Received: 31 July 2021 | Accepted: 2 April 2023

DOI: 10.1111/poms.14010

POMS

ORIGINAL ARTICLE

When should grocery stores adopt time-based pricing? Impact of competition and negative congestion externality

Christopher S. Tang[1] | **Onesun Steve Yoo**[2] | **Dongyuan Zhan**[2]

[1]UCLA Anderson School of Management, Los Angeles, California, USA

[2]UCL School of Management, University College London, London, UK

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

Dongyuan Zhan, UCL School of Management, University College London, London, UK.
Email: d.zhan@ucl.ac.uk

Handling Editor: Tony Cui

Abstract

Consumers dread shopping during peak hours, and the Covid-19 pandemic has created additional safety concerns about overcrowding in addition to long waiting times. In view of consumer's congestion aversion, should competitive brick-and-mortar grocery stores charge higher prices during congested peak hours to smooth demand? To examine "whether and when" stores should adopt intraday time-based pricing under competition, we examine a 2-stage dynamic duopoly game. At the beginning of each stage, each store can make an irreversible decision to adopt time-based pricing by setting the peak-hour and normal-hour prices. We also endogenize consumer's shopping decisions (i.e., when and which store to shop) by incorporating the issue of negative congestion externality. Our equilibrium analysis reveals that time-based pricing is always beneficial for the stores, and both stores would adopt it eventually in equilibrium. As such, only two equilibria can sustain: either both firms adopt time-based pricing immediately in stage 1, or only one firm adopts in stage 1 while the other postpones its adoption until stage 2. Interestingly, due to the competitive dynamics, it is less likely for both firms to adopt immediately when consumers are more averse to congestion. Moreover, although the adoption of time-based pricing leads to differentiated price competition, it can "soften" price competition, causing both peak-hour and normal-hour prices to rise above the status quo equilibrium uniform prices. We find that time-based pricing can always induce demand smoothing and reduce congestion. Although time-based pricing creates value for the stores (through higher prices), it offers no benefit to consumers.

KEYWORDS
consumer negative externality, demand smoothing, duopoly, time-based pricing

1 | INTRODUCTION

Consumers generally dread shopping during peak hours because of the discomfort associated with overcrowdedness and long waiting times. The pandemic has further brought consumers' aversion to congestion to the forefront. Supermarkets, which have 95% of the grocery market share in the United Kingdom and France (Shveda, 2020), have experienced long queues that lead to a rise in verbal and physical abuse of their staff by consumers who dread waiting in line (Harris, 2021; ITV, 2021). To minimize the time consumers spend in indoor spaces, supermarkets have imposed various restrictions, such as assigning specific times to vulnerable groups of consumers and some have converted their parking lots to offer curbside pickups or have sectioned off some store space for click-and-collect order fulfillment (Morgan, 2020).

As crowd management is becoming a priority agenda for many supermarkets and retailers (McKinsey, 2020; Morgan, 2020; Shumsky & Debo, 2020), emerging technologies such as electric shelf labels have kindled brick-and-mortar grocery stores' interest in exploring intraday *time-based pricing*. This form of variable pricing refers to pricing that fluctuates in a "predictable cyclical pattern" within a given day.[1] Specifically, under the time-based pricing scheme, a store would charge higher prices during pre-announced peak hours to effectively *nudge* some consumers to avoid peak hours with the aim to smooth customer traffic throughout the day. In

Accepted by Tony Cui, after three revisions.

doing so, it can enable a store to improve safety and shopping experience for the shoppers.

Conceptually speaking, adopting intraday time-based pricing is not a far-fetched idea for brick-and-mortar retailers. Prior to the pandemic, three large supermarket chains in the United Kingdom (Tesco, Sainsbury's, and Morrisons) had reviewed plans to implement Uber-style time-based pricing that could make items cost more in the busy afternoon hours (Lawrie, 2017; Morley, 2017; Proactive, 2017). Many large supermarkets in the EU have installed electronic price tags and are thus equipped with the potential to implement time-based pricing (Adams, 2017). Besides the EU, Singapore's NTUC FairPrice supermarket had installed e-tags in their stores in 2013 (Actusnews Wire, 2013), while Alibaba's offline retail chain stores in China (Hema) had adopted this technology in 2018 (McKinnon, 2021). During the pandemic, Walmart also conducted pilot tests of electronic shelf labels in the United States (Souza, 2019), and Asda, another major supermarket chain in the United Kingdom, implemented electronic shelf labels in some of its stores (Quinn, 2020).

In fact, industry experts had predicted that many grocery retailers would adopt time-based pricing in due course (Morley, 2017; OliverWyman, 2019; Waddell, 2019), much like energy companies that employ peak-load pricing to smooth demand, public transportation systems in metropolitan areas that charge higher fares during peak hours, and restaurants and bars that charge lower prices during nonpeak "happy" hours (Beckwith & Webb, 2022).

Having said that, consumers generally prefer stable prices over time-dependent prices (under the time-based pricing scheme). Some may even find time-based pricing to be unfair and impractical (MacMillan, 2015; Taylor, 2018).[2] This is especially true in the grocery setting relating to everyday essential items, and thus has important implications for consumers and their welfare (Dholakia, 2015, 2016). The discussions of time-based pricing and potentially unpredictable price changes in grocery stores has sparked consumer anxiety and public interest (Tang, 2018).

1.1 | Research questions and answers

In view of the above context, we aim to examine three research questions in this paper:

(1) Given the concerns over store overcrowdedness and the disenchantment over time-based pricing, *should* brick-and-mortar grocery stores adopt intraday time-based pricing?
(2) Given the competitive environment and the "congestion-averse" consumers (who can decide freely when to shop and which store to shop), *when* should a store adopt time-based pricing?
(3) Given the option for each store to adopt time-based pricing, *what* are the implications for equilibrium prices, congestion levels, and consumer and social welfare?

To answer the above questions, we present a 2-stage dynamic duopoly game to examine "whether and when" competing stores should adopt intraday time-based pricing. In each stage, each store can decide whether or not to adopt time-based pricing and set the peak hour and regular hour prices. Adopting the time-based strategy is *irreversible* for any store: once the time-based prices are set, it will not be changed in subsequent periods.[3] A firm may choose to delay the adoption of time-based pricing so that it can gain an "informational advantage" by observing the strategic choice and pricing decision made by the competing store in stage 1 before determining its own time-based prices in stage 2. However, delaying the adoption will cause a firm to miss out an additional profit opportunities in stage 1 (generated by time-based pricing). Further, our model allows congestion-averse population of consumers to decide on when (time of day) and where (competing stores) to shop. We determine the timing of the adoption and the corresponding pricing decisions in equilibrium, as well as the equilibrium consumer shopping behavior (i.e., when and where to shop) in each stage by taking into account the consumers' aversion to congestion.

Our equilibrium analysis reveals the following insights. First, despite competition, time-based pricing is always beneficial to the stores: both stores should eventually adopt it in equilibrium. Specifically, we find that either both firms adopt time-based pricing immediately in stage 1 or one firm adopts it in stage 1 while the other adopts it in stage 2. Intuitively, we find that as stores become "more myopic" the number of firms that adopt time-based pricing immediately in stage 1 increases (from 1 to 2). Interestingly, when consumers are highly averse to congestion, the number of firms that adopt time-based pricing in stage 1 decreases (from 2 to 1) due to the underlying competitive dynamics.

Although the adoption of time-based pricing results in differentiated price competition, we find an interesting result: relative to the status quo uniform price competition, time-based pricing can *soften* competition and boost both retailers' profits (through higher prices). This finding is in stark contrast to the literature on differentiated price competition (Chen, 2008; Corts, 1998; Shaffer & Zhang, 2002), which suggests that competing with multiple differentiated prices to consumers intensifies the price competition between rival retailers, and lowers the average prices to hurt their profits. In our setting, we find that *both* the regular hour and peak hour prices can rise above the current status quo uniform equilibrium prices, and benefit the retailers.

Our results shed light into whether and when stores should transition from the current status quo uniform pricing to time-based pricing. Also, our results provide insights regarding how time-based pricing adoption would affect demand smoothing, consumer welfare, and social welfare. Under all adoption strategy adopted by the stores in equilibrium, we find that time-based pricing will always induce demand smoothing. In other words, the adoption of time-based pricing strategy by each retailer in equilibrium will successfully shift consumer demand from peak hours to regular hours. However, we find that consumer welfare does not increase in equilibrium because the benefit of time-based pricing is captured by the retailers via the higher (peak-hour) prices charged by the retailers in equilibrium. This increase in the profitability of the retailers brought on by time-based pricing could be marginal, relative to the cost inflicted on the consumers. Consequently, adopting time-based pricing can lower the social welfare below the status quo level.

For robustness check, we examine two extensions: (1) asymmetric competition under which consumer's shopping value is *store-specific*; and (2) when the number of stages is $n > 2$. For the former case, when one retailer has a competitive advantage (i.e., higher value) over the other, we find that a new adoption equilibrium can emerge where only the dominant retailer (that offers a higher value) can afford to adopt immediately in stage 1 (to take advantage of time-based pricing earlier) while the less dominant retailer can only afford to adopt in stage 2 (to take advantage of the informational gain). For the latter case that has $n > 2$ stages, it becomes less likely for both firms to adopt time-based pricing immediately in stage 1. Even so, we obtain similar structural results and key insights as obtained in the main model.

1.2 | Related literature and contributions

Time-based pricing has been studied in the form of peak-load pricing by the utility sector to smooth out demand. The prior literature examines how to allocate the fixed and variable costs of energy between peak-period and regular-period users in order to minimize both system overload and the frequency of blackouts (Wenders, 1976; Williamson, 1966). Recent studies examine how employing "smart meters" to alert consumers about peak prices can reduce consumers' energy usage during peak periods (e.g., Burkhardt et al., 2018). The rise of ride-hailing services has motivated researchers to examine various facets of surge pricing (Angrist et al., 2021; Bai et al., 2019; Cachon et al., 2017; Chen & Sheldon, 2015; Guda & Subramanian, 2019; Ke et al., 2020; Taylor, 2018). This research stream is based on a *monopoly* setting. We contribute to this literature by proposing a *duopoly* model in a competitive retail setting. Tang et al. (2022) examine a competitive setting where retailers compete by setting a surge multiplier in a static setting. To the best of our knowledge, our paper represents an initial attempt to investigate "whether and when" competing stores should adopt time-based pricing in the presence of congestion-aversion.

Our paper investigates technology adoption decision of retailers. A widely used framework is the optimal stopping time framework, which deals with the timing of irreversible technology adoption decisions (Dixit & Pindyck, 1994; McDonald & Siegal, 1986; Pindyck, 1988). We adopt this framework to examine an *adoption timing* game between two competing retailers. However, unlike existing literature that focused on the trade-off between the cost of delaying adoption and the uncertainty on the benefits of adoption, we examine the trade-off between the benefit of "capturing congestion averse consumers" earlier by adopting time-based pricing immediately and the benefit of "gaining information advantage" from the competing firm by delaying the adoption of time-based pricing later. Thus, our paper complements the technology adoption literature by providing insights into the retail sector.

Various research studies on dynamic pricing are intended to: manage demand (when the supply is fixed) (Gallego & van Ryzin, 1994; Petruzzi & Dada, 1999; Stamatopoulos et al., 2019), learn about demand (Araman & Caldentey, 2009; Besbes & Zeevi, 2009), or stimulate demand for new products (Huang et al., 2018). Unlike this research stream, our intraday time-based prices are cyclical (i.e., the regular-hours price and the peak-hours price alternate throughout the day). Also, our context is different: using time-based pricing to manage congestion-averse consumers' shopping behavior under competition.

Congestion has been 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 consumers with heterogeneous valuations (Mendelson, 1985; Mendelson & 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 & Wan, 2003; Lederer & Li, 1997) or on identifying the monotonicity properties of equilibrium prices and profits while assuming exogenous demand functions (e.g., Allon & Federgruen, 2007; Cachon & Harker, 2002). Unlike the queueing game literature, we examine retailers' time-based pricing adoption (or transition) equilibrium strategies and their impact on consumer welfare.

This paper is related to the differentiated price competition literature in which retailers use multiple prices to compete. Compared to the use of a single price, the use of multiple prices intensifies price competition and benefit consumers (Chen, 2008; Corts, 1998; Shaffer & Zhang, 2002; Villas-Boas, 1999). Although these studies focus on consumers' heterogeneity with respect to price sensitivity, we focus on the issue of consumers' negative congestion externality. We demonstrate that this operational-level consideration can yield different conclusions: Unlike the findings of the differentiated price competition literature, we find that time-based pricing *softens* price competition (relative to competition with a single status quo uniform price). Also, we find that time-based pricing can enable both stores to obtain higher profits, whereas consumers would obtain a lower consumer welfare. Our paper thus examines a setting with unique features that has not been formally studied, and presents novel insights into how firm level competition and consumer negative externality interact.

The rest of this paper is organized as follows. We introduce our dynamic 2-stage adoption timing game and pricing and consumer choice model in Section 2. In Section 3, we characterize the consumer demand characterized by the Nash equilibrium and determine the equilibrium status quo uniform prices resulting from the competition. In Section 4,

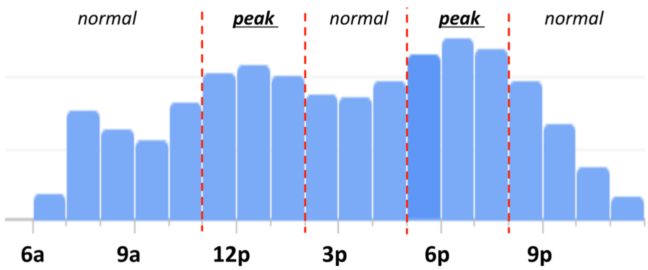

FIGURE 1 Consumer traffic at a grocery store (Tesco) in London on a typical weekday. *Source*: Google. [Color figure can be viewed at wileyonlinelibrary.com]

we analyze the competing retailers' timing of adoption of time-based pricing and the resulting regular and peak hour prices in equilibrium. In Section 5, we address the impact of retailers' time-based pricing on demand smoothing, consumer welfare, and social welfare. In Section 6, we explore two model extensions to examine the impact of asymmetric competition between the retailers and having more than two stages. We conclude the paper in Section 7. All proofs are provided in the Electronic Companion.

