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, Singapore

qiyuan.deng.2015@pbs.smu.edu.sg • xfang@smu.edu.sg • yflim@smu.edu.sg

Oct 02, 2020

Abstract

The growing population in cities and booming e-commerce activities create huge demand for urban last-mile delivery, exerting intense pressure on the cities' well-being. To keep 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 delivery capacity. We provide guidance for the consolidator to choose between these two business models by comparative analysis. We capture the interactions between the consolidator and carriers using a game-theoretical framework. Under each business model, the consolidator first decides a price of delivery service 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 delivery cost. Under the UCC model, the carriers become more dependent on the UCC as their variable delivery cost increases. Under the platform model, the demand and the supply of delivery capacity on the platform are balanced in equilibrium. Between the two business models, the UCC is more profitable than the platform if and only if the carriers' variable delivery cost is sufficiently large. Moreover, the UCC becomes more dominant as there are more carriers. The UCC is also more efficient than the platform in mitigating the negative social-environmental impact of urban last-mile delivery if and only if there are sufficiently many carriers. Otherwise, the platform performs better.

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

History: Received: December 2019; Accepted: September 2020 by Vijay Mookerjee, after 2 revisions.

*: Corresponding author

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).

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 efficiency in mitigating the negative social-environmental impact. Specifically, the consolidator can 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 game-theoretical model to capture the interactions between the consolidator and the carriers. In each model, knowing that each carrier has a delivery task with a random volume to fulfill, the consolidator first determines the price of delivery service 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 delivery 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, as the carriers' variable delivery cost increases, the carriers become more dependent on the UCC for delivering their tasks to the city center. This result confirms the carriers' motivation to save their delivery costs by using the UCC's service in practice.

(ii) If the consolidator operates a capacity sharing platform, we find that the consolidator charges a price such that the demand and the supply of the capacity are balanced on the platform. Since the consolidator can always earn a revenue share from each successful transaction, our result implies that the platform business model can be more financially promising. This may explain the increasing popularity of the capacity sharing platforms in practice.

(iii) In terms of the consolidator's expected profit, we find that it is more profitable for the consolidator to operate the UCC than the platform if and only if the carriers' variable delivery cost is sufficiently large. Furthermore, the UCC becomes more dominant when there are more carriers. In terms of mitigating the negative social-environmental impact of urban last-mile delivery, our analysis shows that it is more efficient for the consolidator to operate the UCC than the platform if and only if there are sufficiently many carriers. Therefore, the UCC outperforms the platform both economically and social-environmentally when the carriers' variable delivery cost and the number of carriers are both sufficiently large. Otherwise, the platform performs better. This comparative analysis provides guidance for a consolidator to choose between the two business models in practice.

After reviewing the related literature in §2, we formulate the problem between the consolidator and the carriers in §3. We analyze the two business models in which the consolidator operates a UCC and a capacity sharing platform in §3.1 and §3.2 respectively. We compare the two business models in terms of the consolidator's expected profit and the efficiency in mitigating the social-environmental impact in §4. We extend our modeling framework in several ways in §5, before we conclude in §6. All proofs are provided in Online Supplement A.

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 paper has 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.

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 multiple carriers $i = 1, 2, \ldots, n$. Each carrier i has a delivery task with volume v_i. We assume v_i equals v_L with a probability λ, or equals v_H ($> v_L$) with a probability $1 - \lambda$, where $\lambda \in [0, 1]$. We refer the former as a low type carrier and the latter as a high type carrier. All the carriers' delivery tasks must be fulfilled. We assume each carrier is initially equipped with logistics capability that has a limited delivery capacity sufficient for his own task.

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 (ASEAN, 2014).

Based on the above problem setting, we provide additional details of each business model and analyze the equilibrium decisions of all the parties in §3.1 and §3.2, where the consolidator operates a UCC and a capacity sharing platform respectively. We then compare the two business models in §4 in terms of maximizing the consolidator's expected profit and reducing the negative social-environmental impact of urban last-mile delivery.

3.1 Business model 1: An urban consolidation center

3.1.1 Model description

In this section, we consider the consolidator operates a UCC to serve the carriers for their last-mile delivery 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. The decision process is as follows. The UCC first decides the price per unit volume $\bar{p}$ of her delivery service. After observing $\bar{p}$, each carrier i waits until his delivery task volume v_i 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 $\bar{d}_i$ denote the decision of carrier i, who has two possible options defined as follows. (i) $\bar{d}_i = 0$: Carrier i delivers on his own. (ii) $\bar{d}_i = 1$: Carrier i uses the UCC's service. Figure 1 shows the sequence of decisions.

To serve any carrier(s), the UCC incurs a fixed cost $C > 0$ and a variable cost per unit volume $M > 0$. To be consistent with reality, we assume that the UCC receives a subsidy $S \geq 0$ per unit volume of shipments from the local government or authority. Note that $S = 0$ means the UCC is not subsidized, which is a special case of our general model. As illustrated in Figure 1, the UCC first sets the price per unit volume $\bar{p}$ of her service to maximize her expected profit. Given the price $\bar{p}$ and the realized task volume v_i, each carrier i determines his decision $\bar{d}_i$ to minimize his cost.

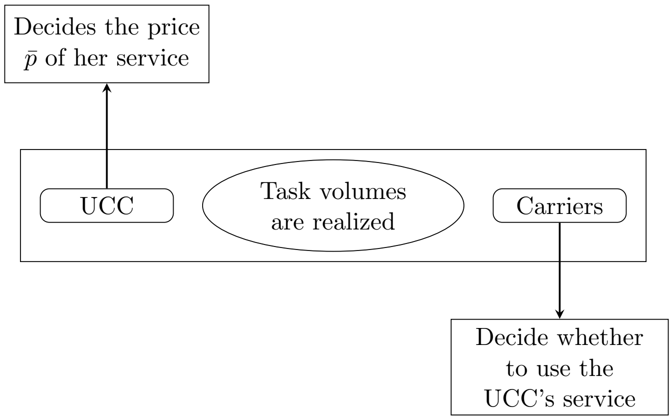

Figure 1: The sequence of decisions under the UCC business model

We can solve the problem in Figure 1 backward by first determining the optimal decisions of the carriers, before we find the optimal decision of the UCC. Given the price $\bar{p}$, each carrier i determines his optimal decision $\bar{d}_i^*$ to minimize his cost. Define $\bar{\phi}_i\left(\bar{d}_i;\bar{p}\right)$ as the cost of carrier i, which is a function of $\bar{d}_i$ given $\bar{p}$. Each carrier i minimizes his cost $\bar{\phi}_i\left(\bar{d}_i;\bar{p}\right)$ by comparing the following two options: (i) $\bar{d}_i = 0$: Carrier i delivers on his own, which incurs a cost $\bar{\phi}_i\left(0;\bar{p}\right) = c + mv_i$. (ii) $\bar{d}_i = 1$: Carrier i uses the UCC's service, which incurs a cost $\bar{\phi}_i\left(1;\bar{p}\right) = \bar{p}v_i$. If the costs of the two options are identical, we assume that the carrier will use the UCC's service.

After identifying each carrier's optimal decision, we can substitute their optimal responses into the UCC's problem to find her optimal price $\bar{p}^*$. Let V denote the expected total task volume of the carriers who use the UCC's service. The UCC will choose a price $\bar{p}$ to maximize her expected profit:

$$\bar{\pi}\left(\bar{p}\right) \quad = \quad \left(\bar{p} + S - M\right)V - C. \tag{1}$$

3.1.2 Equilibrium outcomes

Let $\bar{m} = \frac{c\left[\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right]+(1-\lambda)(M-S)v_H}{(1-\lambda)v_H}$. Theorem 1 summarizes the equilibrium decisions.

Theorem 1. (Equilibrium decisions under the UCC model)

1. *If $m > \bar{m}$, then the UCC charges a price $\bar{p}^* = m + c/v_H$ to attract all the carriers to use her service in equilibrium.*

2. *If $m \leq \bar{m}$, then the UCC charges a price $\bar{p}^* = m + c/v_L$ to attract the low type carriers to use her service in equilibrium.*

If the variable delivery cost m of each carrier is sufficiently large ($m > \bar{m}$), the carriers have a strong incentive to use the UCC's service to save their delivery cost. In this case, the

UCC charges a lower price to attract all the carriers to use her service. On the other hand, if m is small ($m \leq \bar{m}$), the carriers have a weaker incentive to use the UCC's service. They will use the service primarily to avoid the fixed delivery cost c. Anticipating that the low type carriers are more likely to use her service (because they do not want to incur the fixed delivery cost), the UCC charges a price to target only the low type carriers. Theorem 1 implies that as m increases, all the carriers will eventually become dependent on the UCC to deliver their tasks. This result confirms the carriers' motivation to save their delivery cost through the UCC's service in practice. The following proposition determines the equilibrium profit of the consolidator by operating the UCC.

Proposition 1. (Equilibrium profit under the UCC model)

1. *If $m > \bar{m}$, the UCC's expected profit in equilibrium is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c}{v_H} + S - M)(\lambda n v_L + (1-\lambda) n v_H) - C$.*

2. *If $m \leq \bar{m}$, the UCC's expected profit in equilibrium is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c}{v_L} + S - M)\lambda n v_L - C$.*

In addition to the expected profit, we also analyze the efficiency of the UCC in reducing the negative social-environmental impact of urban last-mile delivery. As a result of the consolidation, the UCC can mitigate the social-environmental impact by reducing traffic congestion and pollution in the city center. Define ψ as a social-environmental cost associated with a carrier's delivery to the city center. This includes the cost to the society due to congestion and the cost to the environment due to pollution. Without the UCC, the social-environmental cost incurred by n carriers is $n\psi$.

The UCC can consolidate the delivery tasks of multiple carriers to reduce the total transportation distance. We adopt an approximation scheme from the travelling salesman problem to quantify the transportation distance after consolidation. Specifically, we assume that the UCC's transportation distance of delivering n carriers' tasks is at the scale of $\sqrt{n}$ (Steinerberger, 2015). Let n_u denote the expected number of carriers served by the UCC in equilibrium. We can approximate the expected social-environmental cost with the consolidation by the UCC as $\sqrt{n_u}\psi + VS + (n - n_u)\psi$, where VS is the total subsidy incurred to support the UCC. Define $\bar{\Delta}_\psi = n\psi - [\sqrt{n_u}\psi + VS + (n - n_u)\psi]$ as the *expected social-environmental cost reduction* achieved by the UCC. The following proposition summarizes the equilibrium social-environmental cost reduction achieved by the UCC.

Proposition 2. (Equilibrium social-environmental cost reduction under the UCC model)

1. *If $m > \bar{m}$, then the expected social-environmental cost reduction achieved by the UCC in equilibrium is* $\bar{\Delta}_\psi = n\Big(\psi - (\lambda v_L + (1-\lambda)v_H)S\Big) - \sqrt{n}\psi$.

2. *If $m \leq \bar{m}$, then the expected social-environmental cost reduction achieved by the UCC in equilibrium is* $\bar{\Delta}_\psi = \lambda n\Big(\psi - v_L S\Big) - \sqrt{\lambda n}\psi$.

3.2 Business model 2: A capacity sharing platform

3.2.1 Model description

Instead of having a physical UCC, we consider that the consolidator operates a platform for the carriers to share their delivery capacity in this section. 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 each individual carrier usually has very limited delivery capacity 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, a high type carrier has to deliver by himself to the city center (the other carriers cannot help him) and his remaining capacity is insufficient to help any other carrier to deliver. Only the low type carriers 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. We will relax this assumption in §5.2.

Figure 2 shows the sequence of decisions. The platform first decides the price per unit volume $\hat{p}$ of the delivery service. After observing the price $\hat{p}$, each carrier waits until his delivery task volume is realized. Each low type carrier i then decides independently on how to deliver his task to the city center. Let $\hat{d}_i$ denote his decision, which has two possible options. (i) $\hat{d}_i = 0$: Delivers on his own and sells his remaining capacity to the platform. (ii) $\hat{d}_i = 1$: Purchases capacity from the platform to fulfill his task.

If a low type carrier 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

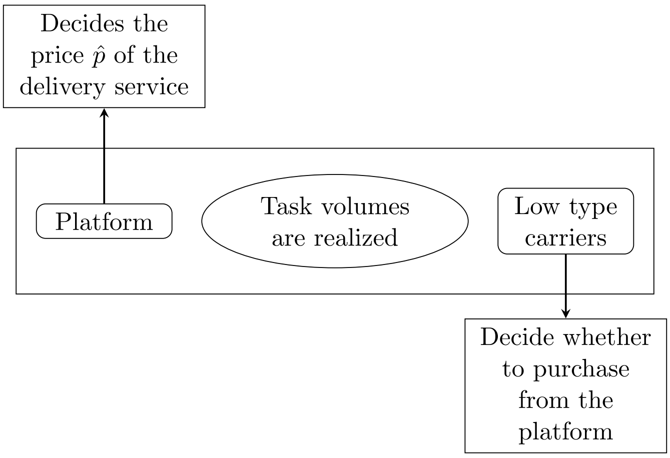

Figure 2: The sequence of decisions under the capacity sharing platform business model

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, if a low type carrier wants to purchase capacity from the platform to fulfill his task, we assume the carrier can always obtain his required capacity v_L. The platform can guarantee this by outsourcing the delivery task to an external party, if necessary. We assume that the platform does not make any profit in this outsourcing process. If a low type carrier i purchases capacity from the platform ($\hat{d}_i = 1$), then he pays $\hat{p}v_L$. If there is enough supply on the platform, the platform receives a portion $\alpha\hat{p}v_L$, where $\alpha \in (0, 1)$ represents the platform's *revenue share*. The remaining portion $(1 - \alpha)\hat{p}v_L$ goes to the other carrier on the platform who serves carrier i. To ensure that selling remaining capacity on the platform is profitable, we assume $(1 - \alpha)\hat{p} > m$.

For notational convenience, define n_s as the expected number of carriers who deliver on their own and sell their remaining capacity to the platform (that is, the carriers who choose $\hat{d}_i = 0$). Define n_p as the expected number of carriers who purchase capacity from the platform to fulfill their tasks (that is, the carriers who choose $\hat{d}_i = 1$). Therefore, the supply and the demand of capacity on the platform are proportional to n_s and n_p respectively. To facilitate the transactions among the carriers, the capacity sharing platform incurs an administrative cost that depends on the number of successful transactions. Specifically, we assume that the administrative cost equals $\min\{n_s, n_p\} \cdot A$, where $A > 0$ is the administrative cost per transaction. To ensure that the platform is profitable, we assume $A < \alpha\hat{p}v_L$.

As illustrated in Figure 2, the platform first sets the price per unit volume $\hat{p}$ of the delivery service to maximize her expected profit. Given the price $\hat{p}$ and the realized task volume v_i, each low type carrier i determines his optimal decision $\hat{d}_i^*$ to minimize his expected cost. We can solve the problem in Figure 2 backward by first identifying the optimal decision of each low type carrier before we find the optimal decision of the capacity sharing platform.

Given the price $\hat{p}$, each low type carrier i minimizes his expected cost by comparing the two options: $\hat{d}_i = 0$ or 1. If carrier i delivers by himself and sells his remaining capacity to the platform ($\hat{d}_i = 0$), then the expected revenue generated from selling his remaining capacity depends on the supply (proportional to n_s) and the demand (proportional to n_p) of capacity on the platform. 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 low type carriers form the same rational beliefs $\tilde{n}_s$ and $\tilde{n}_p$ about n_s and n_p, respectively, when they optimize their decisions. Furthermore, for each low type carrier i, $\tilde{n}_s = n_s\left(\hat{d}_i^*\right)$ and $\tilde{n}_p = n_p\left(\hat{d}_i^*\right)$ in equilibrium. Define $\theta = \min\{\tilde{n}_p/\tilde{n}_s, 1\}$.

