H) - \sqrt{n}C + \delta \left[\left(m + \tfrac{c}{v_L} + S - M\right)\lambda n v_L - \sqrt{\lambda n}C\right], \end{aligned} \tag{14}$$

which increases in $\bar{p}_1$, so it is optimal for the UCC to choose $\bar{p}_1^* = m + \frac{c-h}{v_H}$ to maximize profit. This could be in equilirbium only if $n_e = 0$ satisfies the conditions that $n_e = 0$ (which is satisfied) and $m < b_7$. Substituting $\bar{p}_1^* = m + \frac{c-h}{v_H}$ into Equation (14), we can obtain that $\bar{\Pi}\left(m + \frac{c-h}{v_H}\right) = (m + S - M)((1+\delta)\lambda n v_L + (1-\lambda) n v_H) + \delta\lambda c n + (c-h)n\left(\lambda \frac{v_L}{v_H} + 1 - \lambda\right) - \left(\sqrt{n} + \delta\sqrt{\lambda n}\right)C$.

By comparing $\bar{\Pi}\left(m + \frac{c-h}{v_L}\right)$ and $\bar{\Pi}\left(m + \frac{c-h}{v_H}\right)$ with respect to m, we obtain that $\bar{\Pi}\left(m + \frac{c-h}{v_L}\right) > \bar{\Pi}\left(m + \frac{c-h}{v_H}\right)$ if $m < m_1$. Therefore, we have $\bar{p}_1^* = m + \frac{c-h}{v_L}$ if $m < \min\{b_7, m_1\}$, and $\bar{p}_1^* = m + \frac{c-h}{v_H}$ if $\min\{b_7, m_1\} \leq m < b_7$. This leads to the results in cases 1 and 2 of Theorem 1.

In case 2(b) ($\tilde{n}_e = 0$ and $m - (M - S) \geq b_7$), $\bar{d}_{i1}^* = 0$ if $\bar{p}_1 \leq m + \frac{c}{v_{i1}}$, or $\bar{d}_{i1}^* = -1$ otherwise. Thus, type A carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \leq m + \frac{c}{v_L}$, and type B carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \leq m + \frac{c}{v_H}$. In this case, $n_e = 0$ will never happen which indicates that it will never be in equilibrium.

□

Lemma 4. (Optimal decision of carrier $i \in \mathcal{N}_{L,2}$ in period 2)
1. If $\hat{d}_{i1} = -1$ or 1, then in period 2 carrier i purchases capacity from the platform and eliminates his logistics capability ($\hat{d}_{i2}^* = 0$) if $\hat{p}_2 < \frac{c+(1+\theta_2)m v_L}{[1+\theta_2(1-\alpha)]v_L}$, or delivers on his own ($\hat{d}_{i2}^* = -1$) if $\hat{p}_2 > \frac{c+(1+\theta_2)m v_L}{[1+\theta_2(1-\alpha)]v_L}$.
2. If $\hat{d}_{i1} = 0$, then in period 2, carrier i purchases capacity from the platform ($\hat{d}_{i2}^* = 0$) if $\hat{p}_2 < \frac{c+f+(1+\theta_2)m v_L}{[1+\theta_2(1-\alpha)]v_L}$, or delivers on his own ($\hat{d}_{i2}^* = -1$) if $\hat{p}_2 > \frac{c+f+(1+\theta_2)m v_L}{[1+\theta_2(1-\alpha)]v_L}$.

Proof of Lemma 4. By solving $\hat{\phi}_{i2}(0; \hat{d}_{i1}, \hat{p}_2) \le \hat{\phi}_{i2}(-1; \hat{d}|_{i1}, \hat{p}_2)$ for v_{i2}, we obtain that
1. $\hat{p}_2 < (c + 2mv_L)/((2-\alpha)v_L)$ if $\hat{d}_{i1} = -1$ or 1. Thus, $\hat{d}^*_{i2} = 0$ if $\hat{p}_2 < (c + 2mv_L)/((2-\alpha)v_L)$, and $\hat{d}^*_{i2} = -1$ if $\hat{p}_2 > (c + 2mv_L)/((2-\alpha)v_L)$.
2. $\hat{p}_2 < (c + 2mv_L + f)/((2-\alpha)v_L)$ if $\hat{d}_{i1} = 0$. Thus, $\hat{d}^*_{i2} = 0$ if $\hat{p}_2 < (c + 2mv_L + f)/((2-\alpha)v_L)$, and $\hat{d}^*_{i2} = -1$ if $\hat{p}_2 > (c + 2mv_L + f)/((2-\alpha)v_L)$.

□

Lemma 5. (Optimal decision of the platform in period 2) *Define n_e as the number of carriers who purchase capacity on the platform and elimate their logistics capability in period 1.*
1. If $n_e > n/2$, the optimal price of the platform in period 2 is as follows. If $(c+f)[2(n-n_e)(2n-\alpha n_e) - (2-\alpha)(2n-n_e)n_e] \le 2mv_L[(2-\alpha)nn_e - 2(n-n_e)(2n-\alpha n_e)]$, then $\hat{p}^*_2 = \frac{(2n-n_e)(c+f)+2nmv_L}{(2n-\alpha n_e)v_L}$; if $(c+f)[2(n-n_e)(2n-\alpha n_e) - (2-\alpha)(2n-n_e)n_e] > 2mv_L[(2-\alpha)nn_e - 2(n-n_e)(2n-\alpha n_e)]$, then $\hat{p}^*_2 = \frac{c+2mv_L+f}{(2-\alpha)v_L} - \epsilon$.