2 | MODEL DESCRIPTION

Consider two symmetric competing retailers A and B (e.g., supermarkets) that sell essential items to homogeneous consumers who assign a value V to each retailer's products.[4] Currently, both stores compete by setting their prices at p_A^0 and p_B^0 that represent the *status quo equilibrium uniform prices* (to be computed in Section 3). As illustrated in Figure 1, both stores are currently experiencing multiple peak-demand hours within a single day.[5]

To reduce congestion during peak hours and to improve profit, each retailers $i \in \{A, B\}$ is considering to adopt time-based pricing by charging two different prices depending on the time of day, namely, charge (reference) price p_i during regular hours and charge price $\delta_i p_i$ during peak hours via a peak-hour "multiplier" δ_i with $\delta_i \geq 1$.

2.1 | Retailer's 2-stage adoption decision game

To investigate *whether* and *when* each retailer would adopt intraday time-based pricing, we introduce a parsimonious "adoption timing game" that entails a 2-stage dynamic model. Each stage $t \in \{1, 2\}$ represents a prolonged duration of time (e.g., several months to a few years). Figure 2 illustrates the adoption decision process facing retailer i, $i \in \{A, B\}$ that can be described as follows.

Prior to stage 1, both stores were charging the status quo uniform prices (p_A^0, p_B^0) as shown in Figure 2. At the beginning of stage 1, each store $i \in \{A, B\}$ decides (*endogenously*) whether to adopt time-based pricing. If store i decides to adopt, then it sets the time-based prices p_i (during regular hours) and $\delta_i p_i$ (during peak hours), and these prices will be employed in all subsequent stages. The adoption decision and the time-based prices captured by (p_i, δ_i) are assumed to be *irreversible*: once a retailer adopts time-based pricing, it cannot change back to uniform pricing.[6]

If store i decides not to adopt time-based pricing in stage 1, we assume store i will keep its status quo uniform prices p_i^0 in stage 1 and will re-examine its adoption of time-based pricing in stage 2. Essentially, after both firms established their status quo uniform prices p_i^0 before stage 1, our model assumes that a firm can change its prices *only when* it is accompanied by the adoption of time-based pricing. Besides tractability, limiting the flexibility of changing prices to just once is reasonable when retailers are concerned about consumer backlash caused by frequent price changes (cf., Kok et al., 2008). We shall discuss this limitation in the conclusion.

Figure 3 illustrates three possible pricing trajectories of store i over time as a result of the firm i's time-based pricing adoption strategy as depicted in Figure 2.

Also, by anticipating store j's adoption strategy as depicted in Figure 2, store i intends to decide on whether and when to adopt time-based pricing that can maximize its discounted total profit:

$$\pi_i = \pi_{i,1} + \beta \pi_{i,2}, \tag{1}$$

where the parameter $\beta \in (0, 1)$ captures store i's discount factor on future profits. The retailers determine whether and when to adopt time-based pricing (and set new prices upon adoption) by considering the underlying competition and by anticipating congestion-averse consumers' response to (time-based and uniform) pricing. (To simplify matters without loss of generality, we assume that the electronic shelf-label technology can be adopted at zero cost, scale the variable costs to zero, and normalize the market size to 1.)

2.2 | Congestion-averse consumer's decisions: When and where to shop?

We now model congestion-averse consumers' shopping behavior and characterize the intraday demand. On any given day within stage t, $t \in \{1, 2\}$, a consumer is first presented with a given set of prices set by store $i = A, B$: either the status quo uniform prices p_i^0 or time-based prices captured by (p_i, δ_i). Then each consumer must choose when (peak hours or regular hours) and where (store A or B) to shop. We assume that the consumers are price takers and do not behave strategically with the retailers. This is a reasonable assumption for the grocery shopping setting because consumers usually do not (and cannot) delay their purchase or stockpile when it comes to their grocery needs (McKinsey, 2020).

There are pros and cons for a consumer who shops during peak hours. On the one hand, she places a greater value on shopping during peak hours because of the convenience. We therefore assume that a shopper derives value αV with

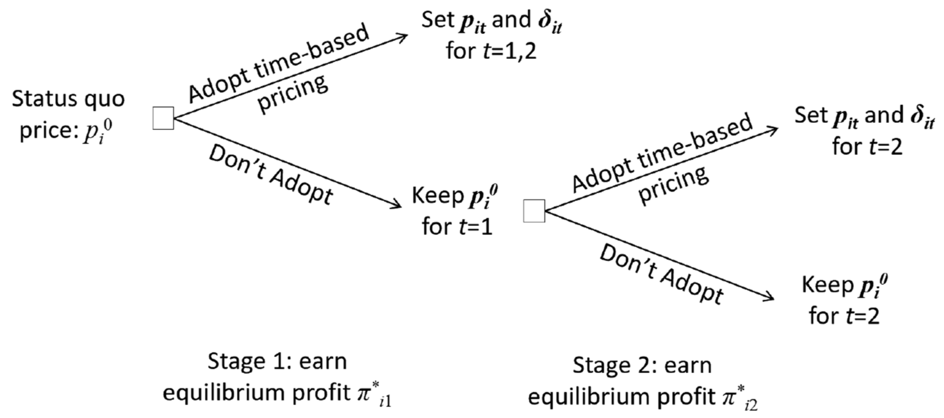

FIGURE 2 Retailer i's adoption timing decision.

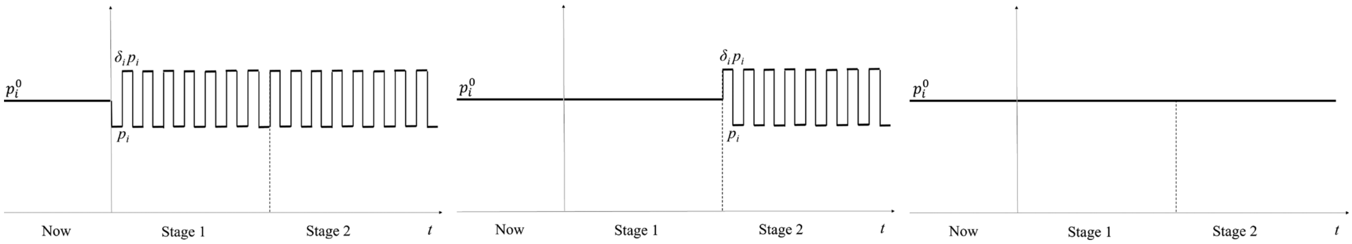

FIGURE 3 Illustrative prices seen by the consumers as a result of the transition strategies adopted by retailer i. Retailer i adopts time-based pricing in stage 1 (left), in stage 2 (middle), or does not adopt (right).

convenience factor $\alpha > 1$ when shopping during peak hours, where V is the value for shopping during nonpeak hours. On the other hand, a shopper experiences disutility when shopping at a congested store (especially during peak hours). That is, a key aspect of retail shopping is the presence of *negative congestion externality*: An additional consumer in the store imposes a negative utility on all other consumers. The extent of such disutility is captured by the parameter γ, denoting the consumers' level of *congestion aversion*.

For ease of exposition, we shall assume the following relationship among these three parameters.

Assumption 1 (Congestion aversion level). $2(\alpha - 1)V \leq \gamma < V$.

The first inequality, $2(\alpha - 1)V \leq \gamma$, assumes that the congestion aversion level γ is high enough that the demand during nonpeak hours at each store is positive under uniform prices. The second inequality, $\gamma < V$, assumes that the value of the essential items V outweighs consumers' disutility of congestion, so that no consumer will elect to not buy their groceries due to inconvenience of congestion. (This assumption enables us to ensure that full market coverage is guaranteed in equilibrium, that is, $q^*_{AP} + q^*_{BP} + q^*_{AR} + q^*_{BR} = 1$, a commonly used assumption in the marketing literature dated back to, for example, Hotelling, 1929.)

Observe that for both inequalities of Assumption 1 to hold, it is necessary that $\alpha < 1.5$, which implies that the extra value of convenience attached to shopping during peak hours relative to regular hours is less than 50%. This is sufficient because the price premiums charged by local convenience stores compared to supermarkets typically range between 5% and 30% (Walsh, 2021). We shall assume that Assumption 1 holds throughout the paper.

TABLE 1 A consumer's utility u_{ij} based on where ($i \in \{A, B\}$) and when ($j \in \{P, R\}$) he shops.

$j \backslash i$	Retailer A	Retailer B
Peak (P)	$\alpha V - \gamma q_{AP} - \delta_A p_A$	$\alpha V - \gamma q_{BP} - \delta_B p_B$
Regular (R)	$V - \gamma q_{AR} - p_A$	$V - \gamma q_{BR} - p_B$

We use q_{ij} to represent the proportion of consumers who shop at store $i \in \{A, B\}$ during period $j \in \{P, R\}$, where P and R denote peak and regular periods, respectively. Each consumer who shops at store i in period j will experience disutility γq_{ij}. Once we account for the value V, convenience α, congestion aversion γ, and prices p_A and p_B (as well as the peak-period multipliers $\delta_A, \delta_B \geq 1$) selected by the retailers, we can capture the focal consumer's net utility u_{ij} from shopping at store $i \in \{A, B\}$ during period $j \in \{P, R\}$ as in Table 1.

To decide when and where to shop, a consumer will choose the option that offers the highest utility among those utilities shown in Table 1. Observe that the consumer does not know the proportion q_{ij} *before* visiting a store and so must decide based on a *belief* about what q_{ij} will be. A Nash equilibrium dictates that a consumer's initial belief should be consistent with the realized demand. Given an appropriate set of prices $(p_A, \delta_A; p_B, \delta_B)$ in each stage set by the retailers, the intraday demand associated with the equilibrium level of q^*_{ij} will be computed in Section 3.

2.3 | Performance metrics: Peak-period demand PQ, consumer welfare CW, and social welfare SW

After examining the equilibrium intraday demand for each store and hours q^*_{ij}, we shall evaluate the impact of the time-based pricing (by considering the status quo uniform prices as a benchmark). In addition to store i's discounted total profit π_i given in (1), we consider three *impact metrics*; namely, peak-period demand PQ, consumer welfare CW, and social welfare SW, that can be defined as follows:

Definition 1 (Impact metrics for time-based pricing). The equilibrium peak-period demand PQ, consumer welfare CW, and social welfare SW are defined as follows:

$$PQ_t(p_A, \delta_A; p_B, \delta_B) \triangleq \sum_{i\in\{A,B\}} q^*_{iP}(p_A, \delta_A; p_B, \delta_B), \tag{2}$$

$$CW_t(p_A, \delta_A; p_B, \delta_B) \triangleq \sum_{i\in\{A,B\}} \sum_{j\in\{R,P\}} q^*_{ij}(p_A, \delta_A; p_B, \delta_B) \cdot u_{ij}, \tag{3}$$

$$SW_t(p_A, \delta_A; p_B, \delta_B) \triangleq CW_t + \sum_{i\in\{A,B\}} \pi_{i,t}, \tag{4}$$

where the consumer utility u_{ij} is given in Table 1.

The first metric, PQ_t, represents the total proportion of consumers who shop during the peak hours in stage t. This metric will enable us to investigate whether time-based pricing adoption in a competitive setting would induce demand smoothing. The second metric, CW_t, represents the impact on consumer welfare by examining the consumers' overall utility in stage t. The final metric, SW_t, represents the effect on both consumers and retailers in stage t. For ease of exposition, we suppress the argument $(p_A, \delta_A; p_B, \delta_B)$.

3 | CONSUMER DEMAND AND STATUS QUO BENCHMARK

To facilitate our analysis, we determine two building blocks in this section. First, for any given set of prices $(p_A, \delta_A; p_B, \delta_B)$ set by both stores, we examine the equilibrium consumer demand q^*_{ij} that is endogenously determined. Second, by setting $\delta_A = \delta_B = 1$ so that both stores charge a uniform price p_i in both peak and regular periods, we determine the *status quo equilibrium uniform prices* (p^0_A, p^0_B).

3.1 | Equilibrium consumer demand q^*_{ij}

We first compute the unique equilibrium consumer demand $q^*_{i,j}$ for each store $i \in \{A, B\}$ during period $j \in \{P, R\}$.

Proposition 1 (Equilibrium demand in each stage). *For any given price structure $(p_A, \delta_A; p_B, \delta_B)$, the equilibrium demand q^*_{ij} for store $i \in \{A, B\}$ in period $j \in \{R, P\}$ satisfy:*

$$q^*_{AP}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} + \frac{(\alpha-1)V}{2\gamma} + \frac{(1-3\delta_A)p_A + (1+\delta_B)p_B}{4\gamma},$$

$$q^*_{BP}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} + \frac{(\alpha-1)V}{2\gamma} + \frac{(1+\delta_A)p_A + (1-3\delta_B)p_B}{4\gamma},$$

$$q^*_{AR}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} - \frac{(\alpha-1)V}{2\gamma} + \frac{(\delta_A-3)p_A + (1+\delta_B)p_B}{4\gamma},$$

$$q^*_{BR}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} - \frac{(\alpha-1)V}{2\gamma} + \frac{(1+\delta_A)p_A + (\delta_B-3)p_B}{4\gamma},$$

provided that the given prices $(p_A, \delta_A, p_B, \delta_B)$ satisfy:

$$q^*_{AP}, q^*_{BP}, q^*_{AR}, q^*_{BR} > 0 \ \ and 2(1+\alpha)V - \gamma - p_A - \delta_A p_A - p_B - \delta_B p_B > 0. \tag{5}$$

The proportion q^*_{ij} can also be interpreted as the probability that a consumer chooses to shop at store i during period j. Observe from Proposition 1 that, as expected, the peak demands q^*_{AP} and q^*_{BP} increase with the peak period booster α (because $\alpha > 1$). Also, notice from the expressions that the congestion aversion coefficient γ determines the "stickiness" of demand. A marginal reduction in price by one retailer does not lead to a discontinuous jump in demand for that retailer because the benefit due to lower prices is partially offset by the higher congestion that it entails.

