Peak-hour Pricing under Negative Externality: Impact of Customer Flexibility and Competitive Asymmetry

Christopher S. Tang
UCLA Anderson School of Management, 110 Westwood Plaza, Los Angeles, CA 90095, USA,
chris.tang@anderson.ucla.edu

Onesun Steve Yoo
UCL School of Management, University College London, 1 Canada Square, London E14 5AB, United Kingdom,
onesun.yoo@ucl.ac.uk

Yufei Huang
Trinity Business School, Trinity College, Dublin 2, Ireland,
yufei.huang@tcd.ie

Several industries that provide services to customers (e.g., public utility and transportation) charge higher prices during peak hours to smooth demand. With technologies (e.g., electronic shelf labels) enabling retailers to change prices easily within each day, should supermarkets employ peak-hour pricing? To examine this question formally, we introduce a stylized duopoly model in the presence of "negative externality," where firms compete for congestion-averse customers. We characterize how customers endogenously segment themselves regarding when and where to shop, and then use the equilibrium outcomes to examine whether the firms should implement peak-hour pricing for varying types of customer flexibility and competitive asymmetry. Our analysis shows that, if customers are not flexible in their store choice, then both firms would always employ peak-hour pricing. However, if store choice flexibility is present, then firms' decisions depend on the competitive asymmetry as follows. If one firm has a clear competitive advantage (in terms of value or price) over the other firm, then the dominant firm will employ peak-hour pricing while the other firm will not. Otherwise, both firms will employ peak-hour pricing if they engage in symmetric competition (in terms of similar value and price), or neither firm will employ it if they engage in differentiated competition (high value vs low cost). Through our analysis of different extensions, we find that a firm's ability to set its regular price would dampen the effect of peak-period pricing. Also, we obtain consistent results when there is heterogeneity in customer valuation and customer congestion aversion level.

Key words: Retailing, peak-hour pricing, customer negative externality

---

1. Introduction

Many industries supplying essential items or services to customers experience "peak hours" of high demand every day. The high concentration of demand reduces the utility experienced by other customers. For example, in the energy sector, over-usage of electricity during the peak hours can lead to system failures or blackouts; and in public transportation networks, high peak hours congestion can result in severe delays. The established practice in these industries to combat the adverse effects of *negative externality* is to steer the customers away from the peak hours by imposing higher prices. Utility companies employ peak-load pricing to smooth demand (Williamson 1966, Wenders 1976), and even alert customers in real-time about the surcharges to discourage usage during peak hours (Kopalle et al. 2018). In public transportation, many cities such as London or Singapore charge higher peak hour prices for trains or road usages to discourage non-commuter traffic. Many private ride hailing services such as Uber, Lyft and DiDi similarly apply peak hour surcharges (Bai et al. 2019).

In the retailing sector, electronic shelf labels[1] and smart shelves[2] are emerging technologies that can enable brick-and-mortar stores to change their prices at the click of a button several times a day. With the lowering cost of their adoption, supermarkets have begun to acquire dynamic pricing capabilities (Souza 2019, OliverWyman 2019, Economist 2021). For example, prior to the pandemic, many countries in the EU (e.g., France, Germany, Iceland, etc.) have seen their larger supermarket chains adopt the electronic price tags to obtain dynamic pricing capabilities (Adams 2017), and those in the UK (Tesco, Sainsbury's, and Morrisons) had reviewed plans to implement Uber-style peak-hour pricing that could make items cost more in the afternoon (Morley 2017, Proactive 2017, Lawrie 2017). During the pandemic, Walmart also conducted pilot test of electronic shelf labels in the US (Souza 2019), and Asda, another major supermarket chain in the UK implemented the electronic shelf label in some of its stores (Quinn 2020).

As the COVID-19 pandemic brings customer's congestion aversion to the forefront, crowd management is becoming a priority agenda for many supermarkets and retailers (McKinsey 2020, Morgan 2020, Shumsky and Debo 2020). As such, peak-hour pricing may emerge as a practical and effective *nudge* to smooth customer traffic throughout the day and ensure safe and pleasant shopping for all shoppers. Indeed, industry experts predict that as the cost of its adoption continues to decline, peak-hour pricing will be inevitably employed by supermarkets as they are in other industries (Morley 2017, OliverWyman 2019). However, supermarkets operate in a market environment that fundamentally differs from those of public utility or transportation sectors. Should supermarkets implement peak-hour pricing?

[1] In Europe, Sweden-based Pricer manufactures electronic shelf labels that can enable stores to manage product positioning and product pricing in stores located in different geographical areas via computer. Carrefour adopted Pricer electronic shelf labels at its flagship Villiers-en-Biere store at the end of 2016. In Singapore, NTUC FairPrice, one of its largest retailer, had installed e-tags in their stores as early as 2013, while in China, Alibaba's offline retail chain Hema has been using them since 2018.

[2] In the US, AWM Smart Shelves use high-definition optical sensors to detect age, gender, or ethnicity. The technology uses data analytics to trigger optimal videos (including product pricing and information) based on shopper distances. Walmart began to adopt AWM Smart Shelves at the end of 2018.

To understand this research question, we examine two key contextual features that are unique to supermarkets. The first feature is the varying types of customer flexibility. In the utility sector, customers have little flexibility in choosing provider (e.g., due to local monopolies), and customers in transportation have little flexibility in choosing service time (e.g., rush hours). In contrast, when it comes to supermarkets, it is possible for customers to enjoy a wider degree of flexibility in both store choice and shopping times. The second feature is the variety of market structures that supermarkets compete in (e.g., quality/value and price). Firms in the utility or transportation sectors often offer undifferentiated services, and therefore the competition structure is less varied. In contrast, competition in supermarket can take many forms. For example, some offer high value at high price (e.g., Bristol Farms) to compete with others that offer low value at low price (e.g., Super King Markets), resulting in asymmetric competition. Thus, depending on the level of customers' flexibility in store/time choice and the competitive environment, supermarkets may benefit from not employing peak-hour pricing.

To gain clarity on how these two contextual features impact a supermarket's decision to adopt peak-hour pricing, we present a parsimonious duopoly model in which two firms (firms A and B) compete for customers who are averse to congestion. To capture the notion of "negative externality," we first determine the equilibrium demand traffic during peak/normal hours at each store when customers decide when (peak or normal hours) and where (firm A or firm B) to shop. Given this equilibrium demand traffic, we examine whether it is in the firms' interest to charge higher peak-hour prices (by setting a "peak-hour multiplier") under different types of customer flexibility and competition structures.

By comparing our equilibrium outcomes, we obtain the following results. First, when customers only have time flexibility (and no store choice flexibility) so that both firms operate as "local monopolies", the firms would always charge a higher price during the peak hours. When customers have store flexibility, then the equilibrium strategy would depend on the underlying competitive environment. If a firm has a dominant competitive advantage (in value or price) over the other firm, then only the dominant firm will employ peak-hour pricing. When customers have further flexibility in shopping time (in addition to store choice), the leverage of the dominant firm increases and makes it more likely for the dominant firm to employ peak-hour pricing in equilibrium. If the competing firms are symmetric (similar value and price), then both firms will employ peak-hour pricing; whereas if the firms engage in differentiated competition (low price vs high value), then neither firm will employ it.

We extend our analysis to examine how a firm's decision to employ peak-hour pricing is impacted when it can alter the price during the normal hours (in addition to the peak hours). We analyze how the focal firm sets its normal-hour and peak-hour prices under the assumption that the competing firm commits to employ or not to employ peak-hour pricing. We observe that having the option to change the normal-period price has the effect of *dampening* the implementation of peak-period pricing. Namely, in response to increase in competitor's normal period price or the competitor's peak-hour surcharge, instead of raising peak hour price, the focal firm will react by increasing the normal price and decreasing the peak-hour price.

Finally, we examine the impact of customer heterogeneity on a firm's peak-hour pricing strategy. An increased heterogeneity in customer valuations would increase the segmentation of customers, resulting in higher peak-hour prices (when customers do not have store flexibility), or in more firms to implement peak-hour pricing (when customers have store flexibility). In contrast, we find that an increased heterogeneity in customers' congestion aversion level can lead to lower peak-hour prices, and it may not necessarily entice more firms to implement peak-hour pricing. Nevertheless, we observe that our general findings concerning the impact of customer flexibility and competitive asymmetry remain robust under customer heterogeneity.

The rest of this paper is organized as follows. After a brief literature review in §1.1, we present our base model in §2. We analyze the equilibrium peak-hour pricing strategies under different shopping flexibility and competitive asymmetry in §3. We examine the peak-hour pricing strategy when the firm can adjust the normal-hour price in §4, and examine the impact of customer heterogeneity in section §5. Finally, we conclude in §6. All proofs are provided in Appendix A.

1.1. Literature Review

Our study of peak-hour pricing is related to the traditional studies of peak-load pricing practice employed in the energy/utility sectors (Williamson 1966, Wenders 1976), and to the recent studies motivated by the real-time surge pricing practice adopted by Uber (Hall et al. 2015) or other ride-hailing services (Bai et al. 2019 and Taylor 2017). The former literature focuses on the optimal allocation of the fixed and variable energy costs to peak-period users and normal-period users; the latter focuses on the operational level considerations such as examining the types of wage contracts to better manage the supply level (Chen and Sheldon 2015, Cachon et al. 2017, Guda and Subramanian 2019). All these studies examine the peak-hour pricing in a monopoly setting. In contrast, we investigate the adoption of peak-hour pricing across monopoly and duopoly settings. In doing so, we focus on the role of competitive dynamics between the firms in the presence of customer negative externality by considering a one-sided (rather than two-sided) market. Our work contribute to these literature by focusing on the adoption of peak-hour pricing in the service context specific to supermarkets.