2. If $n_e \le n/2$, the optimal price of the UCC's service in period 2 is as follows. If $(c+f)[2(n-n_e)(2n-\alpha n_e) - (n-\alpha n_e)(2n-n_e)] \le 2mv_L[n(n-\alpha n_e) - n(2n-\alpha n_e)]$ and $(c+f)(2-\alpha)(2n-n_e)n_e - (2n-\alpha n_e)(n-n_e)c > 2mv_L[(2n-\alpha n_e)(n-n_e) - (2-\alpha)nn_e]$, then $\hat{p}^*_2 = \frac{(2n-n_e)(c+f)+2nmv_L}{(2n-\alpha n_e)v_L}$; if $(c+f)[2(n-n_e)(2n-\alpha n_e) - (n-\alpha n_e)(2n-n_e)] > 2mv_L[n(n-\alpha n_e) - n(2n-\alpha n_e)]$ and $2(c+f)(2-\alpha)(n-n_e)n_e - (n-\alpha n_e)(n-n_e)c > 2mv_L[(n-\alpha n_e)(n-n_e) - (2-\alpha)nn_e]$, then $\hat{p}^*_2 = \frac{(c+f)(n-n_e)+nmv_L}{(n-\alpha n_e)v_L} - \epsilon$; if $2(c+f)(2-\alpha)(n-n_e)n_e - (n-\alpha n_e)(n-n_e)c \le 2mv_L[(n-\alpha n_e)(n-n_e) - (2-\alpha)nn_e]$ and $(c+f)(2-\alpha)(2n-n_e)n_e - (2n-\alpha n_e)(n-n_e)c \le 2mv_L[(2n-\alpha n_e)(n-n_e) - (2-\alpha)nn_e]$, then $\hat{p}^*_2 = \frac{c+2mv_L}{(2-\alpha)v_L}$.

Proof of Lemma 5. To derive $n_{s,2}$ and $n_{p,2}$ in the platform's expected profit function in Equation (3), we need to distinguish the following two types of carriers:
Type 1 ($\hat{d}_{i1} = -1$ or 1): Each carrier i of this type purchases capacity from the platform and eliminates his logistics capability in period 2 ($\hat{d}^*_{i2} = 0$) if $\hat{p}_2 < \frac{c+2mv_L}{(2-\alpha)v_L}$, or delivers on his own and sell capacity on the platform ($\hat{d}^*_{i2} = 1$) if $\hat{p}_2 > \frac{c+2mv_L}{(2-\alpha)v_L}$, or chooses either option with same probability if $\hat{p}_2 = \frac{c+2mv_L}{(2-\alpha)v_L}$. The expected number of carriers of this type is $\lambda(\lambda n - n_e) + \lambda(1-\lambda)n$.
Type 2 ($\hat{d}_{i1} = 0$): Each carrier i of this type purchases capacity from the platform and eliminates his logistics capability in period 2 ($\hat{d}^*_{i2} = 0$) if $\hat{p}_2 < \frac{c+2mv_L+f}{(2-\alpha)v_L}$, or delivers on his own and sell capacity on the platform ($\hat{d}^*_{i2} = 1$) if $\hat{p}_2 > \frac{c+2mv_L+f}{(2-\alpha)v_L}$, or chooses either option with same probability if $\hat{p}_2 = \frac{c+2mv_L+f}{(2-\alpha)v_L}$. The expected number of carriers of this type is λn_e.
To maximize her profit, the optimal choice of the platform is among the following three:
1. Choose a price $\hat{p}_2 = \frac{c+2mv_L+f}{(2-\alpha)v_L}$ to incentivize type 1 carriers to sell capacity, and type 2 carriers to purchase or sell capacity with same probability. Then we can obtain that $n_{s,2} = \lambda(\lambda n - n_e) + \lambda(1-\lambda)n + \lambda n_e/2$, and $n_{p,2} = \lambda n_e/2$. Substituting them into Equation (3), the platform's expected profit is

$$\begin{aligned}\hat{\pi}_2\big(\tfrac{c+2mv_L+f}{(2-\alpha)v_L}\big) &= \alpha\tfrac{c+2mv_L+f}{(2-\alpha)v_L}\min\{[\lambda(\lambda n - n_e) + \lambda(1-\lambda)n + \lambda n_e/2]v_L, \lambda n_e v_L/2\} \\ &= \tfrac{\lambda\alpha(c+2mv_L+f)}{2-\alpha}\min\{n - n_e/2, n_e/2\} \\ &= \tfrac{\lambda\alpha(c+2mv_L+f)n_e}{2(2-\alpha)}.\end{aligned}$$