3.2 | Benchmark: Status quo equilibrium outcomes

By applying Proposition 1 for the case when $\delta_A = \delta_B = 1$, we obtain the corresponding equilibrium demands for the case when both stores compete with uniform prices p_A and p_B prior to stage 1. By using these equilibrium demands, we can determine the current status quo equilibrium uniform prices p^0_A and p^0_B by solving the following pricing problems for retailers A and B *simultaneously*:

$$\pi^0_A = \max_{p_A} \ p_A \cdot \left(q^*_{AP}(p_A, 1; p_B, 1) + q^*_{AR}(p_A, 1; p_B, 1)\right), \text{and}$$

$$\pi^0_B = \max_{p_B} \ p_B \cdot \left(q^*_{BP}(p_A, 1; p_B, 1) + q^*_{BR}(p_A, 1; p_B, 1)\right).$$

Proposition 2 specifies the equilibrium status quo uniform prices p^0_i and store profits π^0_i.

Proposition 2 (Status quo prices). *When both stores compete under uniform pricing, their equilibrium prices and profits satisfy:*

$$\text{(i)}\;\; p_A^0 = p_B^0 = \frac{\gamma}{2}, \quad \delta_A^0 = \delta_B^0 = 1;$$

$$\text{(ii)}\;\; \pi_A^0 = \pi_B^0 = \frac{\gamma}{4}.$$

By substituting the prices p_A^0, p_B^0, δ_A^0, and δ_B^0 into expressions (2)–(4), we get:

Corollary 1 (Status quo impact metrics). *Under the status quo uniform pricing, the impact metrics in equilibrium satisfy:*

$$\text{(i)}\;\; PQ^0 = \frac{1}{2} + \frac{(\alpha-1)V}{\gamma};$$

$$\text{(ii)}\;\; CW^0 = \frac{2(1+\alpha)V - 3\gamma}{4};$$

$$\text{(iii)}\;\; SW^0 = \frac{2(1+\alpha)V - \gamma}{4}.$$

In Section 5, we shall compare the equilibrium outcomes under time-based pricing against these benchmark equilibrium outcomes stated in Proposition 2 and Corollary 1 associated with the status quo uniform pricing.

4 | TIME-BASED PRICING EQUILIBRIUM ANALYSIS: WHEN TO ADOPT AND HOW MUCH TO CHARGE?

We now analyze the adoption timing of time-based pricing and the corresponding prices in equilibrium in a 2-stage competitive game via backward induction. We first examine the equilibrium outcomes in stage 2 in Subsection 4.1, and then analyze the equilibrium outcomes in stage 1 in Subsection 4.2.

4.1 | Stage 2 equilibrium strategies

We begin by examining the adoption and pricing decisions in stage 2, where firm $i \in \{A, B\}$ seeks to maximize the single stage (stage 2) payoff, $\pi_{i,2}$. At the beginning of stage 2, there are three possible settings based on the actions taken by both stores in stage 1. These three possible settings are: (1) both stores have adopted time-based pricing and set the corresponding prices in stage 1; (2) only one store has adopted time-based pricing and set the corresponding prices in stage 1; or (3) neither firm has adopted time-based pricing in stage 1. We shall examine the equilibrium adoption and pricing outcomes associated with these three settings in turn. (We shall use superscripts $^{(1)}$,$^{(2)}$, and $^{(3)}$ to denote Settings (1), (2), and (3), respectively.)

4.1.1 | Setting (1): Both stores have adopted time-based pricing in stage 1

If both stores have adopted time-based pricing in stage 1, then they have set the corresponding time-based prices $(p_{i,1}, \delta_{i,1})$ already. Due to irreversibility, both stores will maintain their prices in stage 2 so that: $(p_{A,2}^{(1)}, \delta_{A,2}^{(1)}) = (p_{A,1}, \delta_{A,1})$ and $(p_{B,2}^{(1)}, \delta_{B,2}^{(1)}) = (p_{B,1}, \delta_{B,1})$. As such, there are no decisions to be made in stage 2 (see Figure 2), and their profits in stage 2 are:

$$\pi_{A,2}^{(1)} = \pi_{A,1} = p_{A,1}\left(\delta_{A,1} \cdot q_{BP}^*(p_{A,1}, \delta_{A,1}; p_{B,1}, \delta_{B,1}) + q_{BR}^*(p_{A,1}, \delta_{A,1}; p_{B,1}, \delta_{B,1})\right), \tag{6}$$

$$\pi_{B,2}^{(1)} = \pi_{B,1} = p_{B,1}\left(\delta_{B,1} \cdot q_{BP}^*(p_{A,1}, \delta_{A,1}; p_{B,1}, \delta_{B,1}) + q_{BR}^*(p_{A,1}, \delta_{A,1}; p_{B,1}, \delta_{B,1})\right). \tag{7}$$

Also, all three impact metrics in stage 2 for case (1) are identical to those of stage 1; that is, the peak demand $PQ_2^{(1)} = PQ_1$, consumer welfare $CW_2^{(1)} = CW_1$, and social welfare $SW_2^{(1)} = SW_1$. (The expressions for PQ_1, CW_1, and SW_1 will be provided in Subsection 4.2.)

4.1.2 | Setting (2): Only one store has adopted time-based pricing in stage 1

Without loss of generality, let store A be the only store that had adopted time-based pricing and had set time-based prices $(p_{A,1}, \delta_{A,1})$ in stage 1. Knowing store A will maintain its pricing structure in stage 2 (see Figure 2), firm B needs to decide on whether or not to adopt time-based pricing and the corresponding prices in stage 2 by solving:

$$\pi_{B,2}^{(2)} = \max_{(p_{B,2}, \delta_{B,2})} p_{B,2}\left(\delta_{B,2} \cdot q_{BP}^*(p_{A,1}, \delta_{A,1}; p_{B,2}, \delta_{B,2}) + q_{BR}^*(p_{A,1}, \delta_{A,1}; p_{B,2}, \delta_{B,2})\right).$$

Although store A will maintain its prices in stage 2 so that $(p_{A,2}^{(2)}, \delta_{A,2}^{(2)}) = (p_{A,1}, \delta_{A,1})$, the prices set by firm B in stage 2 $(p_{B,2}^{(2)}, \delta_{B,2}^{(2)})$ will affect the demand for both stores q_{ij} governed by Proposition 1. These observations imply that firm A's profit in stage 2 is:

$$\pi_{A,2}^{(2)} = p_{A,1}\left(\delta_{A,1} \cdot q_{AP}^*(p_{A,1}, \delta_{A,1}; p_{B,2}, \delta_{B,2}) + q_{AR}^*(p_{A,1}, \delta_{A,1}; p_{B,2}, \delta_{B,2})\right).$$

By solving store B's problem as stated above, we get:

Proposition 3 (Setting (2): When store A adopted time-based pricing in stage 1). *Suppose only store A adopted time-based pricing according to* $(p_{A,1}, \delta_{A,1})$ *in stage* 1. *Then,* (*i*) *it is optimal for store B to adopt time-based pricing in stage* 2*; also,*

(*ii*) *the equilibrium prices for store B, and the profits for both stores in stage* 2 *are:*

(a) $$p_{B,2}^{(2)} = \frac{\gamma + p_{A,1}(1+\delta_{A,1}) - (\alpha-1)V}{4};$$

$$\delta_{B,2}^{(2)} \cdot p_{B,2}^{(2)} = \frac{\gamma + p_{A,1}(1+\delta_{A,1}) + (\alpha-1)V}{4};$$

(b) $$\pi_{A,2}^{(2)} = \frac{\begin{array}{c}-5p_{A,1}^2 + 6p_{A,1}^2\delta_{A,1} - 5p_{A,1}^2\delta_{A,1}^2 \\ +3\gamma(1+\delta_{A,1})p_{A,1} + 4(\alpha-1)(\delta_{A,1}-1)p_{A,1}V\end{array}}{8\gamma};\ and$$

$$\pi_{B,2}^{(2)} = \frac{(\gamma + (1+\delta_{A,1})p_{A,1})^2 + 2(\alpha-1)^2V^2}{16\gamma}.$$

From statement (a), it is easy to check that $\delta_{B,2}^{(2)} = \frac{\gamma + p_{A,1}(1+\delta_{A,1}) + (\alpha-1)V}{\gamma + p_{A,1}(1+\delta_{A,1}) - (\alpha-1)V} > 1$, and that the difference between peak and regular hour prices for store B in stage 2 is: $\delta_{B,2}^{(2)} p_{B,2}^{(2)} - p_{B,2}^{(2)} = (\alpha-1)V/2 > 0$. By using the pricing $(p_{A,2}^{(2)}, \delta_{A,2}^{(2)}) = (p_{A,1}, \delta_{A,1})$ and $(p_{B,2}^{(2)}, \delta_{B,2}^{(2)})$ as stated in Proposition 3, we can first apply Proposition 1 to retrieve the demands for both stores q_{ij} and then apply Equations (2)–(4) to calculate those three impact metrics in stage 2, getting:

Corollary 2 (Stage 2 impact metrics for Setting (2)). *Suppose only store A adopted time-based pricing according to* $(p_{A,1}, \delta_{A,1})$ *in stage* 1*. Then store B will adopt time-based pricing according to* $(p_{B,2}^{(2)}, \delta_{B,2}^{(2)})$ *in stage* 2 *with the following impact metrics:*

(i) $$PQ_2^{(2)} = \frac{3(\alpha-1)V + 2\gamma + 2p_{A,1}(1-\delta_{A,1})}{4\gamma};$$

(ii) $$CW_2^{(2)} = \frac{(\alpha+1)V}{2} - \frac{3\gamma + 3p_{A,1}(1+\delta_{A,1})}{8};$$

(iii) $$SW_2^{(2)} = \frac{2(\alpha-1)^2V^2 + 2\gamma(p_{A,1}(1+\delta_{A,1}) + 4(\alpha+1)V)}{16\gamma} + \frac{\begin{array}{c}8(\alpha-1)Vp_{A,1}(\delta_{A,1}-1) \\ -p_{A,1}^2(9\delta_{A,1}^2 - 14\delta_{A,1} + 9) - 5\gamma^2\end{array}}{16\gamma}.$$

4.1.3 | Setting (3): No firm has adopted time-based pricing in stage 1

When neither firm has adopted time-based pricing in stage 1, both firms face the normal form of the adoption game that involves four pricing subgames displayed in Table 2 and analyzed below. (We use superscript a to denote the adoption of time-based pricing in stage 2, and n to denote no adoption.)

TABLE 2 Stage 2 adoption game if neither firms has adopted in stage 1.

Store A \ Store B	Adopt and set prices	Do not adopt or change prices
Adopt and set prices	$(\pi_{A,2}^{aa}, \pi_{B,2}^{aa})$	$(\pi_{A,2}^{an}, \pi_{B,2}^{an})$
Do not adopt or change prices	$(\pi_{A,2}^{na}, \pi_{B,2}^{na})$	$(\pi_{A,2}^{nn}, \pi_{B,2}^{nn})$

Pricing subgame 1 (*aa*)
When both stores adopt time-based pricing in stage 2, both stores need to set their time-based prices $(p_{i,2}, \delta_{i,2})$ by solving the following problems simultaneously:

$$\pi_{A,2}^{aa} = \max_{(p_{A,2},\delta_{A,2})} p_{A,2}\left(\delta_{A,2} \cdot q_{AP}^*(p_{A,2},\delta_{A,2};p_{B,2},\delta_{B,2}) + q_{AR}^*(p_{A,2},\delta_{A,2};p_{B,2},\delta_{B,2})\right),$$

$$\pi_{B,2}^{aa} = \max_{(p_{B,2},\delta_{B,2})} p_{B,2}\left(\delta_{B,2} \cdot q_{BP}^*(p_{A,2},\delta_{A,2};p_{B,2},\delta_{B,2}) + q_{BR}^*(p_{A,2},\delta_{A,2};p_{B,2},\delta_{B,2})\right),$$

where the demands q_{ij}^* are given in Proposition 1.