The negative congestion externality that we model is broadly related to congestion examined extensively in the queueing literature. Early work addresses how queueing delays affect the pricing and capacity decisions of a monopolistic service provider facing strategic customers with heterogeneous valuations (Mendelson 1985, Mendelson and Whang 1990). Subsequent queueing games literature addresses the pricing and capacity strategies adopted by multiple competing service providers. Due to intractability, many studies focus on establishing the existence or the uniqueness of a Nash equilibrium (Chen and Wan 2003, Lederer and Li 1997) or on identifying the monotonicity properties of equilibrium prices and profits while assuming exogenous demand functions (e.g., Allon and Federgruen 2007, Cachon and Harker 2002). Unlike the queueing game literature, our equilibrium demand model captures negative externality in a tractable manner and allows us to clearly characterize the retailers' equilibrium peak-hour pricing strategies.

Various research studies on dynamic pricing are intended to manage demand when the supply is fixed (Gallego and van Ryzin 1994, Petruzzi and Dada 1999, Stamatopoulos et al 2019), learn about demand (Araman and Caldentey 2009, Besbes and Zeevi 2009), or stimulate demand for new products (Huang et al. 2018). Eliashberg and Jeuland (1986) study the dynamic pricing using a duopoly model to study the context of competitive entry decision. However, unlike this research stream, our peak-hour prices occur cyclically (i.e., the normal-hour price and the peak-hour price alternate throughout the day) rather than dynamically, and our study aims to understand whether the supermarkets will employ peak-hour pricing under different market environments.

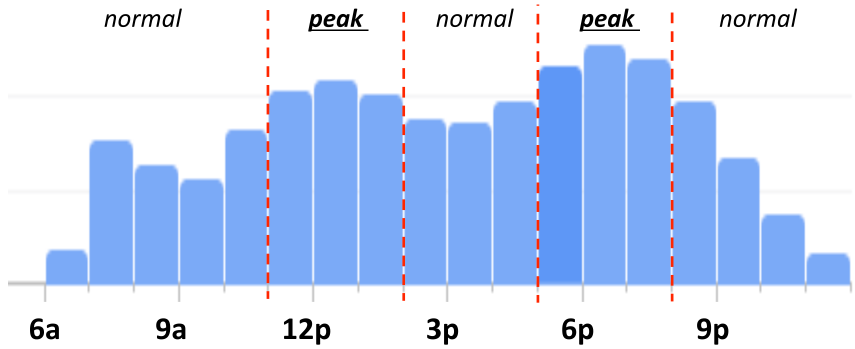
This paper complements a recent study (Tang et al. 2021) which uses a dynamic model to examine how supermarkets should "transition" to peak-hour pricing. By focusing on fully flexible homogeneous customers and symmetrically competing stores, they find that transitioning to peak-hour pricing would be inevitable for supermarkets in the long run. We examine different customer flexibility and competitive structure between the stores that are not covered in that study to offer novel insights. For example, we show that when supermarkets compete in a differentiated manner, it is possible for neither firms to adopt peak-hour pricing. Hence, our results presents nuanced insights into how contextual factors could impact supermarkets' decision to adopt peak-hour pricing.

2. Model

Consider a market in which two competing firms A and B (e.g., supermarkets) sell a durable good[3] to homogeneous customers. (We shall extend our analysis to the case when customers are heterogeneous in §5.) For ease of exposition, we scale the market size of infinitesimal customers to 1. Customers can shop either during peak hours or non-peak (normal) hours. An illustration of the peak and normal hours over the course of a day is provided in Figure 1.

[3] We focus on durable goods such as cereals. Perishable items like vegetables or bread, which can be sold later in the day with heavy discounts, are not the focus of our paper.

Figure 1 **Customer traffic at a grocery store (Tesco) in London on a typical day. (Source: Google Search)**

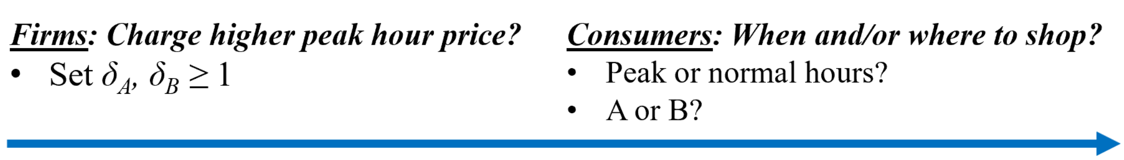


In the base model, homogeneous customers who purchase during normal hours pay price p_i and obtain value V_i from firm $i \in \{A, B\}$, where p_i and V_i are exogenously given. However, a customer who purchases during the peak hours would enjoy a higher valuation $\alpha \cdot V_i$ for $i \in \{A, B\}$ of firm i's product due to convenience, where $\alpha \geq 1$ represents the "extra value multiplier" for shopping during peak hours. Thus, a profit maximizing firm i may consider whether to introduce a *peak-hour multiplier* $\delta_i > 1$ by charging a higher peak-hour price $\delta_i \cdot p_i$ during the peak hours to take advantage of customers' higher willingness to pay.

We consider the settings when the products have been selling for a long time so that customers derive values V_A and V_B from purchasing the product from stores A and B, respectively. Moreover, both stores had been selling their products according to the "regular" prices p_A and p_B for a long time, as is the case when these product features and prices are well established in advance or set by a different party (e.g., national brands) that cannot be changed within a short term. We will thus assume that the prices p_A and p_B and the valuations V_A and V_B are given exogenously (we shall extend our analysis to allow firm A to decide p_A in addition to δ_A in §4). Given both firms have existing patronage, it is reasonable to assume that $V_A \geq p_A$ and $V_B \geq p_B$.

We consider the sequence of events as shown in Figure 2. First, each firm i determines whether to set $\delta_i > 1$ or $\delta_i = 1$. Given the prices and peak-hour surcharges (p_A, δ_A; p_B, δ_B), each customer determines when and where to shop. For simplicity, we assume zero variable cost and assume that firms incur no cost for adopting surge pricing technology (e.g., electronic shelf labels).

Figure 2 **Sequence of Events**



2.1. Contextual Factors: Customer Flexibility and Competitive Asymmetry

Throughout this paper, we shall examine the conditions under which firm i would adopt peak-hour pricing (i.e., set $\delta_i > 1$) by considering two contextual factors:

1. **Customer Shopping Flexibility.** We consider three types of customer flexibility.[4] First, customers may have no store flexibility (e.g., due to store loyalty) but have time flexibility. In this case, a known proportion λ of (loyal) customers will shop only at store A, and the remaining proportion $(1-\lambda)$ of (loyal) customers will shop only at store B. Each store's loyal customer decides when (normal hours or peak hours) to shop. Second, customers may have no time flexibility (e.g., due to work conditions) but have store flexibility. In this case, a known proportion β of customers will shop only during peak hours, and the remaining proportion $(1-\beta)$ of customers will shop only during normal hours. Each customers associated with each shopping hours can choose the store to shop. Third, customers may have both store and time flexibility. In this case, each customer can choose the time and store to shop.

2. **Competitive Asymmetry.** We consider two dimensions of competitive asymmetry. In preparation, we shall restrict our attention to the case when $V_A \geq V_B$ and $p_A \geq p_B$ without loss of generality. Hence, we shall use (1) the ratio $\nu \equiv V_A/V_B \geq 1$ to measure the "value competitive advantage" of firm A over firm B; and (2) the ratio $\rho \equiv p_A/p_B \geq 1$ to measures the "price competitive advantage" of firm B over firm A. These two metrics allow us to characterize different types of competitive asymmetry. For example, it allows for the presence of a dominant firm with a competitive advantage (in value or in price)[5], as well as symmetric competition (same value and cost) or differentiated competition (high value vs low cost).

In §3, we shall examine the three different types of customer shopping flexibility, and examine how competitive asymmetry in terms of ν and ρ would influence each firm's decision to adopt time-based pricing in each setting.

2.2. Equilibrium Demand Traffic with Negative Externality

In the supermarket setting, each customer has a disutility associated with a store's congestion level. This disutility is due to the discomfort of being in a crowded space or having to wait in longer queues. Therefore, a "negative externality" is present: each additional customer's presence in the store at a given time imposes a negative utility for all other customers. We characterize the customer's decision and their equilibrium demand that captures such negative externality.

[4] The framework can be extended to the case when some customers are loyal to their respective stores or time and yet other customers are disloyal and will choose the store and the hours to shop that yield the highest utility. We find that the analytical results remain identical as long as the flexible segments are sufficiently small or large. To avoid repetition, we omit the details.

[5] Due to the negative externality, a firm with significant competitive disadvantage will still attract customers who would avoid the highly congested dominant firm.

To model a customer's net utility from shopping at a store during peak or normal hours, we first define $q_{i,j}$ as the fraction of customer population who shop at firm i during hours j, where $i \in \{A,\, B\}$ and $j \in \{peak,\, normal\}$. Alternatively, q_{ij} can be interpreted as each customer's mixed strategy consisting of probabilities of shopping during at store i during hours j. To capture this disutility, we define a *congestion aversion coefficient* $\gamma \geq 0$ that represents the level of congestion aversion. Taking into account the product's valuation and price and the congestion coefficient γ, a focal customer's net utility that can be obtained from shopping at store i during hours j is given in Table 1.

	Firm A	Firm B
Peak:	$\alpha V_A - \gamma q_{A,peak} - \delta_A p_A$	$\alpha V_B - \gamma q_{B,peak} - \delta_B p_B$
Normal:	$V_A - \gamma q_{A,norm} - p_A$	$V_B - \gamma q_{B,norm} - p_B$

Table 1 **Customer i's utilities based on when and where i shops**

Given an appropriate set of prices $(p_A, \delta_A; p_B, \delta_B)$, each customer compares the net utilities in Table 1 and determines when and where to shop. While each customer does not know the population's average q_{ij} prior to his store visit, we assume each customer believes that all customers (including himself) form a common belief about q_{ij}. Then, as each infinitesimal customer uses this common belief to determine his own shopping strategy via a mixed strategy, $q_{ij} = q^*_{ij}$ in equilibrium so that each customer's initial belief q_{ij} is consistent with the realized equilibrium q^*_{ij} that is based on a mixed strategy Nash equilibrium.