2. Choose a price $\hat{p}_2 = \frac{c+2mv_L+f}{(2-\alpha)v_L} - \epsilon$ to incentivize type 1 carriers to sell capacity, and type 2 carriers to purchase capacity from the platform. Then we can obtain that $n_{s,2} = \lambda(\lambda n - n_e) + \lambda(1-\lambda)n$, and $n_{p,2} = \lambda n_e$. Substituting them into Equation (3), the platform's expected profit is

$$\begin{aligned}\hat{\pi}_2\big(\tfrac{c+2mv_L+f}{(2-\alpha)v_L} - \epsilon\big) &= \alpha\big(\tfrac{c+2mv_L+f}{(2-\alpha)v_L} - \epsilon\big)\min\{[\lambda(\lambda n - n_e) + \lambda(1-\lambda)n]v_L, \lambda n_e v_L\} \\ &= \tfrac{\lambda\alpha(c+2mv_L+f)}{2-\alpha}\min\{n_e, n - n_e\} - \epsilon \\ &= \begin{cases} \tfrac{\lambda\alpha(c+2mv_L+f)n_e}{2-\alpha} - \epsilon, & \text{if } n_e < n/2; \\ \tfrac{\lambda\alpha(c+2mv_L+f)(n-n_e)}{2-\alpha} - \epsilon, & \text{if } n_e \ge n/2. \end{cases}\end{aligned}$$

3. Choose a price $\hat{p}_2 = \frac{c+2mv_L}{(2-\alpha)v_L}$ to incentivize type 1 carriers to sell or purchase capacity with same probability, and type 2 carriers to purchase capacity from the platform. Then we can obtain that $n_{s,2} = [\lambda(\lambda n - n_e) + \lambda(1-\lambda)n]/2$, and $n_{p,2} = [\lambda(\lambda n - n_e) + \lambda(1-\lambda)n]/2 + \lambda n_e$. Substituting them into Equation (3), the platform's expected profit is

$$\begin{aligned}\hat{\pi}_2\big(\tfrac{c+2mv_L}{(2-\alpha)v_L}\big) &= \alpha\tfrac{c+2mv_L}{(2-\alpha)v_L}\min\{[\lambda(\lambda n - n_e) + \lambda(1-\lambda)n]v_L/2, \lambda n_e v_L\} \\ &= \tfrac{\lambda\alpha(c+2mv_L)}{2-\alpha}\min\{(n-n_e)/2, (n+n_e)/2\} \\ &= \tfrac{\lambda\alpha(c+2mv_L)(n-n_e)}{2(2-\alpha)}.\end{aligned}$$

By comparing the profits of the platform under choices 1, 2 and 3, we can obtain that $\hat{\pi}_2\big(\frac{c+2mv_L+f}{(2-\alpha)v_L}\big)$ is the maximum if $n_e \ge \frac{2n}{3}$; $\hat{\pi}_2\big(\frac{c+2mv_L+f}{(2-\alpha)v_L} - \epsilon\big)$ is the maximum if $\frac{(c+2mv_L)n}{2(c+2mv_L)+f} \le n_e < \frac{2n}{3}$; and $\hat{\pi}_2\big(\frac{c+2mv_L}{(2-\alpha)v_L}\big)$ is the maximum if $n_e < \frac{(c+2mv_L)n}{2(c+2mv_L)+f}$. Therefore, the results in Lemma 5 follow.

□

Lemma 6. (Optimal decision of carrier i in period 1) *Assume all carriers and the capacity sharing platform have a common rational belief $\tilde{n}_e$ about n_e.*

1. If $\tilde{n}_e > n/2$; or $\tilde{n}_e \le n/2$, $(c+f)[2(n-n_e)(2n-\alpha n_e)-(2-\alpha)(2n-n_e)n_e] \le 2mv_L[(2-\alpha)nn_e-2(n-n_e)(2n-\alpha n_e)]$, and $(c+f)(2-\alpha)(2n-n_e)n_e-(2n-\alpha n_e)(n-n_e)c > 2mv_L[(2n-\alpha n_e)(n-n_e)-(2-\alpha)nn_e]$; or $\tilde{n}_e \le n/2$, $(c+f)[2(n-n_e)(2n-\alpha n_e)-(2-\alpha)(2n-n_e)n_e] > 2mv_L[(2-\alpha)nn_e-2(n-n_e)(2n-\alpha n_e)]$, and $2(c+f)(2-\alpha)(n-n_e)n_e-(n-\alpha n_e)(n-n_e)c > 2mv_L[(n-\alpha n_e)(n-n_e)-(2-\alpha)nn_e]$, the optimal decisions of carrier i are as follows. If $\hat{p}_1 < \frac{c+2mv_L-h}{(2-\alpha)v_L}$, then $\hat{d}^*_{i1}=1$; if $\hat{p}_1 > \frac{c+2mv_L-h}{(2-\alpha)v_L}$, then $\hat{d}^*_{i1}=-1$; if $\hat{p}_1 = \frac{c+2mv_L-h}{(2-\alpha)v_L}$, then $\hat{d}^*_{i1}=1$ or -1 with an equal probability.