Pricing subgame 2 (*an or na*)
Without loss of generality, suppose store A is the only store that adopts time-based pricing in stage 2, whereas store B will maintain its status quo price p_B^0. Given p_B^0, store A solves the following problem in stage 2:

$$\pi_{A,2}^{an} = \max_{(p_{A,2},\delta_{A,2})} p_{A,2}\left(\delta_{A,2} \cdot q_{AP}^*(p_{A,2},\delta_{A,2};p_B^0,1) + q_{AR}^*(p_{A,2},\delta_{A,2};p_B^0,1)\right),$$

and store B's stage 2 profit that results from store A's pricing $(p_{A,2}, \delta_{A,2})$ in stage 2 is:

$$\pi_{B,2}^{an} = p_B^0\left(q_{BP}^*(p_{A,2},\delta_{A,2};p_B^0,1) + q_{BR}^*(p_{A,2},\delta_{A,2};p_B^0,1)\right). \tag{8}$$

Pricing subgame 3 (*nn*)
When neither stores adopt time-based pricing in stage 2 and maintain their status quo prices, both stores' profits are:

$$\pi_{A,2}^{nn} = p_A^0\left(q_{BP}^*(p_A^0,1;p_B^0,1) + q_{BR}^*(p_A^0,1;p_B^0,1)\right) \tag{9}$$

$$\pi_{B,2}^{nn} = p_B^0\left(q_{BP}^*(p_A^0,1;p_B^0,1) + q_{BR}^*(p_A^0,1;p_B^0,1)\right). \tag{10}$$

By determining each store's profit in each of the 4 pricing subgames as defined above, we can find the equilibrium adoption decision of the normal form game in Table 2 and get:

Proposition 4 (Setting (3): When neither firms adopted time-based pricing in stage 1). *Suppose no store has adopted time-based pricing in stage* 1*. Then:*

(*i*) *both store will adopt time-based pricing in stage* 2*; and*
(*ii*) *the equilibrium time-based prices and profits in stage* 2 *are:*

$$\text{(a)}\quad p^{(3)}_{A,2} = p^{(3)}_{B,2} = \frac{\gamma}{2} - \frac{(\alpha-1)V}{4},$$
$$\delta^{(3)}_{A,2}p^{(3)}_{A,2} = \delta^{(3)}_{B,2}p^{(3)}_{B,2} = \frac{\gamma}{2} + \frac{(\alpha-1)V}{4};$$
$$\text{(b)}\quad \pi^{(3)}_{A,2} = \pi^{(3)}_{B,2} = \frac{\gamma}{4} + \frac{(\alpha-1)^2V^2}{8\gamma}.$$

Observe from statement (ii-a) that the peak-period multiplier $\delta^{(3)}_{i,2} = \frac{\gamma/2+(\alpha-1)V/4}{\gamma/2-(\alpha-1)V/4} > 1$ and that the difference between the peak and regular prices is $\delta^{(3)}_{i,2}p^{(3)}_{i,2} - p^{(3)}_{i,2} = (\alpha-1)V/2 > 0$. By using the same approach as in setting (2), we get:

Corollary 3 (Stage 2 impact metrics for Setting (3)). *Suppose no store has adopted time-based pricing in stage* 1*. Then both stores will adopt time-based pricing in stage* 2 *with the following impact metrics:*

$$\text{(i)}\quad PQ^{(3)}_2 = \frac{1}{2} + \frac{(\alpha-1)V}{2\gamma};$$
$$\text{(ii)}\quad CW^{(3)}_2 = \frac{2(1+\alpha)V - 3\gamma}{4};$$
$$\text{(iii)}\quad SW^{(3)}_2 = \frac{2(1+\alpha)V - \gamma}{4} + \frac{(\alpha-1)^2V^2}{4\gamma}.$$

By examining Propositions 3–5, we can conclude that, if both stores have not adopted time-based pricing in stage 1, they will both adopt time-based pricing in stage 2.

Theorem 1 (Inevitability of adoption). *Regardless of the adoption strategy selected in stage* 1*, both firms will adopt time-based pricing in stage* 2 *if they have not done so in stage* 1.

Theorem 1 suggests that, provided that the implementation cost of time-based pricing is sufficiently low (which is likely to be the case as the cost of implementing electric shelf labels and smart shelves is decreasing over time), both stores will eventually adopt time-based pricing in practice. This result is consistent with the predictions made by various industry analysts (Morley, 2017; OliverWyman, 2019; Waddell, 2019).

4.2 | Stage 1 equilibrium strategies

Anticipating the time-based pricing adoption and the corresponding pricing strategies in stage 2 as presented in Subsection 4.1, we now proceed to analyze the competitive game engaged by both stores in stage 1. At the start of stage 1, both stores were charging the equilibrium status quo uniform prices p^0_A and p^0_B given in Proposition 2, and both stores need to decide whether to adopt time-based pricing and set the corresponding prices in stage 1 to maximize their discounted total profit $\pi_i = \pi_{i,1} + \beta\pi_{i,2}$ given in (1), where each store i's profit $\pi_{i,2}$ is based on the corresponding setting in stage 2 as presented in Subsection 4.1.

TABLE 3 Stage 1 adoption game.

Store A \ Store B	Adopt and set prices	Do not adopt or set prices
Adopt and set prices	(π^{aa}_A, π^{aa}_B)	(π^{an}_A, π^{an}_B)
Do not adopt or set prices	(π^{na}_A, π^{na}_B)	(π^{nn}_A, π^{nn}_B)

By noting that the setting in stage 1 resembles setting (3) in stage 2 as presented in Subsection 4.1.3 (where no store has adopted time-based pricing yet), we need to examine 4 pricing subgames as depicted in Table 3 that are akin to those presented in Table 2. However, the payoff for each firm is now based on the discounted total profit derived from both stages.

We now use the same approach as presented in Subsection 4.1.3 to first determine the payoff of each store in each pricing subgame. Then, by comparing these payoffs associated with different subgames, we can determine the equilibrium adoption strategy of each firm in stage 1.

Subgame 1 *aa: Both stores adopt time-based pricing in stage* 1

When both stores adopt time-based pricing in stage 1 (Subgame 1 *aa*), both stores face the same strategic decisions as in Setting (3) arising in stage 2. As such, we can use the same approach as shown in Subsection 4.1.3 to get:

Proposition 5 (Subgame 1 *aa*: Both stores adopt time-based pricing in stage 1). *Suppose both stores adopt time-based pricing in stage* 1*. Then the equilibrium prices and the discounted total profits satisfy:*

$$\text{(i)}\quad p^{aa}_{A,1} = p^{aa}_{B,1} = \frac{\gamma}{2} - \frac{(\alpha-1)V}{4},$$
$$\delta^{aa}_{A,1}p^{aa}_{A,1} = \delta^{aa}_{B,1}p^{aa}_{B,1} = \frac{\gamma}{2} + \frac{(\alpha-1)V}{4};$$
$$\text{(ii)}\quad \pi^{aa}_A = \pi^{aa}_{A,1} + \beta\pi^{(1)}_{A,2} = (1+\beta)\left(\frac{\gamma}{4} + \frac{(\alpha-1)^2V^2}{8\gamma}\right);$$
$$\pi^{aa}_B = \pi^{aa}_{B,1} + \beta\pi^{(1)}_{B,2} = (1+\beta)\left(\frac{\gamma}{4} + \frac{(\alpha-1)^2V^2}{8\gamma}\right).$$

Subgame 1 *aa* will lead to Setting (1) in stage 2 as discussed in Subsection 4.1.1, where the stores do not make further pricing decisions. For this reason, the equilibrium pricing stated in Proposition 5 is identical to that of Proposition 4. Also, besides the discount factor β, each store's profit in each stage is the same as Proposition 4. Hence, it can be interpreted in the same manner and we omit the details to avoid repetition.

Moreover, by using the pricing $(p^{aa}_{A,1}, \delta^{aa}_{A,1})$ and $(p^{aa}_{B,1}, \delta^{aa}_{B,1})$ as stated in Proposition 5, we can first apply Proposition 1 to retrieve the demands for both stores q_{ij} and then apply

Equations (2)–(4) to calculate those three impact metrics in stage 1, getting:

Corollary 4 (Impact metrics: Subgame 1 (aa)). *Suppose both stores adopt time-based pricing in stage 1. Then the equilibrium impact metrics in stage 1 and stage 2 are:*

$$\text{(i)}\ \ PQ_1^{aa} = PQ_2^{aa} = \frac{1}{2} + \frac{(\alpha-1)V}{2\gamma};$$

$$\text{(ii)}\ \ CW_1^{aa} = CW_2^{aa} = \frac{2(1+\alpha)V - 3\gamma}{4};$$

$$\text{(iii)}\ \ SW_1^{aa} = SW_2^{aa} = \frac{2(1+\alpha)V - \gamma}{4} + \frac{(\alpha-1)^2V^2}{4\gamma}.$$

Observe that the impact metrics for stage 1 for this subgame when both stores adopt time-based pricing are identical to those of Corollary 3, when both firms adopt for the first time in stage 2.

Subgame 2 an (or na): Only one stores adopt time-based pricing in stage 1

Without loss of generality, we consider store A as the only store that adopts time-based pricing in stage 1. Note that this setting will lead to setting (2) in stage 2. Recall from Proposition 3 that the stage 2 profits of each store were functions of $(p_{A,1}, \delta_{A,1})$. By taking this observation into consideration, we can determine the optimal prices for store A in stage 1, and the corresponding total discounted profits for both firms associated with Subgame 2 as follows.

Proposition 6 (Subgame 2 an (or na): Only store A adopts time-based pricing in stage 1). *Suppose store A is the only store that adopts time-based pricing in stage 1. Then the equilibrium prices and discounted total profits of both stores are:*

$$\text{(i)}\ \ p_{A,1}^{an} = \frac{(4+3\beta)\gamma}{4(2+\beta)} - \frac{(\alpha-1)V}{4},$$

$$\delta_{A,1}^{an} p_{A,1}^{an} = \frac{(4+3\beta)\gamma}{4(2+\beta)} + \frac{(\alpha-1)V}{4},$$

$$p_{B,1}^{an} = \frac{\gamma}{2}, \quad \delta_{B,1}^{an} = 1;$$

$$\text{(ii)}\ \ \pi_A^{an} = \pi_{A,1}^{an} + \beta\pi_{A,2}^{(2)} = \frac{(4+3\beta)^2\gamma}{32(2+\beta)} + \frac{(\alpha-1)^2(1+\beta)V^2}{8\gamma}$$

$$\pi_B^{an} = \pi_{B,1}^{an} + \beta\pi_{B,2}^{(2)} = \frac{(64+\beta(144+\beta(104+25\beta)))\gamma}{64(2+\beta)^2}$$

$$+ \frac{(\alpha-1)^2\beta V^2}{8\gamma}.$$

It is easy to check that $\delta_{A,1} > 1$, and that the gap between the peak hour and nonpeak hour prices is $(\alpha-1)V/2 > 0$ for store A. Also, by using the prices as stated in the above proposition, we can determine the following impact metrics associated with Subgame 2 in stage 1.

Corollary 5 (Impact metrics: Subgame 2 (an) or (na)). *Suppose only store A adopts time-based pricing in stage 1. Then the equilibrium impact metrics in stage 1 satisfy:*

$$\text{(i)}\ \ PQ_1^{an} = \frac{1}{2} + \frac{3(\alpha-1)V}{4\gamma};$$

$$\text{(ii)}\ \ CW_1^{an} = \frac{(\alpha+1)V}{2} - \frac{(12+7\beta)\gamma}{8(2+\beta)};$$

$$\text{(iii)}\ \ SW_1^{an} = \frac{(\alpha+1)V}{2} + \frac{(\alpha-1)^2V^2}{8\gamma} - \frac{(16+\beta(16+5\beta))\gamma}{16(2+\beta)^2}.$$

The equilibrium impact metrics in stage 2 satisfy:

$$\text{(i)}\ \ PQ_2^{an} = \frac{1}{2} + \frac{(\alpha-1)V}{2\gamma};$$

$$\text{(ii)}\ \ CW_2^{an} = \frac{(\alpha+1)V}{2} - \frac{3(8+5\beta)\gamma}{16(2+\beta)};$$

$$\text{(iii)}\ \ SW_2^{an} = \frac{(\alpha+1)V}{2} + \frac{(\alpha-1)^2V^2}{4\gamma} - \frac{(64+\beta(64+17\beta))\gamma}{64(2+\beta)^2}.$$

Subgame 3 nn: No store adopts time-based pricing in stage 1

When neither store adopts in stage 1, it will lead to Setting (3) in stage 2 as shown in Subsection 4.1.3. By incorporating the profit function of each store in stage 2 as shown in Proposition 4 and by noting that both stores will keep the status quo uniform pricing as shown in Proposition 2, we get:

Proposition 7 (Case 3: Neither store adopts time-based pricing in stage 1). *Suppose neither stores adopt time-based pricing in stage 1. Then the equilibrium outcomes satisfy:*

$$\text{(i)}\ \ p_{A,1}^{nn} = p_A^0 = p_{B,1}^{nn} = p_B^0 = \frac{\gamma}{2}, \quad \delta_{A,1}^{nn} = \delta_{B,1}^{nn} = 1;$$

$$\text{(ii)}\ \ \pi_A^{nn} = \frac{\gamma}{4} + \beta\pi_{A,2}^{(3)} = \frac{\gamma(1+\beta)}{4} + \frac{\beta(\alpha-1)^2V^2}{8\gamma},$$

$$\pi_B^{nn} = \frac{\gamma}{4} + \beta\pi_{B,2}^{(3)} = \frac{\gamma(1+\beta)}{4} + \frac{\beta(\alpha-1)^2V^2}{8\gamma}.$$

When neither stores adopt time-based pricing in stage 1, they are effectively delaying the adoption in stage 2. Because both stores keep the status quo prices $p_A^0 = p_B^0 = \gamma/2$, we can use Corollary 1 to show that the corresponding impact metrics are: $PQ_1^{nn} = PQ^0$, $CW_1^{nn} = CW^0$, and $SW_1^{nn} = SW^0$. Moreover, the impact metrics for stage 2 would correspond to the Setting (3) in stage 2, illustrated by Corollary 3.

4.3 | Equilibrium adoption strategy: When to adopt time-based pricing?

By using the subgame equilibrium profits associated with all four subgames as stated in in Propositions 5, 6, and 7, we can compare these payoffs (i.e., π_i^{aa}, π_i^{an} (and the corresponding π_i^{na} by symmetry), and π_i^{nn}) for $i \in \{A, B\}$ associated with those four subgames as depicted in Table 3. In doing so, we can determine the equilibrium adoption strategy for each firm in stage 1 in Theorem 2.