To ensure that each customer will shop at one of the stores during given hours and not leave the market for their essential groceries, we shall assume the following.

Assumption 1 **(Full Market Coverage)**. *The product's value V_i and price p_i satisfy*

$$\alpha V_i - \delta_i p_i - \gamma \geq 0 \ \textit{and} \ V_i - p_i - \gamma \geq 0, \ \ i \in \{A, B\}.$$

Assumption 1 holds when V_i is sufficiently large so that the customer utilities are always positive, resulting in full market coverage $q_{A,peak} + q_{A,norm} + q_{B,peak} + q_{B,norm} = 1$. Moreover, it also implies that $\delta_i p_i < (\alpha V_i - \gamma)$, so that peak-hour prices would be bounded from above.

3. Peak-Hour Pricing under Different Flexibility and Competition

In this section, we examine how *each* type of customer flexibility and competitive asymmetry (via ν and ρ) influence the firms' decision to employ time-based pricing. Specifically, we analyze three different aforementioned flexibility settings, and determine the peak-hour multiplier δ_i for firm $i = A, B$, under different levels of competitive asymmetry through the measures $\nu \equiv V_A/V_B \geq 1$ and $\rho \equiv p_A/p_B \geq 1$.

For each customer flexibility setting, we first determine the expressions for the equilibrium demand traffic (via backward induction) $q^*_{i,j}$ given the prices (p_A, δ_A; p_B, δ_B). Using this demand expression, we then determine each firm i's decision on its peak-hour multiplier δ_i that maximizes its profit under different competitive settings (ν, ρ).

3.1. Setting (a): Presence of Time Flexibility Only

When customers have time flexibility but not store flexibility (due to store loyalty), a known proportion λ of loyal customers will only shop at firm A and $(1-\lambda)$ at firm B. For each store, its loyal customers have the flexibility to choose when to shop. Because each store has its own loyal customers, each store operates as a "local monopoly" so that the competitive asymmetries via ν and ρ are irrelevant. Thus, it suffices to present our analysis for a focal firm A to avoid repetition.

Let $q_{A,peak} = \lambda \cdot r_{A,peak}$ denote the initial common belief about the proportion of customers who shop in store A during peak hours, where $r_{A,peak}$ represent the proportion of store A's loyal customers who will shop during the peak hours. Hence, $q_{A,norm} = \lambda(1 - r_{A,peak})$. From Table 1, the customer's utilities for shopping at store A during peak and normal hours are as follows:

$$u_{A,peak} = \alpha V_A - \gamma[\lambda \cdot r_{A,peak}] - \delta_A p_A, \text{ and } u_{A,norm} = V_A - \gamma[\lambda \cdot (1 - r_{A,peak})] - p_A. \tag{1}$$

Recall that Assumption 1 guarantees full market coverage. The following assumption ensures that negative externality is large enough so that shopping during the peak period as opposed to normal period to derive the "extra value" (i.e., $(\alpha-1)V_A$) is not worth it if the peak period is completely full. This assumption ensures that each time period has positive customers, i.e., $r_{A,peak}(\delta^A) \in (0,1)$.

Assumption 2 **(Relevance of Negative Externality)**. $(\alpha-1)V_A \leq \lambda\gamma$.

The following lemma characterizes the equilibrium demand rate.

Lemma 1 **(Equilibrium Demand Rate – Time Flexibility Only)**. *Suppose Assumptions 1 and 2 hold. Then, in the presence of time flexibility only, for any given peak-hour multiplier δ_A, the proportion of customers $r^*_{A,peak}(\delta_A)$ who shop during peak hours in equilibrium satisfies:*

$$r^*_{A,peak}(\delta_A) = \frac{1}{2} + \frac{(\alpha-1)V_A - (\delta_A - 1)p_A}{2\gamma\lambda}. \tag{2}$$

Lemma 1 implies that $r^*_{A,peak} > 0.5$ if and only if $(\alpha-1)V_A - (\delta_A - 1)p_A > 0$. In other words, when the "extra value" for shopping during the peak period (i.e., $(\alpha-1)V_A$) is greater than the "extra premium" in price (i.e., $(\delta_A - 1)p_A$) during the peak period, $r^*_{A,peak} > 0.5$. Also, observe that when $\alpha = \delta_A = 1$, $r^*_{A,peak} = 0.5$, so that customer traffic will be equally divided between the peak and non-peak hours. Finally, notice that the presence of negative externality $\gamma > 0$ helps the firm to smooth out its demand over both periods. For instance, when $\gamma \to \infty$, $r_{A,peak} = 0.5$ so that customer traffic will be equally divided between the peak and non-peak hours.

By considering $r^*_{A,peak}(\delta_A)$ as given in (2), firm A solves the following problem

$$\max_{\delta_A > 1} \; \pi_A(\delta_A) = \delta_A p_A \cdot \lambda r^*_{A,peak}(\delta_A) + p_A \cdot \lambda(1 - r^*_{A,peak}(\delta_A)), \tag{3}$$

which leads to the following result.

Proposition 1 **(Optimal Peak-Hour Multiplier – Time Flexibility Only)**. *Suppose that Assumptions 1 and 2 hold. Then, in the presence of time flexibility only, the optimal peak-hour multiplier* δ^*_A *satisfies*

$$\delta^*_A = 1 + \frac{\gamma\lambda + (\alpha - 1)V_A}{2p_A} > 1.$$

When a firm (firm A in this case) operates as a local monopoly, Proposition 1 reveals that $\delta^*_A > 1$: it is optimal for a firm to charge a higher price during peak hours, or equivalently, employ time-based pricing. (It is not a corner solution as they do not want to charge too high surcharge.) Also observe that, even when customers do not derive extra value from peak-hour shopping, i.e., when $\alpha = 1$, the firm should still adopt time-based pricing by setting $\delta^*_A > 1$, so that (2) implies $r^*_{A,peak}(\delta^*_A) < 0.5$. By doing this, firm A can use the (higher) peak hour price to make up for fewer customers shopping during peak hours (even though more customers will shop during non-peak hours). This result supports the prevalence of time-based pricing in the energy sector, and suggests that supermarkets will employ time-based pricing in settings where customers lack store flexibility.

3.2. Setting (b): Presence of Store Flexibility Only

When customers have store flexibility but not time flexibility (e.g., due to working conditions), a known proportion β of the customers must shop during peak hours and $(1-\beta)$ during normal hours. For each designated time period, all customers have the flexibility to choose between firm A and firm B. Let $q_{A,peak} = \beta r_{A,peak}$ and $q_{A,norm} = (1-\beta) r_{A,norm}$ denote the proportions of peak- and normal-hour customers, respectively, who shop in store A. Here, $r_{A,peak}$ represents the proportion of peak-hour shoppers who will shop at store A. Hence, $q_{B,peak} = \beta(1 - r_{A,peak})$ and $q_{B,norm} = (1-\beta)(1 - r_{A,norm})$. From Table 1, the customer's utilities for shopping at store A and store B are as follows:

$$u_{A,peak} = \alpha V_A - \gamma[\beta r_{A,peak}] - \delta_A p_A, \qquad u_{B,peak} = \alpha V_B - \gamma[\beta(1 - r_{A,peak})] - \delta_B p_B,$$
$$u_{A,norm} = V_A - \gamma(1-\beta) r_{A,norm} - p_A, \qquad u_{B,norm} = V_B - \gamma(1-\beta)(1 - r_{A,norm}) - p_B.$$

We assume, akin to Assumption 2 in §3.1, that the impact of congestion is large enough so that shopping in store A as opposed to store B to derive the "extra value" $\alpha(V_A - V_B)$ is not worth it if store A is completely full. This assumption ensures that each store has positive customers, i.e., $r^*_{A,peak}(\delta_A, \delta_B) \in (0,1)$.

Assumption 3 **(Impact of Congestion)**. *$\alpha(V_A - V_B) \le \gamma\beta$.*

The following lemma characterizes the equilibrium demand rate at store A.[6]

Lemma 2 **(Equilibrium Demand Rate – Store Flexibility Only)**. *Suppose Assumptions 1 and 3 hold. Then, for any given peak hour multipliers δ_A and δ_B, the equilibrium proportion of customers who will shop at firm A during the peak hour and during the normal hours can be expressed as:*

$$\begin{aligned} r^*_{A,peak}(\delta_A, \delta_B) &= \frac{1}{2} + \frac{\alpha(V_A - V_B) - (\delta_A p_A - \delta_B p_B)}{2\gamma\beta}, \\ r^*_{A,norm} &= \frac{1}{2} + \frac{V_A - V_B - p_A + p_B}{2\gamma(1-\beta)}. \end{aligned} \tag{4}$$

Because the regular prices p_A and p_B are given exogenously, it suffices to examine how the equilibrium peak period demands are influenced by the peak-hour multipliers δ_A and δ_B. Lemma 2 implies that $r_{A,peak} > 0.5$ if and only if $\alpha(V_A - V_B) - (\delta_A p_A - \delta_B p_B) > 0$. In other words, when the extra value from shopping in store A ($\alpha(V_A - V_B)$) is greater than the extra premium in price $(\delta_A p_A - \delta_B p_B)$, $r_{A,peak} > 0.5$.