2. If $\tilde{n}_e \le n/2$, $2(c+f)(2-\alpha)(n-n_e)n_e-(n-\alpha n_e)(n-n_e)c \le 2mv_L[(n-\alpha n_e)(n-n_e)-(2-\alpha)nn_e]$, and $(c+f)(2-\alpha)(2n-n_e)n_e-(2n-\alpha n_e)(n-n_e)c \le 2mv_L[(2n-\alpha n_e)(n-n_e)-(2-\alpha)nn_e]$, the optimal decisions of carrier i are as follows.

(a) If $h \le \delta(1-\lambda)f$, then if $\hat{p}_1 < \frac{c+2mv_L-h}{(2-\alpha)v_L}$, $\hat{d}^*_{i1}=1$; if $\hat{p}_1 > \frac{c+2mv_L-h}{(2-\alpha)v_L}$, $\hat{d}^*_{i1}=-1$; if $\hat{p}_1 = \frac{c+2mv_L-h}{(2-\alpha)v_L}$, $\hat{d}^*_{i1}=1$ or -1 with an equal probability.

(b) If $h > \delta(1-\lambda)f$, then if $\hat{p}_1 < \frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}$, $\hat{d}^*_{i1}=0$; if $\hat{p}_1 > \frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}$, $\hat{d}^*_{i1}=-1$; if $\hat{p}_1 = \frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}$, $\hat{d}^*_{i1}=0$ or -1 with an equal probability.

Proof of Lemma 6. We first determine a carrier's optimal decision when $\tilde{n}_e \ge \frac{2n}{3}$. Note that $\tilde{n}_e$ is rational and hence is equal, in equilibrium, to the corresponding actual value n_e. Thus, according to Lemma 5, if $\tilde{n}_e = n_e \ge \frac{2n}{3}$, then $\hat{p}^*_2 = \frac{c+2mv_L+f}{(2-\alpha)v_L}$. Each carrier i minimizes his total discounted cost $\hat{\Phi}_{i1}(\hat{d}_{i1};\hat{p}_1,\hat{p}_2)$ by comparing the following three options:

1. $\hat{d}_{i1}=-1$: In this case, according to Lemma 5, carrier i will deliver on his own and sell capacity in period 2 (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(-1;\hat{p}_1,\hat{p}_2) = c+mv_L-[(1-\alpha)\hat{p}_1-m]v_L+\delta(\lambda(c+mv_L-[(1-\alpha)\hat{p}^*_2-m]v_L)+(1-\lambda)(c+mv_H))$.
2. $\hat{d}_{i1}=0$: In this case, according to Lemma 5, carrier i will purchase capacity from the platform or deliver on his own and sell capacity in period 2 with same probability (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(0;\hat{p}_1,\hat{p}_2) = \hat{p}_1 v_L + \delta(\lambda(\hat{p}^*_2 v_L/2 + (c+mv_L-[(1-\alpha)\hat{p}^*_2-m]v_L+f)/2)+(1-\lambda)(c+mv_H))$.
3. $\hat{d}_{i1}=1$: In this case, according to Lemma 5, carrier i will deliver on his own and sell capacity in period 2 (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(-1;\hat{p}_1,\hat{p}_2) = \hat{p}_1 v_L + h + \delta(\lambda(c+mv_L-[(1-\alpha)\hat{p}^*_2-m]v_L)+(1-\lambda)(c+mv_H))$.

By comparing the above three options, we obtain that, if $h \le \delta\lambda f$, then $\hat{d}^*_{i1}=1$ if $\hat{p}_1 < (c+2mv_L-h)/((2-\alpha)v_L)$, or $\hat{d}^*_{i1}=-1$ if $\hat{p}_1 > (c+2mv_L-h)/((2-\alpha)v_L)$. If $h > \delta\lambda f$, then $\hat{d}^*_{i1}=0$ if $\hat{p}_1 < (c+2mv_L-\delta\lambda f)/((2-\alpha)v_L)$, or $\hat{d}^*_{i1}=-1$ if $\hat{p}_1 > (c+2mv_L-\delta\lambda f)/((2-\alpha)v_L)$.

Next we determine the carrier's optimal decision when $\frac{(c+2mv_L)n}{2(c+2mv_L)+f} \le \tilde{n}_e < \frac{2n}{3}$. Similarly, according to Lemma 5, $\hat{p}^*_2 = \frac{c+2mv_L+f}{(2-\alpha)v_L} - \epsilon$. Each carrier i minimizes his expected total discounted cost $\hat{\Phi}_{i1}(\hat{d}_{i1};\hat{p}_1,\hat{p}_2)$ by comparing the following three options:

1. $\hat{d}_{i1}=-1$: In this case, according to Lemma 5, carrier i will deliver on his own and sell capacity in period 2 (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(-1;\hat{p}_1,\hat{p}_2) = c+mv_L-[(1-\alpha)\hat{p}_1-m]v_L+\delta(\lambda(c+mv_L-[(1-\alpha)\hat{p}^*_2-m]v_L)+(1-\lambda)(c+mv_H))$.
2. $\hat{d}_{i1}=0$: In this case, according to Lemma 5, carrier i will purchase capacity from the platform in period 2 (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(0;\hat{p}_1,\hat{p}_2) = \hat{p}_1 v_L + \delta(\lambda\hat{p}^*_2 v_L + (1-\lambda)(c+mv_H))$.
3. $\hat{d}_{i1}=1$: In this case, according to Lemma 5, carrier i will deliver on his own and sell capacity in period 2 (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(-1;\hat{p}_1,\hat{p}_2) = \hat{p}_1 v_L + h + \delta(\lambda(c+mv_L-[(1-\alpha)\hat{p}^*_2-m]v_L)+(1-\lambda)(c+mv_H))$.