Specifically, each low type carrier i minimizes his expected cost $\hat{\phi}_i\left(\hat{d}_i; \hat{p}\right)$ by comparing the following options. (i) $\hat{d}_i = 0$: Carrier i delivers on his own and sells his remaining capacity to the platform, which incurs an expected cost $\hat{\phi}_i(0; \hat{p}) = c + mv_L - \theta\left[(1-\alpha)\hat{p} - m\right]v_L$. (ii) $\hat{d}_i = 1$: Carrier i purchases capacity from the platform to fulfill his task, which incurs a cost $\hat{\phi}_i(1; \hat{p}) = \hat{p}v_L$. 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 $\hat{d}_i^*$ of each low type carrier i, we can substitute it into the platform's problem to find her optimal price. The platform will choose a price $\hat{p}$ to maximize her expected profit:

$$\hat{\pi}(\hat{p}) = (\alpha\hat{p}v_L - A)\min\{n_s, n_p\}. \tag{2}$$

3.2.2 Equilibrium outcomes

Theorem 2. (Equilibrium decisions under the platform model) *In equilibrium, the platform charges a price $\hat{p}^* = \frac{c+2mv_L}{(2-\alpha)v_L}$ to ensure that each low type carrier purchases capacity from the platform, or delivers on his own and sells his remaining capacity on the platform with an equal probability.*

It is optimal for the platform to charge the market clearance price in Theorem 2 because her expected profit is the highest when the demand and the supply of capacity are balanced, resulting in the largest number of successful transactions on the platform. Since the consolidator can always earn a revenue share from each transaction, Theorem 2 shows that the platform business model is financially promising in equilibrium. This result may explain the increasing popularity of the capacity sharing platforms in practice. The following proposition determines the equilibrium profit of the consolidator by operating the capacity sharing platform.

Proposition 3. (Equilibrium profit under the platform model) *In equilibrium, the capacity sharing platform's expected profit is* $\hat{\pi}^*(\hat{p}^*) = \frac{\alpha\lambda n(c+2mv_L)}{2(2-\alpha)} - \frac{\lambda nA}{2}$.

Similar to the UCC model, we also analyze the efficiency of the capacity sharing platform in mitigating the negative social-environmental impact. By sharing capacity among the low type carriers, the platform can result in fewer trucks used, which reduces congestion and pollution.

Recall that ψ represents a social-environmental cost associated with a carrier's delivery to the city center. Since the delivery task of a carrier who purchases capacity from the platform is fulfilled by another carrier, it leads to a reduction of ψ in the social-environmental cost. Recall that n_p represents the expected number of carriers who purchase capacity from the platform in equilibrium. Theorem 2 reveals that the demand and the supply of delivery capacity on the platform are balanced in equilibrium. Therefore, the *expected social-environmental cost reduction* achieved by the platform in equilibrium is $\hat{\Delta}_\psi = n_p\psi$, which is determined by the following proposition.

Proposition 4. (Equilibrium social-environmental cost reduction under the platform model) *In equilibrium, the expected social-environmental cost reduction achieved by the capacity sharing platform is* $\hat{\Delta}_\psi = \lambda n\psi/2$.

4 Comparing the UCC and the capacity sharing platform

We compare the UCC and the capacity sharing platform in terms of their expected profits and their efficiency in mitigating the negative social-environmental impact.

4.1 Expected profit

Between the UCC and the capacity sharing platform, which business model is more profitable for the consolidator? As discussed in §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 $\bar{\pi}^*(\bar{p}^*)$ of the UCC in §3.1 and $\hat{\pi}^*(\hat{p}^*)$ of the capacity sharing platform in §3.2. Let $\bar{m}' = \frac{C-\frac{\lambda nA}{2}+\frac{\alpha\lambda nc}{2(2-\alpha)}+(M-S-\frac{c}{v_H})(\lambda nv_L+(1-\lambda)nv_H)}{\lambda nv_L(1-\frac{\alpha}{2-\alpha})+(1-\lambda)nv_H}$ and $\bar{m}'' = \frac{C-\frac{\lambda nA}{2}+\frac{\alpha\lambda nc}{2(2-\alpha)}+(M-S-\frac{c}{v_L})\lambda nv_L}{\lambda nv_L(1-\frac{\alpha}{2-\alpha})}$. The following theorem identifies 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)

1. *If $m > \bar{m}$, then the UCC is more profitable than the platform if and only if $m > \bar{m}'$, where $\bar{m}'$ decreases in n.*

2. *If $m \leq \bar{m}$, then the UCC is more profitable than the platform if and only if $m > \bar{m}''$, where $\bar{m}''$ decreases in n.*

Theorem 3 shows that the UCC is more profitable than the platform if the carriers' variable delivery cost m is large. This is because when their delivery cost is large, the carriers have a strong incentive to outsource their delivery tasks. 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. This is because the carriers are reluctant to deliver on their own and sell their remaining capacity on the platform, and thus the supply of capacity is low. Furthermore, Theorem 3 shows that the thresholds $\bar{m}'$ and $\bar{m}''$ decrease with the number of carriers n. As n increases, the UCC can achieve a larger economy of scale and thus become more likely to outperform the platform.

We now consider a fixed market entry cost for the consolidator. Let $\bar{E}$ and $\hat{E}$ denote the fixed market entry costs if the consolidator operates a UCC and a platform respectively. Let $\bar{m}'_E = \bar{m}' + \frac{\bar{E}-\hat{E}}{\lambda nv_L(1-\frac{\alpha}{2-\alpha})+(1-\lambda)nv_H}$ and $\bar{m}''_E = \bar{m}'' + \frac{\bar{E}-\hat{E}}{\lambda nv_L(1-\frac{\alpha}{2-\alpha})}$. The following corollary identifies conditions under which the UCC (or the platform) is more profitable for the consolidator if there is a fixed market entry cost for each business model.

Corollary 1. (Comparing the UCC's and the platform's profits under fixed market entry costs)

1. *If $m > \bar{m}$, then the UCC is more profitable than the platform if and only if $m > \bar{m}'_E$, where $\bar{m}'_E$ decreases in n.*

2. *If $m \leq \bar{m}$, then the UCC is more profitable than the platform if and only if $m > \bar{m}''_E$, where $\bar{m}''_E$ decreases in n.*

In practice, the market entry cost $\bar{E}$ of the UCC may be larger than the market entry cost $\hat{E}$ of the platform. In that case, we have $\bar{m}'_E > \bar{m}'$ and $\bar{m}''_E > \bar{m}''$.

4.2 Social-environmental impact

Between the UCC and the capacity sharing platform, which business model is more efficient to mitigate the negative social-environmental impact of urban last-mile delivery? As a result of the consolidation, both the UCC and the platform can mitigate the negative social-environmental impact (in terms of reduced congestion and pollution). 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 negative social-environmental impact.

In this section, we compare the equilibrium social-environmental cost reductions $\bar{\Delta}_\psi$ under the UCC model in §3.1 and $\hat{\Delta}_\psi$ under the capacity sharing platform model in §3.2. Let $\bar{n} = \frac{\psi^2}{\left[\left(1-\frac{\lambda}{2}\right)\psi-(\lambda v_L+(1-\lambda)v_H)S\right]^2}$ and $\bar{n}' = \frac{\psi^2}{\lambda\left(\frac{\psi}{2}-v_L S\right)^2}$. The following theorem identifies conditions under which the UCC (or the platform) is more efficient to reduce the negative social-environmental impact.

Theorem 4. (Comparing the UCC's and the platform's social-environmental cost reductions)

1. *If $m > \bar{m}$, then the UCC is more efficient in reducing the social-environmental cost than the platform if and only if $n > \bar{n}$.*

2. *If $m \leq \bar{m}$, then the UCC is more efficient in reducing the social-environmental cost than the platform if and only if $n > \bar{n}'$.*

Theorem 4 shows that if the number of carriers n is large, then the UCC is more efficient in reducing the negative social-environmental impact 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 because of the additional UCC trucks. In contrast, the platform, which matches a carrier's task with another carrier without employing any additional trucks, becomes more efficient.

After comparing the expected profits and the expected social-environmental cost reductions of the UCC and the capacity sharing platform, we illustrate the predominant business model with respect to these two performance measures for different parameter regions in Figure 3. In general, if the carriers' variable delivery cost m and the number of carriers n are both large, then the consolidator should operate the UCC which is more profitable and also more efficient in reducing the negative social-environmental impact. On the other hand, if both m and n are small, then the consolidator should choose the capacity sharing platform, which performs better both economically and environmentally. In contrast, in the shaded areas of Figure 3, the UCC or the capacity sharing platform only outperforms the other in one aspect. Therefore, the consolidator may prefer either business model depending on her objective. This comparative analysis provides guidance for consolidators to make better choices between the two business models in practice.

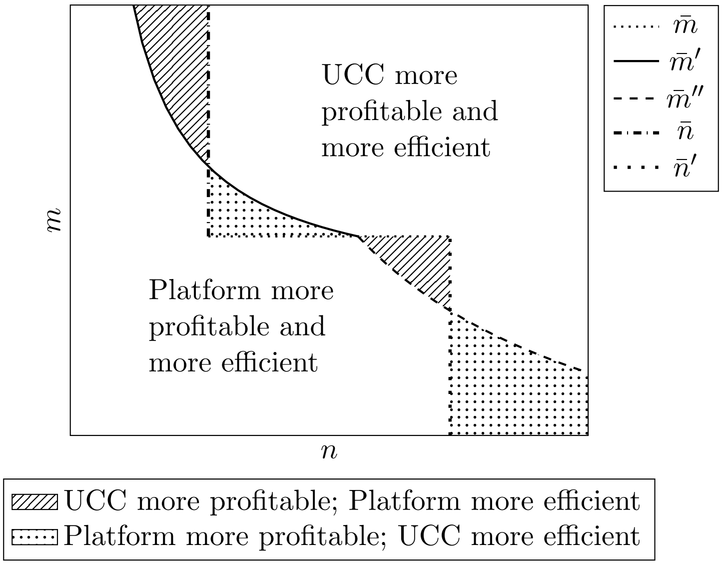

Figure 3: The preferred business model for the consolidator

5 Extensions

5.1 A hybrid model

In our model, we assume that the consolidator can only choose one business model, that is, operating either the UCC or the capacity sharing platform. In this section, we consider a hybrid business model that combines the UCC and the capacity sharing platform. In the hybrid model, the consolidator can simultaneously operate a UCC that fulfills the carriers' delivery tasks, and a platform that matches supply and demand for capacity among the carriers. This hybrid model is inspired by Amazon, which sells products to its consumers and also allows peer-to-peer selling on its platform.

Specifically, we consider a setting 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. A low type 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. A high type 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 under the hybrid model)

1. If $m \leq \min\{\bar{m}', \bar{m}''\}$, then the consolidator charges any $\bar{p}^* > (c + 2mv_L)/((2-\alpha)v_L)$ and $\hat{p}^* = (c + 2mv_L)/((2-\alpha)v_L)$ in equilibrium. Under these prices, each high type carrier delivers on his own, and each low type carrier delivers on his own (and sells his remaining capacity on the platform) or purchases capacity from the platform with an equal probability.

2. If $\bar{m}'' < m \leq \bar{m}$, then the consolidator charges $\bar{p}^* = m + c/v_L$ and any $\hat{p}^* \geq m + c/v_L$ in equilibrium. Under these prices, each high type carrier delivers on his own, and each low type carrier uses the UCC's service.

3. If $m > \max\{\bar{m}, \bar{m}'\}$, then the consolidator charges $\bar{p}^* = m + c/v_H$ and any $\hat{p}^* \geq m + c/v_L$ in equilibrium. Under these prices, all the carriers use the UCC's service.

There are three parameter regions in which the consolidator generates profit from different sources. If the carriers' variable delivery cost m is small, then the consolidator will only 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, more carriers are willing to outsource their delivery tasks. Specifically, if m is moderate, then only the carriers with a high task volume will deliver on their own. If m is large, 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 only generates profit from the UCC.

In this hybrid model, although the consolidator operates both the UCC and the platform concurrently, the consolidator charges a price to incentivize the carriers to participate only in the more profitable business model rather than both. This is consistent with Theorem 3 of our base model, which compares the expected profits of the UCC and the capacity sharing platform.

5.2 A generalized platform model

Motivated by the fact that each individual carrier's delivery capacity is usually very limited, we assume that each carrier on the platform can serve (or can be served by) at most one other carrier in the platform model. In this section, we generalize the platform model such that each carrier can serve (or can be served by) multiple other carriers. Specifically, we assume that each carrier has a finite delivery capacity $\bar{v}$. If a carrier delivers on his own, he can sell his remaining capacity $\bar{v} - v_L$ on the platform, which can be purchased by other carriers. If a carrier purchases capacity from the platform, his delivery task can be fulfilled by multiple other carriers. The number of successful transactions on the platform will be proportional to $\min\{n_s(\bar{v} - v_L), n_p v_L\}$. The rest of the generalized platform model is identical to that in §3.2. The following theorem summarizes the platform's and the carriers' equilibrium decisions.

Theorem 6. (Equilibrium decisions under the generalized platform model)

1. If $\bar{v} > 2v_L$, the platform's price is $\hat{p}^* = \frac{c+2mv_L}{(2-\alpha)v_L}$ in equilibrium.

2. If $\bar{v} \leq 2v_L$, the platform's price is $\hat{p}^* = \frac{c+m\bar{v}}{(1-\alpha)\bar{v}+\alpha v_L}$ in equilibrium.

For both cases, each low type carrier purchases capacity from the platform, or delivers on his own and sells his remaining capacity on the platform with an equal probability.

If the carriers' delivery capacity $\bar{v} > 2v_L$, then a carrier is able to fulfill at least one other carrier's delivery task. If $\bar{v} \leq 2v_L$, the delivery task of a carrier, who purchases capacity from the platform, will be served by multiple other carriers. Although the platform charges a different price in equilibrium for the different cases, the carriers' equilibrium decisions and the insights remain the same as that of the original platform model in §3.2.

5.3 Heterogeneous fixed delivery costs

We assume that the carriers have the same fixed delivery cost c if they deliver on their own, although they may have different total delivery costs given their heterogeneous task volumes. In this section, we generalize the UCC and the platform models in §3.1 and §3.2, respectively, to incorporate heterogeneous fixed delivery costs. Specifically, we assume that a fraction η of the carriers has a low fixed delivery cost c_L, and the remaining fraction $(1 - \eta)$ of the carriers has a high fixed delivery cost $c_H (> c_L)$. Note that the carriers' variable delivery costs are also heterogeneous given the heterogeneity of their delivery task volumes. A detailed analysis of this generalized setting is presented in Online Supplement B. Here, we focus on the impact of heterogeneous fixed delivery costs on the profits of the UCC and the platform.