Theorem 2 (Adoption strategy in stage 1). *Suppose both stores have the option to adopt time-based pricing. Then:*

(*i*) *both firms would adopt in stage* 1 *if* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1 \triangleq \{(\beta, \frac{\gamma}{(\alpha-1)V}) : \frac{\gamma}{(\alpha-1)V} \leq \frac{2+\beta}{4+3\beta}\sqrt{\frac{8}{\beta}}\}$;

(*ii*) *only one firm will adopt in stage* 1 *if* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2 \triangleq \{(\beta, \frac{\gamma}{(\alpha-1)V}) : \frac{\gamma}{(\alpha-1)V} > \frac{2+\beta}{4+3\beta}\sqrt{\frac{8}{\beta}}\}$.

Theorem 2 enables us to trace and retrieve the adoption and pricing strategies in both stages via the results obtained for stage 1 in Subsection 4.2 (namely, Propositions 5 and 6) and the results obtained for stage 2 in Subsection 4.1. Specifically, when both stores adopt in stage 1 as stated in part (i), it will lead to Setting (1) in stage 2 as discussed in Subsection 4.1.1. Similarly, when only one store adopts in stage 1 as stated in statement (ii), it will lead to Setting (2) in stage 2 as presented in Subsection 4.1.2. By combining statement (ii) in stage 1 and Proposition 3 arising in stage 2, we can conclude that both stores will adopt time-based pricing eventually even though it is possible for stores to adopt in different stages.

As illustrated in Figure 4, Theorem 2 enables us to map the equilibrium adoption strategy in stage 1 based on the congestion-aversion level γ, the peak-period value booster α, and the discount factor β. It can be interpreted as follows. First, in zone R_1 where the profit is discounted heavily (i.e., when β is low) or when the congestion-aversion is low relative to the marginal value of shopping during peak hours (i.e., when $\frac{\gamma}{(\alpha-1)V}$ is low), both stores should adopt time-based pricing at once in stage 1. Intuitively, when the discount is steep (i.e., when β is low), both firms have the incentive to adopt time-based pricing in stage 1 to capture more profit sooner.

Second, in zone R_2 where profit is discounted mildly or when the congestion-aversion is high relative to the marginal value of shopping during peak hours, asymmetric equilibrium strategy will emerge to segment the market: only one store will adopt time-based pricing early in stage 1, the other store will adopt later in stage 2 by exploiting the *informational advantage* over the nondelaying store; that is, by observing the nondelaying firm's time-based prices in stage 1 before setting its own time-based pricing in stage 2. However, this delaying store faces a *disadvantage*: it allows the nondelaying store to earn more in stage 1 by introducing time-based pricing earlier with a higher peak-period price.

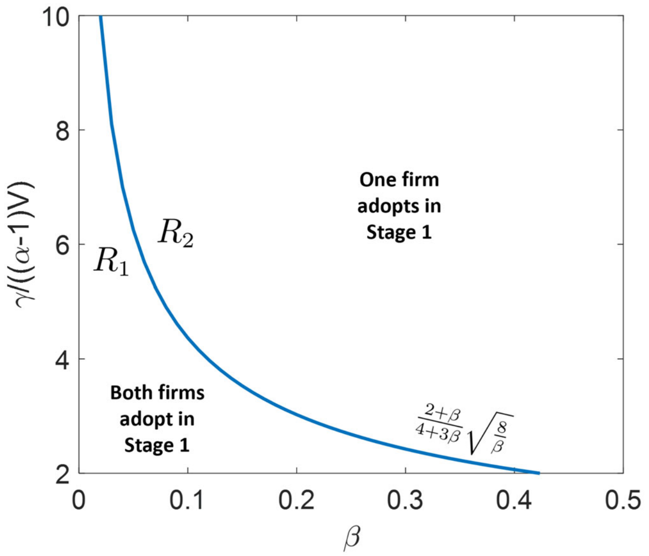

FIGURE 4 Equilibrium adoption decisions illustrated in the $(\beta, \frac{\gamma}{(\alpha-1)V})$-space. $\alpha = 1.1$ and $V = 1$, so $\frac{\gamma}{(\alpha-1)V} \in (2, 10)$. [Color figure can be viewed at wileyonlinelibrary.com]

To examine this trade-off between early adoption versus late adoption, the following corollary reveals a condition under which the delaying firm can earn a higher profit than its competitor who adopts time-based pricing earlier in stage 1. Specifically, the following corollary asserts that, when the congestion aversion γ is sufficiently high, the delaying firm would have better informational advantage on leveraging consumer choices, and the benefit derived from this benefit would outweigh the extra profit generated from early adoption in stage 1.

Corollary 6 (Profit comparison under asymmetric adoption strategy). *Suppose store A is the nondelaying firm who adopts in stage* 1 *and store B is the delaying firm. Then* $\pi_B > \pi_A$ *if and only if* $\frac{\gamma}{(\alpha-1)V} > \frac{2\sqrt{2}(2+\beta)}{\sqrt{\beta(16+20\beta+7\beta^2)}}$.

By combining Corollary 6 and the definition of zone R_2 in statement (ii) of Theorem 2, we can conclude that the zone R_2 (in which only one firm will adopt in stage 1 in Figure 4) can be further divided into two regions: an upper region in which the delaying firm will earn more than the nondelaying firm, and a lower region in which the delaying firm will earn less. When the discount is less steep (i.e., when β is high), the delaying store can afford to earn a lower profit in stage 1, and generate more profit by adopting time-based pricing in stage 2 especially when congestion aversion γ is high. On balance, the asymmetric timing of adoption can soften competition because the stores avoid competing for the same segments of customers in each stage and instead each focuses on capturing consumers in different stages.

In summary, Theorem 2 and Proposition 3 arising in stage 2 as presented in Subsection 4.1.2 imply that, in equilibrium, either both stores adopt time-based pricing immediately in stage 1, or only one store adopts in stage 1 and the other store postpones the adoption until stage 2. In other words, both stores postpone their adoption until stage 2 cannot sustain in equilibrium. Hence, both stores will adopt time-based pricing eventually even though they may adopt in different stages.

5 | IMPACT OF TIME-BASED PRICING ADOPTION

We now examine the implications of time-based pricing adoption in a competitive environment on pricing and those 3 impact metrics (peak demand, consumer welfare, and social welfare) over the course of both stages. To do so, we first apply Theorem 2 to identify the adoption strategy in stage 1. Then we use Propositions 5 and 6, Corollaries 4 and 5, and the corresponding stage 2 results presented in Subsection 4.1 to trace and retrieve the equilibrium outcomes in both stages based on the value of α, β, and γ. (We use the superscript * to denote the outcome in equilibrium.) Armed with these quantities, we can then compare them against the status quo equilibrium outcomes as presented in Proposition 2 and Corollary 1.

5.1 | Impact on pricing trajectories

We first compare the equilibrium prices associated with the adoption strategy depicted in Theorem 2 against the status quo uniform prices p_i^0, $i \in \{A, B\}$ as stated in Proposition 2.

Theorem 3 (Equilibrium time-based prices). *The equilibrium adoption strategies has the following effect on prices:*

(*i*) *If* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1$, *then both stores will adopt time-based pricing in stage* 1 (*and stage* 2) *so that* $p_{i,t}^* < p_i^0 < \delta_{i,t}^* p_{i,t}^*$, $i \in \{A, B\}$, $t \in \{1, 2\}$.

(*ii*) *If* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$, *then only one store* (*say, store A*) *will adopt time-based pricing in stage* 1 *and the other store* (*store B*) *will adopt in stage* 2, *so that:*

- (*a*) *if* $\frac{\gamma}{(\alpha-1)V} \le \frac{2+\beta}{\beta}$, *then* $p_{A,t}^* \le p_A^0 < \delta_{A,t}^* p_{A,t}^*$, $t \in \{1, 2\}$, *and* $p_{B,2}^* < p_{B,2}^0 < \delta_{B,2}^* p_{B,2}^*$;
- (*b*) *if* $\frac{\gamma}{(\alpha-1)V} \in (\frac{2+\beta}{\beta}, \frac{2(2+\beta)}{\beta})$, *then* $p_A^0 < p_{A,t}^* < \delta_{A,t}^* p_{A,t}^*$, $t \in \{1, 2\}$, *and* $p_{B,2}^* < p_B^0 < \delta_{B,2}^* p_{B,2}^*$;
- (*c*) *if* $\frac{\gamma}{(\alpha-1)V} \ge \frac{2(2+\beta)}{\beta}$, *then* $p_A^0 < p_{A,t}^* < \delta_{A,t}^* p_{A,t}^*$, $t \in \{1, 2\}$, *and* $p_B^0 \le p_{B,2}^* < \delta_{B,2}^* p_{B,2}^*$.

The evolution of prices in both stages as presented in Theorem 3 are illustrated in Figure 5. To begin, consider the case when $(\beta, \gamma/((\alpha-1)V)) \in R_1$ so that both stores will adopt in stage 1. From panel a of Figure 5 that illustrates Theorem 3(i), we observe that the normal-hours price $p_{i,t}^*$ is lower than the benchmark status quo uniform price p_i^0, but the peak-hour price $\delta_{i,t}^* p_{i,t}^*$ is higher so that $p_{i,t}^* < p_i^0 < \delta_{i,t}^* p_{i,t}^*$, $t \in \{1, 2\}$. Thus, when both retailers adopt time-based pricing in stage 1, their prices are lower than the status quo uniform price p_i^0 during regular hours, but higher during peak hours. This higher-peak-lower-normal pattern keeps the same average as the status quo because the competition level does not change under this symmetric equilibrium.

Next, when $(\beta, \gamma/((\alpha-1)V)) \in R_2$, only one firm (firm A) adopts in stage 1 and the other firm (firm B) postpones its adoption until stage 2. Theorem 3(ii) reveals three possible scenarios as depicted in panels b, c, and d of Figure 5 that depend on the value of $\gamma/((\alpha-1)V)$. First, when $\gamma/((\alpha-1)V)$ is low as illustrated in panel b of Figure 5 (Theorem 3(ii-a)), retailer B will retain the current uniform price $p_{B,1}^* = p_B^0$ and $\delta_{B,1}^* = 1$ in stage 1 and adopt time-base price in stage 2 when it charges a lower normal-hours price but a higher peak-hours price relative to the benchmark price p_B^0, that is, $p_{B,2}^* < p_B^0 < \delta_{B,2}^* p_{B,2}^*$. In contrast, retailer A will adopt time-based pricing in stage 1 and charge a normal-hours price that is lower than the benchmark p_A^0 and a higher peak-hours price relative to the benchmark p_A^0, that is, $p_{A,t}^* < p_A^0 < \delta_{A,t}^* p_{A,t}^*$, $t \in \{1, 2\}$.

Second, when $\gamma/((\alpha-1)V)$ is relatively higher, as illustrated in panels c and d of Figure 5 (Theorem 3(ii-b) and (ii-c)), we observe a counterintuitive finding: both the regular- and peak-period prices can be higher than the benchmark uniform status quo uniform price p_i^0. Panel c shows this for the case where one retailer (firm A) increases *both* regular hour and peak hour prices above the benchmark uniform price, that is, $p_A^0 \le p_{A,t}^* < \delta_{A,t}^* p_{A,t}^*$, $t \in \{1, 2\}$; and panel d shows that in addition to firm A, retailer B that adopt in stage 2 raises both regular hour and peak hour prices above its benchmark uniform price in stage 2, that is, $p_B^0 \le p_{B,2}^* < \delta_{B,2}^* p_{B,2}^*$.

These observations indicate that, under the asymmetric equilibrium, competing under time-based pricing (as oppose to under status quo uniform pricing) *softens* the intensity of price competition. This result stands in stark contrast to the extant literature on differentiated price competition that shows that, in general, the equilibrium (or average) prices should decline due to intensified competition (Chen, 2008; Corts, 1998; Shaffer & Zhang, 2002; Villas-Boas, 1999). However, we obtain an opposite result. The intuition for this counterintuitive result is driven by the following factors. First, the asymmetric equilibrium allows firms to adopt time-based pricing at different stages, enabling firms to avoid direct competition in stage 1 and soften competition. Then, a higher value of congestion-aversion level γ indicates price inelasticity (Proposition 1), which enables the retailers to increase their price without sacrificing too much demand to improve profit. When the level of congestion aversion γ is high, firms can further increase their prices and increase profits by avoiding direct competition with each other by engaging in asymmetric timing of adoption. Moreover, recall that the