By using the equilibrium demand traffic $r^*_{A,peak}(\delta_A, \delta_B)$ given in (4), firms A and B solve the following problems simultaneously,

$$\max_{\delta_A \ge 1} \; \pi_A(\delta_A, \delta_B) = \delta_A p_A \beta r^*_{A,peak}(\delta_A, \delta_B), \tag{5}$$

$$\max_{\delta_B \ge 1} \; \pi_B(\delta_A, \delta_B) = \delta_B p_B \beta (1 - r^*_{A,peak}(\delta_A, \delta_B)), \tag{6}$$

which results in the equilibrium peak-hour multipliers given in the following proposition.

Proposition 2 **(Equilibrium Peak-Hour Multipliers – Store Flexibility Only)**. *Suppose Assumptions 1 and 3 hold. Then, in the presence of store flexibility only, there exists a unique pair of equilibrium peak-hour multipliers (δ^*_A, δ^*_B) that satisfies:*

(i) If $\nu \le \frac{-\beta\gamma + \alpha V_B - p_B}{\alpha V_B} + \frac{2p_B}{\alpha V_B}\rho$ and $\nu \ge \frac{\beta\gamma + \alpha V_B - 2p_B}{\alpha V_B} + \frac{p_B}{\alpha V_B}\rho$, then

$$(\delta^*_A, \delta^*_B) = (1,\ 1), \quad for\ \rho \ge \frac{2\gamma\beta}{p_B} - 1;$$

(ii) If $\nu \le \frac{\beta\gamma + \alpha V_B - 2p_B}{\alpha V_B} + \frac{p_B}{\alpha V_B}\rho$ and $\nu \le \frac{-3\beta\gamma + \alpha V_B}{\alpha V_B} + \frac{3p_B}{\alpha V_B}\rho$, then

$$(\delta^*_A, \delta^*_B) = \left(1,\ \frac{\beta\gamma - \alpha(V_A - V_B) + p_A}{2p_B}\right),\ \forall\rho;$$

(iii) If $\nu \ge \frac{-\beta\gamma + \alpha V_B - p_B}{\alpha V_B} + \frac{2p_B}{\alpha V_B}\rho$ and $\nu \ge \frac{3\beta\gamma + \alpha V_B - 3p_B}{\alpha V_B}$, then

$$(\delta^*_A, \delta^*_B) = \left(\frac{\beta\gamma + \alpha(V_A - V_B) + p_B}{2p_A},\ 1\right),\ \forall\rho;$$

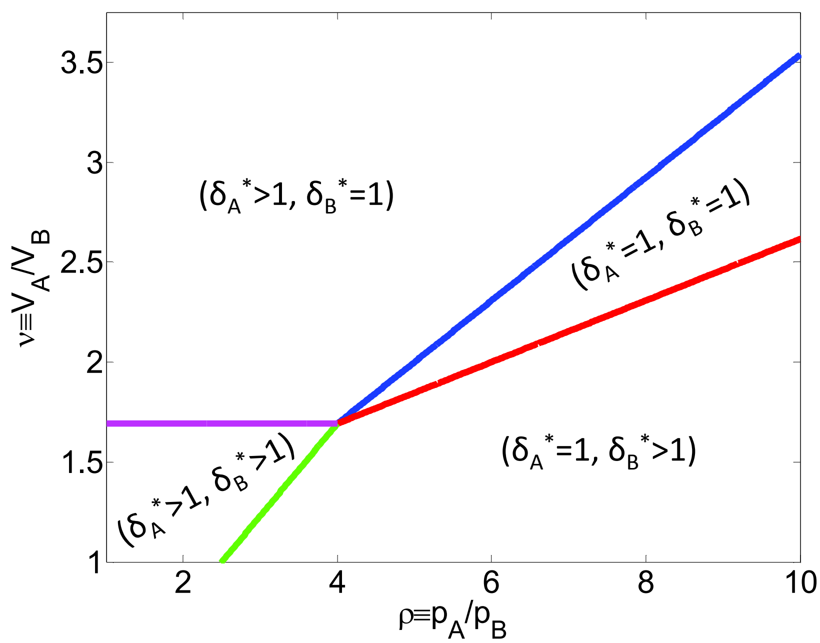
[6] Demand rate for store B can be retrieved immediately. We omit the details for ease of exposition.

(iv) If $\nu \leq \frac{3\beta\gamma+\alpha V_B-3p_B}{\alpha V_B}$ *and* $\nu \geq \frac{-3\beta\gamma+\alpha V_B}{\alpha V_B}+\frac{3p_B}{\alpha V_B}\rho$*, then*

$$(\delta_A^*, \delta_B^*) = \left(\frac{3\beta\gamma+\alpha(V_A-V_B)}{3p_A},\ \frac{3\beta\gamma-\alpha(V_A-V_B)}{3p_B}\right),\ for\ \rho \leq \frac{2\gamma\beta}{p_B}-1.$$

Figure 3 depicts the four regions of equilibrium peak-hour multipliers $(\delta_A^*,\ \delta_B^*)$, as characterized in Proposition 2, over price asymmetry and value asymmetry via the (ρ,ν)-space. We note that it is possible that neither firm adopts time-based pricing (i.e., $\delta_A^*=1,\ \delta_B^*=1$) (Case (i)); exactly one of the firms adopts it (Cases (ii) and (iii)); or both firms adopt it (i.e., $\delta_A^*>1,\ \delta_B^*>1$) (Case (iv)). Unlike Proposition 1, which states that firms would always adopt time-based pricing in the absence of store flexibility, Proposition 2 reveals that asymmetric competitive pressure via ρ and ν facilitated by store flexibility can make employing time-based pricing less desirable.

Figure 3 Equilibrium peak-hour multipliers (δ_A^*, δ_B^*) as a function of $\rho \equiv p_A/p_B$ and $\nu = V_A/V_B$ in the presence of store flexibility only.



Note. $\alpha=1.3$, $\beta=1$, $V_B=10$, $p_B=2$, $\gamma=5$.

Recall from §2.1 that $\nu \equiv V_A/V_B \geq 1$ measures the "value competitive advantage" of A over B and $\rho \equiv p_A/p_B \geq 1$ measures the "price competitive advantage" of B over A. Hence, the equilibrium peak-hour multipliers $(\delta_A^*,\ \delta_B^*)$ depicted in Figure 3 can be interpreted as follows. First, when $\nu \equiv V_A/V_B$ is high relative to $\rho \equiv p_A/p_B$ (upper left region), firm A has a strong value competitive advantage over B, but B has a relatively weak price advantage over A. In this case, only the dominant firm A can afford to charge higher peak-hour prices in equilibrium (i.e., $\delta_A^*>1$ and $\delta_B^*=1$). Similarly, when $\nu \equiv V_A/V_B$ is low relative to $\rho \equiv p_A/p_B$ (lower right region), firm B

has a strong price competitive advantage over A, but A has a relatively weak value competitive advantage over B. Hence, only the dominant firm B can afford to charge higher peak-hour prices in equilibrium (i.e., $\delta_A^* = 1$ and $\delta_B^* > 1$) without losing much market share. In summary, when one firm has a significant competitive advantage over the other, only the dominant firm can afford to employ time-based pricing.

Second, when neither firm has a clear competitive advantage (in terms of price or value) as shown in the middle diagonal region, there are two possibilities. On the one hand, if the firms engage in a differentiated competition (i.e., when both ν and ρ are high), then neither firm employs time-based pricing (i.e., $\delta_A^* = 1$ and $\delta_B^* = 1$). This is because if firm A adopts peak-hour pricing, firm B will be better off not adopting it by virtue of attracting customers to switch from firm A due to firm B's lower prices. This in turn prevents firm A from adopting peak-hour pricing. Similarly, if firm B adopts peak-hour pricing, firm A will be better off not adopting it by attracting customers to switch from firm B due to firm A's higher value. This in turn prevents firm B from employing peak-hour pricing.

On the other hand, if firms engage in more symmetric competition (i.e., when both ν and ρ are low), then both firms can afford to adopt peak-hour pricing by setting $\delta_A^* > 1$ and $\delta_B^* > 1$. This is because the firms can collectively take advantage of the customer's willingness to pay higher price to avoid congestion during peak hours. The next corollary formalizes the effect of customers' aversion to congestion on adoption of peak-hour pricing.

Corollary 1 **(Congestion Effect – Store Flexibility Only)**. *Suppose that Assumptions 1 and 3 hold. Then, in the presence of store flexibility only, the region* $(\delta_A^* > 1, \delta_B^* > 1)$ *expands and the region* $(\delta_A^* = 1, \delta_B^* = 1)$ *contracts in* γ *and* β*.*

When γ is high, customers are more congestion averse; and hence, relatively less sensitive to price. Moreover, when β is high, more customers shop during the peak hours. Thus, an increase in these parameters would soften the competition between the stores so that it becomes more likely for both firms to employ peak-hour pricing. This supports the prevalence of peak-hour pricing in the transportation sector, and suggest that many supermarkets that compete symmetrically would employ peak-hour pricing. However, the supermarkets that engage in a differentiated competition will be less inclined to employ peak-hour pricing.

3.3. Setting (c): Presence of Both Store and Time Flexibility

We now examine the case where customers have both store and time flexibility. From Table 1, each customer's decision regarding when and where to shop hinges on the following net utilities:

$$\begin{aligned} u_{A,peak} &= \alpha V_A - \gamma q_{A,peak} - \delta_A p_A, \quad & u_{B,peak} &= \alpha V_B - \gamma q_{B,peak} - \delta_B p_B, \\ u_{A,norm} &= V_A - \gamma q_{A,norm} - p_A, \quad & u_{B,norm} &= V_B - \gamma q_{B,norm} - p_B. \end{aligned}$$

The following assumption combines the essence of Assumptions 2 and 3 as follows. Specifically, it states that shopping in peak period as opposed to normal period and in store A as opposed to store B to gain a combination of respective extra values $(\alpha-1)V_A$ and $\alpha(V_A-V_B)$ is not worth it if store A at peak period is completely full.