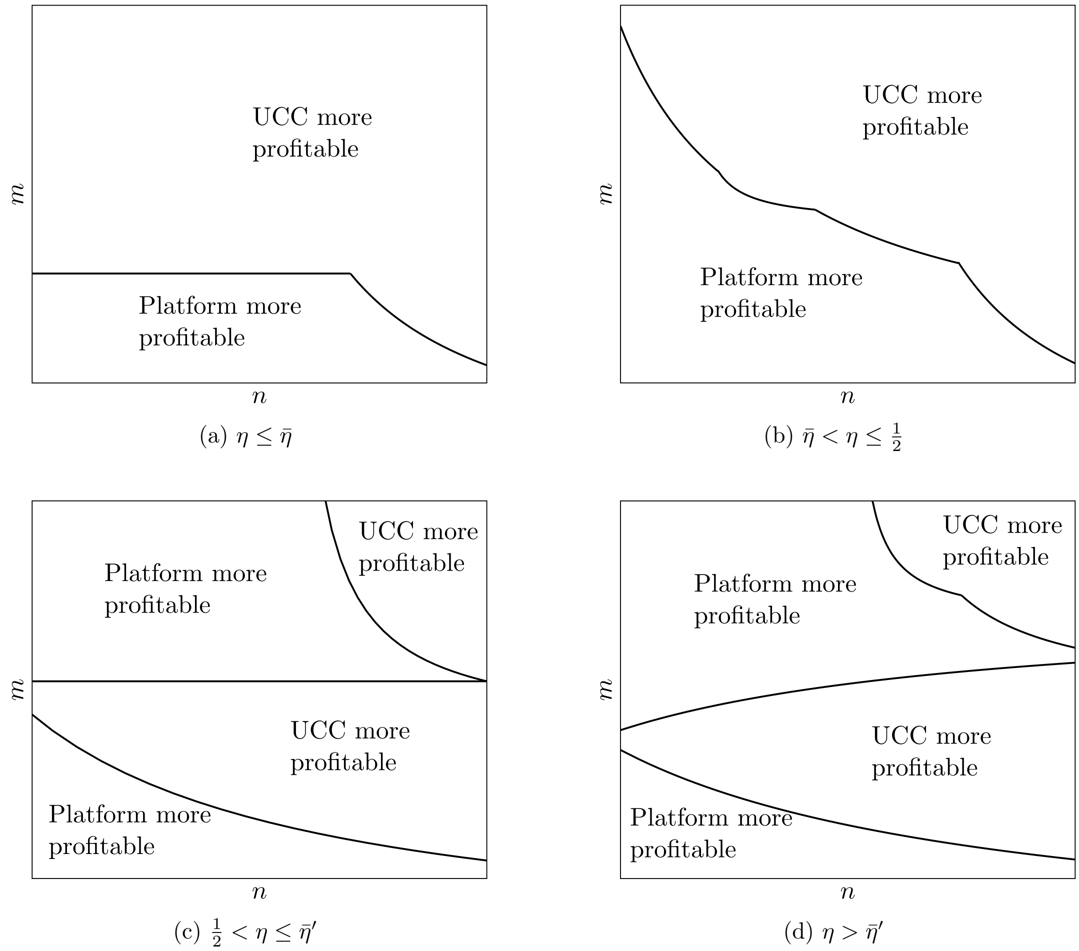

Figure 4: Comparing the UCC's and platform's profits under heterogeneous fixed delivery costs

Figures 4a and 4b show that if the carriers are more likely to have the high fixed delivery cost c_H (that is, $\eta \leq 1/2$), then the UCC tends to be more profitable as m and n become larger. This is similar to the observation from Figure 3 in the original setting in §4.

However, Figures 4c and 4d show that if the carriers are more likely to have the low fixed delivery cost c_L (that is, $\eta > 1/2$), the results become different from that of the original setting. Specifically, the platform may be more profitable even if m is large, whereas the UCC may be more profitable if m is small. This is because in the original setting in §4, it is difficult for the platform to be more profitable (than the UCC) if m is large because of the low supply of capacity. However, in the generalized setting, more carriers deliver on their own and sell their remaining capacity on the platform because of their low fixed delivery cost. This creates more successful transactions on the platform, making it more profitable. In contrast, if m is small, many carriers deliver on their own given that both their fixed and variable delivery costs are low. This leads to excessive supply of capacity on the platform, which may make the UCC more profitable than the platform.

5.4 A two-period setting

As mentioned in §1, some UCC projects are not successful in practice because carriers are reluctant to use a UCC's service. The carriers are concerned with the potential loss of their own logistics capability in the long run if they rely on the UCC. It is possible that after a carrier starts using the UCC's service, he reduces or eliminates his own logistics capability to cut down expenses (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). In this case, if the UCC charges a high price in the future, it will be difficult for the carriers to reestablish their logistics capability and perform their own delivery. The substantial reestablishment cost, which may include 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 the UCC's service.

With this observation, we consider a two-period setting to understand how this long-term factor affects our results. Specifically, we develop a two-period model for each of the UCC and the capacity sharing platform. In each period, the consolidator first determines the price of delivery service to maximize her expected profit. Then, after knowing his task volume, each carrier decides whether to deliver on his own or use the consolidator's service to deliver his task to the city center such that his expected cost is minimized.

In period 1, if a carrier decides to use the consolidator's service, then he can also choose to eliminate or keep his logistics capability for the future. It will incur a holding cost $h > 0$ to the carrier for keeping his logistics capability. 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. It will incur a setup cost $f > 0$ to the carrier for reestablishing his logistics capability. We assume that each carrier's delivery capacity has no value after period 2. 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 $h \leq \delta(1-\lambda)c(v_H - v_L)/v_L$, $f > c(v_H - v_L)/v_L$, and $\lambda \leq v_H/(2v_H - v_L)$. The rest of the models remains the same as the original models in §3.1

and §3.2.

5.4.1 The UCC model

Recall that $\bar{m} = \frac{c\left[\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right]+(1-\lambda)(M-S)v_H}{(1-\lambda)v_H}$. Define $\hat{m}_1 = \frac{\lambda^2(c+f)-\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)c+(M-S)(1-\lambda)(v_H+\lambda v_L)}{(1-\lambda)(v_H+\lambda v_L)}$, $\hat{m}_2 = \frac{\lambda f-(1-\lambda)c+(M-S)(1-\lambda)v_H}{(1-\lambda)v_H}$, and $\hat{m}_3 = \frac{\left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\left(1-\lambda\frac{v_H}{v_L}\right)\right)c+(M-S)(1-\lambda)^2v_H}{(1-\lambda)^2v_H}$. The following theorem characterizes the equilibrium decisions of the UCC and the carriers under the two-period UCC model.

Theorem 7. (Equilibrium decisions under the two-period UCC model)

1. *If $m > \max\{\hat{m}_1, \hat{m}_2, \hat{m}_3\}$, then the equilibrium decisions in each period are as follows.*

   Period 1: The UCC's 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 price is $\bar{p}_2^* = m + c/v_H$. Under this price, all the carriers use the UCC's service.

2. *If $m \leq \bar{m}$, then the equilibrium decisions in each period are as follows.*

   Period 1: The UCC's 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 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.

Note that the threshold $\max\{\hat{m}_1, \hat{m}_2, \hat{m}_3\} > \bar{m}$, which means the two intervals of m in Theorem 7 do not overlap, and there is no equilibrium for $\bar{m} < m \leq \max\{\hat{m}_1, \hat{m}_2, \hat{m}_3\}$. As the threshold $\max\{\hat{m}_1, \hat{m}_2, \hat{m}_3\}$ depends on the carriers' reestablishment cost f, we can characterize the carriers' equilibrium decisions using their variable delivery cost m and their reestablishment cost f. Figures 5a and 5b illustrate the equilibrium decisions of the carriers in periods 1 and 2 respectively. If the carriers' variable delivery cost is small ($m \leq \bar{m}$), then the carriers' equilibrium decisions are consistent with that of the one-period model in Theorem 1. That is, for both periods, only the low type carriers use the UCC's service and the high type carriers deliver on their own. In addition, the carriers who use the UCC's service in period 1 keep their own logistics capability. Since delivering on their own is not costly given the small variable delivery cost m, keeping logistics capability ensures that the carriers can easily switch back to delivery on their own in period 2 if the UCC's service becomes expensive.

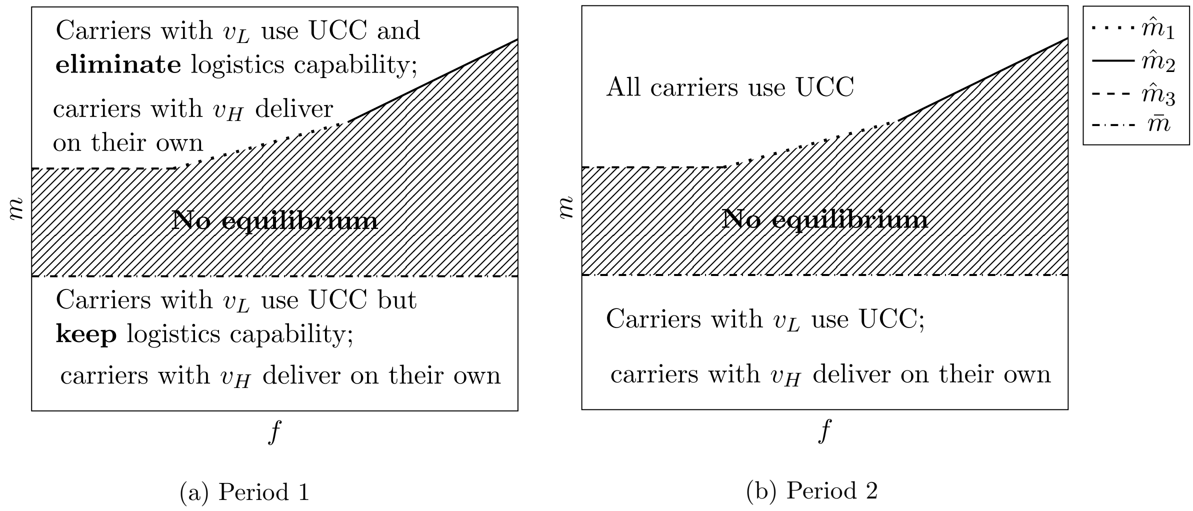

Figure 5: The carriers' equilibrium decisions under the two-period UCC model

On the other hand, if the carriers' variable delivery cost is large ($m > \bar{m}$), there may or may not be an equilibrium outcome, which is different from the one-period model in §3.1. If the reestablishment cost f is sufficiently small (corresponding to the top-left corner of Figure 5a), then the carriers, who use the UCC's service, eliminate their logistics capability. This is because the carriers anticipate that they are likely to use the UCC's service in period 2 given the large m. Having said that, given the small reestablishment cost f, it is easier for these carriers to switch to delivery on their own if the UCC charges a high price in period 2. Anticipating this, the UCC will charge a suitable price in period 2 to retain these carriers for using her service, which results in an equilibrium.

As the reestablishment cost f increases, the equilibrium becomes less achievable (corresponding to the top-right corner of Figure 5a). The expensive reestablishment cost makes it difficult for these carriers (who eliminate their logistics capability in period 1) to switch to delivery on their own in period 2. The UCC anticipates that these carriers are likely to continue using her service in period 2, and therefore she will increase her price in period 2. Knowing that this will happen, these carriers would rather not use the UCC's service in period 1 to avoid the expensive UCC's service or capacity reestablishment in period 2. This leads to no equilibrium.

The above finding echoes our observation in practice. When a carrier finds that the UCC's service is cheaper than delivering on his own (under a large m), he may start using the UCC's service and eliminate his logistics capability to cut down expenses (to avoid the holding cost h). However, if the UCC charges a high price in the future, it will be difficult for the carrier to reestablish his logistics capability and switch back to delivery on his own (given a large f). This deters the carriers from using the UCC's service in the first place. From this perspective, our result partially explains why the carriers are reluctant to use a UCC's service in practice, causing many UCC projects not successful.

5.4.2 The capacity sharing platform model

The following theorem summarizes the equilibrium decisions of the capacity sharing platform and the carriers under the two-period platform model.

Theorem 8. (Equilibrium decisions under the two-period platform model)

Period 1: The platform's price is $\hat{p}_1^* = [c + 2mv_L - h]/[(2-\alpha)v_L]$ in equilibrium. Under this price, each low type carrier purchases capacity from the platform (but keeps his logistics capability), or delivers on his own (and sells his remaining capacity on the platform) with an equal probability.

Period 2: The platform's price is $\hat{p}_2^* = (c+2mv_L)/[(2-\alpha)v_L]$ in equilibrium. Under this price, each low type carrier purchases capacity from the platform, or delivers on his own (and sells his remaining capacity on the platform) with an equal probability.

In equilibrium, the carriers always keep their logistics capability in period 1 even if they purchase capacity from the platform. This means that each carrier always has his logistics capability on hand for both periods, which allows them to flexibly choose a delivery option (without paying a reestablishment cost). Since the carriers can deliver on their own and sell remaining capacity on the platform, the platform will have sufficient capacity available to facilitate successful transactions. This makes the platform financially promising as she can always earn a revenue share from each successful transaction. Furthermore, unlike the two-period UCC model, the two-period platform model can always achieve an equilibrium. Our result provides explanations for the increasing popularity of the capacity sharing platforms in practice.

The relative performance of the UCC and the platform in terms of the profitability and the social-environmental cost reduction under the two-period setting is similar to that of the one-period setting. All the insights in §4 continue to hold, so we omit the details here.

5.5 Correlated demands

In the two-period setting, the carriers can keep or eliminate their logistics capability if they use the consolidator's service in the first period. This decision depends on the carriers' expectation of their delivery task volumes for the next period. In practice, the carriers' demands across the periods can be correlated. In this section, we analyze the UCC and the platform models under the two-period setting with correlated task volumes between the two periods for each carrier.

Specifically, we assume that if the carrier's task volume is low in period 1, then in period 2 his task volume will be low with probability $\xi_L \in [0,1]$, or high with probability $(1-\xi_L)$. If the carrier's task volume is high in period 1, then in period 2 his task volume will be high with probability $\xi_H \in [0,1]$, or low with probability $(1-\xi_H)$. To rule out uninteresting cases where the carriers never keep their logistics capability, we assume $h \leq \min\left\{\delta(1-\xi_L)c\left(\frac{v_H}{v_L}-1\right), \delta\xi_H c\left(\frac{v_H}{v_L}-1\right)\right\}$. The rest of the models is identical to that of §5.4.

5.5.1 The UCC model

Define $\hat{m}_4 = \frac{\lambda[\lambda\xi_L+(1-\lambda)(1-\xi_H)](c+f)-\left([\lambda\xi_L+(1-\lambda)(1-\xi_H)]\frac{v_H}{v_L}+\lambda(1-\xi)+(1-\lambda)\xi_H\right)c}{(\lambda(1-\xi_L)+(1-\lambda)\xi_H)v_H+[\lambda\xi_L+(1-\lambda)(1-\xi_H)](1-\lambda)v_L} + M - S$, $\hat{m}_5 = \frac{\left([\lambda\xi_L+(1-\lambda)(1-\xi_H)]\left(1-\frac{v_H}{v_L}\right)-(\lambda(1-\xi_L)+(1-\lambda)\xi_H)\left(1-\lambda\frac{v_L}{v_H}\right)\right)c}{(1-\lambda)(\lambda(1-\xi_L)+(1-\lambda)\xi_H)v_H} + M - S$, $\hat{m}_6 = \frac{(c-h)\left[\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right]}{(1-\lambda)v_H} + M - S$, and $\hat{m}_7 = \frac{\left([\lambda\xi_L+(1-\lambda)(1-\xi_H)]\left(1-\frac{v_H}{v_L}\right)-(\lambda(1-\xi_L)+(1-\lambda)\xi_H)\right)c}{(\lambda(1-\xi_L)+(1-\lambda)\xi_H)v_H} + M - S$. The following theorem summarizes the carriers' equilibrium decisions under the UCC model.

Theorem 9. (Equilibrium decisions under the two-period UCC model with correlated demands)

1. *If $m > \max\{\hat{m}_2, \hat{m}_4, \hat{m}_5\}$, the carriers' equilibrium decisions in each period are as follows.*

   Period 1: 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: Each carrier i uses the UCC's service.

2. *If $\hat{m}_6 < m \leq \hat{m}_7$, the carriers' equilibrium decisions in each period are as follows.*

   Period 1: Each carrier i uses the UCC's service but keeps his logistics capability.

   Period 2: Each carrier i uses the UCC's service if $v_{i2} = v_L$, and delivers on his own otherwise.

3. *If $m \leq \min\{\hat{m}_6, \hat{m}_7\}$, the carriers' equilibrium decisions in each period are as follows.*

Period 1: Each carrier i uses the UCC's service but keep his logistics capability if $v_{i1} = v_L$, and delivers on his own otherwise.

Period 2: Each carrier i uses the UCC's service if $v_{i2} = v_L$, and delivers on his own otherwise.