By comparing the above three options, we obtain the same results as in the case that $\tilde{n}_e \ge \frac{2n}{3}$. Thus, the carrier's optimal decision is same as in that case.

Finally, we determine the carrier's optimal decision when $\tilde{n}_e < \frac{(c+2mv_L)n}{2(c+2mv_L)+f}$. According to Lemma 5, $\hat{p}^*_2 = \frac{c+2mv_L}{(2-\alpha)v_L}$. Each carrier i minimizes his expected total discounted cost $\hat{\Phi}_{i1}(\hat{d}_{i1};\hat{p}_1,\hat{p}_2)$ by comparing the following three options:

1. $\hat{d}_{i1}=-1$: In this case, according to Lemma 5, carrier i will purchase capacity from the platform or deliver on his own and sell capacity in period 2 with same probability (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(-1;\hat{p}_1,\hat{p}_2) = c+mv_L-[(1-\alpha)\hat{p}_1-m]v_L+\delta(\lambda(\hat{p}^*_2 v_L/2+(c+mv_L-[(1-\alpha)\hat{p}^*_2-m]v_L)/2)+(1-\lambda)(c+mv_H))$.
2. $\hat{d}_{i1}=0$: In this case, according to Lemma 5, carrier i will purchase capacity from the platform in period 2 (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(0;\hat{p}_1,\hat{p}_2) = \hat{p}_1 v_L + \delta(\lambda\hat{p}^*_2 v_L + (1-\lambda)(c+mv_H))$.
3. $\hat{d}_{i1}=1$: In this case, according to Lemma 5, carrier i will purchase capacity from the platform or deliver on his own and sell capacity in period 2 with same probability (if he has low task volume in

period 2, i.e., $v_{i2} = v_L$). This incurs an expected total discounted cost $\hat{\Phi}_{i1}(-1; \hat{p}_1, \hat{p}_2) = \hat{p}_1 v_L + h + \delta(\lambda(\hat{p}_2^* v_L/2 + (c + m v_L - [(1-\alpha)\hat{p}_2^* - m]v_L)/2) + (1-\lambda)(c + m v_H))$.
By comparing the above three options, we obtain that, $\hat{d}_{i1}^* = 0$ if $\hat{p}_1 < (c + 2mv_L)/((2-\alpha)v_L)$, or $\hat{d}_{i1}^* = -1$ if $\hat{p}_1 > (c + 2mv_L)/((2-\alpha)v_L)$. Combining the results in the above three cases together, Lemma 6 follows.

□

Proof of Theorem 2. Similar to the proof of Theorem 1, we analyze each case of Lemma 6 to derive the platform's expected total discounted profit and determine the equilibrium price.

We can obtain that case 1 of Lemma 6 is not in equilibrium, because the conditions of this case cannot be satisfied under any $\hat{p}_1$. For case 2 of Lemma 6, according to Lemma 5, we have $\hat{p}_2^* = \frac{c+2mv_L}{(2-\alpha)v_L}$. If $h \le \delta(1-\lambda)f$, that is $f \ge \frac{h}{\delta(1-\lambda)}$, then according to Lemma 6, each carrier purchases capacity from the platform and keeps his logistics capability if $\hat{p}_1 < \frac{c+2mv_L-h}{(2-\alpha)v_L}$, or delivers on his own and sell remaining capacity if $\hat{p}_1 > \frac{c+2mv_L-h}{(2-\alpha)v_L}$, or with same probability to choose either option if $\hat{p}_1 = \frac{c+2mv_L-h}{(2-\alpha)v_L}$. It's optimal for the platform to choose $\hat{p}_1^* = \frac{c+2mv_L-h}{(2-\alpha)v_L}$ to maximize her profit. This leads to $n_e = 0 = \tilde{n}_e$, with which the conditions of case 2 are always satisified. This completes the proof of case 1 of Theorem 2.