Assumption 4 **(Impact of Congestion)**. $\frac{2}{3}(\alpha-1)V_A+\frac{(1+\alpha)}{3}(V_A-V_B)\leq\gamma$.

Observe that this condition is based on a linear combination of $(\alpha-1)V_A$ and $\alpha(V_A-V_B)$ captured in Assumptions 2 and 3, respectively. Also, Assumption 4 ensures that the equilibrium $q^*_{i,j}\in(0,1)$ for all $i\in A,B$ and $j\in\{peak,norm\}$. By using the same approach as before, we can determine the equilibrium proportion $q^*_{i,j}$ as follows:

Lemma 3 **(Equilibrium Demand Rate – Full Flexibility)**. *Suppose Assumptions 1 and 4 hold. Then, for any given peak-hour multipliers δ_A and δ_B, the equilibrium proportions $q_{i,j}$ satisfy:*

$$\begin{aligned}
q^*_{A,peak}(\delta_A,\delta_B) &= \frac{\gamma+(3\alpha-1)V_A-(1+\alpha)V_B+p_A+(1+\delta_B)p_B}{4\gamma}-\frac{3p_A}{4\gamma}\delta_A,\\
q^*_{A,norm}(\delta_A,\delta_B) &= \frac{\gamma+(3-\alpha)V_A-(1+\alpha)V_B-3p_A+(1+\delta_B)p_B}{4\gamma}+\frac{p_A}{4\gamma}\delta_A,\\
q^*_{B,peak}(\delta_A,\delta_B) &= \frac{\gamma-(1+\alpha)V_A-(1-3\alpha)V_B+(1+\delta_A)p_A+p_B}{4\gamma}-\frac{3p_B}{4\gamma}\delta_B,\\
q^*_{B,norm}(\delta_A,\delta_B) &= \frac{\gamma-(1+\alpha)V_A-(\alpha-3)V_B+(1+\delta_A)p_A-3p_B}{4\gamma}+\frac{p_B}{4\gamma}\delta_B.
\end{aligned}$$

By using the equilibrium proportions of customers who shop at the different stores during the different hours as given above, we can express the firms' profit functions as:

$$\pi_A(\delta_A,\delta_B)=\delta_A p_A\cdot q^*_{A,peak}(\delta_A,\delta_B)+p_A\cdot q^*_{A,norm}(\delta_A,\delta_B), \tag{7}$$

$$\pi_B(\delta_A,\delta_B)=\delta_B p_B\cdot q^*_{B,peak}(\delta_A,\delta_B)+p_B\cdot q^*_{B,norm}(\delta_A,\delta_B). \tag{8}$$

By maximizing the above profit functions simultaneously, we can determine the equilibrium peak-hour multipliers as follows.

Proposition 3 **(Unique Equilibrium Peak-Hour Multipliers – Full Flexibility)**. *Suppose Assumptions 1 and 4 hold, and suppose we let $\hat{\tau}\equiv\frac{2\alpha\gamma+4\alpha(\alpha-1)V_B+(3-5\alpha)p_B}{(3-\alpha)p_B}$. Then the equilibrium peak-hour multipliers (δ^*_A,δ^*_B) satisfy:*

(i) If $\nu\leq\frac{-\gamma+(1+\alpha)V_B-2p_B}{(3\alpha-1)V_B}+\frac{4p_B}{(3\alpha-1)V_B}\rho$ and $\nu\geq\frac{\gamma-(1-3\alpha)V_B-4p_B}{(1+\alpha)V_B}+\frac{2p_B}{(1+\alpha)V_B}\rho$,

$$(\delta^*_A,\delta^*_B)=(1,\ 1),\ \ for\ \rho\geq\hat{\tau};$$

(ii) If $\nu\leq\frac{\gamma-(1-3\alpha)V_B-4p_B}{(1+\alpha)V_B}+\frac{2p_B}{(1+\alpha)V_B}\rho$ and $\nu\leq\frac{-7\gamma+(3\alpha+7)V_B-8p_B}{(17\alpha-7)V_B}+\frac{22p_B}{(17\alpha-7)V_B}\rho$,

$$(\delta^*_A,\delta^*_B)=\left(1,\ \frac{\gamma-(1+\alpha)V_A-(1-3\alpha)V_B+2p_A+2p_B}{6p_B}\right),\ \forall\rho;$$

(iii) If $\nu \geq \frac{-\gamma+(1+\alpha)V_B-2p_B}{(3\alpha-1)V_B} + \frac{4p_B}{(3\alpha-1)V_B}\rho$ *and* $\nu \geq \frac{7\gamma+(17\alpha-7)V_B-22p_B}{(3\alpha+7)V_B} + \frac{8p_B}{(3\alpha+7)V_B}\rho$,

$$(\delta_A^*, \delta_B^*) = \left(\frac{\gamma+(3\alpha-1)V_A-(1+\alpha)V_B+2p_A+2p_B}{6p_A},\ 1\right),\ \forall\rho;$$

(iv) If $\nu \leq \frac{7\gamma+(17\alpha-7)V_B-22p_B}{(3\alpha+7)V_B} + \frac{8p_B}{(3\alpha+7)V_B}\rho$ *and* $\nu \geq \frac{-7\gamma+(3\alpha+7)V_B-8p_B}{(17\alpha-7)V_B} + \frac{22p_B}{(17\alpha-7)V_B}\rho$,

$$\delta_A^* = \frac{7\gamma+(17\alpha-7)V_A-(7+3\alpha)V_B+13p_A+8p_B}{35p_A} \textit{and}$$

$$\delta_B^* = \frac{7\gamma-(7+3\alpha)V_A+(17\alpha-7)V_B+8p_A+13p_B}{35p_B},\ \textit{for}\ \rho \leq \hat{\tau}.$$

Figure 4 illustrates Proposition 2. We observe that it resembles Proposition 3 in how the conditions under which a firm would adopt peak-hour pricing depend on competitive asymmetry (via ν and ρ). We examine the impact of γ in the following corollary, which also resembles Corollary 1.

Corollary 2 **(Congestion Effect – Full Flexibility)**. *Suppose Assumptions 1 and 4 hold. Then, when customers are fully flexible, the region* $(\delta_A^* > 1, \delta_B^* > 1)$ *expands and the region* $(\delta_A^* = 1, \delta_B^* = 1)$ *contracts in* γ.

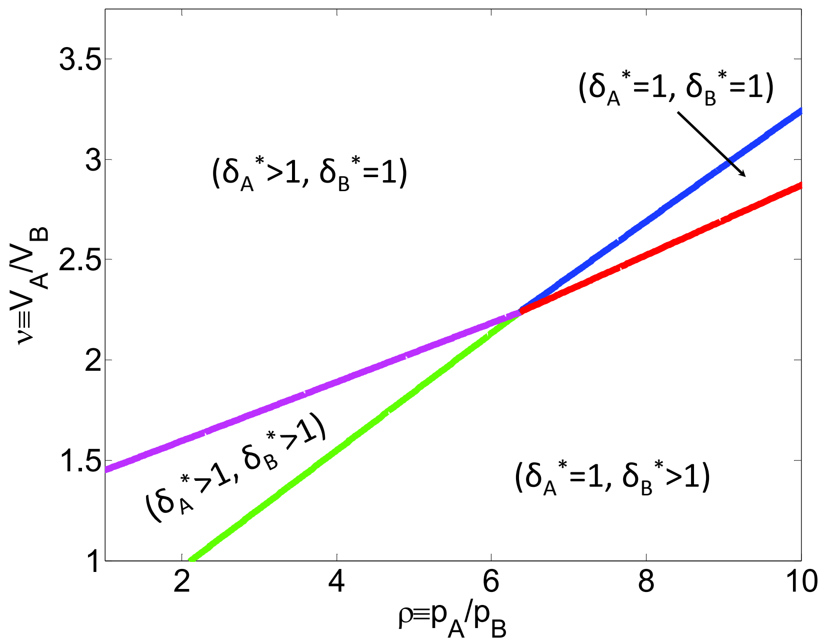
The main difference between §3.3 and §3.2 is that customers have an additional shopping time flexibility in §3.3, so that the proportion of peak-hour shoppers is endogenously determined (rather than the exogenously given β). The additional time flexibility impacts the boundaries delineating the regions. Comparing the corresponding panels of Figures 3 and 4, the regions for $(\delta_A^* > 1, \delta_B^* > 1)$ and $(\delta_A^* = 1, \delta_B^* = 1)$ are smaller in the presence of additional time flexibility. In other words, when customers have additional time flexibility, the firm that has a competitive advantage is more likely to adopt time-based pricing. The next corollary formalizes this observation.

Corollary 3 **(Interaction between Time and Store Flexibility)**. *Suppose Assumptions 1, 3, and 4 hold. Then the region in which only one firm adopts time-based pricing is larger when customers have full flexibility than when they have store flexibility only.*

This corollary is based on the fact that, when customers are fully flexible (rather than flexible in store choice only), they have the option of shopping at the dominant firm during normal hours even when it charges a higher price during the peak hours. Hence, the dominant firm is able to behave closer to a "local monopoly" and can afford to adopt time-based pricing without losing too much market. This suggests that in settings when customers are fully flexible, it becomes less likely for both supermarkets to employ peak-hour pricing compared to when customers are flexible in store choice only.

In summary, we obtain the following results. First, in the presence of time flexibility only, each firm operates as a local monopoly, and will adopt peak-hour pricing. Second, when customers

Figure 4 **Equilibrium peak-hour multipliers (δ_A^*, δ_B^*) as a function of $\rho \equiv p_A/p_B$ and $\nu = V_A/V_B$ in the presence of both time and store flexibility.**



Note. $V_B = 10$, $p_B = 2$, $\alpha = 1.2$, $\gamma = 5$.

have store flexibility, peak-hour pricing adoption of each firm depends on competitive asymmetry. When customers have time flexibility, in addition to store flexibility, the additional flexibility makes the dominant firm behave more like a local monopoly, which favors peak-hour pricing adoption. In all cases, greater aversion to congestion encourages firms to adopt peak-hour pricing because customers become less price sensitive.