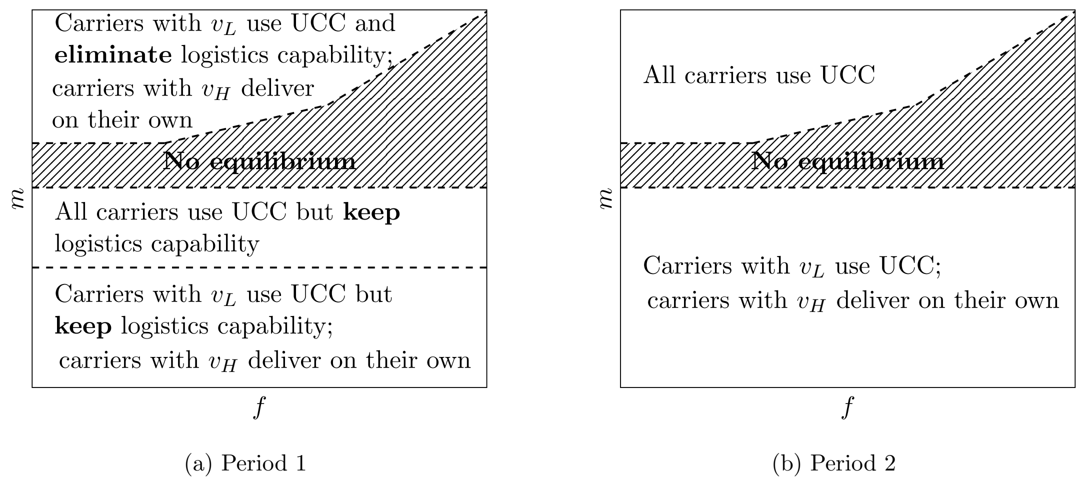

Figure 6: The carriers' equilibrium decisions under the two-period UCC model with correlated demands

Figure 6 shows the carriers' equilibrium decisions under the two-period UCC model with correlated demands. Compared to the equilibrium results with independent demands in Figure 5, we observe one additional case in equilibrium: All the carriers use the UCC's service but keep their logistics capability in period 1. If the demands are correlated, the carriers become less conservative in using the UCC's service. This is because the carriers can make a more informed decision about their logistics capability, and thus they are less concerned about the increase of the UCC's price in period 2. This implies that the UCC's service may become more appealing when the demands are correlated.

5.5.2 The capacity sharing platform model

The following theorem summarizes the equilibrium decisions of the low type carriers under the platform model.

Theorem 10. (Equilibrium decisions under the two-period platform model with correlated demands) *If $f > A/\alpha - (c + m v_L)$, then the carriers' equilibrium decisions in each period are as follows.*

Period 1: Each low type carrier purchases capacity from the platform (but keeps his logistics capability), or delivers on his own (and sells his remaining capacity on the platform) with an equal probability.

Period 2: Each low type carrier purchases capacity from the platform, or delivers on his own (and sells his remaining capacity on the platform) with an equal probability.

Although the carriers make the same decisions as in the platform model with independent demands (see Theorem 8), we find that the correlated demands make the platform model less viable. Specifically, there is no equilibrium when the reestablishment cost f is too small. The reason is as follows. When the demands are correlated, if the carriers anticipate that they are likely to have a high task volume (and have to deliver on their own) in period 2, they would keep their logistics capability in period 1. However, a small reestablishment cost f incentivizes the carriers to eliminate their logistics capability, leading to deviation. On the other hand, if the carriers anticipate a low task volume in period 2, they would eliminate their logistics capability in period 1 given a small f. The platform then will charge a high price in period 2, deterring the carriers from eliminating their logistics capability in period 1, leading to deviation.

6 Conclusion

The consistent growth of urban population and e-commerce activities significantly increases the demand for last-mile delivery to urban areas. This causes more traffic congestion in a city center, creating negative impact on the well-being of the city economically, socially, and environmentally. 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 to consolidate delivery tasks from multiple carriers. Under the UCC business model, the consolidator requires a sorting facility and a fleet of trucks to deliver the tasks of the 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 or trucks, but there is an administrative cost incurred to the consolidator for matching the supply and demand of the capacity on the platform. She receives a revenue share from each successful transaction of capacity on the platform.

For each business model, we develop a game-theoretical model capturing the interactions between the consolidator and the multiple carriers. Under each model, the consolidator first determines the price per unit volume of the delivery service to maximize her expected profit.

After knowing his task volume, each carrier then minimizes the cost to fulfill his delivery task by (i) delivering on his own, or (ii) using the consolidator's service.

In practice, by using the UCC, the carriers can potentially save their delivery costs because of the consolidation. Our game-theoretical model demonstrates this potential benefit through its equilibrium results. We observe that as the carriers' variable delivery cost increases, they become more dependent on the UCC to fulfill their delivery tasks and eventually all the carriers will use the UCC's service in equilibrium.

Under the capacity sharing platform model, the consolidator will charge a market clearance price such that the supply matches the demand on the platform in equilibrium. This facilitates sufficient successful transactions and ensures that the platform can always earn the revenue share from each transaction in equilibrium. This makes the platform business model financially promising. Our equilibrium result may explain the increasing popularity of the capacity sharing platforms in practice.

To provide guidance for the consolidator to choose between the two business models, we first compare their expected profits. In general, the UCC is more profitable than the platform if the carriers' variable delivery cost is large. In this situation, the carriers have a strong incentive to outsource their delivery tasks. This will benefit the consolidator if she operates a UCC because there will be many carriers using her service. On the other hand, this situation will lead to high demand but low supply of capacity on the platform as the carriers tend to outsource their delivery tasks. The low supply of capacity makes the platform less profitable than the UCC.

We also determine which business model is more efficient in mitigating the negative social-environmental impact of urban last-mile delivery. 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 has limited capacity. We find that if the total number of carriers is sufficiently large, then the UCC is more efficient than the platform in mitigating the social-environmental impact. In this case, 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 of urban last-mile delivery.

Based on the above findings, we identify the predominant business model for the consolidator with respect to both the profitability and the efficiency in reducing negative social-environmental impact. In general, the UCC outperforms the platform in both perspectives as long as the carriers' variable delivery cost and the number of carriers are sufficiently large. Otherwise, the platform performs better, even though the UCC and the platform may outperform each other in only one perspective. Following our comparative analysis, the consolidator can always choose a business model that suits her essential need (profitability or efficiency in reducing the social-environmental cost). For example, a nonprofit organization in practice may prefer the business model that is more efficient in reducing the negative social-environmental impact, whereas a private company may prefer the business model that yields a larger profit.

We study several extensions of our modeling framework. The first extension considers a hybrid model in which the consolidator concurrently operates a UCC and a platform. We have also generalized the platform model such that each carrier can serve or can be served by multiple other carriers. The third extension assumes heterogeneous fixed delivery costs of the carriers. Finally, we analyze both the UCC and the platform models in a two-period setting to capture their long-term impact. We also consider demand correlation across the two periods.

Acknowledgment

The authors thank the senior editor and the two anonymous referees for their valuable comments that have substantially improved the paper. Portions of this paper have been presented in Arizona State University, 2018; Cai Niao (Alibaba Group), 2018; Nanyang Technological University, 2018; Northeastern University (China), 2018; Zhejiang University, 2018; Chinese University of Hong Kong (Shenzhen), 2020; and Southwest Jiaotong University, 2020. The authors thank the audiences for many insightful comments and stimulating questions. The second author is grateful for the support from the Singapore Management University (SMU) under the Lee Kong Chian Fellowship. The third author thanks the support from SMU under the Maritime and Port Authority (MPA) Research Fellowship and the Key Program of National Natural Science Foundation of China (No. 71931009). Both second and third authors thank the support from SMU under the Retail Centre of Excellence (RCoE) research grant.

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.

ASEAN (2014) *Logistics Planning and Analysis.*

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.

Online Supplement

A Proofs

Lemma 1. (Optimal decision of carrier i) *Carrier i uses the UCC's service ($\bar{d}_i^* = 1$) if $\bar{p} \le m + c/v_i$, or delivers on his own ($\bar{d}_i^* = 0$) otherwise.*

Proof of Lemma 1. By solving $\bar{\phi}_i(1;\bar{p}) \le \bar{\phi}_i(0;\bar{p})$ for v_i, we obtain $\bar{p} \le m + c/v_i$. Thus, $\bar{d}_i^* = 1$ if $\bar{p} \le m + c/v_i$, and $\bar{d}_i^* = 0$ otherwise.

□

Lemma 2. (Optimal decision of the UCC) *If $m > \frac{c\left[\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right]+(1-\lambda)(M-S)v_H}{(1-\lambda)v_H}$, then the UCC's optimal price is $\bar{p}^* = m + c/v_H$. Otherwise, $\bar{p}^* = m + c/v_L$.*

Proof of Lemma 2. According to Lemma 1, we derive V (which is in the UCC's expected profit function in Equation (1)) for the two types of carriers as below.

Low type ($v_i = v_L$): Each carrier i of this type uses the UCC's service ($\bar{d}_i^* = 1$) if $\bar{p} \le m + c/v_L$. The expected number of carriers of this type is λn, and if those carriers use the UCC's service, then the expected task volumes served by the UCC are $\lambda n v_L$.

High type ($v_i = v_H$): Each carrier i of this type uses the UCC's service ($\bar{d}_i^* = 1$) if $\bar{p} \le m + c/v_H$. The expected number of carriers of this type is $(1-\lambda)n$, and if those carriers use the UCC's service, then the expected task volumes served by the UCC are $(1-\lambda)nv_H$.

Note that $m + c/v_L > m + c/v_H$. So, the optimal choice of the UCC is among the following two:

1. Choose a price $\bar{p} \in (m + c/v_H, m + c/v_L]$ to attract Type 1 carriers, then V equals to the total expected task volumes of those carriers, that is $V = \lambda n v_L$. Substituting V into Equation (1), the UCC's expected profit is

$$\bar{\pi}(\bar{p}) = (\bar{p} + S - M)(\lambda n v_L) - C, \tag{3}$$

which increases in $\bar{p}$, so it is optimal for the UCC to choose $\bar{p}^* = m+c/v_L$ to maximize profit. Substituting $\bar{p}^*$ into Equation (3), we obtain that $\bar{\pi}\left(m + \frac{c}{v_L}\right) = \left(m + \frac{c}{v_L} + S - M\right)\lambda n v_L - C$.

2. Choose a price $\bar{p} \in (0, m + c/v_H]$ to attract both Type 1 and Type 2 carriers, then V equals to the total expected task volumes of all the carriers, that is $V = \lambda n v_L + (1-\lambda)nv_H$. Substituting V into Equation (1), the UCC's expected profit is

$$\bar{\pi}(\bar{p}) = (\bar{p} + S - M)(\lambda n v_L + (1-\lambda)nv_H) - C, \tag{4}$$

which increases in $\bar{p}$, so it is optimal for the UCC to choose $\bar{p}^* = m+c/v_H$ to maximize profit. Substituting $\bar{p}^*$ into Equation (4), we obtain that $\bar{\pi}\left(m + \frac{c}{v_H}\right) = \left(m + \frac{c}{v_H} + S - M\right)(\lambda n v_L + (1-\lambda)nv_H) - C$.

By comparing the profits of the UCC under choices 1 and 2, we can obtain that $\bar{\pi}\left(m + \frac{c}{v_L}\right) \ge \bar{\pi}\left(m + \frac{c}{v_H}\right)$ if $m \le \frac{c[\lambda(1-\frac{v_L}{v_H})-(1-\lambda)]+(1-\lambda)(M-S)v_H}{(1-\lambda)v_H}$. Thus, the results in Lemma 2 follow. □

Proof of Theorem 1. According to lemmas 1 and 2, the results in Theorem 1 follows. □

Lemma 3. (Optimal decision of low type carrier i) *Low type carrier i purchases capacity from the platform to fulfil his task ($\hat{d}_i^* = 1$) if $\hat{p} < \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$, or delivers on his own and sells his remaining capacity to platform ($\hat{d}_i^* = 0$) if $\hat{p} > \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$, or chooses either option with probability 0.5 if $\hat{p} = \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$.*

Proof of Lemma 3. By solving $\hat{\phi}_i(1;\hat{p}) < \hat{\phi}_i(0;\hat{p})$ for v_i, we obtain that $\hat{p} < \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$. Thus, $\hat{d}_i^* = 1$ if $\hat{p} < \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$, $\hat{d}_i^* = 0$ if $\hat{p} > \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$, and $\hat{d}_i^* = 1$ or 0 with an equal probability if $\hat{p} = \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$. □

Lemma 4. (Optimal decision of the platform) *The optimal price of the capacity sharing platform is $\hat{p}^* = \frac{c+2mv_L}{(2-\alpha)v_L}$.*

Proof of Lemma 4. According to Lemma 3, the optimal choice of the platform is choosing a price $\hat{p} = \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$ to incentivize the low type carriers to purchase capacity from the platform or deliver on their own and sell remaining capacity to the platform with an equal probability. Otherwise, there will be either no supply or no demand on the platform. We can obtain that $n_s = \lambda n/2$, $n_p = \lambda n/2$, and $\theta = 1$. Substituting them into $\hat{p} = \frac{c+(1+\theta)mv_L}{[1+\theta(1-\alpha)]v_L}$ and Equation (2), we can obtain $\hat{p}^* = \frac{c+2mv_L}{(2-\alpha)v_L}$ and $\hat{\pi}^* = \frac{\alpha\lambda n(c+2mv_L)}{2(2-\alpha)} - \frac{\lambda n A}{2}$. □

Proof of Theorem 2. According to lemmas 3 and 4, the results in Theorem 2 follows. □

Proof of Theorem 3. According to propositions 1 and 3, by solving $\bar{\pi}^*(\bar{p}^*) > \hat{\pi}^*(\hat{p}^*)$ for m in the cases $m > \bar{m}$ and $m \leq \bar{m}$, we obtain the results in Theorem 3. □

Proof of Corollary 1. Given the market entry cost $\bar{E}$, the UCC's profit in equilibrium becomes $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c}{v_H} + S - M)(\lambda n v_L + (1-\lambda) n v_H) - C - \bar{E}$ if $m > \bar{m}$, and $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c}{v_L} + S - M)\lambda n v_L - C - \bar{E}$ if $m \leq \bar{m}$. Given the market entry cost $\hat{E}$, the platform's profit in equilibrium becomes $\hat{\pi}^*(\hat{p}^*) = \frac{\alpha\lambda n(c+2mv_L)}{2(2-\alpha)} - \frac{\lambda n A}{2} - \hat{E}$. By solving $\bar{\pi}^*(\bar{p}^*) > \hat{\pi}^*(\hat{p}^*)$ for m in the cases $m > \bar{m}$ and $m \leq \bar{m}$, we obtain the results in Corollary 1. □

Proof of Theorem 4. According to propositions 2 and 4, by solving $\bar{\Delta}_\psi > \hat{\Delta}_\psi$ for n in the cases $m > \bar{m}$ and $m \leq \bar{m}$, we obtain the results in Theorem 4. □

Proof of Theorem 5. 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 proof of Lemma 1, we can derive the optimal decision of each carrier as follows.