If $h > \delta(1-\lambda)f$, that is $f < \frac{h}{\delta(1-\lambda)}$, according to Lemma 6, each carrier purchases capacity from the platform and eliminates his logistics capability if $\hat{p}_1 < \frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}$ or delivers on his own and sell remaining capacity if $\hat{p}_1 > \frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}$, or with same probability to choose either option if $\hat{p}_1 = \frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}$. It is optimal for the platform to choose $\hat{p}_1 = \frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}$ to maximize her profit. This leads to $n_e = \frac{\lambda}{2}n = \tilde{n}_e$. Substituting them into the conditions of case 2, we obtain that $f < \frac{(2-2\lambda+\frac{\alpha\lambda^2}{4})mv_L+(1-\frac{3\lambda}{2}+\frac{\lambda(\lambda+\alpha)}{4})c}{(2-\alpha)\frac{\lambda}{2}(1-\frac{\lambda}{4})}$ and $f < \frac{(2-3\lambda+\frac{\alpha\lambda^2}{2})mv_L+(1-\frac{5\lambda}{2}+\lambda^2+\frac{\alpha\lambda(2-\lambda)}{4})c}{(2-\alpha)\frac{\lambda}{2}(2-\lambda)}$. Combining them with the condition $f < \frac{h}{\delta(1-\lambda)}$, the result in case 2 of Theorem 2 follows.

□

Proof of Theorem 3. Define $m_5 = \frac{\frac{(2-\alpha)\left(1-\frac{\lambda}{4}\right)\lambda h}{2\delta(1-\lambda)} - \left(1-\frac{3\lambda}{2}+\frac{\lambda(\lambda+\alpha)}{4}\right)c}{\left(2-2\lambda+\frac{\alpha\lambda^2}{4}\right)v_L}$, $m_6 = \frac{\frac{(2-\alpha)(2-\lambda)\lambda h}{2\delta(1-\lambda)} - \left(1-\frac{5\lambda}{2}+\lambda^2+\frac{\alpha\lambda(2-\lambda)}{4}\right)c}{\left(2-3\lambda+\frac{\alpha\lambda^2}{2}\right)v_L}$,
$f_1 = \frac{[(1-\lambda)v_H+\lambda(1-2\lambda)v_L]\left[\left(\sqrt{n}-\sqrt{\lambda(1-\lambda)n+\lambda n}\right)C+\left(\lambda n\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\left(1-\lambda\frac{v_H}{v_L}\right)n\right)c\right]}{\lambda^2(1-\lambda)^2 n v_H} + \frac{\left(\lambda\frac{v_L}{v_H}+(1-\lambda)^2\right)nc-(1-\lambda)\sqrt{n}C}{\lambda^2 n}$,
$f_2 = \frac{[(1-\lambda)v_H+\lambda v_L]\left[\left(\sqrt{n}-\sqrt{\lambda(1-\lambda)n+\lambda n}\right)C+\left(\lambda n\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\left(1-\lambda\frac{v_H}{v_L}\right)n\right)c\right]}{\lambda(1-\lambda)n v_H\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)} + \frac{(1-\lambda)\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)nc-\left(\sqrt{n}-\sqrt{\lambda n}\right)C}{\lambda n\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)}$,
$f_3 = \frac{[m-(M-S)][(1-\lambda)nv_H+\lambda(1-2\lambda)nv_L]-(1-\lambda)\sqrt{n}C+\left(\lambda\frac{v_L}{v_H}+(1-\lambda)^2\right)nc}{\lambda^2 n}$, and
$f_4 = \frac{[m-(M-S)](1-\lambda)(\lambda n v_L+(1-\lambda)nv_H)-\left(\sqrt{n}-\sqrt{\lambda n}\right)C+(1-\lambda)\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)nc}{\lambda n\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)}$.

In Region (i), the equilibrium expected total discounted profits of the UCC and the platform are $\bar{\Pi}(m+\frac{c}{v_L})$ and $\hat{\Pi}\left(\frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}\right)$ respectively. Substituting $\bar{p}_1^*$ and $\bar{p}_2^*$ into Equation (2), $\hat{p}_1^*$ and $\hat{p}_2^*$ into Equation (4), we can obtain that $\bar{\Pi}\left(m+\frac{c}{v_L}\right) = (1+\delta)(m+S-M)\lambda n v_L + \delta(1-\lambda)(m+S-M)nv_H + \lambda nc + \delta nc\left(\lambda\frac{v_L}{v_H}+1-\lambda\right) - \left(\sqrt{\lambda n}+\delta\sqrt{n}\right)C$, and $\hat{\Pi}\left(\frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}\right) = \frac{\alpha\lambda n\left[\left(1+\delta\left(1-\frac{\lambda}{2}\right)\right)(c+2mv_L)-\delta(1-\lambda)f\right]}{2(2-\alpha)}$. By comparing $\bar{\Pi}\left(m+\frac{c}{v_L}\right)$ and $\hat{\Pi}\left(\frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}\right)$ in terms of c, we obtain that $\bar{\Pi}\left(m+\frac{c}{v_L}\right) > \hat{\Pi}\left(\frac{c+2mv_L-\delta(1-\lambda)f}{(2-\alpha)v_L}\right)$ if and only if

$$c > \frac{\left(\sqrt{\lambda}+\delta\right)\frac{C}{\sqrt{n}} + \frac{\alpha\lambda\left[2\left(1+\delta\left(1-\frac{\lambda}{2}\right)\right)mv_L-\delta(1-\lambda)f\right]}{2(2-\alpha)} - (m+S-M)[(1+\delta)\lambda v_L+\delta(1-\lambda)v_H]}{\lambda\left(1-\frac{\alpha\left(1+\delta\left(1-\frac{\lambda}{2}\right)\right)}{2(2-\alpha)}\right)+\delta\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)} \equiv c_1,$$

where c_1 decreases in n.