4. Impact of Regular Price Flexibility

So far, we have examined the peak-hour pricing competition under the assumption that the regular prices p_A and p_B are exogenously given. In this section, we relax this assumption in order to understand whether supermarkets have the economic incentives to employ peak-hour pricing if they have the flexibility to set their regular prices.

4.1. Competitor Commits to Non-Adoption of Peak-hour Pricing

To derive clear insights with tractable results, we first consider the case when one firm (firm B) has committed not to adopt peak-hour pricing (i.e., $\delta_B = 1$), and examine the focal firm's (firm A) decision to adopt peak-hour pricing when it has the flexibility to set both p_A and δ_A. This setting is reflective of a situation when a new entrant (firm A) is willing to try innovative strategies against an established incumbent (firm B) that commits to its traditional ways of operation with an established price p_B.

Proposition 4 reveals the optimal decision in different levels of customer flexibility and competition structures.

PROPOSITION 4 **(Optimal Normal-hour and Peak-hour Prices)**. *Suppose Assumptions 1-4 hold and firm B has committed not to implement peak-hour pricing (i.e., δ_B=1). Then firm A's optimal normal-hour prices and peak-hour multipliers satisfy:*
(i) In the presence of time flexibility only,

$$p_A^* = \frac{(\alpha+1)V_A - \gamma(2+\lambda)}{2}, \quad \delta_A^* = 1 + \frac{(\alpha-1)V_A + \gamma\alpha}{(\alpha+1)V_A - \gamma(2+\lambda)} > 1;$$

(ii) In the presence of store flexibility only,

$$p_A^* = \frac{V_A - V_B + \gamma(1-\beta) + p_B}{2};$$
$$\delta_A^* = \begin{cases} \frac{\alpha(V_A - V_B) + \gamma\beta + p_B}{V_A - V_B + \gamma(1-\beta) + p_B} > 1, & \text{if } (\alpha-1)(V_A - V_B) > \gamma(1-2\beta), \\ 1, & \text{otherwise}, \end{cases}$$

(iii) In the presence of both time and store flexibility,

$$p_A^* = \frac{2V_A - (\alpha+1)V_B + 2p_B + \gamma}{4}, \quad \delta_A^* = 1 + \frac{2(\alpha-1)V_A}{2V_A - (\alpha+1)V_B + 2p_B + \gamma} > 1.$$

Proposition 4 reveals the following insights. First, when customers have time flexibility (parts (i) and (iii)), the firm will employ peak-hour pricing by charging a higher peak-hour price. This is because the firm seeks to take advantage of customers' higher valuation when shopping during peak hours. When customers have additional store flexibility (part (iii)), the competitor's price p_B has an impact. Namely, a higher price p_B makes firm A to raise its normal-hour price price p_A and to decrease its peak-hour multiplier δ_A. This indicates that against a high priced competitor, the firm's implementation of peak-hour pricing will be marginal.

Second, when customers do not have time flexibility (part (ii)), firm A may not employ peak-hour pricing. Specifically, firm A will charge peak-hour prices only when its value advantage over its competitor $(V_A - V_B)$ is sufficiently large. Interestingly, the decision regarding whether or not to implements peak-hour pricing does not depend on competing firm's price, p_B (though it impacts the magnitudes of p_A and δ_A). This suggests that, in addition to the contextual features, a non-adoption of peak-hour pricing by a supermarket with a value advantage can also deter competing firms from adopting peak-hour pricing.

4.2. Competitor Commits to Adoption of Peak-hour Pricing

We now consider the case when firm B is always committed to adopt peak-hour pricing (i.e., $\delta_B > 1$), and examine firm A's decision to adopt peak-hour pricing when it has the flexibility to set both p_A and δ_A. Such reflects the setting when an established incumbent (firm B) has adopted the innovative strategy and the new entrant (firm A) is deciding whether to follow or not.

Proposition 5 reports the focal firm's optimal decisions for varying levels of customer flexibility and competition structures.

Proposition 5 **(Optimal Normal-hour and Peak-hour Prices)**. *Suppose Assumptions 1-4 hold and firm B has committed to implement peak-hour pricing (i.e., $\delta_B > 1$). Then firm A's optimal normal-hour prices and peak-hour multipliers satisfy:*
(i) In the presence of time flexibility only,

$$p_A^* = \frac{(\alpha+1)V_A - \gamma(2+\lambda)}{2}, \quad \delta_A^* = 1 + \frac{(\alpha-1)V_A + \gamma\alpha}{(\alpha+1)V_A - \gamma(2+\lambda)} > 1;$$

(ii) In the presence of store flexibility only,

$$p_A^* = \frac{V_A - V_B + \gamma(1-\beta) + p_B}{2};$$
$$\delta_A^* = \begin{cases} \frac{\alpha(V_A-V_B)+\gamma\beta+\delta_B p_B}{V_A-V_B+\gamma(1-\beta)+p_B} > 1, & \text{if } (\alpha-1)(V_A-V_B)+(\delta_B-1)p_B > \gamma(1-2\beta), \\ 1, & \text{otherwise,} \end{cases}$$

(iii) In the presence of both time and store flexibility,

$$p_A^* = \frac{2V_A - (\alpha+1)V_B + (1+\delta_B)p_B + \gamma}{4}, \quad \delta_A^* = 1 + \frac{2(\alpha-1)V_A}{2V_A - (\alpha+1)V_B + (1+\delta_B)p_B + \gamma} > 1.$$

Proposition 5 shows the following insights. Observe that when customers have time flexibility only (part (i)), the results are the same as Proposition 4(i) since firms A and B act as two separate monopolies in their own market. In the presence of competition, we observe the impact of δ_B on focal firm's decisions.

When customers have store flexibility only, firm B's peak-hour pricing strategy δ_B does not impact firm A's normal period price p_A. However, it influences whether and the extent to which firm A should employ peak pricing. Specifically, a higher δ_B makes firm A more likely to adopt peak-period pricing and to charge a higher peak-period surcharge.

When customers have both time and store flexibility, a higher normal-hour price and peak-hour multiplier from firm B can lead firm A to charge a higher normal-hour price p_A. However, unlike the store flexibility only case, firm A's peak-hour multiplier δ_A is decreasing in p_B and δ_B. This indicates that, when customers have both time and store flexibility, if the competing firm B employs a high surcharge δ_B, firm A would respond by increasing the normal period price p_A and apply a marginal surcharge δ_A.

In summary, we observe that in the supermarket settings (with full flexibility), having the option to change the normal-period price p_A *dampens* the implementation of peak-period pricing. Namely, in response to increase in competitor's price (p_B) or the competitor's introduction of increase peak-hour surcharge ($\delta_B > 1$), the focal firm will react by increasing the price p_A and decreasing the peak-period multiplier δ_A.

5. Impact of Customer Heterogeneity

In this section, we generalize our base model to incorporate heterogeneous customers. We begin by examining heterogeneity in customer valuations (§5.1) and then heterogeneity in customer congestion aversion level (§5.2).

5.1. Impact of Heterogeneous Valuations

We now extend our base model to incorporate the issue of heterogeneous customer valuations. For tractability, we assume that customers have a fixed benchmark valuation for store B (V_B), but they have heterogeneous valuations V_A for store A.[7] Thus, we capture the "relative" heterogeneity of store A over store B, where store B has a reference valuation V_B. To capture this relative heterogeneity, we let $V_A \sim U[(\nu-\epsilon)V_B, (\nu+\epsilon)V_B]$ so that $V_A/V_B \sim U[\nu-\epsilon, \nu+\epsilon]$, where ν represents the expected value of V_A/V_B as examined in the base model presented in §3. By noting that $\epsilon > 0$ represents the level of valuation heterogeneity, we shall examine the impact of valuation heterogeneity ϵ on the firms' decision to adopt time-base pricing in this section.

Using the same approach as presented in §3, we analyze the three settings of customer flexibility and the differing competition structures, which leads to the following result.

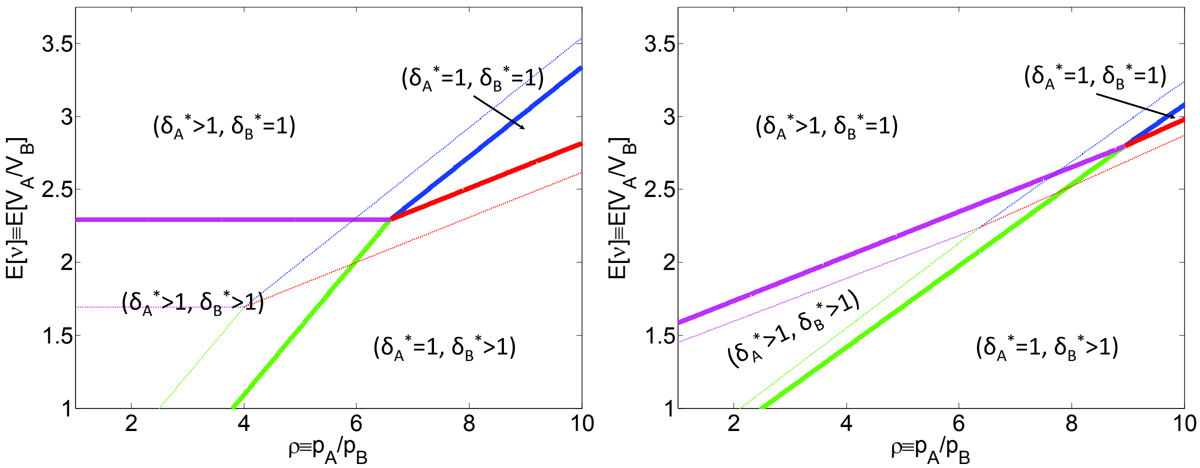
Proposition 6 **(Impact of Heterogeneous Customer Valuations)**. *Suppose Assumptions 1 –4 hold. Then when customers have:*
(i) time flexibility only, the optimal peak-hour multiplier $\delta_A^* > 1$, and increases in the valuation heterogeneity ϵ.[8]
(ii) store flexibility only, the region that has $(\delta_A^* > 1, \delta_B^* > 1)$ expands and the region that has $(\delta_A^* = 1, \delta_B^* = 1)$ contracts in the valuation heterogeneity ϵ. Also, within the $(\delta_A^* > 1, \delta_B^* > 1)$ region, δ_A^* and δ_B^* are independent of the valuation heterogeneity ϵ.
(iii) time and store flexibility, the region that has $(\delta_A^* > 1, \delta_B^* > 1)$ expands and the region that has $(\delta_A^* = 1, \delta_B^* = 1)$ contracts in the valuation heterogeneity ϵ. Also, within the $(\delta_A^* > 1, \delta_B^* > 1)$ region, δ_A^* and δ_B^* are independent of the valuation heterogeneity ϵ.