1. Each high type carrier uses the UCC's service if $\bar{p} \leq m + \frac{c}{v_H}$, or delivers on his own if $\bar{p} > m + \frac{c}{v_H}$.
2. Each low type carrier uses the UCC's service if $\bar{p} \leq m + \frac{c}{v_L} - \theta[(1-\alpha)\hat{p} - m]$ and $\hat{p} \geq \bar{p}$, 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 the carrier 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 2, we can obtain that the optimal pricing 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 high type carrier delivers on his own, and each low type carrier is indifferent between delivering on his own (and selling his remaining capacity to the platform) and purchasing capacity on the platform. The consolidator's expected profit is $\frac{\alpha\lambda n(c+2mv_L)}{2(2-\alpha)} - \lambda n A$.
2. Choose $\bar{p}^* = m + \frac{c}{v_L}$ and $\hat{p}^* \geq m + \frac{c}{v_L}$. Under these prices, each high type carrier delivers on his own, and each low type carrier uses the UCC's service. The consolidator's profit is $\left(m + \frac{c}{v_L} + S - M\right)\lambda n v_L - C$.
3. Choose $\bar{p}^* = m + \frac{c}{v_H}$ and $\hat{p}^* \geq m + \frac{c}{v_L}$. Under these prices, each carrier uses the UCC's service. The consolidator's profit is $\left(m + \frac{c}{v_H} + S - M\right)(\lambda n v_L + (1-\lambda) n v_H) - C$.

It is optimal for the consolidator to choose the price 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. The proof is similar to the proof of Theorem 2 and thus omitted. □

Under the two-period UCC model, we define $\bar{\phi}_{i2}\left(\bar{d}_{i2}; \bar{d}_{i1}, \bar{p}_2\right)$ as the cost of carrier i in period 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 5. (Optimal decision of carrier i in period 2 under the UCC model)
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 and eliminates his logistics capability ($\bar{d}^*_{i2} = 0$) if $\bar{p}_2 \leq m + c/v_{i2}$, 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 $\bar{p}_2 \leq m + (c+f)/v_{i2}$, or delivers on his own ($\bar{d}^*_{i2} = -1$) otherwise.

Proof of Lemma 5. 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. □

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 5, the UCC chooses the price $\bar{p}_2$ to maximize her expected profit in period 2:

$$\bar{\pi}_2(\bar{p}_2) \quad = \quad (\bar{p}_2 + S - M) V_2 - C. \tag{5}$$

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 6. (Optimal decision of the UCC in period 2 under the UCC model)
1. If $n_e > 0$, the optimal price of the UCC's service in period 2 is

$$\bar{p}_2^* = \begin{cases} m + (c+f)/v_L, & \text{if } m \le \min\{m_1, m_2, m_3\}; \\ m + (c+f)/v_H, & \text{if } m_1 < m \le \min\{m_4, m_5\}; \\ m + c/v_L, & \text{if } \max\{m_2, m_4\} < m \le m_6; \\ m + c/v_H, & \text{if } m > \max\{m_3, m_5, m_6\}. \end{cases}$$

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

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

Proof of Lemma 6. Define $m_1 = M - S + \frac{(c+f)\left[\lambda\left(1 - \frac{v_L}{v_H}\right) - (1-\lambda)\right]}{(1-\lambda)v_H}$, $m_2 = M - S + \frac{\lambda n_e f - \left((1-\lambda)n_e \frac{v_H}{v_L} + \lambda(n-n_e)\right)c}{(1-\lambda)n_e v_H + \lambda(n-n_e)v_L}$, $m_3 = M - S + \frac{\lambda(c+f)n_e - \left(\lambda\frac{v_L}{v_H} + (1-\lambda)\right)cn}{(1-\lambda)n v_H + \lambda(n-n_e)v_L}$, $m_4 = M - S + \frac{\left(\lambda\frac{v_L}{v_H} + (1-\lambda)\right)(c+f)n_e - \left(\lambda n + (1-\lambda)n_e\frac{v_H}{v_L}\right)c}{\lambda(n-n_e)v_L}$, $m_5 = M - S + \frac{\left(\lambda\frac{v_L}{v_H} + (1-\lambda)\right)(c+f)n_e - \left(\lambda\frac{v_L}{v_H} + (1-\lambda)\right)cn}{\lambda(n-n_e)v_L + (1-\lambda)(n-n_e)v_H}$, $m_6 = M - S + \frac{\left(\lambda n\left(1 - \frac{v_L}{v_H}\right) + (1-\lambda)n_e\frac{v_H}{v_L} - (1-\lambda)n\right)c}{(1-\lambda)(n-n_e)v_H}$.

To derive V_2 in the UCC's expected profit function in Equation (5), 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 $\bar{p}_2 \le m + \frac{c}{v_L}$. 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 $\bar{p}_2 \le m + \frac{c}{v_H}$. 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 $\bar{p}_2 \le m + \frac{c+f}{v_L}$. 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 $\bar{p}_2 \le m + \frac{c+f}{v_H}$. 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 $n_e = 0$, which will be identical to the proof of Lemma 2. Thus, we omit the analysis for the case that $n_e = 0$. In the following, we analyze the UCC's optimal decision in 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 $V_2 = \lambda n_e v_L$. Substituting it into Equation (5), the UCC's expected profit is

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

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

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 $V_2 = \lambda n_e v_L + (1-\lambda)n_e v_H$. Substituting it into Equation (5), the UCC's expected profit is

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

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 (7), we obtain that $\bar{\pi}_2\left(m + \frac{c+f}{v_H}\right) = \left(m + \frac{c+f}{v_H} + S - M\right)(\lambda n_e v_L + (1-\lambda)n_e v_H) - C$.

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 $V_2 = \lambda n_e v_L + (1-\lambda)n_e v_H + \lambda(n-n_e)v_L$. Substituting it into Equation (5), the UCC's expected profit is

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

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

4. Choose a price $\bar{p}_2 \in \left(0, m+\frac{c}{v_H}\right]$ to attract all types of carriers, then $V_2 = \lambda n_e v_L + (1-\lambda)n_e v_H + \lambda(n-n_e)v_L + (1-\lambda)(n-n_e)v_H = \lambda n v_L + (1-\lambda)n v_H$. Substituting it into Equation (5), the UCC's expected profit is

$$\bar{\pi}_2(\bar{p}_2) = (\bar{p}_2 + S - M)(\lambda n v_L + (1-\lambda)n v_H) - C, \tag{9}$$

which increases in $\bar{p}_2$, so it is optimal for the UCC to choose $\bar{p}_2^* = m+\frac{c}{v_H}$ to maximize profit. Substituting $\bar{p}_2^* = m+\frac{c}{v_H}$ into Equation (9), we obtain that $\bar{\pi}_2\left(m+\frac{c}{v_H}\right) = \left(m+\frac{c}{v_H}+S-M\right)(\lambda n v_L + (1-\lambda)n v_H) - C$.

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 $m \le \min\{m_1, m_2, m_3\}$; $\bar{\pi}_2\left(m+\frac{c+f}{v_H}\right)$ is the maximum if $m_1 < m \le \min\{m_4, m_5\}$; $\bar{\pi}_2\left(m+\frac{c}{v_L}\right)$ is the maximum if $\max\{m_2, m_4\} < m \le m_6$; and $\bar{\pi}_2\left(m+\frac{c}{v_H}\right)$ is the maximum if $m > \max\{m_3, m_5, m_6\}$. Therefore, the corresponding prices $\bar{p}_2^*$ under those choices are optimal for the UCC, and the results in Lemma 6 follow.

□

To identify a subgame perfect Nash Equilibrium with rational expectations, we assume 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, $\tilde{n}_e = n_e\left(\bar{p}_1^*; \bar{d}_{i1}^*, i=1,2,\ldots,n\right)$. 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 $\bar{\Phi}_i(-1; \bar{p}_1) = c + m v_{i1} + \delta\bar{\phi}_{i2}^*(-1)$. (ii) $\bar{d}_{i1} = 0$: Carrier i uses the UCC's service and eliminates his logistics capability, which incurs an expected total discounted cost $\bar{\Phi}_i(0; \bar{p}_1) = \bar{p}_1 v_{i1} + \delta\bar{\phi}_{i2}^*(0)$. (iii) $\bar{d}_{i1} = 1$: Carrier i uses the UCC's service and keeps his logistics capability, which incurs an expected total discounted cost $\bar{\Phi}_i(1; \bar{p}_1) = \bar{p}_1 v_{i1} + h + \delta\bar{\phi}_{i2}^*(1)$. The following lemma shows the optimal decision of carrier i in period 1.

Lemma 7. (Optimal decision of carrier i in period 1 under the UCC model)

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

(a) If $m \le \min\{m_1, \tilde{m}_2, \tilde{m}_3\}$, 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 $m_1 < m \le \min\{\tilde{m}_4, \tilde{m}_5\}$, 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 $\max\{\tilde{m}_2, \tilde{m}_4\} < m \le \tilde{m}_6$, 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 $m > \max\{\tilde{m}_3, \tilde{m}_5, \tilde{m}_6\}$, 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 $m \le \bar{m}$, 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 $m > \bar{m}$, then

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

Proof of Lemma 7. Define $\tilde{m}_2 = M - S + \frac{\lambda \tilde{n}_e f - \left((1-\lambda)\tilde{n}_e \frac{v_H}{v_L} + \lambda(n-\tilde{n}_e)\right)c}{(1-\lambda)\tilde{n}_e v_H + \lambda(n-\tilde{n}_e)v_L}$,
$\tilde{m}_3 = M - S + \frac{\lambda(c+f)\tilde{n}_e - \left(\lambda \frac{v_L}{v_H} + (1-\lambda)\right)cn}{(1-\lambda)nv_H + \lambda(n-\tilde{n}_e)v_L}$, $\tilde{m}_4 = M - S + \frac{\left(\lambda \frac{v_L}{v_H} + (1-\lambda)\right)(c+f)\tilde{n}_e - \left(\lambda n + (1-\lambda)\tilde{n}_e \frac{v_H}{v_L}\right)c}{\lambda(n-\tilde{n}_e)v_L}$,
$\tilde{m}_5 = M - S + \frac{\left(\lambda \frac{v_L}{v_H} + (1-\lambda)\right)(c+f)\tilde{n}_e - \left(\lambda \frac{v_L}{v_H} + (1-\lambda)\right)cn}{\lambda(n-\tilde{n}_e)v_L + (1-\lambda)(n-\tilde{n}_e)v_H}$, $\tilde{m}_6 = M - S + \frac{\left(\lambda n\left(1-\frac{v_L}{v_H}\right) + (1-\lambda)\tilde{n}_e \frac{v_H}{v_L} - (1-\lambda)n\right)c}{(1-\lambda)(n-\tilde{n}_e)v_H}$.

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 6, if $m \le \min\{m_1, \tilde{m}_2, \tilde{m}_3\}$, 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 5 and 6, 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 5 and 6, 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 $\bar{\Phi}_i(0; \bar{p}_1) = \bar{p}_1 v_{i1} + \delta(\lambda \bar{p}_2^* v_L + (1-\lambda)(c + mv_H + f)) = \bar{p}_1 v_{i1} + \delta(\lambda(c + mv_L) + (1-\lambda)(c + mv_H) + f)$.
3. $\bar{d}_{i1} = 1$: In this case, according to Lemmas 5 and 6, 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 $\bar{d}_{i1}^* = -1$ otherwise. This proves case 1(a) of Lemma 7. Next we determine the carrier's optimal decision in case 1(b) of Lemma 7. Similarly, according to case 1 of Lemma 6, if $m_1 < m \le \min\{\tilde{m}_4, \tilde{m}_5\}$, 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 5 and 6, 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 5 and 6, 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 5 and 6, 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 7. 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. ☐

Let V_1 denote the expected total task volume of the carriers who use the UCC's service in period 1. Assuming all the carriers respond optimally according to Lemma 7, the UCC optimizes her price $\bar{p}_1$ to maximize her expected total discounted profit over the two periods:

$$\bar{\Pi}(\bar{p}_1) = (\bar{p}_1 + S - M)V_1 - C + \delta \bar{\pi}_2(\bar{p}_2^*(\bar{p}_1)). \tag{10}$$

Proof of Theorem 7. The UCC's expected profit $\bar{\Pi}(\bar{p}_1)$ in Equation (10) depends on V_1. The different cases in Lemma 7 corresponding to different decisions of each carrier will lead to different values of V_1. In the following, we analyze each case of Lemma 7 to derive V_1 and obtain the UCC's expected total discounted profit and then determine the equilibrium price. To derive V_1, we need to distinguish the following two types of carriers:

Type 1 ($v_{i1} = v_L$): The expected number of carriers of this type is λn.

Type 2 ($v_{i1} = v_H$): The expected number of carriers of this type is $(1-\lambda)n$.

We first analyze the cases that $\tilde{n}_e > 0$ of Lemma 7, 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 $\tilde{n}_e = n_e(\bar{p}_1^*, \bar{p}_2^*) > 0$, $\tilde{m}_2 = m_2$, $\tilde{m}_3 = m_3$, $\tilde{m}_4 = m_4$, $\tilde{m}_5 = m_5$, and $\tilde{m}_6 = m_6$.

In case 1(a) ($\tilde{n}_e > 0$ and $m \le \min\{m_1, \tilde{m}_2, \tilde{m}_3\}$), $\bar{d}_{i1}^* = 1$ if $\bar{p}_1 \le m + \frac{c-h}{v_{i1}}$, or $\bar{d}_{i1}^* = -1$ otherwise. Thus, type 1 carriers use the UCC's service and keep their logistics capability if $\bar{p}_1 \le m + \frac{c-h}{v_L}$, and type 2 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 $m_1 < m \le \min\{\tilde{m}_4, \tilde{m}_5\}$) and 1(c) ($\tilde{n}_e > 0$ and $\max\{\tilde{m}_2, \tilde{m}_4\} < m \le \tilde{m}_6$), since we assume 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 $m \geq \max\{\tilde{m}_3, \tilde{m}_5, \tilde{m}_6\}$), $\bar{d}^*_{i1} = 0$ if $\bar{p}_1 \leq m + \frac{c}{v_{i1}}$, or $\bar{d}^*_{i1} = -1$ otherwise. Thus, type 1 carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \leq m + \frac{c}{v_L}$, and type 2 carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \leq m + \frac{c}{v_H}$. In case 1(d), we have obtained that $\bar{p}^*_2 = m + \frac{c}{v_H}$ according to Lemma 6. The optimal choice of the UCC 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 1 carriers only, then $V_1 = \lambda n v_L$. Since type 1 carriers use the UCC's service and eliminate their logistics capability, thus $n_e = \lambda n$. Substituting them into Equation (10), the UCC's expeted total discounted profit is

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

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 $n_e > 0$ (which is satisfied) and $m > \max\{m_3, m_5, m_6\}$. Substituting $n_e = \lambda n$ into m_3, m_5, and m_6, we can rewrite the latter conition as $m > \max\{\hat{m}_1, \hat{m}_2, \hat{m}_3\}$. This leads to the results in case 1 of Theorem 7.

2. Choose a price $\bar{p}_1 \in \left(0, m + \frac{c}{v_H}\right]$ to attract both types of carriers, then $V_1 = \lambda n v_L + (1-\lambda) n v_H$. Since all the carriers use the UCC's service and eliminate their logistics capability, thus $n_e = n$. Substituting them into Equation (10), the UCC's expeted total discounted profit is

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

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 $n_e > 0$ (which is satisfied) and $m > \max\{m_3, m_5, m_6\}$. Substituting $n_e = n$ into m_3, m_5, and m_6, we find that the latter condition can never be satisfied as m_5 and m_6 go to infinity. Thus, this choice is not in equilibrium.

Next we analyze the cases that $\tilde{n}_e = 0$ of Lemma 7, 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 $m \leq \bar{m}$, since we assume that $h \leq \min\left\{\delta(c+f)\left(\lambda \frac{v_L}{v_H} + 1 - \lambda\right) - \delta c, \delta c \left(\lambda + (1-\lambda)\frac{v_H}{v_L}\right) - \delta c\right\}$, and thus we can obtain $\bar{d}^*_{i1} = 1$ if $\bar{p}_1 \leq m + \frac{c-h}{v_{i1}}$, or $\bar{d}^*_{i1} = -1$ otherwise. Therefore, type 1 carriers use the UCC's service and keep their logistics capability if $\bar{p}_1 \leq m + \frac{c-h}{v_L}$, and type 2 carriers use the UCC's service and keep 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 6. Thus, the optimal choice of the UCC 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 1 carriers only, then $V_1 = \lambda n v_L$. Since no carrier will use the UCC's service and eliminate his logistics capability, thus $n_e = 0$. Substituting them into Equation (10), the UCC's expeted total discounted profit is

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

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 $n_e = 0$ (which is satisfied) and $m \leq \bar{m}$. Substituting $\bar{p}^*_1 = m + \frac{c-h}{v_L}$ into Equation (13), we can obtain that $\bar{\Pi}\left(m + \frac{c-h}{v_L}\right) = (1+\delta)(m+S-M)\lambda n v_L + ((1+\delta)c - h)\lambda n - (1+\delta)C$.