In Region (ii), the equilibrium expected total discounted profits of the UCC and the platform are $\bar{\Pi}(m+\frac{c-h}{v_H})$ and $\hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right)$ respectively. Substituting $\bar{p}_1^*$ and $\bar{p}_2^*$ into Equation (2), $\hat{p}_1^*$ and $\hat{p}_2^*$ into Equation (4), we can obtain that $\bar{\Pi}\left(m+\frac{c-h}{v_H}\right) = (m+S-M)((1+\delta)\lambda n v_L + (1-\lambda)nv_H) + \delta\lambda nc + (c-h)n\left(\lambda\frac{v_L}{v_H}+1-\lambda\right) - \left(\sqrt{n}+\delta\sqrt{\lambda n}\right)C$, and $\hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right) = \frac{\alpha\lambda n[(1+\delta)(c+2mv_L)-h]}{2(2-\alpha)}$. By comparing $\bar{\Pi}\left(m+\frac{c-h}{v_H}\right)$ and $\hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right)$ in terms of c and δ, we that $\bar{\Pi}\left(m+\frac{c-h}{v_H}\right) > \hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right)$ if and only if

$$c > \frac{\left(1+\delta\sqrt{\lambda}\right)\frac{C}{\sqrt{n}} + h\left(\lambda\frac{v_L}{v_H}+1-\lambda\right) + \frac{\alpha\lambda[(1+\delta)2mv_L-h]}{2(2-\alpha)} - (m+S-M)[(1+\delta)\lambda v_L + (1-\lambda)v_H]}{\delta\lambda + (\lambda\frac{v_L}{v_H}+1-\lambda) - \frac{\alpha\lambda(1+\delta)}{2(2-\alpha)}} \equiv c_2$$

and $\delta > \frac{\frac{\lambda\alpha}{2(2-\alpha)} - \left(\lambda\frac{v_L}{v_H}+1-\lambda\right)}{\lambda\left(1-\frac{\alpha}{2(2-\alpha)}\right)} \equiv \delta_1$; or $c < c_2$ and $\delta < \delta_1$.

In Region (iii), the equilibrium expected total discounted profits of the UCC and the platform are $\bar{\Pi}(m+\frac{c-h}{v_L})$ and $\hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right)$ respectively. Substituting $\bar{p}_1^*$ and $\bar{p}_2^*$ into Equation (2), we can obtain that $\bar{\Pi}\left(m+\frac{c-h}{v_L}\right) = (1+\delta)(m+S-M)\lambda n v_L + \lambda n((1+\delta)c-h) - (1+\delta)\sqrt{\lambda n}C$. By comparing $\bar{\Pi}\left(m+\frac{c-h}{v_L}\right)$ and $\hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right)$, we obtain the following results.

1. $\bar{\Pi}\left(m+\frac{c-h}{v_L}\right) > \hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right)$ if and only if $c > \frac{(1+\delta)\frac{\sqrt{\lambda}C}{\sqrt{n}} + \frac{\alpha\lambda[2(1+\delta)mv_L-h]}{2(2-\alpha)} + \lambda h - (m+S-M)(1+\delta)\lambda v_L}{(1+\delta)\lambda\left(1-\frac{\alpha}{2(2-\alpha)}\right)} \equiv c_3$, where c_3 decreases in n.
2. $\bar{\Pi}\left(m+\frac{c-h}{v_L}\right) > \hat{\Pi}\left(\frac{c+2mv_L-h}{(2-\alpha)v_L}\right)$ if and only if $h < \frac{(1+\delta)(m+S-M)\lambda v_L + (1+\delta)\lambda c - (1+\delta)\frac{\sqrt{\lambda}C}{\sqrt{n}} - \frac{\alpha\lambda(1+\delta)(c+2mv_L)}{2(2-\alpha)}}{\lambda\left(1-\frac{\alpha}{2(2-\alpha)}\right)} \equiv h_1$, where h_1 increases in n.

□

Proof of Theorem 4. In Region (i), according to Theorems 1 and 2, we can obtain that $n_1 = \lambda n$, $n_2 = n$, $n_{p,1} = \frac{\lambda n}{2}$, and $n_{p,2} = \frac{\lambda n}{2}$. Thus, we have $\bar{\Delta}_\psi = (\lambda n - \sqrt{\lambda n} + n - \sqrt{n})\psi$ and $\hat{\Delta}_\psi = \frac{5}{4}\lambda n\psi$. By comparing $\bar{\Delta}_\psi$ and $\hat{\Delta}_\psi$ in terms of n, we obtain that $\bar{\Delta}_\psi > \hat{\Delta}_\psi$ if and only if $n > \left(\frac{1+\sqrt{\lambda}}{1-\lambda/4}\right)^2$. Similarly, the results for Regions (ii) and (iii) can be determined. □