By comparing the results stated in Proposition 6 and the results for the base model stated in Propositions 1-3 in §3, we can conclude that the presence of customer valuation heterogeneity $\epsilon > 0$ does not fundamentally affect a firm's decision in adopting peak-hour pricing. That is, when customers only have time flexibility, both firms will always employ peak-hour pricing, and when customers have store flexibility, both firms, one firm, or neither firm will employ peak-hour pricing depending on the competitive structure. Nevertheless, we observe that an increase in the heterogeneity ϵ has the following effects, as represented in Figure 5.

[7] Heterogeneous valuations between shopping during peak and during normal hours α can be analyzed in a similar manner. However, this extension is less interesting and we therefore omit the details for the sake of brevity.

[8] This result holds for store B also.

Figure 5 **Equilibrium peak-hour multipliers (δ_A^*, δ_B^*) as a function of $\rho \equiv p_A/p_B$ and $\nu = V_A/V_B$ in the presence of customer valuation heterogeneity.**



Note. Left panel (store flexibility only): $\alpha = 1.3$, $\beta = 1$, $V_B = 10$, $p_B = 2$, $\epsilon = 0.2$, $\gamma = 5$. Thin (dotted) curves ($\epsilon = 0$) coincide with Figure 3. Right panel (time and store flexibility): $V_B = 10$, $p_B = 2$, $\epsilon = 0.05$, $\alpha = 1.2$, $\gamma = 5$. Thin (dotted) curves ($\epsilon = 0$) coincide with Figure 4.

When customers have no store flexibility (case (i) of Proposition 6), firms can increase their peak-period multiplier with increased heterogeneity. The presence of valuation heterogeneity implies that those customers with higher valuations are more willing to shop during the peak-period than in normal period while those with lower valuations prefer shopping during normal period. As such, heterogeneity in valuation also indirectly creates segmentation towards time preference, allowing the firm to charge higher peak-hour prices.

When customers have store flexibility (cases (ii) and (iii) of Proposition 6), we observe that an increased heterogeneity ϵ would expand the region in which both firms employ peak hour pricing and contract the region in which neither firms employs peak-hour pricing. The heterogeneity in valuations between the firms increases the customer segmentation, which reduces the intensity of competition between the firms for peak-hour customers. Consequently, an increase in the heterogeneity ϵ encourages both firms to employ peak-hour pricing. However, we observe that when both firms employ peak-hour pricing, the peak-hour multipliers are independent of ϵ. This suggests that when firms engage in more symmetric competition, the extent of peak-period prices would not be impacted by customer heterogeneity as the symmetry of competition increases the intensity of price competition to offset the effects of increased segmentation.

5.2. Impact of Heterogeneity in Congestion Aversion Level

We now extend our base model by incorporating the issue of heterogeneous congestion aversion. To facilitate this analysis with tractable results, we shall assume that $\gamma \sim U[\gamma - \epsilon, \gamma + \epsilon]$, where ϵ now represents the level of heterogeneity in the customers' congestion aversion. Our goal is to examine how $\epsilon > 0$ affects the firms' decision regarding peak-hour pricing. We first begin by examining the case when customers have only time flexibility.

Proposition 7 **(Impact of Heterogeneous Congestion Aversion)**. *Suppose Assumptions 1 and 2 hold. Then, when customers have time flexibility only, the optimal peak-hour multiplier* $\delta_A^* > 1$.[9]

Proposition 7 reveals that, in this case, both firms will always employ peak-hour pricing.

However, unlike the analysis associated with heterogeneous valuation as shown in §5.1, the analysis associated with congestion aversion heterogeneity is highly complex (See Appendix B for details). The complexity precludes us from analytically characterizing not only the impact of heterogeneity on the magnitude of δ_A^*, but also from obtaining analytical results for other settings (i.e., when customers have only store flexibility or full flexibility). Nevertheless, for any given set of parameter values we are able to numerically compute the firm's peak-hour pricing decisions.

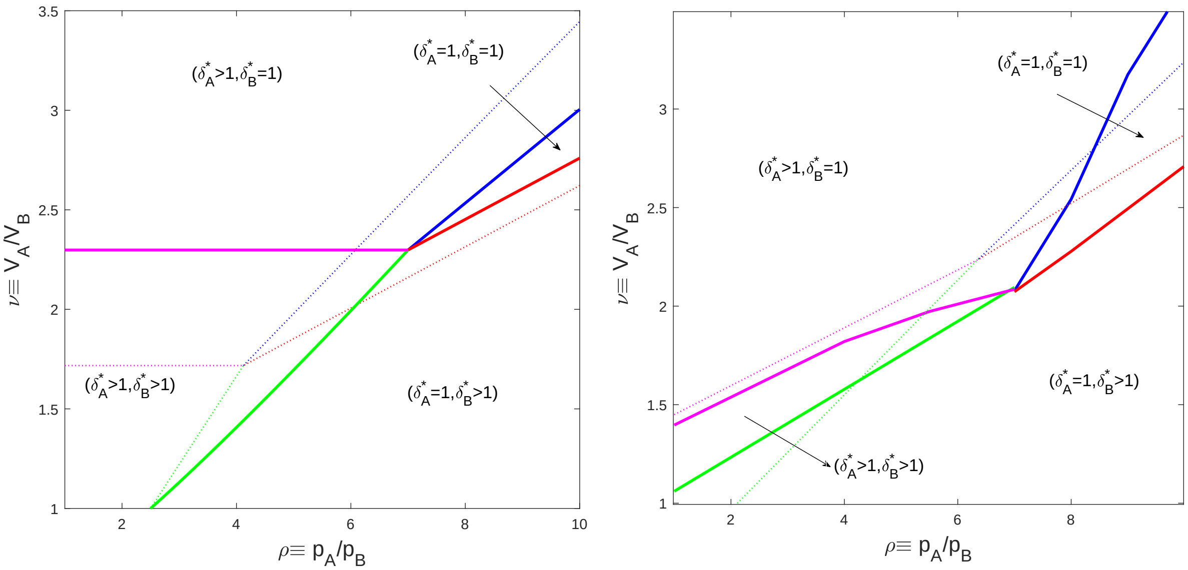
Our extensive numerical study enabled us to obtain the following insights. First, when customers have only time flexibility (Proposition 7), an increased congestion aversion heterogeneity decreases the peak-hour multiplier (See Appendix B for illustration). Similar to the increased heterogeneity in customer valuation, an increased heterogeneity in congestion level increases customer segmentation (customers with lower (higher) congestion aversion level are more inclined to purchase during the peak hours (normal hours)) and pushes for higher peak-hour prices. However, increased heterogeneity in congestion aversion also decreases the attractiveness of shopping during the peak-hour, which offsets the impact of segmentation and contributes to the decrease in peak-hour prices.

When customers have store flexibility only, those customers with lower congestion aversion level prefer to shop in firm A while those with higher congestion aversion level prefers to shop in firm B. The increased customer segmentation makes peak-hour pricing more attractive for the firms under competition. Thus, we observe from the left panel of Figure 6 that, an increased heterogeneity in congestion aversion ϵ would expand the region in which both firms employ peak hour pricing and contract the region in which neither firms employs peak-hour pricing (similar to the effect of heterogeneity in customer valuations).

When customers have both time and store flexibility, the interaction between the two types of customer flexibility complicates the impact of heterogeneity in congestion aversion. On the one hand, heterogeneity in congestion aversion indirectly increases customer segmentation and motivates firms to employ peak-hour pricing under competition (caused by store flexibility). On the other hand, it also increases the number of customers that seeks to avoid shopping during peak hours (caused by time flexibility). Due to its complex impact on the competitive dynamics,

[9] This result holds for firm B also.

Figure 6 **Equilibrium peak-period multipliers (δ_A^*, δ_B^*) as a function of $\rho \equiv p_A/p_B$ and $\nu = V_A/V_B$ in the presence of congestion aversion heterogeneity.**



Note. Left panel (store flexibility only): $V_B = 10$, $p_B = 2$, $\epsilon = 2$, $\alpha = 1.2$, $\gamma = 5$. Thin (dotted) curves ($\epsilon = 0$) coincide with Figure 3. Right panel (time and store flexibility): $V_B = 10$, $p_B = 2$, $\epsilon = 2$, $\alpha = 1.2$, $\gamma = 5$. Thin (dotted) curves ($\epsilon = 0$) indicates the case without heterogeneity in γ as in Figure 4.

an increase in heterogeneity in congestion aversion does not have a monotonic impact on any peak-hour regions when customers have both time and store flexibility, as shown in the right panel of Figure 6. Nevertheless, we observe that the presence of customer valuation heterogeneity $\epsilon > 0$ does not fundamentally influence the firms' decision regarding peak-hour pricing adoption, as we continue to observe that both firms, one firm, or neither firm will employ peak-hour pricing depending on the competitive structure (via ν and ρ).