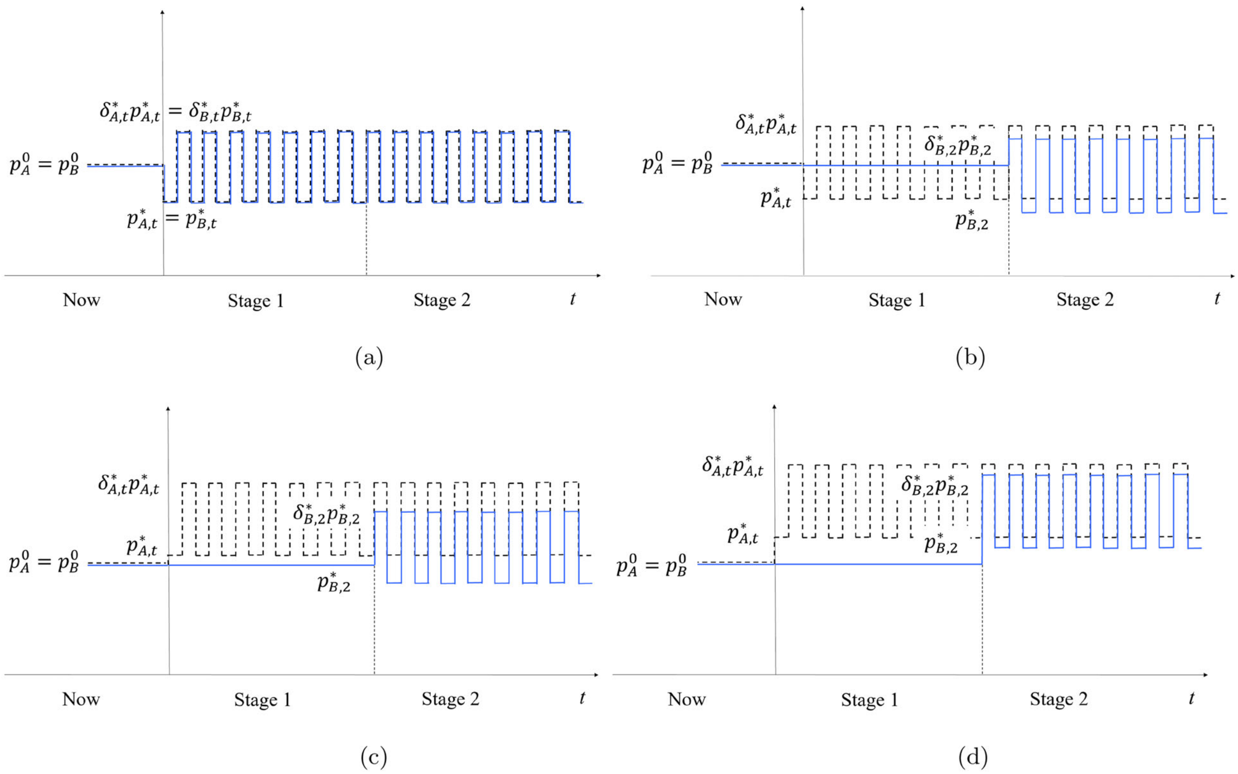

FIGURE 5 Four scenarios of price changes as consequences of retailers' transition to time-based pricing. (a) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1$. (b) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$, $\frac{\gamma}{(\alpha-1)V} \leq \frac{2+\beta}{\beta}$. (c) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$, $\frac{\gamma}{(\alpha-1)V} \in (\frac{2+\beta}{\beta}, \frac{2(2+\beta)}{\beta})$. (d) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$, $\frac{\gamma}{(\alpha-1)V} \geq \frac{2(2+\beta)}{\beta}$. [Color figure can be viewed at wileyonlinelibrary.com]

difference between the peak-hours price and the normal-hours price $\delta^*_i p^*_i - p^*_i = (\alpha - 1)V/2$ does not depend on γ, yet the starting benchmark price depends on γ, as $p^0_i = \gamma/2$. Thus, it can be seen that when the level of γ is high, the percentage increase in the prices is less. Our counterintuitive finding points to the importance of considering operational issues such as *negative externality* in the context of consumers shopping for essential items in supermarkets.

5.2 | Impact on demand smoothing, consumer welfare, and social welfare

We now examine the impact of time-based pricing adoption by both stores over time on demand smoothing, consumer welfare, and social welfare by using the status quo equilibrium outcomes as benchmarks. To do so, we compare the impact metrics presented in Subsections 4.1 and 4.2 against the benchmark impact metrics stated in Subsection 3.2 associated with the case of status quo uniform pricing.

5.2.1 | Demand smoothing

Comparing the expressions for the peak-hours demand PQ^*_t, $t \in \{1, 2\}$ (given in Subsection 4.1.1 and Corollary 2 for stage 2, and Corollaries 4 and 5 for stage 1) against the status quo value PQ^0 given in Corollary 1, we get:

Theorem 4 (Impact on demand smoothing). *Time-based pricing has the following effect on the total peak-hours demand:*

(i) if $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1$ *so that both firms adopt in stage* 1, *then* $PQ^*_2 = PQ^*_1 < PQ^0$;
(ii) if $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$ *so that one firm adopts in stage* 1, *then* $PQ^*_2 < PQ^*_1 < PQ^0$.

Theorem 4 is illustrated in Figure 6. We find that for any time-based transition strategies adopted by the retailers in equilibrium as stated in Theorem 2, the total peak-hours demand is strictly lower than that of the status quo value PQ^0. Thus, time-based pricing facilitates demand smoothing.

5.2.2 | Consumer welfare

Through the adoption of time-based pricing, Theorem 4 suggests that consumers will benefit from a safer and more pleasant shopping experience due to demand smoothing. However, Theorem 3 reveals that consumers may end up

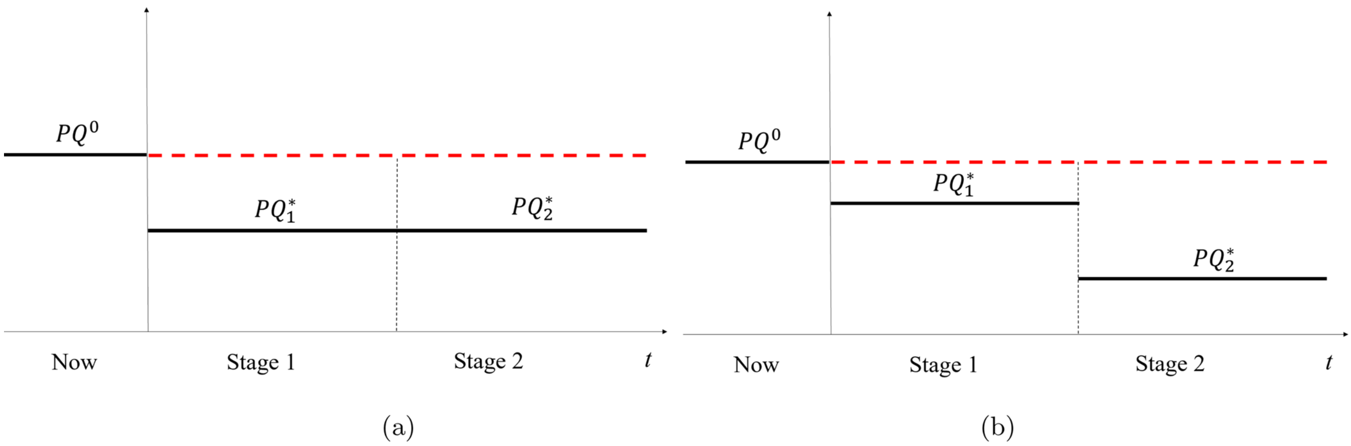

FIGURE 6 Effects of transition to time-based pricing on peak-hour congestion; dashed line represents the benchmark (current) level of peak-hour congestion. (a) Both firms adopt in stage 1. (b) One firm adopts in stage 1, the other in stage 2. [Color figure can be viewed at wileyonlinelibrary.com]

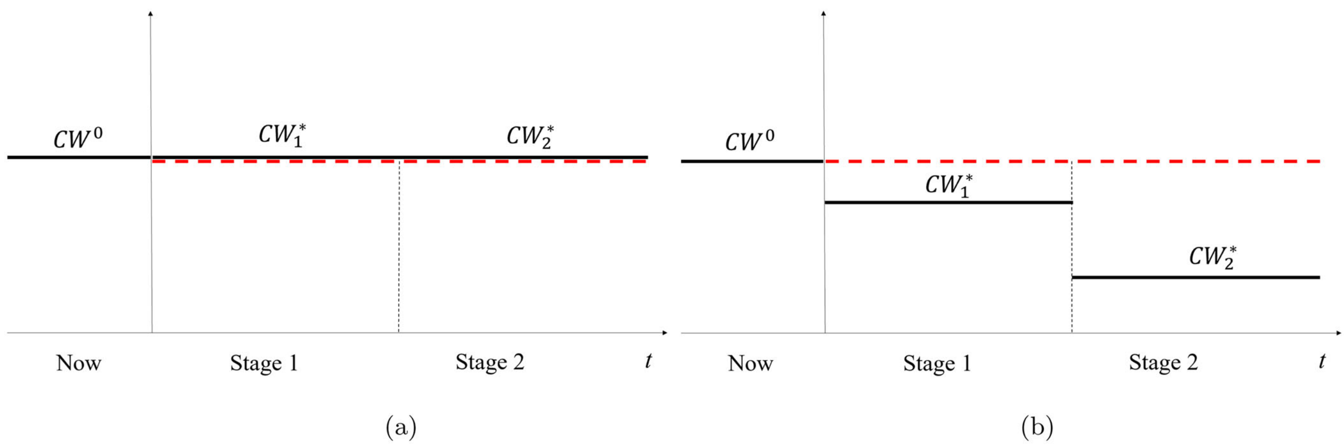

FIGURE 7 Effects of transition to time-based pricing on consumer welfare; dashed line represents the benchmark (current) level of consumer welfare. (a) Both firms adopt in stage 1. (b) One firm adopts in stage 1, the other in stage 2. [Color figure can be viewed at wileyonlinelibrary.com]

paying more as stores may charge a higher price (during both regular- and peak-periods) than the status quo uniform price p_i^0. As such, the net effect of time-based pricing on consumer welfare is unclear. By using the same approach as explained above, we obtain the following result:

Theorem 5 (Impact on consumer welfare). *Time-based pricing has the following effect on consumer welfare:*

(*i*) *If* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1$ *so that both firms adopt in stage* 1, *then* $CW_1^* = CW_2^* = CW^0$;
(*ii*) *If* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$ *so that one firm adopts in stage* 1, *then* $CW_2^* < CW_1^* < CW^0$.

Theorem 5 is illustrated in Figure 7. First, when $(\beta, \gamma/(\alpha-1)V) \in R_1$ so that both retailers adopt in stage 1 in equilibrium, time-based pricing has no overall effect on consumer welfare; that is, $CW_1^* = CW_2^* = CW^0$ (panel a of Figure 7). Under symmetric equilibrium, the competition level does not change compared with status quo, and neither does the consumer welfare.

Second, when $(\beta, \gamma/(\alpha-1)V) \in R_2$, one retailer adopts in stage 1 while the other adopts in stage 2. In this case, we find that time-based pricing has a strictly negative effect on consumer welfare in both stages relative to the status quo. Because only one firm adopts in stage 2 and yet both firms adopt time-based pricing in stage 2, consumer welfare decreases over time (as shown in panel b of Figure 7). Under asymmetric equilibrium, the competition level decreases and consumer welfare drops. In particular, consumers suffer more in stage 2 when both firms adopt time-based pricing.

5.2.3 | Social welfare

We use the same approach to examine the impact of time-based pricing on social welfare, which combines consumer welfare and the retailers' profits.

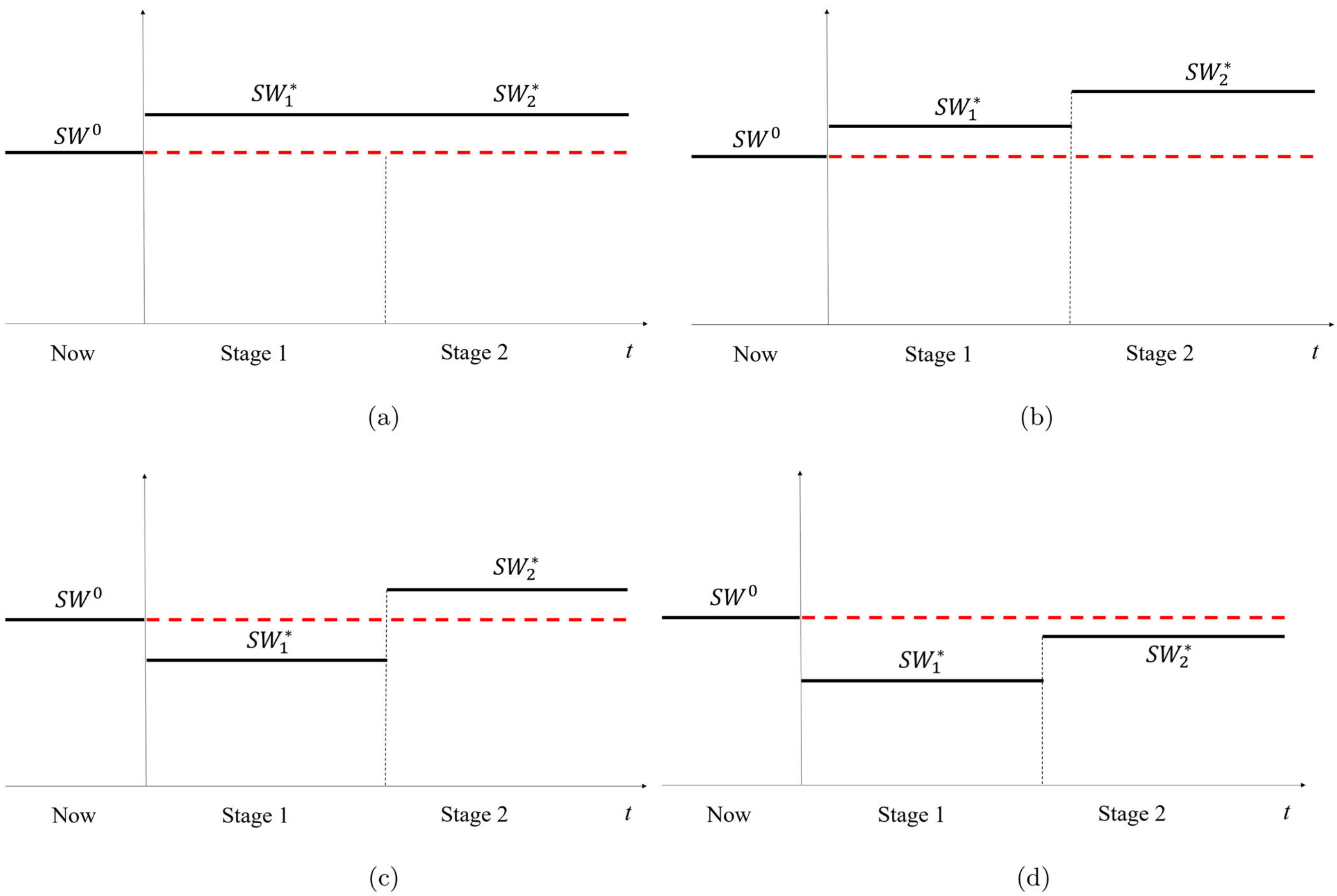

FIGURE 8 Effects of transition to time-based pricing on social welfare; dashed line represents the benchmark (current) level of social welfare. (a) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1$. (b) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$, $\frac{\gamma}{(\alpha-1)V} \leq \frac{\sqrt{2}(2+\beta)}{\beta}$. (c) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$, $\frac{\gamma}{(\alpha-1)V} \in (\frac{\sqrt{2}(2+\beta)}{\beta}, \frac{4(2+\beta)}{\beta})$. (d) $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$, $\frac{\gamma}{(\alpha-1)V} \geq \frac{4(2+\beta)}{\beta}$. [Color figure can be viewed at wileyonlinelibrary.com]

Theorem 6 (Effect of time-based pricing on social welfare). *Time-based pricing has the following effect on social welfare:*

(i) *If* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1$ *so that both retailers adopt in stage* 1, *then* $SW_1^* = SW_2^* > SW^0$;
(ii) *If* $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2$ *so that one retailer adopts in stage* 1,
  (a) *if* $\frac{\gamma}{(\alpha-1)V} \leq \frac{\sqrt{2}(2+\beta)}{\beta}$, *then* $SW^0 \leq SW_1^* < SW_2^*$;
  (b) *if* $\frac{\gamma}{(\alpha-1)V} \in (\frac{\sqrt{2}(2+\beta)}{\beta}, \frac{4(2+\beta)}{\beta})$, *then* $SW_1^* < SW^0 < SW_2^*$,
  (c) *if* $\frac{\gamma}{(\alpha-1)V} \geq \frac{4(2+\beta)}{\beta}$, *then* $SW_1^* < SW_2^* \leq SW^0$.