Proof of Theorem 5. Define $m_7 = \frac{(2-\alpha)\left[(M-S)\lambda n v_L - \lambda n c + \sqrt{\lambda n}C\right] + \frac{\alpha\lambda n c}{2}}{2(1-\alpha)\lambda n v_L}$,
$m_8 = \frac{(M-S)(\lambda n v_L + (1-\lambda)n v_H) - \left(\lambda\frac{v_L}{v_H}+1-\lambda\right)nc + \sqrt{n}C + \frac{\alpha\lambda n c}{2(2-\alpha)}}{\frac{2(1-\alpha)\lambda n v_L}{2-\alpha} + (1-\lambda)n v_L}$, and $m_9 = \frac{(M-S)(1-\lambda)n v_H + \left[\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right]nc + (\sqrt{n}-\sqrt{\lambda n})C}{(1-\lambda)n v_H}$.
One can see that $\max\{m_8, m_9\}$ decreases with S. Define $\theta = \min\left\{\frac{\tilde{n}_p}{\tilde{n}_s}, 1\right\}$, where $\tilde{n}_p$ and $\tilde{n}_s$ are the rational beliefs about the number of carriers who purchase capacity from the platform and who sell capacity on the platform, respectively.

Similar to the proofs of Lemma 1, we can derive the optimal decision of each carrier i as follows.
1. Each carrier i with $v_i = v_H$ uses the UCC's service if $\bar{p} \le m + \frac{c}{v_H}$, or delivers on his own if $\bar{p} > m + \frac{c}{v_H}$.
2. Each carrier i with $v_i = v_L$ uses the UCC's service if $\bar{p} \le m + \frac{c}{v_L} - \theta[(1-\alpha)\hat{p} - m]$ and $\hat{p} \ge \bar{p}$, or purchases capacity from the platform if $\bar{p} > \hat{p}$ and $\hat{p} < \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$, or delivers on his own if $\bar{p} > m + \frac{c}{v_L} - \theta[(1-\alpha)\hat{p} - m]$ and $\hat{p} > \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$. Note that carrier i is indifferent between purchasing capacity from the platform and delivering on his own if $\hat{p} = \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$.

According to the assumption $(1-\alpha)\hat{p} - m < (\frac{1}{v_L} - \frac{1}{v_H})c$, we can obtain that $m + \frac{c}{v_L} - \theta[(1-\alpha)\hat{p} - m] > m + \frac{c}{v_H}$. Similar to the proof of Lemma 1, we can obtain that the optimal choice of the consolidator is among the following:

1. Choose $\bar{p}^* > \frac{c+2mv_L}{(2-\alpha)v_L}$ and $\hat{p}^* = \frac{c+2mv_L}{(2-\alpha)v_L}$. Under these prices, each carrier i with $v_i = v_H$ delivers on his own, and each carrier i with $v_i = v_L$ is indifferent between delivering on his own (and selling his remaining capacity to the platform) and purchasing capacity on the platform. The consolidator's profit is $\frac{\alpha\lambda n(c+2mv_L)}{2(2-\alpha)}$.

2. Choose $\bar{p}^* = m + \frac{c}{v_L}$ and $\hat{p}^* \ge m + \frac{c}{v_L}$. Under these prices, each carrier i with $v_i = v_H$ delivers on his own, and each carrier i with $v_i = v_L$ uses the UCC's service. The consolidator's profit is $(m+S-M)\lambda n v_L + \lambda n c - \sqrt{\lambda n}C$.

3. Choose $\bar{p}^* = m + \frac{c}{v_H}$ and $\hat{p}^* \ge m + \frac{c}{v_L}$. Under these prices, each carrier i uses the UCC's service. The consolidator's profit is $(m+S-M)(\lambda n v_L + (1-\lambda)n v_H) + (\lambda\frac{v_L}{v_H} + 1 - \lambda)nc - \sqrt{n}C$.

It is optimal for the consolidator to choose the choice that leads to a largest profit. Comparing the consolidator's profit under the above three choices, we can obtain the results in Theorem 5.

□

Proof of Theorem 6. Define $m_{10} = M - S + \frac{(\sqrt{n}-\sqrt{\lambda n})C + \lambda n c - \left(\lambda\frac{v_L}{v_H}+1-\lambda\right)(c-h)n}{(1-\lambda)n v_H}$,
$m_{11} = M - S + \frac{\left(\sqrt{\lambda(1-\lambda)+\lambda n} - \lambda\sqrt{n}\right)C + \lambda^2 n f - \lambda(1-\lambda)\left(1+\frac{v_H}{v_L}\right)nc}{\lambda(1-\lambda)n(v_L+v_H)}$, and
$m_{12} = M - S + \frac{\left(\sqrt{\lambda(2-\lambda)n} - \sqrt{\lambda n}\right)C + \left(\lambda\frac{v_L}{v_H}+1-\lambda\right)(c+f)\lambda n - \left(1+(1-\lambda)\frac{v_H}{v_L}\right)\lambda n c}{\lambda(1-\lambda)n v_L}$. The proof is similar to the proof of Theorem 1 and thus omitted. □