2. Choose a price $\bar{p}_1 \in \left(0, m + \frac{c-h}{v_H}\right]$ to attract both types of carriers, then $V_1 = \lambda n v_L + (1-\lambda) n v_H$. Since no carrier will use the UCC's service and eliminate logistics capability, thus $n_e = 0$. Substituting them into Equation (10), the UCC's expeted total discounted profit is

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

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 $n_e = 0$ (which is satisfied) and $m \leq \bar{m}$. Substituting $\bar{p}^*_1 = m + \frac{c-h}{v_H}$ into Equation (14), we can obtain that $\bar{\Pi}\left(m + \frac{c-h}{v_H}\right) = (m + S - M)((1+\delta)\lambda n v_L + (1-\lambda) n v_H) + \delta \lambda c n + (c-h) n \left(\lambda \frac{v_L}{v_H} + 1 - \lambda\right) - (1+\delta)C$.

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 $\bar{\Pi}\left(m+\frac{c-h}{v_L}\right) \geq \bar{\Pi}\left(m+\frac{c-h}{v_H}\right)$ if $m \leq \frac{\left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right)(c-h)+(M-S)(1-\lambda)v_H}{(1-\lambda)v_H}$. Since we assume that $\lambda \leq v_H/(2v_H - v_L)$, then we can obtain $\frac{\left(\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right)(c-h)+(M-S)(1-\lambda)v_H}{(1-\lambda)v_H} \geq \bar{m}$. Therefore, $\bar{\Pi}\left(m+\frac{c-h}{v_L}\right) \geq \bar{\Pi}\left(m+\frac{c-h}{v_H}\right)$ always holds if $m \leq \bar{m}$, and thus in equilibrium, the optimal price is $\bar{p}_1^* = m + \frac{c-h}{v_L}$. This leads to the results in case 2 of Theorem 7.

In case 2(b) ($\tilde{n}_e = 0$ and $m > \bar{m}$), $\bar{d}_{i1}^* = 0$ if $\bar{p}_1 \leq m + \frac{c}{v_{i1}}$, or $\bar{d}_{i1}^* = -1$ otherwise. Thus, type 1 carriers use the UCC's service and eliminate their logistics capability if $\bar{p}_1 \leq m + \frac{c}{v_L}$, and type 2 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 this case is not in equilibrium. □

Under the two-period capacity sharing platform model, we define $\hat{\phi}_{i2}\left(\hat{d}_{i2}; \hat{d}_{i1}, \hat{p}_2\right)$ as the expected cost of period 2 low type carrier i. If carrier i delivers by himself and sells his remaining capacity to the platform, then the expected revenue generated from selling his remaining capacity depends on the supply (proportional to the number of carriers who sell remaining capacity on the platform, which is denoted by $n_{s,2}$) and the demand (proportional to the number of carriers who purchase capacity on the platform, which is denoted by $n_{p,2}$) of capacity on the platform in period 2. To identify a subgame perfect Nash Equilibrium with rational expectations, we assume all the carriers 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, $\tilde{n}_{s,2} = n_{s,2}\left(\hat{d}_{i2}^*\right)$ and $\tilde{n}_{p,2} = n_{p,2}\left(\hat{d}_{i2}^*\right)$ in equilibrium. Define $\theta_t = \min\{\tilde{n}_{p,t}/\tilde{n}_{s,t}, 1\}$, for $t = 1, 2$. Each low type carrier i 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 same as in the one-period platform model, 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.

Lemma 8. (Optimal decision of the period 2 low type carrier i under the platform model)
1. If $\hat{d}_{i1} = -1$ or 1, then in period 2 carrier i purchases capacity from the platform ($\hat{d}_{i2}^* = 0$) if $\hat{p}_2 < \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or delivers on his own and sells remaining capacity on the platform ($\hat{d}_{i2}^* = -1$) if $\hat{p}_2 > \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or chooses either option with probability 0.5 if $\hat{p}_2 = \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$.
2. If $\hat{d}_{i1} = 0$, then in period 2, carrier i purchases capacity from the platform ($\hat{d}_{i2}^* = 0$) if $\hat{p}_2 < \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or delivers on his own and sells remaining capacity on the platform ($\hat{d}_{i2}^* = -1$) if $\hat{p}_2 > \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or chooses either option with probability 0.5 if $\hat{p}_2 = \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$.

Proof of Lemma 8. By solving $\hat{\phi}_{i2}(0; \hat{d}_{i1}, \hat{p}_2) < \hat{\phi}_{i2}(-1; \hat{d}_{i1}, \hat{p}_2)$ for v_{i2}, we obtain that
1. $\hat{p}_2 < \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$ if $\hat{d}_{i1} = -1$ or 1. Thus, $\hat{d}_{i2}^* = 0$ if $\hat{p}_2 < \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, and $\hat{d}_{i2}^* = -1$ if $\hat{p}_2 > \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$.
2. $\hat{p}_2 < \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$ if $\hat{d}_{i1} = 0$. Thus, $\hat{d}_{i2}^* = 0$ if $\hat{p}_2 < \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, and $\hat{d}_{i2}^* = -1$ if $\hat{p}_2 > \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$. □

Anticipating the carriers' optimal decision $\hat{d}_{i2}^*$, the capacity sharing platform chooses $\hat{p}_2$ to maximize her expected profit in period 2:

$$\hat{\pi}_2(\hat{p}_2) = (\alpha\hat{p}_2 v_L - A)\min\{n_{s,2}, n_{p,2}\}. \tag{15}$$

Lemma 9. (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.

$$\hat{p}_2^* = \begin{cases} \frac{(2n-n_e)(c+f)+2nmv_L}{(2n-\alpha n_e)v_L}, & \text{if } (2-\alpha)n_e[(2n-n_e)(c+f)+2nmv_L] \\ & \quad -(2n-\alpha n_e)(n-n_e)(c+2mv_L) > \frac{(2-\alpha)(2n-\alpha n_e)(2n_e-n)A}{\alpha} \text{ and} \\ & (2-\alpha)n_e[(2n-n_e)(c+f)+2nmv_L] \\ & \quad -2(2n-\alpha n_e)(n-n_e)(c+f+2mv_L) \\ & \quad > \frac{(2-\alpha)(3n_e-2n)(2n-\alpha n_e)A}{\alpha}; \\ \frac{c+f+2mv_L}{(2-\alpha)v_L} - \epsilon, & \text{if } (2-\alpha)n_e[(2n-n_e)(c+f)+2nmv_L] \\ & \quad -2(2n-\alpha n_e)(n-n_e)(c+f+2mv_L) \\ & \quad \leq \frac{(2-\alpha)(3n_e-2n)(2n-\alpha n_e)A}{\alpha} \text{ and} \\ & c+2f+2mv_L > \frac{A}{\alpha}; \\ \frac{c+2mv_L}{(2-\alpha)v_L}, & \text{if } (2-\alpha)n_e[(2n-n_e)(c+f)+2nmv_L] \\ & \quad -(2n-\alpha n_e)(n-n_e)(c+2mv_L) \leq \frac{(2-\alpha)(2n-\alpha n_e)(2n_e-n)A}{\alpha} \text{ and} \\ & c+2f+2mv_L \leq \frac{A}{\alpha}. \end{cases}$$

2. If $n_e \leq n/2$, the optimal price of the UCC's service in period 2 is as follows.

$$\hat{p}_2^* = \begin{cases} \frac{(2n-n_e)(c+f)+2nmv_L}{(2n-\alpha n_e)v_L}, & \text{if } 2n^2mv_L + (c+f)[2n(n-n_e)-n_e(n-\alpha n_e)] \leq \\ & \quad \frac{(n-\alpha n_e)(2n-\alpha n_e)A}{\alpha} \text{ and} \\ & (2-\alpha)n_e[(2n-n_e)(c+f)+2nmv_L] \\ & \quad -(2n-\alpha n_e)(n-n_e)(c+2mv_L) > \frac{(2-\alpha)(2n-\alpha n_e)(2n_e-n)A}{\alpha}; \\ \frac{(n-n_e)(c+f)+nmv_L}{(n-\alpha n_e)v_L} - \epsilon, & \text{if } 2n^2mv_L + (c+f)[2n(n-n_e)-n_e(n-\alpha n_e)] > \\ & \quad \frac{(n-\alpha n_e)(2n-\alpha n_e)A}{\alpha} \text{ and} \\ & 2(2-\alpha)n_e[(n-n_e)(c+f)+nmv_L] \\ & \quad -(n-\alpha n_e)(n-n_e)(c+2mv_L) > \frac{(2-\alpha)(n-\alpha n_e)(3n_e-n)A}{\alpha}; \\ \frac{c+2mv_L}{(2-\alpha)v_L}, & \text{if } (2-\alpha)n_e[(2n-n_e)(c+f)+2nmv_L] \\ & \quad -(2n-\alpha n_e)(n-n_e)(c+2mv_L) \leq \frac{(2-\alpha)(2n-\alpha n_e)(2n_e-n)A}{\alpha} \text{ and} \\ & 2(2-\alpha)n_e[(n-n_e)(c+f)+nmv_L] \\ & \quad -(n-\alpha n_e)(n-n_e)(c+2mv_L) \leq \frac{(2-\alpha)(n-\alpha n_e)(3n_e-n)A}{\alpha}. \end{cases}$$

Proof of Lemma 9. To derive $n_{s,2}$ and $n_{p,2}$ in the platform's expected profit function in Equation (15), we need to distinguish the following two types of carriers:

Type 1 ($\hat{d}_{i1} = -1$ or 1, and $v_{i2} = v_L$): Each carrier i of this type purchases capacity from the platform in period 2 if $\hat{p}_2 < \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or delivers on his own and sell remaining capacity on the platform if $\hat{p}_2 > \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or chooses either option with same probability if $\hat{p}_2 = \frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$. The expected number of carriers of this type is $\lambda(\lambda n - n_e) + \lambda(1-\lambda)n$.

Type 2 ($\hat{d}_{i1} = 0$, and $v_{i2} = v_L$): Each carrier i of this type purchases capacity from the platform in period 2 if $\hat{p}_2 < \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or delivers on his own and sell capacity on the platform if $\hat{p}_2 > \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$, or chooses either option with same probability if $\hat{p}_2 = \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$. 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 $\hat{p}_2 = \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$ to incentivize type 1 carriers to deliver on their own and sell their remaining capacity, and type 2 carriers to purchase or sell capacity with same probability. Then we can obtain $n_{s,2} = \lambda(\lambda n - n_e) + \lambda(1-\lambda)n + \frac{\lambda n_e}{2}$ and $n_{p,2} = \frac{\lambda n_e}{2}$. Substituting them into θ_2, we obtain $\theta_2 = \frac{n_e}{2n-n_e}$. Substituting them to $\hat{p}_2$ and Equation (15), we obtain the platform's expected profit:

$$\begin{aligned} \hat{\pi}_2\left(\frac{(2n-n_e)(c+f)+2nmv_L}{(2n-\alpha n_e)v_L}\right) &= \left(\frac{\alpha[(2n-n_e)(c+f)+2nmv_L]}{2n-\alpha n_e} - A\right)\min\left\{\lambda(\lambda n - n_e) + \lambda(1-\lambda)n + \frac{\lambda n_e}{2}, \frac{\lambda n_e}{2}\right\} \\ &= \frac{\alpha\lambda n_e[(2n-n_e)(c+f)+2nmv_L]}{2(2n-\alpha n_e)} - \frac{\lambda n_e A}{2}. \end{aligned}$$

2. Choose a price $\hat{p}_2 = \frac{c+f+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L} - \epsilon$ to incentivize type 1 carriers to deliver on their own and sell their remaining capacity, and type 2 carriers to purchase capacity from the platform. Then we can obtain $n_{s,2} = \lambda(\lambda n - n_e) + \lambda(1-\lambda)n$ and $n_{p,2} = \lambda n_e$. Substituting them into θ_2, we obtain $\theta_2 = \min\{\frac{n_e}{n-n_e}, 1\}$. Substituting them to $\hat{p}_2$, we obtain that

$$\hat{p}_2 = \begin{cases} \frac{(n-n_e)(c+f)+nmv_L}{(n-\alpha n_e)v_L} - \epsilon, & \text{if } n_e \leq n/2; \\ \frac{c+f+2mv_L}{(2-\alpha)v_L} - \epsilon, & \text{if } n_e > n/2. \end{cases}$$

Substituting $\hat{p}_2$, $n_{s,2}$, and $n_{p,2}$ into Equation (15), we obtain the platform's expected profit:

(1) If $n_e \leq n/2$, then

$$\begin{aligned}\hat{\pi}_2\left(\frac{(n-n_e)(c+f)+nmv_L}{(n-\alpha n_e)v_L}-\epsilon\right) &= \left(\frac{\alpha[(n-n_e)(c+f)+nmv_L]}{n-\alpha n_e}-A-\epsilon\right)\min\{\lambda(\lambda n-n_e)+\lambda(1-\lambda)n,\lambda n_e\}\\ &= \frac{\alpha\lambda n_e[(n-n_e)(c+f)+nmv_L]}{n-\alpha n_e}-\lambda n_e A-\epsilon.\end{aligned}$$

(2) If $n_e > n/2$, then

$$\begin{aligned}\hat{\pi}_2\left(\frac{c+f+2mv_L}{(2-\alpha)v_L}-\epsilon\right) &= \left(\frac{\alpha[(n-n_e)(c+f)+nmv_L]}{n-\alpha n_e}-A-\epsilon\right)\min\{\lambda(\lambda n-n_e)+\lambda(1-\lambda)n,\lambda n_e\}\\ &= \frac{\alpha\lambda(n-n_e)(c+f+2mv_L)}{2-\alpha}-\lambda(n-n_e)A-\epsilon.\end{aligned}$$

3. Choose a price $\hat{p}_2=\frac{c+(1+\theta_2)mv_L}{[1+\theta_2(1-\alpha)]v_L}$ 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 $n_{s,2}=\frac{\lambda(\lambda n-n_e)+\lambda(1-\lambda)n}{2}$, and $n_{p,2}=\frac{\lambda(\lambda n-n_e)+\lambda(1-\lambda)n}{2}+\lambda n_e$. Substituting them into θ_2, we obtain $\theta_2=1$. Substituting them to $\hat{p}_2$ and Equation (15), we obtain the platform's expected profit:

$$\begin{aligned}\hat{\pi}_2\left(\frac{c+2mv_L}{(2-\alpha)v_L}\right) &= \left(\frac{\alpha(c+2mv_L)}{2-\alpha}-A\right)\min\left\{\frac{\lambda(\lambda n-n_e)+\lambda(1-\lambda)n}{2},\frac{\lambda(\lambda n-n_e)+\lambda(1-\lambda)n}{2}+\lambda n_e\right\}\\ &= \frac{\alpha\lambda(c+2mv_L)(n-n_e)}{2(2-\alpha)}-\frac{\lambda(n-n_e)A}{2}.\end{aligned}$$

The capacity sharing platform's optimal price will be the one yields the largest profit, and thus by comparing the profits of the platform under choices 1, 2 and 3, we can obtain the results in Lemma 9. □

In period 1, if a low type carrier delivers on his own and sells his remaining capacity on the platform, then the expected cost of this carrier depends on $n_{s,1}$ and $n_{p,1}$, which are the numbers of carriers who sell capacity and who purchase capacity respectively. To identify a subgame perfect Nash Equilibrium with rational expectations, we assume all the low type carriers in period 1 form the same rational beliefs $\tilde{n}_{s,1}$ and $\tilde{n}_{p,1}$ about $n_{s,1}$ and $n_{p,1}$, respectively, when optimizing their decisions in period 1. In addition, we assume they form the same rational belief $\tilde{n}_e$ about n_e. Furthermore, $\tilde{n}_{s,1}=n_{s,1}\left(\hat{d}^*_{i1}\right)$, $\tilde{n}_{p,1}=n_{p,1}\left(\hat{d}^*_{i1}\right)$, and $\tilde{n}_e=n_e$ in equilibrium. Define $\hat{\Phi}_i\left(\hat{d}_{i1};\hat{p}_1\right)$ as the expected total discounted cost of each low type carrier i in period 1. Given $\hat{p}_1$, each carrier i 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 $\hat{\Phi}_i\left(-1;\hat{p}_1\right)=c+mv_L-\theta_1\left[(1-\alpha)\hat{p}_1-m\right]v_L+\delta\hat{\phi}^*_{i2}(-1)$.