Figure 8 illustrates the results as stated in Theorem 6 and it can be interpreted as follows. When $(\beta, \gamma/((\alpha-1)V)) \in R_1$, so that both retailers transition immediately in stage 1, as illustrated in panel a (Theorem 6(i)), social welfare under time-base pricing is strictly higher than the status quo benchmark SW^0. This is because time-based pricing can smooth demand by enticing more consumers to shop during regular hours so that the total congestion is reduced. Combining this observation with statement (i) of Theorem 6 that the consumer welfare remains unchanged when $(\beta, \gamma/(\alpha-1)V) \in R_1$, we can conclude that the increase in social welfare is driven by the retailers' higher profits under time-based pricing.

Next, consider the case when $(\beta, \gamma/((\alpha-1)V)) \in R_2$ so that one retailer adopts in stage 1 while the other delays its adoption to stage 2. Under this asymmetric equilibrium, firms can avoid using time-based pricing to compete in stage 1. Consequently, the social welfare in stage 1 may drop due to softened competition (as seen in statements (ii)(b) and (ii)(c) especially when the congestion aversion $\frac{\gamma}{(\alpha-1)V} > \frac{\sqrt{2}(2+\beta)}{\beta}$). In this case, the social welfare increases from stage 1 to stage 2 as illustrated in panels b, c, and d. However, relative to the benchmark, the social welfare in either stage may increase or decrease, depending on the consumers' level of congestion aversion ($\gamma/((\alpha-1)V)$). Recall from Theorem 5(ii) that the consumer welfare is decreasing over time when more retailers adopt time-based pricing. Thus, an increase in social welfare occurs because the increase in the retailers' profit outweighs the decrease in consumer welfare. Interestingly, we see that it is possible for the social welfare to remain below the level of the status quo when γ is high, as illustrated in panel d (Theorem 6(ii-c)). This indicates that the decrease in consumer welfare is significantly worse than the increase in the profit of the retailers, and points to the possibility that time-based pricing could make the society worse off overall.

6 | EXTENSIONS

We now extend our base model presented in Section 2 in two ways. In Subsection 6.1, we analyze the case of *asymmetric competition* between two stores. Then we extend our analysis to $n = 3$ stages in Subsection 6.2.

6.1 | Extension 1: Impact of asymmetric competition

Instead of assuming symmetric competition that has $V_A = V_B = V$, we extend our analysis to the case when $V_A \neq V_B$. (Without loss of generality, we assume $V_A > V_B$). We can use the same approach as presented in Subsection 3.1 to determine the equilibrium demand q^*_{ij} for store $i \in \{A, B\}$ in period $j \in \{R, P\}$ that resembles Proposition 1 as follows:

Proposition 8 (Equilibrium intra-day demand in each stage). *For any given price structure $(p_A, \delta_A; p_B, \delta_B)$, if $V_A \neq V_B$, the equilibrium demand q^*_{ij} for retailer $i \in \{A, B\}$ in period $j \in \{R, P\}$ can be expressed as:*

$$q^*_{AP}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} + \frac{(3\alpha - 1)V_A - (\alpha + 1)V_B}{4\gamma} + \frac{(1 - 3\delta_A)p_A + (1 + \delta_B)p_B}{4\gamma},$$

$$q^*_{BP}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} + \frac{(3\alpha - 1)V_B - (\alpha + 1)V_A}{4\gamma} + \frac{(1 + \delta_A)p_A + (1 - 3\delta_B)p_B}{4\gamma},$$

$$q^*_{AR}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} - \frac{(3 - \alpha)V_A - (\alpha + 1)V_B}{4\gamma} + \frac{(\delta_A - 3)p_A + (1 + \delta_B)p_B}{4\gamma},$$

$$q^*_{BR}(p_A, \delta_A; p_B, \delta_B) = \frac{1}{4} - \frac{(3 - \alpha)V_B - (\alpha + 1)V_A}{4\gamma} + \frac{(1 + \delta_A)p_A + (\delta_B - 3)p_B}{4\gamma},$$

provided that the given prices $(p_A, \delta_A; p_B, \delta_B)$ satisfy:

$$q^*_{AP}, q^*_{BP}, q^*_{AR}, q^*_{BR} > 0 \quad \text{and} \quad (1 + \alpha)(V_A + V_B) - p_A - p_A\delta_A - p_B - p_B\delta_B - \gamma > 0. \tag{11}$$

As expected, we observe that as V_A increases, q^*_{Aj} increases while q^*_{Bj} decreases.

Using the expression for q^*_{ij}, we analyze our two stage game by using the same approach presented in §4. However, due to the asymmetric competition, the case of having only one store adopt in stage t requires us to analyze two settings that depend on the identity of the firm that adopts time-based pricing in period t. For brevity, we shall defer the analysis to the Appendix in the Supporting Information. The following theorem illustrates the equilibrium adoption strategy in the asymmetric competition setting.

Theorem 7 (Adoption strategy under asymmetric competition when $V_A > V_B$). *Under asymmetric competition that has $V_A > V_B$, the adoption strategy of each firm over both stages can be described as follows:*

(*i*) *In stage 2, firm $i \in \{A, B\}$ will adopt time-based pricing if it has not done so in stage 1.*
(*ii*) *In stage 1, there exists two thresholds $T_1(\beta|V_A, V_B)$ and $T_2(\beta|V_A, V_B)$ such that*
  (*a*) *both firms would adopt in stage 1 if $(\beta, \gamma) \in R_1 \triangleq \{(\beta, \gamma) : \gamma \leq T_1(\beta|V_A, V_B)\}$,*
  (*b*) *only firm A would adopt in stage 1 if $(\beta, \gamma) \in R_2 \triangleq \{(\beta, \gamma) : T_1(\beta|V_A, V_B) \leq \gamma < T_2(\beta|V_A, V_B)\}$,*
  (*c*) *either firm A or B (but not both) would adopt in stage 1 if $(\beta, \gamma) \in R_3 \triangleq \{(\beta, \gamma) : \gamma > T_2(\beta|V_A, V_B)\}$.*

Due to the complexity of the expressions, we are unable to express $T_1(\beta|V_A, V_B)$ and $T_2(\beta|V_A, V_B)$ in closed form. Nevertheless, we are able to illustrate the three mutually exclusive regions numerically as shown in Figure 9.

Analogous to the result presented in Figure 4 that illustrates Theorem 2 for the symmetric competition case, Figure 9 depicts a similar adoption strategy for the stores in stage 1. Specifically, when the congestion-aversion is low and when the future profit is discounted heavily (i.e., when $(\beta, \gamma) \in R_1$), both stores would adopt time-based pricing all at once in stage 1.

However, due to asymmetric competition, the zone that has only one store to adopt in stage 1 is further divided into two regions: in the "lower region" (i.e., R_2) as depicted in Figure 9, the dominant store A will be the only store who would adopt in stage 1; however, either the dominant store A or the subordinate store B would adopt in stage 1 in the "upper region" (i.e., R_3). This result is driven by the fact that the dominant store A that offers a higher value V_A can afford to adopt in stage 1 by charging a higher peak-period price to earn more. However, it is prudent for the subordinate store B to postpone its adoption until stage 2 so that it can set its peak/normal period prices after observing store A's prices.

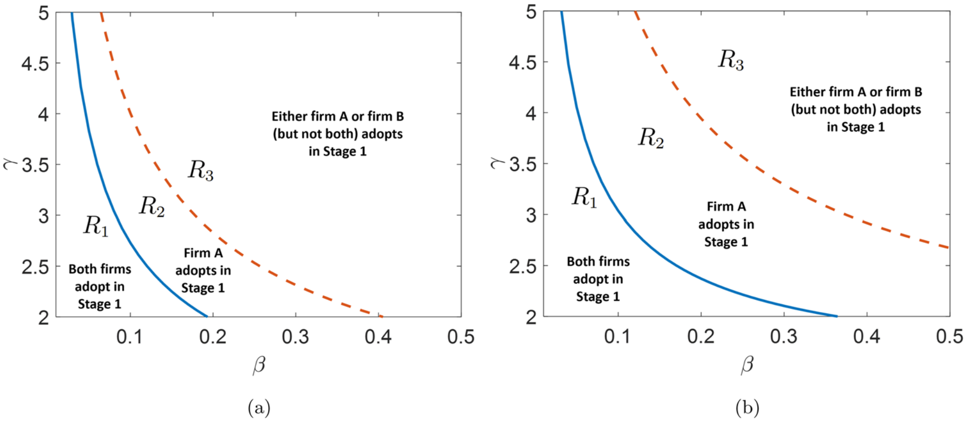

FIGURE 9 Impact of asymmetric competition on equilibrium stage 1 adoption decisions. (a) $V_A = 3, V_B = 2, \alpha = 1.3$. (b) $V_A = 4, V_B = 2, \alpha = 1.3$. [Color figure can be viewed at wileyonlinelibrary.com]

6.2 | Extension 2: Impact of number of stages

We now extend our symmetric competition 2-stage model to three stages so that the total discounted profit over 3 stages generalizes (1) as:[7]

$$\pi_i = \pi_{i,1} + \beta\pi_{i,2} + \beta^2\pi_{i,3}. \tag{12}$$

To analyze this three stage game, we extend the backward induction analysis of Section 4 by adding one extra stage. Essentially, stage 3 of our extension is analogous to stage 2 of our base model as presented in Subsection 4.1. Hence, we know both stores would adopt by stage 3 if they have not done so in earlier stages.

Stage 2 of our extension is akin to stage 1 of our base model. However, unlike stage 1 in the base model, we must analyze the pricing subgames for the same three settings presented in Subsection 4.1: Namely, no firm, only one firm, or both firms have have adopted time-based pricing in stage 1. As the equilibrium profit $\pi_{i,3}$ of stage 3 is known, we can compute $V_{i,2} \triangleq \pi_{i,2} + \beta\pi_{i,3},\ \ i \in \{A, B\}$ in stage 2 for each of the subgames.

Stage 1 of our extension is similar to stage 2 of our extension. However, unlike in stage 2, the equilibrium future profit $V_{i,2}$ is not necessarily known in stage 1. For analyzing the pricing subgame involving asymmetric timing of adoption (store A adopts in stage 2 while store B adopts in stage 3), store i does not know in stage 1 whether it will be the early adopter that adopts in stage 2 or the late adopter that adopts in stage 3. Given we consider symmetric firms, we take the average profit between the two adoption timing decisions and compute $\pi = \pi_1 + \beta\mathbb{E}(V_{i,2})$, where the profit-to-go expression $V_{i,2}$ is stated above.

After the analysis of the four subgames in stage 1, we analyze stage 1 normal form game that is analogous to that presented in Table 3, to determine the adoption strategy of each firm in equilibrium as follows:

Theorem 8 (Adoption strategy in stage 1). *Suppose both stores have the option to adopt time-based pricing at the beginning of each of the three stages. Then:*

(i) both firms would adopt in stage 1 if $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_1 \triangleq \{(\beta, \frac{\gamma}{(\alpha-1)V}) : \frac{\gamma}{(\alpha-1)V} \leq \frac{\sqrt{8}(2+\beta+\beta^2)}{\sqrt{\beta(1+\beta)}(4+3\beta+3\beta^2)}\}$;

(ii) only one firm would adopt in stage 1 if $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_2 \triangleq \{(\beta, \frac{\gamma}{(\alpha-1)V}) : \frac{\gamma}{(\alpha-1)V} \in (\frac{\sqrt{8}(2+\beta+\beta^2)}{\sqrt{\beta(1+\beta)}(4+3\beta+3\beta^2)}, \frac{4(2+\beta)^{3/2}\sqrt{2+\beta+\beta^2}}{\beta\sqrt{32+2\beta(2+\beta)(12+\beta+7\beta^2)}})\}$;

(iii) neither firms would adopt in stage 1 if $(\beta, \frac{\gamma}{(\alpha-1)V}) \in R_3 \triangleq \{(\beta, \frac{\gamma}{(\alpha-1)V}) : \frac{\gamma}{(\alpha-1)V} > \frac{4(2+\beta)^{3/2}\sqrt{2+\beta+\beta^2}}{\beta\sqrt{32+2\beta(2+\beta)(12+\beta+7\beta^2)}}\}$.