6. Conclusion

The recent advances of technologies, such as electronic shelf labels that enables brick and mortar retailers to implement dynamic pricing, has prompted supermarkets to contemplate peak-hour pricing much like other industries like energy and transportation. Some industry experts predict that all retailers will eventually adopt peak-hour pricing (Morley 2017, OliverWyman 2019). As the COVID-19 pandemic brings customers' aversion to congestion to the forefront, crowd management is becoming a priority (Shumsky and Debo 2020) and peak-hour pricing may emerge as an effective mechanism to smooth customer traffic in supermarkets throughout any given day. Our analysis provides more fine-grained insights regarding this prediction. In this paper, we have examined how the environmental features of supermarkets – customer flexibility and competitive asymmetry – can influence their calculus to employ peak-hour pricing.

Our results revealed that if customers are not flexible in their store choice (due to store loyalty), then firms operate as "local monopolies" and would always employ peak-hour pricing. However, if customers are flexible in their store choice, then depending on the competitive structures, it is possible for both firms, one firm, or neither firm to employ peak-hour pricing. Also, we have found that a firm's ability to adjust its normal period price can dampen the implementation of peak-period pricing and that a competitor with a valuation advantage can deter its adoption. Finally, the presence of customer heterogeneity can make it more likely for both firms and less likely for neither firms to employ peak-hour pricing.

Our analysis has practical implications for both supermarkets and technology (e.g., electronic shelf label) providers. The technology providers may wish to focus on industry settings where universal adoption of peak-hour pricing is more likely. This corresponds in our analysis where both firms employ peak-hour pricing. This will be the case where firms operate as local monopolies or are located in highly congested areas with symmetric firms competing on prices. They should avoid regions where customers' level of congestion aversion is low (e.g., low population density areas), regions with asymmetric competition between supermarkets, or low levels of valuation heterogeneity.

If the supermarkets were to decide to employ peak-hour pricing, our results provide some meaningful insights. First, we have seen that when customers are not flexible in their choice of stores, peak-hour pricing is always optimal for firms. Thus, they can focus on implementing peak-hour pricing at locations where they operate as local monopolies. In addition to location considerations, customers' inflexibility in their store choice can also be due to customers' well-entrenched habits or loyalty to preferred stores (Tang et al. 2001). Thus, to successfully implement peak-hour pricing, firms should develop customer loyalty programs. Also, we have seen that when customers are flexible in their store choice, the dominant firm will benefit from peak-hour pricing. Thus, to maximize its benefit, firms should improve their value propositions.

Our model presents several interesting directions for future research. First, while peak-hour pricing has many advantages—including boosting revenues and reducing congestion—it can also alienate customers who might object to "price gouging" – a spike in prices when they need or want the service or product the most (Tang 2018). One interesting investigation could consider a potential risk of employing peak-hour pricing in the form of behavioral customer backlash. Second, retailers may adopt electronic shelf labels for reasons other than revenue. For example, they can enable firms to collect more accurate customer data in an effort to digitize physical retail and provide synergy with customers' showroom behaviors. It would be interesting to examine such interactions. Finally, if a firm wants to employ peak-hour pricing, what would be the best way to implement it? Investigating the peak-period prices for an assortment of items would be another practically relevant question. For example, to minimize the sting of charging higher prices for the "surge" items, firms might decide to bundle them with non-surge items. Although these topics are beyond the scope of the present paper, we believe that they would be fruitful directions for future research.

References

Adams, T. 2017. Surge pricing comes to the supermarket. *The Guardian*, 4 June. https://www.theguardian.com/technology/2017/jun/04/surge-pricing-comes-to-the-supermarket-dynamic-personal-data

Allon, G., Federgruen, A. 2007. Competition in service industries. *Operations Research*, **55**(1), 37–55.

Araman, V. F., Caldentey, R. 2009. Dynamic pricing for nonperishable products with demand learning. *Operations Research*, **57**(5), 1169–1188.

Bai J, So KC, Tang CS, Chen X, Wang H. 2019. Coordinating supply and demand on an on-demand service platform: Price, wage, and payout ratio. *Manufacturing & Service Operations Management*, **21**(3), 556–570.

Besbes, O., Zeevi, A. 2009. Dynamic pricing without knowing the demand function: Risk bounds and near-optimal algorithms. *Operations Research*, **57**(6), 1407–1420.

Cachon GP, Daniels KM, Lobel R. 2017. The role of surge pricing on a service platform with self-scheduling capacity. *Manufacturing & Service Operations Management*, **19**(3):68–384.

Cachon, G. P., Harker, P. T. 2002. Competition and outsourcing with scale economies. *Management Science*, **48**(10), 1314–1333.

Chen MK, Sheldon M. 2015. Dynamic pricing in a labor market: Surge pricing and flexible work on the Uber platform. Working paper, SSRN.

Chen, H., Wan, Y. W. 2003. Price competition of make-to-order firms. *IIE Transactions*, **35**(9), 817–832.

Economist. 2021. The importance of "omnichannel" strategies. Reports of the death of the supermarket have been exagerated. March 13. https://www.economist.com/special-report/2021/03/11/the-importance-of-omnichannel-strategies

Eliashberg, J., A.P. Jeuland. 1986. The impact of competitive entry in a developing market upon dynamic pricing strategies. *Marketing Science*, **5**(1), 20–36.

Gallego, G., Van Ryzin, G. 1994. Optimal dynamic pricing of inventories with stochastic demand over finite horizons. *Management Science*, **40** (8), 999–1020.

Guda H, Subramanian U. 2019. Your Uber is arriving: Managing on-demand workers through surge pricing, forecast communication, and worker incentives. *Manag. Sci.* Advance article.

Hall J, Kendrick C, Nosko C. 2015. The effects of Uber's surge pricing: A case study. Case study.

Huang, Y., Gokpinar, B., Tang, C. S., Yoo, O. S. 2018. Selling innovative products in the presence of externalities. *Production and Operations Management*, **27**(7), 1236–1250.

Kopalle P, Burkhardt J, Gillingham K. 2018. Can't take the heat? Field experiments in residential energy conservation on hot Texas days. Working paper.

Lawrie, E., 2017. Why your bananas could soon cost more in the afternoon. BBC News, June 30. https://www.bbc.com/news/business-40423114

Lederer, P. J., Li, L. 1997. Pricing, production, scheduling, and delivery-time competition. *Operations research*, **45**(3), 407–420.

McKinsey. 2020. How European shoppers will buy groceries in the next normal. December 2. https://www.mckinsey.com/industries/retail/our-insights/how-european-shoppers-will-buy-groceries-in-the-next-normal

Mendelson, H. 1985. Pricing computer services: Queueing effects. *Communications of the ACM*, **28**(3), 312–321.

Mendelson, H., Whang, S. 1990. Optimal incentive-compatible priority pricing for the M/M/1 queue. *Operations Research*, **38**(5), 870–883.

Morgan, B. 2020. 3 lasting changes to grocery shopping after covid-19. Forbes, December 14. https://www.forbes.com/sites/blakemorgan/2020/12/14/3-lasting-changes-to-grocery-shopping-after-covid-19/?sh=76327ccd54e7

Morley K (2017) Exclusive: End of fixed prices within five years as supermarkets adopt electronic price tags. *The Telegraph* (June 24), http://www.telegraph.co.uk/news/2017/06/24/exclusive-end-fixed-prices-within-five-years-supermarkets-adopt.

OliverWyman. 2019. The future supermarket. https://www.oliverwyman.com/our-expertise/insights/2019/jan/boardroom-volume-4/new-marketplace–changes-in-store/the-future-supermarket.html

Petruzzi, N. C., Dada, M. 1999. Pricing and the newsvendor problem: A review with extensions. *Operations Research*, **47**(2), 183–194.

Proactive. 2017. June. Tesco, Sainsbury's and Morrisons all set to trial 'Uber-style' surge pricing. http://ca.proactiveinvestors.com/companies/news/179826

Quinn, I., 2020. Asda launches biggest trial of electronic shelf labels to date. The Grocer, November 12. https://www.thegrocer.co.uk/store-design/asda-launches-biggest-trial-of-electronic-shelf-labels-to-date/650311.article

Shumsky, R., L. Debo. 2020. What safe shopping looks like during the pandemic. Harvard Business Review, June 24. https://hbr.org/2020/07/what-safe-shopping-looks-like-during-the-pandemic

Stamatopoulos, I., Chehrazi, N., Bassamboo, A. 2019. Welfare implications of inventory-driven dynamic pricing. *Management Science*, **65**(12), 5741–5765.

Souza, K. 2019. Walmart conducting pilot test of electronic shelf labels, LED strips. Talk Business & Politics, February 6. https://talkbusiness.net/2019/02/walmart-conducting-pilot-test-of-electronic-shelf-labels-led-strips/

Tang CS. 2018. The secrets of making surge pricing work without turning off customers. *Wall Street Journal* (February 20).

Tang CS, Bell DR, Ho T. 2001. Store choice and shopping behavior: How price format works. *California Management Review*, 43(2):56–74.

Tang CS, Yoo OS, Zhan D. 2021. Time-based pricing at grocery stores? Equilibrium transition under retail competition and negative congestion externality. Working paper.

Taylor TA (2017) On-demand service platforms. *Manufacturing & Service Operations Management*, 20(4):704–720.

Wenders JT. 1976. Peak load pricing in the electric utility industry. *Bell Journal of Economics*, 7(1):232–241.

Williamson OE. 1966. Peak-load pricing and optimal capacity under indivisibility constraints. *American Economic Review*, 56(4):810–827.