(ii) $\hat{d}_{i1}=0$: Carrier i purchases capacity from the platform and eliminates his logistics capability, which incurs an expected total discounted cost $\hat{\Phi}_i\left(0;\hat{p}_1\right)=\hat{p}_1v_L+\delta\hat{\phi}^*_{i2}(0)$.

(iii) $\hat{d}_{i1}=1$: Carrier i purchases capacity from the platform and keeps his logistics capability, which incurs an expected total discounted cost $\hat{\Phi}_i\left(1;\hat{p}_1\right)=\hat{p}_1v_L+h+\delta\hat{\phi}^*_{i2}(1)$.

Lemma 10. (Optimal decision of the period 1 low type carrier i under the platform model) *Each carrier i purchases capacity from the platform and keep his logistics capability ($\hat{d}^*_{i1}=1$) if $\hat{p}_1<\frac{c+2mv_L-h}{(2-\alpha)v_L}$, or delivers on his own and sells remaining capacity on the platform ($\hat{d}^*_{i1}=-1$) if $\hat{p}_1>\frac{c+2mv_L-h}{(2-\alpha)v_L}$, or chooses either option with probability 0.5 if $\hat{p}_1=\frac{c+2mv_L-h}{(2-\alpha)v_L}$.*

Proof of Lemma 10. We first determine the carrier's optimal decision in the case that $\tilde{n}_e>n/2$, $(2-\alpha)\tilde{n}_e[(2n-\tilde{n}_e)(c+f)+2nmv_L]-(2n-\alpha\tilde{n}_e)(n-\tilde{n}_e)(c+2mv_L)>\frac{(2-\alpha)(2n-\alpha\tilde{n}_e)(2\tilde{n}_e-n)A}{\alpha}$ and $(2-\alpha)\tilde{n}_e[(2n-\tilde{n}_e)(c+f)+2nmv_L]-2(2n-\alpha\tilde{n}_e)(n-\tilde{n}_e)(c+f+2mv_L)>\frac{(2-\alpha)(3\tilde{n}_e-2n)(2n-\alpha\tilde{n}_e)A}{\alpha}$; or the case that $\tilde{n}_e\le n/2$, $2n^2mv_L+(c+f)[2n(n-\tilde{n}_e)-\tilde{n}_e(n-\alpha\tilde{n}_e)]\le\frac{(n-\alpha\tilde{n}_e)(2n-\alpha\tilde{n}_e)A}{\alpha}$ and $(2-\alpha)\tilde{n}_e[(2n-\tilde{n}_e)(c+f)+2nmv_L]-(2n-\alpha\tilde{n}_e)(n-\tilde{n}_e)(c+2mv_L)>\frac{(2-\alpha)(2n-\alpha\tilde{n}_e)(2\tilde{n}_e-n)A}{\alpha}$. In these cases, according to Lemma 9, $\hat{p}^*_2=\frac{(2n-\tilde{n}_e)(c+f)+2nmv_L}{(2n-\alpha\tilde{n}_e)v_L}$. Each carrier i minimizes his total discounted cost $\hat{\Phi}_i\left(\hat{d}_{i1};\hat{p}_1\right)$ by comparing the following three options:

1. $\hat{d}_{i1}=-1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(-1;\hat{p}_1)=c+mv_L-\theta_1[(1-\alpha)p_1-m]v_L+\delta(\lambda(c+mv_L-\theta_2[(1-\alpha)\hat{p}^*_2-m]v_L)+(1-\lambda)(c+mv_H))$.

2. $\hat{d}_{i1}=0$: In this case, according to lemmas 8 and 9, carrier i will purchase capacity from the platform or deliver on his own and sell capacity in period 2 with the same probability (if he has low task volume in period 2, i.e., $v_{i2}=v_L$). This incurs an expected total discounted cost $\hat{\Phi}_i(0;\hat{p}_1)=p_1v_L+\delta(\lambda(\hat{p}^*_2v_L/2+(c+mv_L-\theta_2[(1-\alpha)\hat{p}^*_2-m]v_L+f)/2)+(1-\lambda)(c+mv_H+f))$.

3. $\hat{d}_{i1}=1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(1;\hat{p}_1)=p_1v_L+h+\delta(\lambda(c+mv_L-\theta_2[(1-\alpha)\hat{p}^*_2-m]v_L)+(1-\lambda)(c+mv_H))$.

By comparing the above three options, we obtain that

$$\hat{d}_{i1} = \begin{cases} -1, & \text{if } p_1 > (c + 2mv_L - h)/((2-\alpha)v_L); \\ 1, & \text{if } p_1 < (c + 2mv_L - h)/((2-\alpha)v_L). \end{cases}$$

Next we determine the carrier's optimal decision in the case that $\tilde{n}_e > n/2$, $(2-\alpha)\tilde{n}_e[(2n-\tilde{n}_e)(c+f) + 2nmv_L] - 2(2n - \alpha\tilde{n}_e)(n-\tilde{n}_e)(c+f+2mv_L) \le \frac{(2-\alpha)(3\tilde{n}_e-2n)(2n-\alpha\tilde{n}_e)A}{\alpha}$, and $c + 2f + 2mv_L > \frac{A}{\alpha}$. In this case, according to Lemma 9, $\hat{p}_2^* = \frac{c+f+2mv_L}{(2-\alpha)v_L} - \epsilon$. Each carrier i minimizes his total discounted cost $\hat{\Phi}_i\left(\hat{d}_{i1}; \hat{p}_1\right)$ by comparing the following three options:

1. $\hat{d}_{i1} = -1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(-1; \hat{p}_1) = c + mv_L - \theta_1[(1-\alpha)p_1 - m]v_L + \delta(\lambda(c + mv_L - \theta_2[(1-\alpha)\hat{p}_2^* - m]v_L) + (1-\lambda)(c + mv_H))$.
2. $\hat{d}_{i1} = 0$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(0; \hat{p}_1) = p_1 v_L + \delta(\lambda\hat{p}_2^* v_L + (1-\lambda)(c + mv_H + f))$.
3. $\hat{d}_{i1} = 1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(1; p_1) = p_1 v_L + h + \delta(\lambda(c + mv_L - \theta_2[(1-\alpha)\hat{p}_2^* - m]v_L) + (1-\lambda)(c + mv_H))$. By comparing the above three options, we obtain the same results as in the above case.

Next, we determine the carrier's optimal decision in the case that $\tilde{n}_e \le n/2$, $2n^2mv_L + (c+f)[2n(n-\tilde{n}_e) - \tilde{n}_e(n-\alpha\tilde{n}_e)] > \frac{(n-\alpha\tilde{n}_e)(2n-\alpha\tilde{n}_e)A}{\alpha}$, and $2(2-\alpha)\tilde{n}_e[(n-\tilde{n}_e)(c+f) + nmv_L] - (n-\alpha\tilde{n}_e)(n-\tilde{n}_e)(c+2mv_L) > \frac{(2-\alpha)(n-\alpha\tilde{n}_e)(3\tilde{n}_e-n)A}{\alpha}$. In this case, according to Lemma 9, $\hat{p}_2^* = \frac{(n-\tilde{n}_e)(c+f)+nmv_L}{(n-\alpha\tilde{n}_e)v_L} - \epsilon$. Each carrier i minimizes his total discounted cost $\hat{\Phi}_i\left(\hat{d}_{i1}; \hat{p}_1\right)$ by comparing the following three options:

1. $\hat{d}_{i1} = -1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(-1; \hat{p}_1) = c + mv_L - \theta_1[(1-\alpha)p_1 - m]v_L + \delta(\lambda(c + mv_L - \theta_2[(1-\alpha)\hat{p}_2^* - m]v_L) + (1-\lambda)(c + mv_H))$.
2. $\hat{d}_{i1} = 0$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(0; \hat{p}_1) = p_1 v_L + \delta(\lambda\hat{p}_2^* v_L + (1-\lambda)(c + mv_H + f))$.
3. $\hat{d}_{i1} = 1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(1; p_1) = p_1 v_L + h + \delta(\lambda(c + mv_L - \theta_2[(1-\alpha)\hat{p}_2^* - m]v_L) + (1-\lambda)(c + mv_H))$. By comparing the above three options, we obtain the same results as in the above two cases.

Finally, we determine the carrier's optimal decision in the case that $\tilde{n}_e > n/2$, $(2-\alpha)\tilde{n}_e[(2n-\tilde{n}_e)(c+f)+2nmv_L] - (2n-\alpha\tilde{n}_e)(n-\tilde{n}_e)(c+2mv_L) \le \frac{(2-\alpha)(2n-\alpha\tilde{n}_e)(2\tilde{n}_e-n)A}{\alpha}$, and $c+2f+2mv_L \le \frac{A}{\alpha}$; or the case that $\tilde{n}_e \le n/2$, $(2-\alpha)\tilde{n}_e[(2n-\tilde{n}_e)(c+f)+2nmv_L] - (2n-\alpha\tilde{n}_e)(n-\tilde{n}_e)(c+2mv_L) \le \frac{(2-\alpha)(2n-\alpha\tilde{n}_e)(2\tilde{n}_e-n)A}{\alpha}$, and $2(2-\alpha)\tilde{n}_e[(n-\tilde{n}_e)(c+f) + nmv_L] - (n-\alpha\tilde{n}_e)(n-\tilde{n}_e)(c+2mv_L) \le \frac{(2-\alpha)(n-\alpha\tilde{n}_e)(3\tilde{n}_e-n)A}{\alpha}$. In these cases, according to Lemma 9, $\hat{p}_2^* = \frac{c+2mv_L}{(2-\alpha)v_L}$. Each carrier i minimizes his total discounted cost $\hat{\Phi}_i\left(\hat{d}_{i1}; \hat{p}_1\right)$ by comparing the following three options:

1. $\hat{d}_{i1} = -1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(-1; p_1) = c + mv_L - \theta_1[(1-\alpha)p_1 - m]v_L + \delta(\lambda(\hat{p}_2^* v_L/2 + (c + mv_L - \theta_2[(1-\alpha)\hat{p}_2^* - m]v_L)/2) + (1-\lambda)(c + mv_H))$.
2. $\hat{d}_{i1} = 0$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(0; p_1) = p_1 v_L + \delta(\lambda\hat{p}_2^* v_L + (1-\lambda)(c + mv_H + f))$.
3. $\hat{d}_{i1} = 1$: In this case, according to lemmas 8 and 9, 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 $\hat{\Phi}_i(1; p_1) = p_1 v_L + h + \delta(\lambda(\hat{p}_2^* v_L/2 + (c + mv_L - \theta_2[(1-\alpha)\hat{p}_2^* - m]v_L)/2) + (1-\lambda)(c + mv_H))$.

By comparing the above three options, we obtain the same results as in the above three cases. Therefore, we have the same result for all the cases, and thus Lemma 10 follows. ☐

Proof of Theorem 8. Anticipating the carriers' responses $\hat{d}_{i1}^*$, the platform optimize her price $\hat{p}_1$ to maximize her expected total discounted profit $\hat{\Pi}(\hat{p}_1) = (\alpha\hat{p}_1 v_L - A)\min\{n_{s,1}, n_{p,1}\} + \delta\hat{\pi}_2(\hat{p}_2^*(\hat{p}_1))$. According to Lemma 10, each low type carrier in period 1 either delivers on his own and sells his remaining capacity on the platform, or purchases capacity on the platform and keeps his own logistics capability. Thus,

$\tilde{n}_e = n_e = 0$ in equilibrium. Substituting it into lemmas 8, 9 and 10, we can identify the following three candidates for equilibrium.

(1) If $m \le \min\left\{\frac{A-\alpha(c+f)}{\alpha v_L}, \frac{(2-\alpha)A-\alpha c}{2\alpha v_L}\right\}$, then in period 1, 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 choose either option with 0.5 probability if $\hat{p}_1 = \frac{c+2mv_L-h}{(2-\alpha)v_L}$. In period 2, $\hat{p}_2^* = m + \frac{c+f}{v_L}$ and each carrier delivers on his own and sells remaining capacity on the platform. It's optimal for the platform to choose $\hat{p}_1^* = \frac{c+2mv_L-h}{(2-\alpha)v_L}$ to maximize her expected total profit. Since $A < \alpha\hat{p}_1^* v_L$ and $A < \alpha\hat{p} *_2 v_L$, the condition $m \le \min\left\{\frac{A-\alpha(c+f)}{\alpha v_L}, \frac{(2-\alpha)A-\alpha c}{2\alpha v_L}\right\}$ cannot hold, and thus this case is not in equilibrium.

(2) If $\frac{A-\alpha(c+f)}{\alpha v_L} < m \le \frac{(2-\alpha)A-\alpha c}{2\alpha v_L}$, then in period 1, 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 choose either option with 0.5 probability if $\hat{p}_1 = \frac{c+2mv_L-h}{(2-\alpha)v_L}$. In period 2, $\hat{p}_2^* = m + \frac{c+f}{v_L} - \epsilon$ and each carrier delivers on his own and sells remaining capacity on the platform. It's optimal for the platform to choose $\hat{p}_1^* = \frac{c+2mv_L-h}{(2-\alpha)v_L}$ to maximize her expected total profit. Since $A < \alpha\hat{p}_1^* v_L$, the condition $m \le \frac{(2-\alpha)A-\alpha c}{2\alpha v_L}$ cannot hold, and thus this case is not in equilibrium.

(3) If $m > \frac{(2-\alpha)A-\alpha c}{2\alpha v_L}$, then in period 1, 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 choose either option with 0.5 probability if $\hat{p}_1 = \frac{c+2mv_L-h}{(2-\alpha)v_L}$. In period 2, $\hat{p}_2^* = \frac{c+2mv_L}{(2-\alpha)v_L}$ and each carrier delivers on his own and sells remaining capacity on the platform or purchase capacity from the platform with the same probability . It's optimal for the platform to choose $\hat{p}_1^* = \frac{c+2mv_L-h}{(2-\alpha)v_L}$ to maximize her expected total profit. Since $A < \alpha\hat{p}_1^* v_L$ and $A < \alpha\hat{p} *_2 v_L$, the condition $m > \frac{(2-\alpha)A-\alpha c}{2\alpha v_L}$ always holds, and thus this case leads to the result in this theorem. $\square$

B Heterogeneous fixed delivery costs

Suppose that there are two groups of carriers: a fraction η of them have low fixed delivery cost c_L and a fraction $(1-\eta)$ of them have high fixed delivery cost $c_H (> c_L)$. Everything else remains the same as the base model. The following two theorems describe the equilibrium outcomes under the UCC model and under the platform model respectively.