The above theorem resembles Theorem 2 in that the adoption strategy in stage 1 hinges on the value of $(\beta, \frac{\gamma}{(\alpha-1)V})$. However, unlike the 2-stage case in our base model, our extension to three stages provide both stores an extra option to delay their timing of the adoption until stage 2 or stage 3. This observation explains why, relative to Theorem 2, we have an extra statement (iii) in our 3-stage extension.

To examine the impact of one extra stage in our extension, let us present the following corollary that compares the threshold $\frac{\sqrt{8}(2+\beta+\beta^2)}{\sqrt{\beta(1+\beta)}(4+3\beta+3\beta^2)}$ given in statement (i) of Theorem 8 against the threshold $\frac{2+\beta}{4+3\beta}\sqrt{\frac{8}{\beta}}$ given in Theorem 2 for the 2-stage base model.

Corollary 7 (Impact of additional stage). $\frac{\sqrt{8}(2+\beta+\beta^2)}{\sqrt{\beta(1+\beta)}(4+3\beta+3\beta^2)} < \frac{2+\beta}{4+3\beta}\sqrt{\frac{8}{\beta}}$.

Figure 10 illustrates Theorem 8. By applying Corollary 7, we can conclude that zone R_1 defined in statement (i) of Theorem 8 is smaller than that of Theorem 2. Hence, we can conclude that, with an additional stage, it becomes less

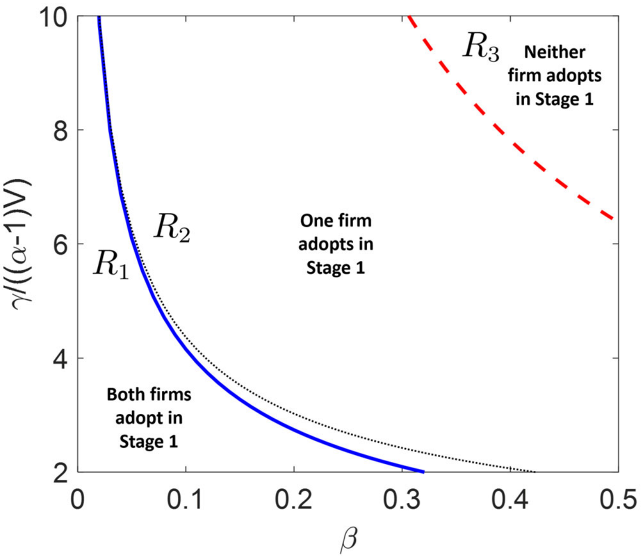

FIGURE 10 Equilibrium adoption decisions in stage 1 in the 3-stage (and 2-stage) model. The solid and dash curves indicate the stage 1 decision in 3-stage model; the dotted curve indicate the stage 1 decision in 2-stage model. Parameters: $\alpha = 1.1$ and $V = 1$, so $\frac{\gamma}{(\alpha-1)V} \in (2, 10)$. [Color figure can be viewed at wileyonlinelibrary.com]

likely for both firms to adopt in stage 1 (because the region R_1 is now smaller relative to the 2-stage base model). Thus, with more stages, the number of firms that adopt in stage 1 decreases, as firms benefit from postponing their adoption to exploit the information advantage.

The equilibrium timing of adoption of Theorem 8 imply that the stores would adopt time-based pricing in one of the following three manner: (a) Either both firms adopt in stage 1, (b) one firm adopts in stage 1 while the other adopts in stage 2, or (c) one firm adopts in stage 2 while the other adopts in stage 3. Observe that the equilibrium adoption timing between the competing stores differs only by one stage. This suggests that while stores may not adopt time-based pricing simultaneously, their adoption timing would not be too far apart in practice.

7 | CONCLUSION

Motivated by the adoption of electronic shelf labels and the rising concerns over congestion, we have explored whether and when competing retailers (e.g., supermarkets) have incentives to adopt time-based pricing. In a duopoly setting, we have formally examined whether and when retailers adopt time-based pricing in the presence of negative externality.

Our paper makes the following contributions. First, we find that time-based pricing will be adopted by retailers eventually as the cost of adoption continues to decline, supporting the predictions made by industry experts (Morley, 2017; Oliver-Wyman, 2019; Waddell, 2019). However, despite symmetry, stores may adopt time-based pricing in different stages, depending on the level of consumers' congestion aversion γ and the level of the retailers' myopia β. When the retailers place greater emphasis on short-term profit, both retailers will adopt time-based pricing immediately in stage 1. Interestingly, when consumers are highly averse to congestion, there will be less number of retailers adopting time-based pricing immediately. This is because of competitive dynamics making it beneficial for the retailers to postpone their adoption that would allow them to observe early adopters' pricing decisions.

Second, we find that when consumer congestion aversion level is high, differentiated price competition (via time-based pricing) can "soften" competition so that both stores can afford to charge higher prices in equilibrium. This result stands in stark contrast to the existing literature (Chen, 2008; Corts, 1998; Shaffer & Zhang, 2002). Finally, we observe that time-based pricing successfully can enable stores to achieve demand smoothing, making shopping safer and more pleasant. However, due to the rise in prices, consumer welfare would not increase. Examining the social welfare, we find that the increase in the retailers' profits may not be able to offset the decrease in consumer welfare, and could reduce the social welfare below the status quo.

Our paper represents an initial attempt to study the viability of time-based pricing in a retail setting. More research is needed to improve our understanding of how realistic such time-based pricing programs are, as well as how they will affect consumer welfare. Our study suggests several interesting directions for future research that could aid this effort.

First, our model can also be used to examine several variants of time-based pricing. For example, if we consider p_i as the peak-hours price and $\delta_i < 1$ as the normal-hours discount, the transformed model setup can be used to examine "happy hour" price competition. Second, although time-based pricing has many advantages—including boosting revenues and reducing congestion—it can also alienate consumers who might object to a spike in prices when they most need the service or product. Hence, it would be instructive to assess the risk of consumer backlash against time-based pricing. Third, there are multiple reasons why retailers adopt electronic shelf labels, some of which are not directly related to enhancing revenue. For example, electronic shelf labels can enable retailers to collect more accurate consumer data in an effort to "digitize" physical retail while generating synergies with consumers' so-called showrooming behavior. It would be interesting to empirically examine such interactions.

ACKNOWLEDGMENTS

We would like to express our gratitude to the Department Editor Prof. Tony Cui, the anonymous senior editor, and the reviewers for their constructive feedback and valuable suggestions. Their guidance has been instrumental in helping us improve the quality of this manuscript.

ORCID

Christopher S. Tang https://orcid.org/0000-0001-9597-7620
Onesun Steve Yoo https://orcid.org/0000-0002-5270-7011
Dongyuan Zhan https://orcid.org/0000-0001-8242-1332

ENDNOTES

[1] Time-based pricing is different from other dynamic pricing mechanisms employed by hotels and airlines under which prices change dynamically based on the real-time supply and market demand.

[2] Imagine, for example, that you walk into a supermarket and notice that an item is priced at \$2, but by the time you check out, the price has changed to \$4. How would you feel?

[3] This form of irreversibility is consistent with the optimal stopping time framework (Dixit & Pindyck, 1994).

[4] The case of asymmetric stores will be examined in Subsection 6.1.

[5] Our setting can also be generalized to "interday," where the peak times can correspond to weekends and the regular hours to weekdays, or a combination of intraday and interday.

[6] The assumption that price changes only occur when time-based pricing is adopted reflects the retailers' commitment to keeping prices as stable as possible to respect consumers' preferences for stable prices and avoid public scrutiny (Dholakia, 2015, 2016), and is consistent with the assumptions of the optimal stopping time framework (Dixit & Pindyck, 1994).

[7] One can use the same approach to analyze the case when the number of stages $n > 3$.

REFERENCES

Actusnews Wire. (2013, March 19). SES signs the largest roll out of electronic shelf labels in South East Asia. *Actusnews Wire*. https://www.actusnews.com/en/ses-imagotag/pr/2013/03/19/ses-signs-the-largest-roll-out-of-electronic-shelf-labels-in-south-east-asia

Adams, T. (2017, June 4). Surge pricing comes to the supermarket. *The Guardian*. 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.

Angrist, J. D., Caldwell, S., & Hall, J. V. (2021). Uber versus taxi: A driver's eye view. *American Economic Journal: Applied Economics*, *13*(3), 272–308.

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

Bai, J., So, K. C., Tang, C. S., 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.

Beckwith, B., & Webb, C. (2022). How to build the most profitable restaurant pricing strategy. https://blog.saucepricing.com/How-to-Build-the-Most-Profitable-Restaurant-Pricing-Strategy

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

Burkhardt, J., Gillingham, K., & Kopalle, P. (2018). Can't Take the Heat? Randomized Field Experiments in Household Electricity Consumption. Extended Abstract published in Advances in Consumer Research, Duluth, MN: Association for Consumer Research.

Cachon, G. P., Daniels, K. M., & Lobel, R. (2017). The role of surge pricing on a service platform with self-scheduling capacity. *Manufacturing & Service Operations Management*, *19*(3), 368–384.

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

Chen, Y. (2008). Dynamic price discrimination with asymmetric firms. *Journal of Industrial Economics*, *LVI*(4), 729–750.

Chen, M. K., & 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.

Corts, K. S. (1998). Third-degree price discrimination in oligopoly: All-out competition and strategic commitment. *Rand Journal of Economics*, *29*(2), 306–323.

Dholakia, U. M. (2015). The risk of changing your prices too often. https://hbr.org/2015/07/the-risks-of-changing-your-prices-too-often

Dholakia, U. M. (2016). Why shoppers hate frequent price changes. https://www.psychologytoday.com/us/blog/the-science-behind-behavior/201612/why-shoppers-hate-frequent-price-changes

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton University Press.

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

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. *Management Science*, *65*(5), 1995–2014.

Harris, S. (2021, March 2). Tesco, Asda, Sainsbury's and Aldi: Quietest time to grocery shop—How to avoid queues. Express. https://www.express.co.uk/life-style/life/1403957/tesco-asda-sainsburys-aldi-supermarket-shopping-rules-quietest-hours-queue-latest

Hotelling, H. (1929). Stability in competition. *The Economic Journal*, *39*(153), 41–57.

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.

ITV news. (2021). Supermarket worker punched by customer who didn't want to queues—The rising abuse of staff during Covid. https://www.itv.com/news/westcountry/2021-04-06/supermarket-worker-punched-by-customer-who-didnt-want-to-queue-the-rising-abuse-of-staff-during-covid

Ke, J., Yang, H., Li, X., Wang, H., & Ye, J. (2020). Pricing and equilibrium in on-demand ride-pooling markets. *Transportation Research Part B: Methodological*, *139*, 411–431.

Kok, G., Fisher, M., & Vaidyanathan, R. (2008). Assortment planning: Review of literature and industry practice, *Retail supply chain management* (pp. 99–153), edited by Narendra Agrawal, Stephen A. Smith. Springer Publishers.

Lawrie, E. (2017, June 30). Why your bananas could soon cost more in the afternoon. BBC News. 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.

MacMillan, D. (2015, June 16). The \$50 billion question: Can Uber deliver? *Wall Street Journal*, A1–A12.

McDonald, R., & Siegel, D. (1986). The value of waiting to invest. *Quarterly Journal Economics*, *101*(4), 707–727.

McKinnon, T. (2021). The future of retail: 9 ways Alibaba is redefining retail stores. https://www.indigo9digital.com/blog/futureofretailalibaba

McKinsey. (2020). How European shoppers will buy groceries in the next normal. 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, December 14). 3 lasting changes to grocery shopping after Covid-19. Forbes. https://www.forbes.com/sites/blakemorgan/2020/12/14/3-lasting-changes-to-grocery-shopping-after-covid-19/?sh=76327ccd54e7

Morley, K. (2017, June 24). Exclusive: End of fixed prices within five years as supermarkets adopt electronic price tags. *The Telegraph*. 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.

Pindyck, R. S. (1988). Irreversible investment, capacity choice, and the value of the firm. *American Economic Review*, *78*(5), 969–985.

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

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

Shaffer, G., & Zhang, Z. J. (2002). Competitive one-to-one promotions. *Management Science*, *48*(9), 1143–1160.

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

Shveda, K. (2020). How coronavirus is changing grocery shopping. https://www.bbc.com/future/bespoke/follow-the-food/how-covid-19-is-changing-food-shopping.html

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

Spence, M. (1977). Entry, capacity, investment and oligopolistic pricing. *Bell Journal of Economics*, *8*, 534.

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

Tang, C. S. (2018, February 20). The secrets of making surge pricing work without turning off customers. *Wall Street Journal*, R4.

Tang, C. S., Yoo, O. S., & Huang, Y. (2022). Peak-hour pricing under negative externality: Impact of customer flexibility and competitive asymmetry. *Service Science*, Published Online: 21 Oct 2022.

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

Villas-Boas, J. M. (1999). Dynamic competition with customer recognition. *The Rand Journal of Economics*, *30*(4), 604–631.

Waddell, K. (2019, April 30). The death of prices. Axios. https://www.axios.com/future-of-retail-amazon-surge-pricing-brick-and-mortar-b6a5f9fe-130f-4601-b96f-a3dc7a69b54e.html

Walsh, H. (2021, February 5). The cost of convenience: How much extra will you pay at Sainsbury's Local and Tesco Express? *Which News*. https://www.which.co.uk/news/article/the-cost-of-convenience-how-much-extra-will-you-pay-at-sainsburys-local-and-tesco-express-arOQq7k73hf4

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

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

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Tang, C. S., Yoo, O. S., & Zhan, D. (2023). When should grocery stores adopt time-based pricing? Impact of competition and negative congestion externality. *Production and Operations Management*, 1–20. https://doi.org/10.1111/poms.14010