Theorem 11. (Equilibrium decisions under the UCC model with heterogenous carriers' delivery cost) *Define* $\bar{m}_1 = M - S + \frac{\lambda(1-\eta)c_H - c_L\left(\lambda\frac{v_L}{v_H}+1-\lambda\right)}{\lambda\eta v_L+(1-\lambda)v_H}$, $\bar{m}_2 = M - S + \frac{(1-\eta)c_H - c_L}{\eta v_H}$, $\bar{m}_3 = M - S + \frac{c_L\left[\lambda\left(1-\frac{v_L}{v_H}\right)+(1-\lambda)\left((1-\eta)\frac{v_H}{v_L}-1\right)\right]}{\eta(1-\lambda)v_H}$, $\bar{m}_4 = M - S + \frac{(1-\eta)\left(\lambda c_H-(1-\lambda)c_L\frac{v_H}{v_L}\right)-\lambda c_L}{\lambda\eta v_L+(1-\lambda)(1-\eta)v_H}$, $\bar{m}_5 = M - S + \frac{\lambda\left[(1-\eta)c_H\frac{v_L}{v_H}-c_L\right]+(1-\lambda)(1-\eta)(c_H-c_L\frac{v_H}{v_L})}{\lambda\eta v_L}$, $\bar{m}_6 = M - S + \frac{\lambda c_H\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)c_H}{(1-\lambda)v_H}$, $\bar{m}'_2 = M - S + \frac{c_L\left[\lambda\left(1-\frac{v_L}{v_H}\right)-(1-\lambda)\right]}{(1-\lambda)v_H}$, $\bar{m}'_3 = M - S + \frac{c_H\left(\lambda\frac{v_L}{v_H}+(1-\lambda)(1-\eta)\right)-c_L(\lambda\frac{v_L}{v_H}+1-\lambda)}{\eta(1-\lambda)v_H}$, $\bar{m}'_4 = M - S + \frac{c_H\left[(2\lambda-1)(1-\eta)-\lambda\frac{v_L}{v_H}\right]}{\lambda\eta v_L+(1-\lambda)(1-\eta)v_H}$, $\bar{m}'_5 = M - S + \frac{\lambda\left(c_L-c_H\frac{v_L}{v_H}\right)-(1-\lambda)(1-\eta)c_H}{(1-\lambda)(1-\eta)v_H}$, *and* $\bar{m}'_6 = M - S + \frac{(1-\eta)c_H-c_L}{\eta v_L}$.

1. *If* $\frac{c_L}{c_H} \le \frac{v_L}{v_H}$, *and*
   (a) $m > \max\{\bar{m}_1, \bar{m}_2, \bar{m}_3\}$, *then the UCC's optimal price is* $\bar{p}^* = m + c_L/v_H$. *Under this price, each carrier uses the UCC's service.*
   (b) $\max\{\bar{m}_4, \bar{m}_5\} < m \le \bar{m}_3$, *then the UCC's optimal price is* $\bar{p}^* = m + c_L/v_L$. *Under this price, each low type carrier uses the UCC's service, and each high type carrier uses the UCC's service if he has high fixed cost* c_H *and delivers on his own otherwise.*
   (c) $\bar{m}_6 < m \le \min\{\bar{m}_2, \bar{m}_5\}$, *then the UCC's optimal price is* $\bar{p}^* = m + c_H/v_H$. *Under this price, each carrier uses the UCC's service if he has high fixed cost* c_H *and delivers on his own otherwise.*
   (d) $m \le \min\{\bar{m}_1, \bar{m}_4, \bar{m}_6\}$, *then the UCC's optimal price is* $\bar{p}^* = m + c_H/v_L$. *Under this price, each low type carrier uses the UCC's service if he has high fixed cost* c_H*, and delivers on his own otherwise. Each high type carrier delivers on his own.*

2. *If* $\frac{c_L}{c_H} > \frac{v_L}{v_H}$, *and*
   (a) $m > \max\{\bar{m}_1, \bar{m}'_2, \bar{m}'_3\}$, *then the UCC's optimal price is* $\bar{p}^* = m + c_L/v_H$. *Under this price, each carrier uses the UCC's service.*
   (b) $\max\{\bar{m}'_4, \bar{m}'_5\} < m \le \bar{m}'_3$, *then the UCC's optimal price is* $\bar{p}^* = m + c_H/v_H$. *Under this price, each low type carrier uses the UCC's service, and each high type carrier uses the UCC's service if he has high fixed cost* c_H *and delivers on his own otherwise.*
   (c) $\bar{m}'_6 < m \le \min\{\bar{m}'_2, \bar{m}'_5\}$, *then the UCC's optimal price is* $\bar{p}^* = m + c_L/v_L$. *Under this price, each low type carrier uses the UCC's service and each high type carrier delivers on his own.*
   (d) $m \le \min\{\bar{m}'_1, \bar{m}'_4, \bar{m}'_6\}$, *then the UCC's optimal price is* $\bar{p}^* = m + c_H/v_L$. *Under this price, each low type carrier uses the UCC's service if he has high fixed cost* c_H*, and delivers on his own otherwise. Each high type carrier delivers on his own.*

Theorem 12. (Equilibrium decisions under the platform model with heterogenous carriers' delivery cost) *Define* $\bar{m}_7 = \frac{[2-\alpha(1-\eta)][1-\alpha(1-\eta)]A-2\alpha\eta c_H(2-\alpha(1-\eta))+\alpha c_H(1+\eta)(1-\alpha(1-\eta))}{2\alpha v_L}$, $\bar{m}_8 = \frac{[1-\alpha(1-\eta)](2-\alpha)(2-3\eta)A+\alpha\eta[1-\alpha(1-\eta)]c_L-2\alpha(2-\alpha)(1-\eta)\eta c_H}{2\alpha v_L((2-\alpha)(1-\eta)-\eta[1-\alpha(1-\eta)])}$, $\bar{m}_9 = \frac{(2\eta-1)(2-\alpha)(2-\alpha(1-\eta))A+\alpha(2-\alpha)(1-\eta)(1+\eta)c_H-\alpha\eta(2-\alpha(1-\eta))c_L}{2\alpha v_L(\eta(2-\alpha(1-\eta))-(2-\alpha)(1-\eta))}$, *and* $\bar{m}_{10} = \frac{(2-\alpha)(2-\alpha(1-\eta))(1-3\eta)A+2\alpha\eta(2-\alpha(1-\eta))c_H-\alpha(2-\alpha)(1+\eta)c_H}{2\alpha v_L(2-\alpha-2\eta[2-\alpha(1-\eta)])}$.

1. *If* $\eta \le\equiv \bar{\eta}$, *and*
   (a) $\bar{m}_{10} < m \le \bar{m}_9$, *then the platform's optimal price is* $\hat{p}^* = \frac{(1+\eta)c_H+2mv_L}{[2-\alpha(1-\eta)]v_L}$. *Under this price, each low type carrier delivers on his own if he has low fixed cost* c_L*. Otherwise, he delivers on his own or purchases capacity from the platform with same probability.*
   (b) $m \le \bar{m}_{10}$, *then the platform's optimal price is* $\hat{p}^* = \frac{c_H+2mv_L}{(2-\alpha)v_L} - \epsilon$. *Under this price, each low type carrier purchases capacity from the platform if he has high fixed cost* c_H *and delivers on his own otherwise.*

2. *If* $\bar{\eta} < \eta \le \frac{1}{2}$, *and*

(a) *$m > \bar{m}_{10}$, then the platform's optimal price is $\hat{p}^* = \frac{c_H + 2mv_L}{(2-\alpha)v_L} - \epsilon$. Under this price, each low type carrier purchases capacity from the platform if he has high fixed cost c_H and delivers on his own otherwise.*

(b) *$m \leq \min\{\bar{m}_9, \bar{m}_{10}\}$, then the platform's optimal price is $\hat{p}^* = \frac{(1+\eta)c_H + 2mv_L}{[2-\alpha(1-\eta)]v_L}$. Under this price, each low type carrier delivers on his own if he has low fixed cost c_L. Otherwise, he delivers on his own or purchases capacity from the platform with same probability.*

3. *If $\frac{1}{2} < \eta \leq 1 - \frac{3-\sqrt{9-4\alpha}}{2\alpha} \equiv \bar{\eta}'$, and*

   (a) *$m > \max\{\bar{m}_8, \bar{m}_9\}$, then the platform's optimal price is $\hat{p}^* = \frac{c_L + 2mv_L}{(2-\alpha)v_L}$. Under this price, each low type carrier purchases capacity from the platform if he has high fixed cost c_H. Otherwise, he delivers on his own or purchases capacity from the platform with same probability.*

   (b) *$\bar{m}_7 < m \leq \bar{m}_8$, then the platform's optimal price is $\hat{p}^* = \frac{\eta c_H + mv_L}{[1-\alpha(1-\eta)]v_L} - \epsilon$. Under this price, each low type carrier purchases capacity from the platform if he has high fixed cost c_H and delivers on his own otherwise.*

   (c) *$m \leq \min\{\bar{m}_7, \bar{m}_9\}$, then the platform's optimal price is $\hat{p}^* = \frac{(1+\eta)c_H + 2mv_L}{[2-\alpha(1-\eta)]v_L}$. Under this price, each low type carrier delivers on his own if he has low fixed cost c_L. Otherwise, he delivers on his own or purchases capacity from the platform with same probability.*

4. *If $\eta > \bar{\eta}'$, and*

   (a) *$m > \max\{\bar{m}_7, \bar{m}_8\}$, then the platform's optimal price is $\hat{p}^* = \frac{\eta c_H + mv_L}{[1-\alpha(1-\eta)]v_L} - \epsilon$. Under this price, each low type carrier purchases capacity from the platform if he has high fixed cost c_H and delivers on his own otherwise.*

   (b) *$\bar{m}_9 < m \leq \bar{m}_8$, then the platform's optimal price is $\hat{p}^* = \frac{c_L + 2mv_L}{(2-\alpha)v_L}$. Under this price, each low type carrier purchases capacity from the platform if he has high fixed cost c_H. Otherwise, he delivers on his own or purchases capacity from the platform with same probability.*

   (c) *$m \leq \min\{\bar{m}_7, \bar{m}_9\}$, then the platform's optimal price is $\hat{p}^* = \frac{(1+\eta)c_H + 2mv_L}{[2-\alpha(1-\eta)]v_L}$. Under this price, each low type carrier delivers on his own if he has low fixed cost c_L. Otherwise, he delivers on his own or purchases capacity from the platform with same probability.*

The following two propositions summarize the equilibrium profits of the consolidator under the UCC model and under the platform model respectively.

Proposition 5. (Equilibrium profit of the UCC under heterogenous carriers' delivery cost)

1. *If $\frac{c_L}{c_H} \leq \frac{v_L}{v_H}$, and*

   (a) *$m > \max\{\bar{m}_1, \bar{m}_2, \bar{m}_3\}$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_L}{v_H} + S - M)(\lambda n v_L + (1-\lambda)n v_H) - C$.*

   (b) *$\max\{\bar{m}_4, \bar{m}_5\} < m \leq \bar{m}_3$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_L}{v_L} + S - M)(\lambda n v_L + (1-\lambda)(1-\eta)n v_H) - C$.*

   (c) *$\bar{m}_6 < m \leq \min\{\bar{m}_2, \bar{m}_5\}$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_H}{v_H} + S - M)(1-\eta)(\lambda n v_L + (1-\lambda)n v_H) - C$.*

   (d) *$m \leq \min\{\bar{m}_1, \bar{m}_4, \bar{m}_6\}$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_H}{v_L} + S - M)(1-\eta)\lambda n v_L - C$.*

2. *If $\frac{c_L}{c_H} > \frac{v_L}{v_H}$, and*

   (a) *$m > \max\{\bar{m}_1, \bar{m}'_2, \bar{m}'_3\}$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_L}{v_H} + S - M)(\lambda n v_L + (1-\lambda)n v_H) - C$.*

   (b) *$\max\{\bar{m}'_4, \bar{m}'_5\} < m \leq \bar{m}'_3$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_H}{v_H} + S - M)(\lambda n v_L + (1-\lambda)(1-\eta)n v_H) - C$.*

   (c) *$\bar{m}'_6 < m \leq \min\{\bar{m}'_2, \bar{m}'_5\}$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_L}{v_L} + S - M)\lambda n v_L - C$.*

   (d) *$m \leq \min\{\bar{m}'_1, \bar{m}'_4, \bar{m}'_6\}$, then the UCC's expected profit is $\bar{\pi}^*(\bar{p}^*) = (m + \frac{c_H}{v_L} + S - M)(1-\eta)\lambda n v_L - C$.*

Proposition 6. (Equilibrium profit of the platform under heterogenous carriers' delivery cost)

1. *If $\eta \leq \bar{\eta}$, and*

(a) $\bar{m}_{10} < m \leq \bar{m}_9$, then the platform's expected profit is
$\hat{\pi}^*(\hat{p}^*) = \frac{\lambda(1-\eta)n}{2}\left(\frac{\alpha((1+\eta)c_H+2mv_L)}{2-\alpha(1-\eta)} - A\right)$.

(b) $m \leq \bar{m}_{10}$, then the platform's expected profit is $\hat{\pi}^*(\hat{p}^*) = \lambda\eta n\left(\frac{\alpha(c_H+2mv_L)}{2-\alpha} - A\right) - \epsilon$.

2. If $\bar{\eta} < \eta \leq \frac{1}{2}$, and

(a) $m > \bar{m}_{10}$, then the platform's expected profit is $\hat{\pi}^*(\hat{p}^*) = \lambda\eta n\left(\frac{\alpha(c_H+2mv_L)}{2-\alpha} - A\right) - \epsilon$.

(b) $m \leq \min\{\bar{m}_9, \bar{m}_{10}\}$, then the platform's expected profit is
$\hat{\pi}^*(\hat{p}^*) = \frac{\lambda(1-\eta)n}{2}\left(\frac{\alpha((1+\eta)c_H+2mv_L)}{2-\alpha(1-\eta)} - A\right)$.

3. If $\frac{1}{2} < \eta \leq \bar{\eta}'$, and

(a) $m > \max\{\bar{m}_8, \bar{m}_9\}$, then the platform's expected profit is $\hat{\pi}^*(\hat{p}^*) = \frac{\lambda\eta n}{2}\left(\frac{\alpha(c_L+2mv_L)}{2-\alpha} - A\right)$.

(b) $\bar{m}_7 < m \leq \bar{m}_8$, then the platform's expected profit is
$\hat{\pi}^*(\hat{p}^*) = \lambda(1-\eta)n\left(\frac{\alpha(\eta c_H+mv_L)}{1-\alpha(1-\eta)} - A\right) - \epsilon$.

(c) $m \leq \min\{\bar{m}_7, \bar{m}_9\}$, then the platform's expected profit is
$\hat{\pi}^*(\hat{p}^*) = \frac{\lambda(1-\eta)n}{2}\left(\frac{\alpha((1+\eta)c_H+2mv_L)}{2-\alpha(1-\eta)} - A\right)$.

4. If $\eta > \bar{\eta}'$, and

(a) $m > \max\{\bar{m}_7, \bar{m}_8\}$, then the platform's expected profit is
$\hat{\pi}^*(\hat{p}^*) = \lambda(1-\eta)n\left(\frac{\alpha(\eta c_H+mv_L)}{1-\alpha(1-\eta)} - A\right) - \epsilon$.

(b) $\bar{m}_9 < m \leq \bar{m}_8$, then the platform's expected profit is $\hat{\pi}^*(\hat{p}^*) = \frac{\lambda\eta n}{2}\left(\frac{\alpha(c_L+2mv_L)}{2-\alpha} - A\right)$.

(c) $m \leq \min\{\bar{m}_7, \bar{m}_9\}$, then the platform's expected profit is
$\hat{\pi}^*(\hat{p}^*) = \frac{\lambda(1-\eta)n}{2}\left(\frac{\alpha((1+\eta)c_H+2mv_L)}{2-\alpha(1-\eta)} - A\right)$.